Strength and Stability Assessment of the Alpha Magnetic Spectrometer-02 (AMS-02) Unique Support Structure (USS-02), Vacuum Case, Payload Attach System (PAS), and STS and ISS Integration Hardware

Engineering & Science Contract Group (ESCG)

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Strength and Stability Assessment of the Alpha Magnetic Spectrometer-02 (AMS-02) Unique Support Structure (USS-02), Vacuum Case, Payload Attach System (PAS), and STS and ISS Integration Hardware

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0.1 Abstract

This report contains the structural assessment of the AMS-02 components that includes the Unique Support Structure, the Vacuum Case, the Payload Attach System, and the Payload Integration Hardware. The analysis was performed per the requirements specified in the Alpha Magnetic Spectrometer - 02 (AMS-02) Structural Verification Plan for the Space Transportation System and the International Space Station (ISS) JSC-28792. This report contains descriptions of the math model, load factors for design and analysis of structural components, design factors of safety, thermal considerations, and verification approach. A detailed stress analysis was performed for components in the USS, Vacuum Case, PAS, and the payload integration hardware. Portions of this stress analysis were performed by Lockheed Martin under the SEAT contract, but as of 02/01/05, the remaining analysis was performed by Jacobs under the Engineering & Science Contract Group (ESCG) contract.
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<td>Shear</td>
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Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. u = ultimate, y = yield
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<td>Bolts from Lower Vacuum Case Interface Plate to USS</td>
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<td>Abort Landing LC2031</td>
<td>Total Tension Yield</td>
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<td>2.4.1.2-11</td>
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<td>Bolts from Upper Vacuum Case Joint to TRD Corner Bracket</td>
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<td>Total Tension Yield</td>
<td>0.095 (y)</td>
<td>2.4.1.3-13</td>
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<td>Total Tension Yield</td>
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<td>2.4.1.4-11</td>
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<td>EWB 0420-8-16</td>
<td>Bolts from Diagonal Sill Bracket to Sill Joint</td>
<td>A286</td>
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<td>Joint Separation</td>
<td>-0.157</td>
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<td>NAS1953C6</td>
<td>Bolts from WIF Adapter Plate to Sill Tube</td>
<td>A286</td>
<td>On-Orbit</td>
<td>Joint Separation</td>
<td>-0.269</td>
<td>2.4.1.6.1-7</td>
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<td>NAS1954C6</td>
<td>Bolts from WIF Adapter Plate to side mounted WIF</td>
<td>A286</td>
<td>Launch</td>
<td>Total Tension Yield</td>
<td>0.003 (y)</td>
<td>2.4.1.6.2-7</td>
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Fatigue analysis shows that at 92% of loads M.S. is positive.

3 out of 12 bolts are negative. Acceptable since loads are non cyclic.
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<tr>
<th>Part / Dwg number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
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<td>NAS1352N02-6</td>
<td>Bolts from Bushing Plate to Vacuum Case Joint</td>
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<td>NAS1102E04-6</td>
<td>Bolts from Sill Plate to Sill Joint</td>
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<td>NAS1958C15</td>
<td>Bolts from Lower USS-02 to Upper USS-02</td>
<td>A286</td>
<td>Nominal Landing</td>
<td>Total Tension Yield</td>
<td>0.033 (y)</td>
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<td>EWB 0420-8-13</td>
<td>Bolts from Lower Angle Beam Flange to Centerbody Box Joint</td>
<td>A286</td>
<td>Abort Landing</td>
<td>Total Tension Yield</td>
<td>0.055 (y)</td>
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<td>EWB 0420-8</td>
<td>Bolts from Keel Angle Joint to Lower USS-02 Assembly</td>
<td>A286</td>
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<td>Total Thread Shear Ultimate</td>
<td>0.068 (y)</td>
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<td>NAS8103PU8</td>
<td>Bolts from Keel Retainer to Keel Trunnion</td>
<td>A286</td>
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<td>Total Tension Yield</td>
<td>0.076 (y)</td>
<td>2.4.3.2-7</td>
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<td>HTH1978-3-3</td>
<td>Bolts from Keel Retainer to Keel Block</td>
<td>A286</td>
<td>Nominal Landing</td>
<td>Total Tension Yield</td>
<td>0.131 (y)</td>
<td>2.4.3.2-16</td>
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Notes:
1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. $u = \text{ultimate}, y = \text{yield}$
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<tr>
<th>Part / Dwg number</th>
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<th>Failure Mode</th>
<th>Minimum Margin of Safety</th>
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<th>Comments</th>
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<tr>
<td>NAS1398 type M 0.25&quot; blind</td>
<td>Upper VC to Upper Trunnion bridge rivets</td>
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<td>0.171 (u)</td>
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<td>NAS1398 type M 0.25&quot; blind</td>
<td>Lower Trunnion Bridge Beam Elbow to Sill Joint Rivets</td>
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<td>Abort Landing</td>
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<td>0.025 (u)</td>
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<td>Sill Bracket to Sill Tube</td>
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<td>0.37 (u)</td>
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<td>Nominal Landing</td>
<td>Total Shear</td>
<td>0.213 (u)</td>
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<td>Lower Trunnion Bridge Beam to Lower Vacuum Case Joint</td>
<td>Monel</td>
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<td>Total Shear</td>
<td>0.137 (u)</td>
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Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. u = ultimate, y = yield
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<th>Part / Dwg number</th>
<th>Part Name / Description</th>
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<th>Failure Mode</th>
<th>Minimum Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
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<td>Vacuum Case - Conical Flange SEG39135778</td>
<td>Vacuum Case - Conical Flange Stability Assessment</td>
<td>AL ALY 2219-T62</td>
<td>Launch</td>
<td>Yield</td>
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<td>Vacuum Case - Conical Flange</td>
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<td>0.05</td>
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<td>Vacuum Case Outer Cylinder</td>
<td>AL ALY 7050-T7451 Rolled Ring Forging</td>
<td>Abort Landing</td>
<td>Ultimate</td>
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<td>3.2.1-14</td>
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<td>Abort Landing</td>
<td>Buckling</td>
<td>0.11</td>
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<td>No buckling at FS =2.0 Closes RID AMS-CDR-1-13</td>
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<td>Vacuum Case Inner Cylinder SDG39135781</td>
<td>Vacuum Case Inner Cylinder</td>
<td>AL ALY 2219 T852 Hand Forged</td>
<td>Launch LC1045</td>
<td>Ultimate</td>
<td>0.311 (u)</td>
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<td>Vacuum Case Inner Cylinder</td>
<td>AL ALY 2219 T852 Hand Forged</td>
<td>Launch LC1045</td>
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<td>Reference Page</td>
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<td>Upper Support Ring SDG39135786</td>
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<td>AL ALY 7050-T7451</td>
<td>Launch LC1007</td>
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<td>Analysis is Enveloped by Upper Support Ring</td>
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<td>AL ALY 7050-T7451</td>
<td>Launch LC1007</td>
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<td>Upper Interface Plate Assembly</td>
<td>AL ALY 7050-T7451</td>
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<td>Ultimate</td>
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<td>3.6-5</td>
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<td>Ultimate</td>
<td>2.36 (u)</td>
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<td>VC Feed-thru-port Cover Plate SDG39135791</td>
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<td>AL ALY 6061-T651</td>
<td>Launch/ Landing Plus Pressure</td>
<td>Tension</td>
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Notes:
1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. u = ultimate, y = yield
### TABLE 0.3.1-5  Vacuum Case Fastener Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg number</th>
<th>Part Name / Description</th>
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<td>Bolts from Vacuum Case Feed-thru-port Cover Plate to Vacuum Case Support Ring</td>
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<td>Launch / Landing Plus Pressure</td>
<td>Total Tension Yield</td>
<td>0.131 (y)</td>
<td>3.9-14</td>
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<tr>
<td>EWB 0420-4H-9</td>
<td>Bolts from Conical Flange to Upper Support Ring</td>
<td>A286</td>
<td>Landing LC2003</td>
<td>Total Tension Yield</td>
<td>0.079 (y)</td>
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<tr>
<td>EWB 0420-4H-9</td>
<td>Bolts from Conical Flange to Lower Support Ring</td>
<td>A286</td>
<td>Landing LC2027</td>
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<tr>
<td>EWB 0420-4H-13</td>
<td>Bolts from Outer Cylinder to Upper Support Ring</td>
<td>A286</td>
<td>Landing LC2038</td>
<td>Total Tension Yield</td>
<td>0.078 (y)</td>
<td>3.10.3-7</td>
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<tr>
<td>EWB 0420-4H-7</td>
<td>Bolts from Outer Cylinder to Upper Support Ring</td>
<td>A286</td>
<td>Landing LC2057</td>
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<td>Bolts from Outer Cylinder to Lower Support Ring</td>
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<td>Bolts Outer Cylinder to from Lower Support Ring</td>
<td>A286</td>
<td>Landing LC2031</td>
<td>Total Tension Yield</td>
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<td>Part / Dwg number</td>
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<td>NAS1958C9</td>
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<td>Launch LC1032</td>
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<td>NAS1956C10</td>
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<tr>
<td>NAS1956C8</td>
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<td>Landing LC2049</td>
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<td>Landing LC2049</td>
<td>Total Tension Yield</td>
<td>0.103 (y)</td>
<td>3.10.7.2-11</td>
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Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. \( u = \text{ultimate}, \ y = \text{yield} \)
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<td>Consistent On-Orbit Load Factor</td>
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<td>PAS Bridge</td>
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<td>Bearing Housing SEG39135845</td>
<td>Bearing Housing</td>
<td>CRES 15-5PH</td>
<td>Resultant Preload Combined On-Orbit/Mating</td>
<td>Tensile ultimate</td>
<td>0.20 (u)</td>
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<td>Tensile ultimate</td>
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<td>Handle Extension SDG39135853</td>
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<td>Handle Load</td>
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<td>Handle Load</td>
<td>Max. principal stress ultimate</td>
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Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield. For tested hardware, use Factors of Safety of 1.5 for Ultimate and 1.1 for Yield. The tested hardware factors of safety were applied to the Vertex Bracket analysis.
2. u = ultimate, y = yield
<table>
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<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
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<th>Failure Mode</th>
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<th>Comments</th>
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<tr>
<td>NAS1351N4-8</td>
<td>Bolts from PAS Handle to PAS Handle Extension</td>
<td>A286</td>
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<td>NAS1351N-16</td>
<td>Bolts from PAS Handle Extension to handle Base</td>
<td>A286</td>
<td>Handle Load</td>
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<td>Bolts from PAS Handle Base to Capture Bar</td>
<td>A286</td>
<td>Handle Load</td>
<td>Total Tension Yield</td>
<td>0.09 (y)</td>
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<td>NAS1351N6-28</td>
<td>Bolts from PAS Guide Pin to PAS Platform</td>
<td>A286</td>
<td>On-Orbit</td>
<td>Total Tension Yield</td>
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<td>NAS1956C30</td>
<td>Bolts from PAS Vertex Bracket to PAS Platform</td>
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<td>On-Orbit LC5031</td>
<td>Joint Separation</td>
<td>0.01</td>
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<td>NAS1160-6-30</td>
<td>PAS Vertex Bracket to PAS Platform Shear Bolt</td>
<td>A286</td>
<td>On-Orbit LC5031</td>
<td>Total Tension Yield</td>
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<td>Part / Dwg number</td>
<td>Part Name / Description</td>
<td>Material &amp; Heat Treatment</td>
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<td>Failure Mode</td>
<td>Minimum Margin of Safety</td>
<td>Reference Page</td>
<td>Comments</td>
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<td>EWB0420-6-30</td>
<td>Bolts from PAS Aft Bracket to PAS Platform</td>
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<td>On-Orbit LC5056</td>
<td>Total Tension Yield</td>
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<td>4.12.7.1-9</td>
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<td>PAS Aft Bracket to PAS Platform Shear Bolt</td>
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<td>On-Orbit</td>
<td>Total Tension Yield</td>
<td>0.01 (y)</td>
<td>4.12.7.2-5</td>
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<td>NAS1351N4-10</td>
<td>Bolts from BCS Avionics Bracket to PAS Platform</td>
<td>A286</td>
<td>Launch/Landing</td>
<td>Total Tension Yield</td>
<td>0.124 (y)</td>
<td>4.12.8-6</td>
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<tr>
<td>NAS1956C76H</td>
<td>Bolts from PAS Vertex Bracket to Lower USS-02</td>
<td>A286</td>
<td>On-Orbit LC5006</td>
<td>Total Tension Yield</td>
<td>0.071 (y)</td>
<td>4.12.9.1-12</td>
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<tr>
<td>NAS1956C14</td>
<td>Bolts from PAS Aft Bracket to Lower USS-02</td>
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<td>On-Orbit LC5014</td>
<td>Total Tension Yield</td>
<td>0.10 (y)</td>
<td>4.12.10.1-9</td>
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Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. u = ultimate, y = yield
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<th>Part / Dwg number</th>
<th>Part Name / Description</th>
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<th>Failure Mode</th>
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<th>Comments</th>
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<td>PVGF Bracket SDG39135860</td>
<td>PVGF Bracket</td>
<td>AL ALY 7075-T7351</td>
<td>SSRMS Interface Loads</td>
<td>Max Principal Stress</td>
<td>0.082 (u)</td>
<td>5.2-13</td>
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<td>FRGF Bracket SDG39135861</td>
<td>FRGF Bracket</td>
<td>AL ALY 7075-T7351</td>
<td>SSRMS Induced Loads</td>
<td>Max Principal Stress</td>
<td>0.498 (u)</td>
<td>5.4-12</td>
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<tr>
<td>ROEU Clevis Assembly SEG39137677</td>
<td>ROEU Clevis Assembly</td>
<td>AL ALY 7050-T7451</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Ultimate Shear</td>
<td>6.64 (u)</td>
<td>5.5.1-35</td>
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<tr>
<td>Scuff Plate, USS-02 Assembly SDG39135867</td>
<td>Scuff Plate, USS-02 Assembly</td>
<td>AL ALY 7050T7451</td>
<td>Impact</td>
<td>Principal Stress</td>
<td>0.449 (u)</td>
<td>5.8-12</td>
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<td>ROEU/USS SEG39137677</td>
<td>ROEU/USS</td>
<td>AL ALY 7050-T7451</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Bearing Failure Analysis</td>
<td>38.828 (u)</td>
<td>5.11.6.2-5</td>
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<td>ROEU PDA Bracket Lug SEG39137676 &amp; 78</td>
<td>ROEU PDA Bracket Lug</td>
<td>AL ALY 7050-T7451</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Combined Ultimate</td>
<td>6.394 (u)</td>
<td>5.11.6.3-14</td>
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<td>ROEU Harness Bracket SDG39135865</td>
<td>ROEU Harness Bracket</td>
<td>AL ALY 7050-T7451</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Bearing Ultimate</td>
<td>9.981 (u)</td>
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<td>SDG39135878</td>
<td>Handle Bracket -303, USS-02 Assembly</td>
<td>AL ALY 6061-T651</td>
<td>Load Case 1 Right End</td>
<td>Principal Stress</td>
<td>0.04 (u)</td>
<td>5.12.1-19</td>
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<td>SDG39135878</td>
<td>Handle Bracket -305, USS-02 Assembly</td>
<td>AL ALY 6061-T651</td>
<td>Load Case 8 Left End</td>
<td>Shear</td>
<td>0.049 (u)</td>
<td>5.12.1-32</td>
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<td>AL ALY 7075-T73</td>
<td>Kick Load</td>
<td>Ultimate</td>
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Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. $u =$ ultimate, $y =$ yield
<table>
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<th>Part / Dwg number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
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<th>Failure Mode</th>
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<td>EWB0420-6-17</td>
<td>Bolts from PVGF Bracket to PVGF</td>
<td>A286</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.03 (u)</td>
<td>5.11.2-11</td>
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<tr>
<td>NAS1351N4H14</td>
<td>Bolts from PVGF Bracket to Upper Trunnion Bridge Beam</td>
<td>A286</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.008 (y)</td>
<td>5.11.3-6</td>
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<td>NAS1351N4H16</td>
<td>Bolts from PVGF Bracket to Upper Trunnion Bridge Beam</td>
<td>A286</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.04 (y)</td>
<td>5.11.3-11</td>
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<td>NAS1351N4H16</td>
<td>Bolts from PVGF Bracket to Upper Trunnion Bridge Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
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<td>Bolts from FRGF Bracket to Upper Trunnion Bridge Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.02 (y)</td>
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<td>Bolts from FRGF Bracket to Upper Trunnion Bridge Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.02 (y)</td>
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<td>Bolts from FGGF Bracket to Upper Trunnion Bridge Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.07 (y)</td>
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<td>Part / Dwg number</td>
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<td>Bolts Attaching ROEU Arm Flange to Sill Joint</td>
<td>A286</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.199 (y)</td>
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<td>NAS1351N3</td>
<td>Bolts from ROEU Harness Bracket to PDA Mounting Bracket</td>
<td>A286</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.19 (y)</td>
<td>5.11.6.4-7</td>
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<tr>
<td>NAS1004-8A</td>
<td>Bolts - Shared Fasteners Connecting Lower Edge of IPA to Trunnion Beam</td>
<td>A286</td>
<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.14 (y)</td>
<td>5.11.11-13</td>
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<td>NAS1004-6A</td>
<td>0.25&quot; Bolts - Shared Fasteners Connecting Lower Edge of IPA to Trunnion Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Total Tension Yield</td>
<td>0.16 (y)</td>
<td>5.11.11-19</td>
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<tr>
<td>NAS1954C6</td>
<td>Bolts from Handle Bracket -303 to Bridge Beam Elbow</td>
<td>A286</td>
<td>Load Case 1 Right End</td>
<td>Combined shear, tension and bending ult</td>
<td>0.154 (u)</td>
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<td>NAS1351N3</td>
<td>Bolts from Handle Bracket -303 to ISS Handrail</td>
<td>A286</td>
<td>Load Case 1 Right End</td>
<td>Total Tension Yield</td>
<td>0.033</td>
<td>5.12.2-17</td>
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<td>Part / Dwg number</td>
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<td>Failure Mode</td>
<td>Minimum Margin of Safety</td>
<td>Reference Page</td>
<td>Comments</td>
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<td>Load Case 8 Left End</td>
<td>Total Tension Yield</td>
<td>0.181</td>
<td>5.12.2-28</td>
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<tr>
<td>NAS1351N3</td>
<td>Bolts from Handle Bracket -305 to ISS Handrail</td>
<td>A286</td>
<td>Load Case 8 Left End</td>
<td>Total Tension Yield</td>
<td>0.038</td>
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<tr>
<td>NAS1153E36</td>
<td>Fasteners Connecting Front Sub-Panel to Standoff to Rear Sub-Panel</td>
<td>A286</td>
<td>40 g Vertical</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.07 (u)</td>
<td>5.13-42</td>
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<tr>
<td>NAS1133E4</td>
<td>Bolts from Base Panel A to Base Panel Stiffener</td>
<td>A286</td>
<td>40 g Vertical</td>
<td>Total Tension Yield</td>
<td>0.33 (y)</td>
<td>5.13-48</td>
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<td>NAS1133E4</td>
<td>Bolts from Angle Bracket to C-Channel A Assembly</td>
<td>A286</td>
<td>40 g Vertical</td>
<td>Total Tension Yield</td>
<td>0.32 (y)</td>
<td>5.13-54</td>
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</tbody>
</table>

Notes:

1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. u = ultimate, y = yield
### TABLE 0.3.1-10  Miscellaneous Hardware Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Minimum Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Vacuum Case Cable Bracket SDG39135877</td>
<td>Vacuum Case Cable Bracket</td>
<td>Al ALY 6061-T651</td>
<td>Small Secondary Structures Loads</td>
<td>Ultimate</td>
<td>5.264 (u)</td>
<td>6.1-10</td>
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</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. $u = \text{ultimate}, y = \text{yield}$

### TABLE 0.3.1-11  Miscellaneous Hardware Fastener Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Minimum Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
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<tr>
<td>NAS1351N3-24</td>
<td>Bolts from Lower Support Ring/Outer Cylinder to Vacuum Case Cable Bracket</td>
<td>A286</td>
<td>Small Secondary Structures Loads</td>
<td>Total Tension Yield</td>
<td>0.20 (y)</td>
<td>6.1-15</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. $u = \text{ultimate}, y = \text{yield}$
### 0.4 Fail-Safe Minimum Margins of Safety

**TABLE 0.4.1-1 Upper USS-02 Fastener Fail-Safe Minimum Margin of Safety Summary**

<table>
<thead>
<tr>
<th>Part / Dwg number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Minimum Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
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<tbody>
<tr>
<td>SDG39135892-805</td>
<td>Bolts from Upper Vacuum Case Interface Plate to USS</td>
<td>A286</td>
<td>Shear Pin Failure Abort Landing LC2035</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.411 (u)</td>
<td>2.4.1.1-13</td>
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<td>NAS1958C15</td>
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<tr>
<td>SDG39135892-805</td>
<td>Bolts from Upper Vacuum Case Interface Plate to USS</td>
<td>A286</td>
<td>Abort Landing LC2038</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.404 (u)</td>
<td>2.4.1.1-19</td>
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<td>Bolts from Lower Vacuum Case Interface Plate to USS</td>
<td>A286</td>
<td>Shear Pin Failure Abort Landing LC2011</td>
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<td>Bolts from Lower Vacuum Case Interface Plate to USS</td>
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<td>Combined Shear Tension Bending Ultimate</td>
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<td>Bolts from Upper Vacuum Case Joint to TRD Corner Bracket</td>
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<td>Bolts from Upper Vacuum Case Joint to TRD Corner Bracket</td>
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<td>Launch LC1032</td>
<td>Combined Shear Tension Bending Ultimate</td>
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<td>SDG39135892-815</td>
<td>Bolts from Sill Bracket to Sill Joint</td>
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<td>Launch LC1004</td>
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<td>Bolts from Sill Bracket to Sill Joint</td>
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<td>Launch LC1032</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.115 (u)</td>
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<td>Joint Separation -0.156 acceptable for Fail safe</td>
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<td>Bolts from WIF Adapter Plate to Sill Tube</td>
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<td>Total Thread Shear Ultimate</td>
<td>0.049 (u)</td>
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<td>Joint Separation -0.209 acceptable for fail safe</td>
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<td>NAS1954C6</td>
<td>Bolts from WIF Adapter Plate to Side Mounted WIF</td>
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<td>Launch LC1001</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.333 (u)</td>
<td>2.4.1.6.2-8</td>
<td>Joint Separation -0.27 acceptable for fail safe</td>
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<td>NAS1352N02-6</td>
<td>Bolts from Bushing Plate to Vacuum Case Joint</td>
<td>A286</td>
<td>40 g</td>
<td>Combined Shear Tension Bending Ultimate</td>
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<td>NAS1102E04-6</td>
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<td>Bolts from Lower USS-02 to Upper USS-02</td>
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<td>Bolts from Lower USS-02 to Upper USS-02</td>
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<td>Landing LC4028</td>
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<td>EWB 0420-8-13</td>
<td>Bolts from Lower Angle Beam Flange to Centerbody Box Joint</td>
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<td>Abort Landing LC2032</td>
<td>Total Thread shear Ultimate</td>
<td>0.088 (u)</td>
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<td>EWB 0420-8</td>
<td>Bolts from Keel Angle Joint to Lower USS-02 Assembly</td>
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<td>Total Thread Shear Ultimate</td>
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<td>Bolts from Keel Retainer to Keel Trunnion</td>
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Notes:
1. Factors of Safety are 1.0 for Ultimate and 1.0 for Yield for Fail-Safe analysis.
2. u = ultimate, y = yield
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<td>Bolts from Vacuum Case Feed-thru-port Cover Plate to Vacuum Case Support Ring</td>
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<td>Launch /Landing Plus Pressure</td>
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<td>Bolts from Conical Flange to Lower Support Ring</td>
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<td>Landing LC2027</td>
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<td>Bolts from Upper Support Ring to Outer Cylinder</td>
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<td>Landing LC2038</td>
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<td>Landing LC2057</td>
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<td>0.188 (u)</td>
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<td>Landing LC2031</td>
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<td>Shear Pin Failure Landing LC2011</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.485 (u)</td>
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<td>Bolts from Lower Interface Plate to Lower Support Ring</td>
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<td>Bolts from Lower Interface Plate to Lower Support Ring</td>
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<td>Landing LC2038</td>
<td>Total Thread Shear Ultimate</td>
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Notes:

1. Factors of Safety are 1.0 for Ultimate and 1.0 for Yield for Fail-Safe analysis.
2. u = ultimate, y = yield
## TABLE 0.4.1-3 Payload Attach System Fastener Fail-Safe Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Minimum Margin of Safety</th>
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<td>NAS1351N6-28</td>
<td>Bolts from PAS Guide Pin to PAS Platform</td>
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<td>On-Orbit LC5032</td>
<td>Joint Separation</td>
<td>-0.33</td>
<td>4.12.5.1-30</td>
<td>Acceptable for Fail-Safe</td>
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<td>NAS1956C30</td>
<td>Bolts from PAS Vertex Bracket to PAS Platform</td>
<td>A286</td>
<td>On-Orbit LC5031</td>
<td>Joint Separation</td>
<td>-0.40</td>
<td>4.12.6.1-15</td>
<td>Acceptable for Fail-Safe</td>
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<td>NAS1160-6-30</td>
<td>PAS Vertex Bracket to PAS Platform Shear Bolt</td>
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<td>Launch LC1007</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.55</td>
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<td>EWB0420-6-30</td>
<td>Bolts from PAS Aft Bracket to PAS Platform</td>
<td>A286</td>
<td>On-Orbit LC5056</td>
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<td>On-Orbit LC5031</td>
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<td>Bolts from PAS Aft Bracket to Lower USS-02</td>
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**Notes:**

1. Factors of Safety are 1.0 for Ultimate and 1.0 for Yield for Fail-Safe analysis.
2. u = ultimate, y = yield
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<th>Part / Dwg number</th>
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<th>Comments</th>
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<td>Bolts from PVGF Bracket to PVGF</td>
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<td>Launch &amp; Abort Landing Case</td>
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<td>0.041 (u)</td>
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<td>Bolts from PVGF Bracket to Upper Trunnion Bridge Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
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<td>Non-cyclic load</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Combined Shear Tension Bending Ultimate</td>
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<td>Launch &amp; Abort Landing Case</td>
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<td>Bolts from FRGF Bracket to Upper Trunnion Bridge Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
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<td>Launch &amp; Abort Landing Case</td>
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<td>NAS1351N420</td>
<td>Bolts Attaching ROEU Arm Flange to Sill Joint</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Combined Shear Tension Bending Ultimate</td>
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<td>Bolts - Shared Fasteners Connecting Lower Edge of IPA to Trunnion Beam</td>
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<td>Launch &amp; Abort Landing Case</td>
<td>Total Thread Shear Ultimate</td>
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<td>Bolts from Handle Bracket -303 to Bridge Beam Elbow Bottom</td>
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<td>Load Case 1 Right End</td>
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<td>Bolts from Handle Bracket -303 to ISS Handrail</td>
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<td>Joint Separation</td>
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Notes:
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Notes:

1. Factors of Safety are 1.0 for Ultimate and 1.0 for Yield for Fail-Safe analysis.
2. \( u = \text{ultimate}, \ y = \text{yield} \)
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0.7 Acronyms

ACC  Anti-Coincidence Counter
AMS  Alpha Magnetic Spectrometer
AMS-02  Alpha Magnetic Spectrometer – 02 (ISS Mission)
BOSOR  Buckling of Shells of Revolution
CAB  Cryomagnet Avionics Box
CAS  Common Attach System
CDR  Critical Design Review
CERN  Centre Européen de Recherche Nucléaire
CG  Center of Gravity
CMR  Cold-Mass Replica
DCLA  Design Cycle Coupled Loads Analysis
DP  Design Pressure
ECAL  Electromagnetic Calorimeter
EMC  Electro-magnetic Compatibility
EMI  Electro-magnetic Interference
ETH  Eidgenossische Technische Hochschule (Zurich)
EVA  Extravehicular Activity
EVR  Extravehicular Robotics
FRGF  Flight Releasable Grapple Fixture
FS  factor of safety
g  gravity
GMAW  Gas Metal Arc Welding
GTAW  Gas Tungsten Arc Welding
ICD  Interface Control Document
IHET  Institute of High Energy Physics
INFN  Instituto Nazionale di Fisica Nucleare (Italy)
ISS  International Space Station
JS  Jacobs Sverdrup
JSC  Johnson Space Center
KSC  Kennedy Space Center
LESC  Lockheed Engineering and Sciences Company (Now LMSO)
LM  Lockheed Martin
LMATC  Lockheed Martin Advanced Technology Center
LMSS  Lockheed Martin Michoud Space Systems
LMSO  Lockheed Martin Space Operations
MDP  Maximum Design Pressure
MEFL  Maximum Expected Flight Level
MIT  Massachusetts Institute of Technology
MMOD  Micro-Meteoroid and Orbital Debris
MS  Margin of Safety
MSFC  Marshall Space Flight Center
MWL  Minimum Workmanship Level
n/a  not applicable
NASTRAN  National Aeronautics and Space Administration Structural Analysis
    Computer Program
NBL    Neutral Buoyancy Laboratory
NSTS   National Space Transportation System
PAS    Payload Attach System
PAW    Plasma Arc Welding
PCU    Plasma Contactor Unit
PDR    Preliminary Design Review
PEDS   Passive Electrical Disconnect System
PVGF   Power Video Grapple Fixture
RICH   Ring Imaging Cherenkov Counter
ROEU   Remotely Operated Electrical Umbilical
SED    Structural Engineering Division
SFHe   Superfluid Helium
SHOOT  Superfluid Helium On-Orbit Transfer
SRMS   Shuttle Remote Manipulator System
SSP    Space Station Program
SSRMS  Space Station Remote Manipulator System
STA    Structural Test Article
STE    Special Test Equipment
STS    Space Transportation System
SWG    Structures Working Group
TBD    To Be Determined
TCS    Thermal Control System
TOF    Time of Flight
TRD    Transition Radiation Detector
UF     Uncertainty Factor
UF-4.1 Space Station Utilization Flight #4.1
UMA    Umbilical Mechanism Assembly
USS    Unique Support Structure
USS-02 Unique Support Structure – 02
VC     Vacuum Case
VLA    Verification Loads Analysis
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55. MMPDS-01/03, Metallic Materials Properties Development and Standardization.
59. NSTS 1700.7, ISS Addendum, Safety Policy and Requirements Document for Payloads Using the International Space Station.
1.0 Introduction

The NASA project management for the AMS-02 comes from the Office of the Director (code EA1) of the Engineering Directorate at JSC. Jacobs Engineering Sciences Contract Group (ESCG) is contracted by NASA to provide integration of the AMS-02 payload to the Space Shuttle and the ISS. Jacobs ESCG is responsible for designing, analyzing, and fabricating the Unique Support Structure-02 (USS-02) with an integral cryogenic magnet Vacuum Case for the AMS-02.

The science objectives of the AMS-02 experiment are to conduct astrophysical research and to search for dark matter and antimatter. To acquire this scientific data, the AMS-02 will employ a very large cryogenic superfluid helium electro-magnet, a Transition Radiation Detector (TRD), two Time of Flight (TOF) detectors, a tracker composed of eight layers of silicon wafer detectors, an Anti-Coincidence Counter (ACC), a Ring Imaging Cherenkov Counter (RICH), an Electromagnetic Calorimeter (ECAL), as well as numerous electronics and other avionics devices.

The AMS-02 will remain on ISS through the lifetime of the station. It consists of a cryogenic superconducting magnet, cooled by superfluid helium, and a USS to support the experiment on the Shuttle.

The Vacuum Case of the magnet is an integral part of the USS-02, and will be built and certified by Jacobs ESCG. There will be two (2) Vacuum Cases built: a Structural Test Article (STA) and a flight article. The STA will be used to demonstrate fabrication and assembly techniques and for structural verification testing. The STA will be built as a flight spare, and is therefore identical to the flight article.

The experiment's electronics, scintillators, and detectors shall be designed and built at multiple institutes in Europe and Asia. Final assembly will occur at the Centre Européen de Recherche Nucléaire (CERN) in Geneva.

The liftoff and landing configurations of AMS-02 are shown in Figures 1.0-1 through 1.0-4.
Figure 0.1-1: Alpha Magnetic Spectrometer – 02 Configuration - Launch, Landing, and On-Orbit
Figure 1.0-2: Alpha Magnetic Spectrometer – 02 Configuration - Launch, Landing, and On-Orbit
Figure 1.0-3: Alpha Magnetic Spectrometer – 02 Configuration - Launch, Landing, and On-Orbit

See Detail A

PVGF
Figure 1.0-4: Alpha Magnetic Spectrometer – 02 Configuration Close-up of Payload Attach System (PAS)
The AMS-02 experiment consists of a large cryogenic superconducting magnet, cooled by superfluid helium and supported by the USS-02. The Cryomagnet Vacuum Case is constructed of Aluminum 2219 and Aluminum 7050-T7451. The toroidal Vacuum Case has a 2679.8-millimeter (mm) outer diameter, an 1115-mm inner diameter, an 858-mm Inner Cylinder height, and a 1464-mm Outer Cylinder height (Figure 4). The outer skin of the Cryomagnet Vacuum Case is a ring-stiffened cylinder made of Aluminum 7050-T7451. There are two large support rings on the top and bottom of the Outer Cylinder. These support rings are made of Aluminum 7050-T7451 and mate to the Conical Flanges and the Outer Cylinder through bolted/double O-ring interfaces. The Inner Cylinder is a monocoque design made of Aluminum 2219-T852. The top and bottom Conical Flanges will be made of one plate of Aluminum 2219-T62 that is spun and machined to their final rib-stiffened conical shape. The Conical Flanges and Inner Cylinder are welded together to make the final closeout structural weld.

Suspended inside the Cryomagnet Vacuum Case is the magnet, a large annular superfluid helium tank, and 200 layers of super-insulation and four vapor cooled shields. All of this ‘cold-mass’ is supported at eight locations that interface to the USS-02 using sixteen non-linear support straps. The use of the pre-tensioned non-linear composite straps is necessary in order to reduce the heat leak from the Cryomagnet Vacuum Case to the cold mass. Although linear straps do not present the same dynamic characteristics, the design approach, strap materials, arrangement, and assembly techniques are similar for non-linear straps.

Several secondary structural components are mounted to the outside of the Cryomagnet Vacuum Case. These components include the Tracker, the Anti-Coincidence Counter (ACC), and parts of the cryogenic pumps. The Tracker and ACC are very similar, if not identical to the STS-91 version of AMS.

The USS-02 primary members consist of extruded aluminum tubing with a minimum wall thickness of 0.25-inch made from 7075-T73511. Most USS-02 joints are made of 7050-T7451 6-inch thick plate and are machined. The USS-02 attaches to the Space Shuttle Orbiter with four (4) longeron trunnions and one (1) keel trunnion. The degrees of freedom at the Orbiter interface are X and Z for the two (2) primary longeron trunnions, Z for the two (2) stabilizer longeron trunnions, and Y for the keel trunnion. The STS interfaces will meet the requirements defined in NSTS-21000-IDD-ISS [15]. The AMS-02 payload attaches to the ISS via the Payload Attach System (PAS). The PAS hardware on the AMS-02 consists of three guide pins and a capture bar. The PAS design will meet the requirements defined in SSP-57003 [9] and SSP-57004 [10]. The design will be documented in SSP-57213, AMS-02 to ISS Hardware ICD [35].

Several secondary structural components are mounted to the USS-02. These components include the Electromagnetic Calorimeter (ECAL), the Transition Radiation Detector (TRD), the TRD gas supply system, the Ring Imaging Cherenkov Counter (RICH), various electronics crates, various components of the Thermal Control System (TCS), and the Meteoroid and Orbital Debris (MMOD) shields. Most of these systems have been added to the AMS-02 when compared to the STS-91 version.
Figure 1.0-5: View of Alpha Magnetic Spectrometer – 02
Figure 1.0-6: Bottom and Top View of Alpha Magnetic Spectrometer – 02
Figure 1.0-7: Back and Front View of Alpha Magnetic Spectrometer – 02
Figure 1.0-8: Left and Right View of Alpha Magnetic Spectrometer – 02
1.1 MODEL DESCRIPTION

This report documents the stress analysis for a subset of the AMS-02 components that includes the Unique Support Structure, the Vacuum Case, the Payload Attach System, and the payload integration hardware. These components were included in a finite element model of the full AMS-02 payload.

The finite element model of the AMS-02 payload was initially developed during the design phase of the payload. The math model was prepared for use with the NASA Structural Analysis (NASTRAN) computer program. Since the initial version of the math model, updates have been made to account for changes to the payload components and increase the model fidelity. The 2-06 version of the math model (released in February 2006) was used as the “loads model” for the stress analysis documented in this report.

The loads model represents the payload components with varying levels of modeling fidelity. The primary structure and the secondary components that have a significant effect on the overall payload response are modeled at a relatively high level of fidelity. Smaller components and items that do not have a significant effect on the global payload response are represented by concentrated mass elements and rigid elements.

For areas of the structure that are highly loaded or that have lower structural margins, a more detailed model of the component was typically used in a separate static analysis to produce the data required for the stress analysis. The responses from the loads model would then be used as the input force in this detailed stand-alone analysis of the component.

The payload components are all represented as linear, elastic structure with the exception of the cryogenic magnet support system. The magnet support system straps are modeled using tension-only elements with nonlinear, elastic stress-strain characteristics.

1.1.1 Unique Support Structure (USS) Component Model

The unique support structure model is comprised primarily of beam elements. The cross sectional properties for the elements were formulated in FEMAP using the CAD model for the individual beams. For locations where USS members intersect, the beam elements use the combined inner and outer most profiles to define the total cross section at that location. The main joints (i.e. the upper and lower vacuum case joints and the lower center body joints) are modeled with plate elements. The trunnion sill joints are modeled using RBE2 elements that connect all of the intersecting beam elements at that joint. The mass of the individual components is tuned to match the actual hardware by adjusting the mass density of that components material entry. Other USS components such as the fasteners and shims are represented by concentrated mass elements at each bolted connection. The mass of the rivets in the major joints is accounted for by adding non-structural mass entries to the beam elements at the riveted...
joints. Electronic components that are relatively stiff compared to the USS beams are represented with concentrated mass elements.

1.1.2 Vacuum Case (VC) Component Model

The vacuum case component model consists primarily of plate elements. Beam elements with offsets are used to model the ribs of the conical flanges, the ribs of the outer cylinder, and portions of the support rings. Solid elements are used to model the interface plates. Fasteners joining the conical flanges to the support ring and the outer cylinder to the support ring are modeled with CBUSH elements which include stiffness for the axial and shear directions. Instead of representing all of the fasteners around the perimeter of the support rings with individual CBUSH elements, the combined stiffness of several adjacent fasteners is represented by a CBUSH with the equivalent stiffness for the group of fasteners.

Various experiment components are located on the perimeter of the support rings. This hardware has been represented with concentrated mass and rigid elements.

1.1.3 Payload Attach System (PAS) Component Model

The PAS hardware in the loads model is represented mostly by beam elements. Structure with more complex geometry is represented by plate elements. Concentrated mass elements are used to represent nonstructural components. The bolted joints are represented by CBUSH elements.

1.1.4 Shuttle and ISS Integration Hardware Component Models

The integration hardware generally consists of brackets with complex shapes, so plate elements are used for these components. Nonstructural items are represented by concentrated mass and rigid elements. Bolted joints are represented by CBUSH elements.
1.2 LOADING CONDITIONS

For the majority of the payload components documented in this report, the critical loading conditions occur during the liftoff or landing phase of the Shuttle flight. These components include the Unique Support Structure (USS), Vacuum Case (VC), and most of the STS and ISS integration hardware. The liftoff and landing loads were represented by load factors that are applied as inertial loads to the full payload math model in a nonlinear static analysis. The liftoff and landing load factors were obtained from a Design Coupled Loads Analysis which consisted of a nonlinear, dynamic analysis. These load factors are documented in “AMS-02 Structural Verification Plan for the Space Transportation System and International Space Station”, JSC-28792.

The nonlinear aspects of the payload require that loading conditions prior to liftoff and landing be accounted for. These preflight conditions include the following:

1. mechanical preload for the support straps;
2. loads due to differential pressure on the vacuum case (an internal vacuum and external atmospheric pressure);
3. loads due to gravity;
4. loads due to large thermal gradients on the interior of the vacuum case; and
5. preloads in the trunnions due to misalignment with the Orbiter payload retention latch assembly.

The loads due these preflight conditions are applied to the payload as preloads to the appropriate payload structure.

The Payload Attach System (PAS) was assessed for Shuttle liftoff and landing loads, but the most significant loading condition for the PAS is when the payload is berthed to the ISS and the Common Attach System (CAS) capture claw is fully engaged with the PAS capture bar. These on-orbit loads were obtained from an analysis performed by Boeing as part of the International Space Station Design Analysis Cycle 8 (D684-10019-02-01-02 Rev E). The interface loads for AMS-02 are also documented in JSC-28792 and further described in Section 4.06 of this report.

The significant loading condition for the Flight Releasable Grapple Fixture (FRGF) and the Power Video Grapple Fixture (PVGF) occur during on-orbit operations when the payload is grappled by the Shuttle Remote Manipulator (SRMS) System or the Space Station Remote Manipulator System (SSRMS). These load are documented in JSC-28792.

The significant loading condition for the scuff plates is defined as an impact load using the payload mass and an impact velocity of 0.11 feet per second. This loading condition is documented in NSTS-21000-IDD-ISS.

All components that are within 24 inches of an EVA translation path or EVA worksite have been analyzed for crew kick loads in addition to any other applicable loading.
conditions. EVA kick loads are defined as a quasi-static concentrated force applied over a 0.5 inch diameter circular area. The requirements for this loading condition are documented in Table 3.1.1.2.6-1 of SSP-57003.
1.3 FACTORS OF SAFETY

Various factors of safety will be used on different hardware depending on its intended use, level of complexity, and level of testing. The minimum primary and secondary structure factors of safety are detailed in Appendix A of the AMS-02 Structural Verification Plan, JSC-28792. All of the factors of safety shown in Appendix A of document JSC-28792 have been approved by the SWG and NASA/EM2 [26].

The minimum factors of safety (FS) for structural component design of the AMS-02 experiment and integration hardware for flight environments are also listed in Appendix A of document JSC-28792. If the component is not specifically mentioned in Appendix A of document JSC-28792, assume a factor of safety of 2.0 (ultimate) and 1.25 (yield) with no structural testing. For all joints that do not have the matched drilled or reamed holes, a fitting factor of 1.15 shall be used for all modes of failure associated with structural joints, including bolts and bearing surfaces.

The Unique Support Structure-02 and Vacuum Case are analyzed with an ultimate factor of safety of 1.4 and a yield factor of safety of 1.1 against limit loads. The Payload Attach System and Payload Integration Hardware are analyzed with an ultimate factor of safety of 2.0 and a yield factor of safety of 1.25 against limit loads.

For tested hardware, a factor of safety of 1.5 for ultimate and a factor of safety of 1.1 for yield were applied. These factors of safety were applied in the Vertex Bracket analysis.

In the fastener fail-safe analysis, an ultimate factor of safety of 1.0 was applied. A factor of safety of 1.0 is applied for joint separation.
1.4 MATERIALS AND TEMPERATURE

All material used are verified in accordance with applicable requirements in the AMS-02 SVP and in the Safety Policy and Requirements Document for Payloads Using the International Space Station (NSTS 1700.7, ISS Addendum).

Material Properties

Material properties of metallic materials meet those called out in the Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures (MIL-HDBK-5, Revision H or J). Material properties were also obtained from Metallic Material Properties Development and Standardization (MMPDS-01 and 03).

Temperature Effects

The temperature specified in Appendix C2 shall be used for the structural analysis, and the material properties shall be degraded accordingly.
1.5 Fracture Assessment

A fatigue and fracture assessment was performed for the AMS-02 components that includes the Unique Support Structure, the Vacuum Case, the Payload Attach System, and the Payload Integration Hardware. For details of this assessment, refer to document ESCG-4450-08-STAN-DOC-0115, *Fatigue and Fracture Assessment of the Alpha Magnetic Spectrometer-02 (AMS-02) Unique Support Structure (USS-02), Vacuum Case, and Payload Attach System (PAS)* and document ESCG-4450-09-STAN-DOC-0032, *Fracture Control Summary of the Alpha Magnetic Spectrometer-02 (AMS-02)*.
2.0 Strength and Stability Assessment for USS-02
2.1  Upper USS-02 Assembly
2.1.1 Upper Vacuum Case Interface Joint
### Table 2.1.1-1  Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135727</td>
<td>Upper VC Joints</td>
<td>7050-T7451 Al. Aly.</td>
<td>Launch</td>
<td>Tension</td>
<td>0.035</td>
<td>2.1.1-10</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Factor of Safety is 1.4 for Ultimate and 1.1 for Yield
The Stress Analysis of the Upper VC Joints

1. Introduction of the Upper VC Joints
Four Upper VC Joints are used to connect the USS-02 to the four locations of the Upper Support Ring, which is one component of the Vacuum Case. The pictures of Figure 2.1.1-1 show how the Upper VC Joints interface with the Vacuum Case and USS-02. One side of the Upper VC Joint is connected to the Upper Trunion Bridge Beam. Other side of the Upper VC Joint is connected to the Interface Plate and the TRD Corner Brackets.
The pictures of Figure 2.1.1-2 show that one of the Upper VC Joints interfaces with the TRDGAS Assembly. The TRDGAS Assembly has two interface connections with the USS-02 structure. One is the upper USS interface bolting the Box_S Support Structure to the upper trunnion bridge and upper VC joint. The lower USS interface consists of a triangular aluminum bracket on which a helicoidal stainless steel spring is attached.
The Upper VC Joint is machined from 7050-T7451 plate as a single piece. The details of the Upper VC Joint is shown in Figure 2.1.1-3. Rivets are used to connect the Upper VC Joints and Upper Trunnion Bridge Beams. Bolts are used to connect the Upper VC Joint with the Interface Plates and the Corner Bracket of the TRD Assembly.

**Figure 2.1.1-3 Details of the Upper VC Joint**

2. Method used to Perform the Stress Analysis of the Upper VC Joints

The FEA math models of the Upper VC Joints were made using FEMAP software. The FEA model of the Upper VC Joint consists of the plate elements (CQUAD4 and CTRIA3) and solid elements (CHEXA and CPENTA). The picture of Figure 2.1.1-4 below is showing the FEA models of the Upper VC Joints are embedded into the USS-02 FEA model.

**Figure 2.1.1-4 Upper VC Joint models embedded into the USS-02 model**
After completion, the models of the Upper VC Joints were integrated with the USS-02 FEA model. The rivet connections between the Upper VC Joints and Upper Trunnion Bridge Beams are modeled using rigid elements (RBE2). The bolt connections between the Upper VC Joints and either the Interface Plates or the TRD Corner Brackets are using rigid elements and CBUSH elements.

The TRDGAS FEA model was also embedded into the USS-02 FEA model. The connections Between the TRDGAS and Upper VC Joint were modeled using Rigid Elements (RBE2) and CBUSH Elements. The connections from TRDGAS model to the Upper and Lower Trunnion Bridge Beams were modeled using rigid elements (RBE2). Figure 2.1.1-5 is showing the details of the FEA model between the Upper VC Joint model and TRDGAS.

![Figure 2.1.1-5 TRDGAS model connected to the Upper VC Joint model](image)

3. FEA models of the Upper VC Joints and Assumptions

When the FEA models of the Upper VC Joints are put into the USS-02 FEA model, we assume the USS02 FEA math model is correct. All the boundary conditions including the constraints and loading cases are also modeled correctly. The stress analysis only focuses on the FEA models of the Upper VC Joints.

The NASTRAN data file of the Upper VC Joint models is put under the directory: /hsm/swang/ams02/uppermodel-newel, and named as "uss-upper403.nas"
4. FEA model check of the Upper VC Joint Models

The model check was performed before embedding the Upper VC Joint models into the USS-02 FEA model. The results of the model check were including the four FEA models of the Upper VC Joints. The results are listed below.

**OUTPUT FROM GRID POINT WEIGHT GENERATOR**

<table>
<thead>
<tr>
<th>MASS AXIS SYSTEM (S)</th>
<th>MASS</th>
<th>X-C.G.</th>
<th>Y-C.G.</th>
<th>Z-C.G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>3.900795E-01</td>
<td>-4.013955E-14</td>
<td>3.821729E-19</td>
<td>-7.592238E-05</td>
</tr>
</tbody>
</table>

\[ I(S) \]

\[
\begin{bmatrix} * \ 8.359843E+02 & 1.726397E-13 & 1.198922E-14 * \\
* \ 1.726397E+13 & 6.077592E+02 & 4.662970E-15 * \\
* \ 1.198922E-14 & 4.662970E-15 & 1.431934E+03 * 
\end{bmatrix}
\]

\[ I(Q) \]

\[
\begin{bmatrix} * \ 8.359843E+02 & * \\
* \ 6.077592E+02 & * \\
* \ 1.431934E+03 & * 
\end{bmatrix}
\]

\[ Q \]

\[
\begin{bmatrix} * \ 1.000000E+00 & 0.000000E+00 & 0.000000E+00 * \\
* \ 0.000000E+00 & 1.000000E+00 & 0.000000E+00 * \\
* \ 0.000000E+00 & 0.000000E+00 & 1.000000E+00 * 
\end{bmatrix}
\]

**STIFFNESS MATRIX**

\[
KGG \ (6 \times 6)
\]

\[
\begin{bmatrix} 2.9790D-08 & -3.0401D-07 & -9.6990D-09 & -5.6947D-06 & 4.9090D-06 & -9.3070D-06 \\
3.1480D-06 & 7.9183D-06 & -7.4836D-06 & 5.3853D-05 & 2.4789D-04 & 5.2515D-06 \\
\end{bmatrix}
\]

**STIFFNESS MATRIX**

\[
KNN \ (6 \times 6)
\]

\[
\begin{bmatrix} 2.5817D-06 & -2.5419D-06 & -9.2638D-09 & 6.2746D-06 & 8.0027D-06 & -3.2705D-06 \\
-1.2287D-06 & 1.6137D-06 & 4.1913D-08 & -2.9971D-08 & 2.9199D-06 & -8.1395D-06 \\
1.7211D-09 & 2.1156D-08 & -1.2131D-07 & 1.6211D-05 & -5.4169D-06 & 2.1370D-06 \\
1.0145D-06 & 1.5269D-05 & 1.7247D-06 & -2.8296D-04 & 5.5353D-04 & 4.4215D-05 \\
8.8053D-06 & 4.3271D-06 & 1.1676D-06 & -5.6183D-05 & -2.3531D-05 & 1.1692D-03 \\
\end{bmatrix}
\]
The NASTRAN data file used for the model check is put under the directory:/hsm/swang/ams02/checkmodel/ckupperussjoint, and named as “uss-upper203-2.f06”

First twenty-four rigid body modes are listed here since the four FEA models of the Upper VC Joints were put together to run the model check.

The results of the model check show that the FEA models of the Upper VC Joints are correct because the underlined translation values of each matrix are close to zero. The first twenty-four modes are also close to zero and transition modes are well separated.
5. Loads and Constraints

The entire AMS-02 FEA model is constrained at the five Trunnion locations after the FEA models of the Upper VC Joints are connected with the USS-02 FEA models using RBE’s and CBUSH elements.

A number of load cases under the launch, landing and thermal conditions were investigated in order to identify the worst load cases. The NASTRAN data files of the load cases are within the directories below. The Load Factors of the load cases are applied at the C.G. of the entire AMS02 FEA model when running NASTRAN. The combined Load Factors are taken from Table 4.1 of Page 17 in AMS02 Structural Verification Plan for STS and ISS (JSC-28792, Rev.C).

In the directory: /hsm/swang/ams02/nonlin/upperjoint/1000, the data files are for launch condition named from R1001.dat to R1064.dat.

In the directory: /hsm/swang/ams02/nonlin/upperjoint/2000, the data files are for landing condition named from R2001.dat to R2064.dat.

In the directory: /hsm/swang/ams02/nonlin/upperjoint/4000, the data files are for thermal condition named from R4001.dat to R4064.dat.

6. Maximum Stresses and Calculation for the Margins of Safety

The maximum stresses of the elements and the relative worst load cases are listed in Table 2.1.1-2. The maximum stresses were sorted out from the pch data files of the load cases using the NASPOST. The sorted-out data files for the load cases are attached in Appendix A11. The f06 files of the load cases are used to perform the post-processing of the FEA models of the Upper VC Joints. The f06 and pch files of NASTRAN for the FEA models of the Lower Center Body Assembly are put under directory below.

/hsm/swang/ams02/nonlin/upperjoint/1000/3-03, and on April, 2003.
/hsm/swang/ams02/nonlin/upperjoint/2000/3-03, and on April, 2003.
/hsm/swang/ams02/nonlin/upperjoint/4000/3-03, and on April, 2003.

<table>
<thead>
<tr>
<th>Element ID</th>
<th>Element Type</th>
<th>Load Case</th>
<th>Max-PRIN (Top)</th>
<th>Von-MISES (Top)</th>
<th>Max-shear (Top)</th>
<th>Max-PRIN (Bot)</th>
<th>Von-MISES (Bot)</th>
<th>Max-Shear (Bot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5113635 QUAD4</td>
<td>1049</td>
<td>43810.74</td>
<td>39373.56</td>
<td>21905.37</td>
<td>17338.28</td>
<td>20956.73</td>
<td>11644.19</td>
<td></td>
</tr>
<tr>
<td>5443007 QUAD4</td>
<td>2020</td>
<td>26072.30</td>
<td>26995.53</td>
<td>13916.30</td>
<td>43216.23</td>
<td>43158.28</td>
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<td>5114281 QUAD4</td>
<td>1016</td>
<td>0.00</td>
<td>41522.42</td>
<td>21810.66</td>
<td>15213.01</td>
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<td></td>
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<tr>
<td>5104077 QUAD4</td>
<td>2020</td>
<td>32111.92</td>
<td>29678.45</td>
<td>16055.96</td>
<td>673.02</td>
<td>43882.30</td>
<td>22107.47</td>
<td></td>
</tr>
<tr>
<td>5114281 QUAD4</td>
<td>1016</td>
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<td>41522.42</td>
<td>21810.66</td>
<td>0.00</td>
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<tr>
<td>5104077 QUAD4</td>
<td>2020</td>
<td>0.00</td>
<td>29678.45</td>
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<td>-43541.91</td>
<td>43882.30</td>
<td>22107.47</td>
<td></td>
</tr>
</tbody>
</table>
Based on Table 2.1.1-2, the following maximum stresses will be used to perform the margin calculation of the stress analysis for the Upper VC Joints.

\[ \sigma_t := 43810.74 \text{ psi} \quad (\text{max. tensile at R1049, Ele 5113635, Max-prin on Page 2.1.1-16}) \]
\[ \sigma_y := 43882.3 \text{ psi} \quad (\text{max. yield at R2020, Ele 5104077, Von-MISES on Page 2.1.1-17}) \]
\[ \sigma_s := 22107.47 \text{ psi} \quad (\text{max. shear at R2020, Ele 5104077, Von-MISES on Page 2.1.1-18}) \]

Upper VC Joints (thickness = 6 - 7 inches), 7050-T7451 Al. Aly. (AMS 4050)

- \( F_{tu} := 69000 \text{ psi} \) ultimate tensile strength
- \( F_{ty} := 59000 \text{ psi} \) tensile yield strength
- \( F_{su} := 44000 \text{ psi} \) shear strength

\( F_{tu} \) and \( F_{ty} \) are in psi, \( F_{su} \) is in ksi.

Factors of Safety:
- Yield Factor of Safety (FSy): 1.1
- Ultimate Factor of Safety (FSu): 1.4

Thermal Factors:
- Ultimate Thermal Factor (\( \eta_{ult} \)): 0.92
- Yield Thermal Factor (\( \eta_{yld} \)): 0.98

\( \eta_{ult} \) and \( \eta_{yld} \) are in percent.

**Margins of Safety**

- **Ultimate**
  
  \[ MSu := \frac{n_{ult} \cdot F_{tu}}{\sigma_t \cdot F_{su}} - 1 \]
  
  \( MSu = 0.035 \)

- **Yield**
  
  \[ MSy := \frac{n_{yld} \cdot F_{ty}}{\sigma_y \cdot F_{sy}} - 1 \]
  
  \( MSy = 0.198 \)

- **Shear**
  
  \[ MSs := \frac{n_{ult} \cdot F_{su}}{\tau_s \cdot F_{su}} - 1 \]
  
  \( MSs = 0.308 \)
7. Locations of the Maximum Stresses in the Upper VC Joints

a. Locations of the Elements with the Maximum Stresses

The Figure 1.2.1.15-6 below shows the FEA models of the Upper VC Joints isolated from the USS-02 FEA models. The locations of the elements with high stresses are also indicated in Figure 2.1.1-6.

![Diagram showing locations of maximum stresses](image)

Figure 2.1.1-6 Locations of the Elements with the Max. Stresses
b. Locations of the Maximum Stresses

![Location of the Max. Tensile Stress on the Plate Element](image1)

Figure 2.1.1-7a. Location of the Max. Tensile Stress on the Plate Element

![Location of Max. Von Mises at Ele 5104077 under Load Case R2020](image2)

Figure 2.1.1-7b. Location of the Max. Yield Stress on the Plate Element
Figure 2.1.1-7c. Location of the Max. Shear Stress on the Plate Element
2.1.2  Upper Trunnion Bridge Beam Assembly
Upper Trunnion Bridge Beam Analysis

Buckling Analysis:

Since part is a slender beam with compressive loads, buckling is critical.

In Finite Element Model of USS-02 version 2-04 shown in Figure 2.1.2-1, Upper Trunnion Bridge Beam includes Element Ids of 1101-1103, 1104-1106, 1107-1109, and 1110-1112. These elements have a Property Id of 1002.

![Figure 2.1.2-1: Upper Trunnion Bridge Beam shown in 2-04 Loads Model](image-url)
<table>
<thead>
<tr>
<th>Factor of Safety, ultimate</th>
<th>FSu := 1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material: AL 7075-T73511</td>
<td></td>
</tr>
<tr>
<td>(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2), Thickness: 0.250-0.499)</td>
<td></td>
</tr>
<tr>
<td>Compressive modulus, Ec := 10700000-psi</td>
<td></td>
</tr>
<tr>
<td>Ultimate tensile strength, ftu := 68000-psi</td>
<td></td>
</tr>
<tr>
<td>Tensile yield strength, fty := 57000-psi</td>
<td></td>
</tr>
<tr>
<td>Compression yield strength, fcy := 60000-psi</td>
<td></td>
</tr>
<tr>
<td>Ultimate shear strength, fsu := 38000-psi</td>
<td></td>
</tr>
<tr>
<td>Section: 5.062&quot; x 6.312&quot; x 0.3125&quot; Tube (Ref. Dwg# SDG39135728)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factor of Safety, yield</th>
<th>FSy := 1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. correction factor, ult &amp; yield:</td>
<td></td>
</tr>
<tr>
<td>(Ref. MIL-HDBK-5J, fig.3.7.6.1.1(c) &amp; (d), fig.3.7.6.1.4, and Appendix C2)</td>
<td></td>
</tr>
<tr>
<td>Maximum Temperature occurs during abort landing</td>
<td></td>
</tr>
<tr>
<td>Tmax := 150-deg</td>
<td></td>
</tr>
<tr>
<td>Temperature correction factor, ultimate: ctu := 0.94</td>
<td></td>
</tr>
<tr>
<td>Temperature correction factor, yield: cty := .96</td>
<td></td>
</tr>
<tr>
<td>Temperature correction factor, Ec: ccc := .98</td>
<td></td>
</tr>
</tbody>
</table>

Diagram:

```
5.062 ±.010

.250

(8.062) 6.312 ±.010

4X (.312)

4X .250
```
Shape Factor, \( f := 1.22 \)  

Supported length, \( L := 16.99 \text{ in} \)

Width, \( \text{Width, } D_y := 5.062 \text{ in} \)  
For torsional calculation, use: \( D_{ytor} := 5.062 \text{ in} \)

Depth, \( D_z := 6.312 \text{ in} \)  
For torsional calculation, use: \( D_{ztor} := 6.312 \text{ in} \)

Thickness, \( t := 0.3125 \text{ in} \)

Define: \( b := 2 \cdot t \)  

Properties of cross-section:  
\( \text{Area, } A := 6.718 \text{ in}^2 \)  
\( \text{Moment of Inertia, } I_y := 38.074 \text{ in}^4 \)  
\( I_z := 26.829 \text{ in}^4 \)  
\( \text{First moments, } Q_y := 7.272 \text{ in}^3 \)  
\( Q_z := 6.222 \text{ in}^3 \)  

Ref. Table 2.1.2-1
Table 2.1.2-1a: Property about Y-Y axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Az</th>
<th>Az^2</th>
<th>Icy</th>
<th>Iy'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.0620</td>
<td>0.3125</td>
<td>1.5819</td>
<td>6.1558</td>
<td>9.7376</td>
<td>59.9424</td>
<td>0.0129</td>
<td>59.9553</td>
</tr>
<tr>
<td>2</td>
<td>0.3125</td>
<td>5.6870</td>
<td>1.7772</td>
<td>3.1560</td>
<td>5.6088</td>
<td>17.7014</td>
<td>4.7898</td>
<td>22.4912</td>
</tr>
<tr>
<td>3</td>
<td>5.0620</td>
<td>0.3125</td>
<td>1.5819</td>
<td>0.1563</td>
<td>0.2472</td>
<td>0.0386</td>
<td>0.0129</td>
<td>0.0515</td>
</tr>
<tr>
<td>4</td>
<td>0.3125</td>
<td>5.6870</td>
<td>1.7772</td>
<td>3.1560</td>
<td>5.6088</td>
<td>17.7014</td>
<td>4.7898</td>
<td>22.4912</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>6.718</td>
<td>21.2024</td>
<td>104.9892</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ z_{\text{bar}} = 3.156 \]
\[ I_{yy} = 38.074 \]

Table 2.1.2-1b: Property about Z-Z axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>y</th>
<th>Ay</th>
<th>Ay^2</th>
<th>Icz</th>
<th>Iz'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3125</td>
<td>5.0620</td>
<td>1.5819</td>
<td>2.5310</td>
<td>4.0037</td>
<td>10.1334</td>
<td>3.3778</td>
<td>13.5112</td>
</tr>
<tr>
<td>2</td>
<td>5.6870</td>
<td>0.3125</td>
<td>1.7772</td>
<td>4.9058</td>
<td>8.7184</td>
<td>42.7705</td>
<td>0.0145</td>
<td>42.7849</td>
</tr>
<tr>
<td>3</td>
<td>0.3125</td>
<td>5.0620</td>
<td>1.5819</td>
<td>2.5310</td>
<td>4.0037</td>
<td>10.1334</td>
<td>3.3778</td>
<td>13.5112</td>
</tr>
<tr>
<td>4</td>
<td>5.6870</td>
<td>0.3125</td>
<td>1.7772</td>
<td>0.1563</td>
<td>0.2777</td>
<td>0.0434</td>
<td>0.0145</td>
<td>0.0579</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>6.718</td>
<td>17.0036</td>
<td>69.8653</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ y_{\text{bar}} = 2.531 \]
\[ I_{zz} = 26.829 \]

Table 2.1.2-1c: First Moment about Y-Y axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Qyy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.0620</td>
<td>0.3125</td>
<td>1.581875</td>
<td>2.9998</td>
<td>4.7452</td>
</tr>
<tr>
<td>2</td>
<td>0.3125</td>
<td>2.8435</td>
<td>0.88859375</td>
<td>1.4218</td>
<td>1.2634</td>
</tr>
<tr>
<td>4</td>
<td>0.3125</td>
<td>2.8435</td>
<td>0.88859375</td>
<td>1.4218</td>
<td>1.2634</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>Qyy= 7.272</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1.2-1d: First Moment about Z-Z axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>y</th>
<th>Qzz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3125</td>
<td>2.5310</td>
<td>0.7909375</td>
<td>1.2655</td>
<td>1.0009</td>
</tr>
<tr>
<td>2</td>
<td>5.6870</td>
<td>0.3125</td>
<td>1.7771875</td>
<td>2.3748</td>
<td>4.2204</td>
</tr>
<tr>
<td>3</td>
<td>0.3125</td>
<td>2.5310</td>
<td>0.7909375</td>
<td>1.2655</td>
<td>1.0009</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>Qzz= 6.222</td>
<td></td>
</tr>
<tr>
<td>Prepared By</td>
<td>Name</td>
<td>Date</td>
<td>File Name</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>---------------</td>
<td>--------</td>
<td>---------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brent Dyer</td>
<td>02/15/06</td>
<td>UTBB-bklg.mcd</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Checked By</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C. Bala</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Title</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USS-02 Upper Trunnion Bridge Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Section modulus,
\[
Sy := \frac{Iy}{\frac{1}{2} \cdot Dz} \quad Sy = 12.1 \text{ in}^3
\]

\[
Sz := \frac{Iz}{\frac{1}{2} \cdot Dy} \quad Sz = 10.6 \text{ in}^3
\]

Torsional constant / distance,
\[
JoR := 2 \cdot t \cdot (Dz_{tor} - t) \cdot (Dy_{tor} - t) \quad JoR = 17.8 \text{ in}^3
\]

Radii of gyration,
\[
ry := \sqrt{\frac{Iy}{A}} \quad ry = 2.4 \text{ in}
\]
\[
rz := \sqrt{\frac{Iz}{A}} \quad rz = 2 \text{ in}
\]

Fixity coefficient,
\[
K := 1.2 \quad (Ref. \ Structural \ Engineering \ Handbook, \ 4th \ Edition, \ Figure \ 5, \ p.8-10)
\]

Slenderness ratios,
\[
SRy := \frac{K \cdot L}{ry} \quad SRy = 8.6
\]
\[
SRz := \frac{K \cdot L}{rz} \quad SRz = 10.2
\]

Constants depending upon the mechanical properties of the material from Ref. Structural Engineering Handbook, 4th Edition, Formulas 5a-c, p.11-6:

\[
Bc := \text{fey} \cdot \text{cty} \cdot \left[ 1 + \left( \frac{\text{fey} \cdot \text{cty}}{2250000 \cdot \text{psi}} \right)^{\frac{1}{2}} \right] \quad Bc = 66816 \text{ psi}
\]

\[
Dc := \left( \frac{Bc}{10} \cdot \left( \frac{Bc}{E_c \cdot c_e c} \right)^{\frac{1}{2}} \right) \quad Dc = 533 \text{ psi}
\]

\[
Cc := 0.41 \cdot \frac{2 \cdot Bc}{3 \cdot Dc} \quad Cc = 34.2
\]
Title: USS-02 Upper Trunnion Bridge Beam

Compression allowables:

\[ F_{cy} := \begin{cases} \frac{B_c - D_c \cdot S_{Ry}}{E_c \cdot c_e \cdot \left( \frac{\pi}{S_{Ry}} \right)^2} & \text{if } S_{Ry} \leq C_c \\ F_{cy} = 62248 \text{ psi} \\ \end{cases} \]

\[ F_{cz} := \begin{cases} \frac{B_c - D_c \cdot S_{Rz}}{E_c \cdot c_e \cdot \left( \frac{\pi}{S_{Rz}} \right)^2} & \text{if } S_{Rz} \leq C_c \\ F_{cz} = 61375 \text{ psi} \\ \end{cases} \]

Ultimate shear allowables:

\[ V_{uly} := \frac{f_{su} \cdot c_{tu} \cdot I_z \cdot b}{Q_z} \quad V_{uly} = 96264 \text{ lbf} \]

\[ V_{ultz} := \frac{f_{su} \cdot c_{tu} \cdot I_y \cdot b}{Q_y} \quad V_{ultz} = 116887 \text{ lbf} \]

Ultimate torsion allowable:

\[ T_{ult} := f_{su} \cdot c_{tu} \cdot J_o \quad T_{ult} = 636143 \text{ in-lbf} \]

Axial tensile allowable:

\[ P_{t} := f_{tu} \cdot c_{tu} \cdot A \quad P_{t} = 429415 \text{ lbf} \]

Axial compression allowable:

\[ P_{cr} := \begin{cases} F_{cz} \cdot A & \text{if } F_{cy} \geq F_{cz} \\ F_{cy} \cdot A & \text{otherwise} \\ P_{cr} = 412315 \text{ lbf} \end{cases} \]

Ultimate bending allowables:

\[ M_{ulty} := S_y \cdot [f_{tu} \cdot c_{tu} + (f - 1) \cdot f_{ty} \cdot c_{ty}] \quad M_{ulty} = 916363 \text{ in-lbf} \]

\[ M_{ultz} := S_z \cdot [f_{tu} \cdot c_{tu} + (f - 1) \cdot f_{ty} \cdot c_{ty}] \quad M_{ultz} = 805171 \text{ in-lbf} \]

Combined bending and axial allowables:

\[ P_{ey} := F_{ey} \cdot A \quad P_{ey} = 6673465 \text{ lbf} \]

\[ P_{ez} := F_{ez} \cdot A \quad P_{ez} = 4702484 \text{ lbf} \]
Input for NASPOST was taken from 192 punch files in three different folders:

/hsm/bsommer/ams/nonlin/1000/2-04  
/hsm/bsommer/ams/nonlin/2000/2-04  
/hsm/bsommer/ams/nonlin/4000/2-04

MathCAD will read in all the load data from "utbb.txt" for the calculations below.

load := READPRN("utbb.txt")     i := 1 .. rows(load)

Element ID: ID := load(1)  
Load case number: LC := load(3)

+ At end A of beam element:

  Moment: M1a := load(3)*in-lbf  
           M2a := load(4)*in-lbf
  Shear force: V1a := load(5)*lbf  
                V2a := load(6)*lbf
  Axial force: Pa := load(7)*lbf
  Total torque: Toa := load(8)*in-lbf
  Warp torque: Warpa := load(9)*in-lbf

+ At end B of beam element:

  Moment: M1b := load(10)*in-lbf  
           M2b := load(11)*in-lbf
  Shear force: V1b := load(12)*lbf 
                V2b := load(13)*lbf
  Axial force: Pb := load(14)*lbf
  Total torque: Tob := load(15)*in-lbf
  Warp torque: Warpb := load(16)*in-lbf
Modify end torque by subtracting warping torque:

\[ T_{a,i} := |T_{oa,i}| - |Warp_{a,i}| \]
\[ T_{b,i} := |T_{ob,i}| - |Warp_{b,i}| \]

Shear ratios:

\[ R_{Sa,i} := \frac{\sqrt{V_{1a,i}}}{V_{ulty}} + \frac{\sqrt{V_{2a,i}}}{V_{ultz}} + \frac{T_{a,i}}{T_{ult}} \]
\[ R_{Sb,i} := \frac{\sqrt{V_{1b,i}}}{V_{ulty}} + \frac{\sqrt{V_{2b,i}}}{V_{ultz}} + \frac{T_{b,i}}{T_{ult}} \]

Tensile ratio at end A:

\[ R_{Ta,i} := \begin{cases} \frac{P_{a,i}}{P_{t}} + \frac{M_{2a,i}}{M_{ulty}} + \frac{M_{1a,i}}{M_{ultz}} & \text{if } P_{a,i} \geq 0 \text{-lbf} \\ \frac{P_{a,i}}{P_{cr}} + \frac{M_{2a,i}}{M_{ulty}} - \frac{1}{1 - \frac{P_{a,i}}{P_{ey}}} + \frac{M_{1a,i}}{M_{ultz}} - \frac{1}{1 - \frac{P_{a,i}}{P_{ez}}} & \text{otherwise} \end{cases} \]

Tensile ratio at end B:

\[ R_{Tb,i} := \begin{cases} \frac{P_{b,i}}{P_{t}} + \frac{M_{2b,i}}{M_{ulty}} + \frac{M_{1b,i}}{M_{ultz}} & \text{if } P_{b,i} \geq 0 \text{-lbf} \\ \frac{P_{b,i}}{P_{cr}} + \frac{M_{2b,i}}{M_{ulty}} - \frac{1}{1 - \frac{P_{b,i}}{P_{ey}}} + \frac{M_{1b,i}}{M_{ultz}} - \frac{1}{1 - \frac{P_{b,i}}{P_{ez}}} & \text{otherwise} \end{cases} \]

Combined Ratios:

\[ R_{ATIOa,i} := \sqrt{\left( R_{Ta,i} \right)^2 + \left( R_{Sa,i} \right)^2} \]
\[ R_{ATIOb,i} := \sqrt{\left( R_{Tb,i} \right)^2 + \left( R_{Sb,i} \right)^2} \]
\[ R_{ATIO,i} := \text{if } \left( R_{ATIOa,i} \geq R_{ATIOb,i}, R_{ATIOa,i}, R_{ATIOb,i} \right) \]

Margin of Safety:

\[ M_{S,i} := \frac{1}{R_{ATIO,i} \cdot F_{Su}} - 1 \]

\[ \min(MS) = 1.64 \]
**Reference - Buckling Margin of Safety**

The worst load case that yielded minimum margin of safety is shown below:

\[
\text{output} := \text{augment}((\text{ID, LC, MS}) \quad \text{sorted} := \text{csort}((\text{output, 3}))
\]

\[
\left(\text{sorted}^T\right)^{(i)^T} = (1103 \quad 4016 \quad 1.64)
\]

Based upon the output of SORT function above, it reads:

- **Element ID** = 1103
- **Load ID** = 4016
- **MS** = 1.64

**Beam and Socket Analysis: Sill Joint Side**

The following loop stacks element IDs 1101, 1104, 1109, and 1112 so that the data can be used only on the Sill Joint side of the beam element. The loop below takes the original data from the "loads" database and pulls out only the data for element IDs 1101, 1104, 1109, and 1112. This includes loads and moments from beam end A and B, although only end A loads and moments are used for the beam and socket analysis.

\[
\text{rows(load)} = 2304 \quad \text{cols(load)} = 16
\]

\[
\text{sillside} := k \leftarrow 0 \\
\text{for } i \in 1..\text{rows(load)} \\
\text{if load}_{i,1} = 1101 \lor \text{load}_{i,1} = 1104 \lor \text{load}_{i,1} = 1109 \lor \text{load}_{i,1} = 1112 \\
\text{then } k \leftarrow k + 1 \\
\text{newdata}_{k} \leftarrow (\text{load}^T)^{(i)}
\]

2.1.2-10 ESCG-4005-05-AMS-0039
Beam and Socket Analysis: Sill Joint Side (Moment about Y)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[ s_i = \text{rows(sillside)} \quad \text{rows(sillside)} = 768 \]

\[ \text{ID}_{1,i} := \text{sillside}_{i,1} \quad \text{Element ID} \]

\[ \text{LC}_{1,i} := \text{sillside}_{i,2} \quad \text{Load case number} \]

\[ b = 2a \]

\[ \text{S}_{1a_i} := \text{sillside}_{i,5} \cdot \text{lbf} \quad \text{S}_{2a_i} := \text{sillside}_{i,6} \cdot \text{lbf} \quad \text{Picking End A Shear from data} \]

\[ s_i := \sqrt{\left(\text{S}_{1a_i}\right)^2 + \left(\text{S}_{2a_i}\right)^2} \quad \text{Combined End A Shear} \]

\[ \text{P}_{i} := \text{sillside}_{i,7} \cdot \text{lbf} \quad \text{Picking End A Tension from data} \]

\[ \text{M}_{i} := \text{sillside}_{i,4} \cdot \text{in} \cdot \text{lbf} \quad \text{Picking Y Moment from data} \]

\[ \text{L}_{i} := 4.981 \cdot \text{in} \quad \text{Length of beam inside socket} \]

\[ \text{mls} \text{ ratio}_{i} := \begin{cases} 0, \text{ if } S_{i} \\
1000 \end{cases}, \frac{M_{i}}{S_{i}L_{i}} \quad \text{slm} \text{ ratio}_{i} := \begin{cases} 0, \text{ if } M_{i} \\
1000, \frac{L_{i}}{M_{i}} \end{cases} \]
Calculated values are then:

\[ w_{1i} := \begin{cases} \frac{K_{1i} \cdot M_{1i}}{L_i^2} & \text{if } \left| \text{slm} \right| \leq 1 \\ \frac{K_{1i} \cdot S_{1i}}{L_i} & \text{otherwise} \end{cases} \]

\[ w_{2i} := \begin{cases} \frac{K_{2i} \cdot M_{1i}}{L_i^2} & \text{if } \left| \text{slm} \right| \leq 1 \\ \frac{K_{2i} \cdot S_{1i}}{L_i} & \text{otherwise} \end{cases} \]

\[ a_i := K_a \cdot L_i \]

Max. shear

\[ S_{\text{max}} := \begin{cases} \frac{(-K_3) \cdot M_{1i}}{L_i} & \text{if } \left| \text{slm} \right| \leq 1 \\ -K_{2i} \cdot S_{1i} & \text{otherwise} \end{cases} \]

Max. Bending moment

\[ M_{\text{max}} := \begin{cases} K_m \cdot M_{1i} & \text{if } \left| \text{slm} \right| \leq 1 \\ K_m \cdot S_{1i} \cdot L_i & \text{otherwise} \end{cases} \]

Now check:

\[ S_{c_i} := \frac{w_{1i} - w_{2i}}{2} \cdot L_i \]

\[ M_{c_i} := \frac{(-w_{1i}) + 2 \cdot w_{2i}}{6} \cdot L_i^2 \]

Percent error:

\[ S_{\text{percentdiff}} := \frac{S_{c_i} - S_{1i}}{S_{1i}} \]

\[ M_{\text{percentdiff}} := \frac{M_{c_i} - M_{1i}}{M_{1i}} \]
To view graph with a specific load case, assign j a value \( j := 61 \)

Beam and Socket Coefficients
Note if \( \text{abs}(SL/M) \leq 1 \), Ratio = \( SL/M \), otherwise Ratio = \( M/SL \).
For this specific load case,

\[ S_j = 2978 \text{ lbf} \]

\[ M_j = 56189 \text{ in-lbf} \]

Max Shear: \[ S_{\text{max}} = 17547 \text{ lbf} \]

Shear Check: \[ S_c = 2978.4 \text{ lbf} \]

Max moment: \[ M_{\text{max}} = 56193 \text{ in-lbf} \]

Moment Check: \[ M_j = 56189 \text{ in-lbf} \]

With percent error

\[ S_{\text{percentdiff}} = -0\% \]

\[ M_{\text{percentdiff}} = 0\% \]

Actual Shear and Moment Distribution Inside Socket
Stresses

Total moment

Bending Tensile stress
\[ \sigma_i := \frac{M_{\text{maxi}}}{S_y} \]
\[ \max(\sigma) = 6988.3 \text{ psi} \]

Shear stress
\[ \tau_{\text{soc}i} := \frac{S_{\text{maxi}}}{A} \]
\[ \max(\tau_{\text{soc}}) = 3932.5 \text{ psi} \]

Axial tension stress
\[ \sigma_{ai} := \frac{P_i}{A} \]
\[ \max(\sigma_{a}) = 5306.49 \text{ psi} \]

Stress Ratios

Axial (ult)
\[ R_a := \frac{\sigma_{a} - FS_u}{\text{fluct}} \]

Bending (ult)
\[ R_b := \frac{F_{S_u} \cdot \sigma}{\text{fluct}} \]

Shear (ult)
\[ R_s := \frac{F_{S_u} \cdot \tau_{\text{soc}}}{\text{fluct}} \]

Axial (yld)
\[ R_{ay} := \frac{\sigma_{a} - FS_y}{\text{flyct}} \]

Bending (yld)
\[ R_{by} := \frac{F_{S_y} \cdot \sigma}{\text{flyct}} \]

Shear(yld)
\[ R_{sy} := \frac{F_{S_y} \cdot \tau_{\text{soc}}}{\text{flyct}} \]

Margins of safety

Margin of safety ultimate
\[ MS_{1u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \]
\[ \min(MS_{1u}) = 2.27 \]

Margin of safety yield
\[ MS_{1y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\[ \min(MS_{1y}) = 2.85 \]
Reference - Beam and Socket Margin of Safety - Sill Joint Side - Moment Y

See below for the ultimate minimum margin of safety with element and load case information:

\[
\begin{align*}
\text{output1} & := \text{augment(ID1,LC1,MS1u)} & \text{sorted} & := \text{csort(output1,3)} \\
\left(\text{sorted}^T\right)^T & = (1112 \ 4058 \ 2.27) \\
\text{Based upon the output of SORT function above, it reads:} \\
\text{Element ID} & = 1112 \\
\text{Load ID} & = 4058 \\
\text{MS1u} & = 2.27 \\
\text{match}(\text{min(MS1u)}, \text{MS1u}) & = (744)
\end{align*}
\]

See below for the yield minimum margin of safety with element and load case information:

\[
\begin{align*}
\text{output1} & := \text{augment(ID1,LC1,MS1y)} & \text{sorted} & := \text{csort(output1,3)} \\
\left(\text{sorted}^T\right)^T & = (1112 \ 4058 \ 2.85) \\
\text{Based upon the output of SORT function above, it reads:} \\
\text{Element ID} & = 1112 \\
\text{Load ID} & = 4058 \\
\text{MS1y} & = 2.85
\end{align*}
\]
Beam and Socket Analysis: Sill Joint Side (Moment about Z)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[ S_s \quad M \quad L \]

S and M are respectively beam shear in lbf and moment in in-lbf at end of socket. W is unit loading in lbf/in.

\[ i := 1 \text{...rows(sillside)} \]
\[ \text{rows(sillside)} = 768 \]

\[ \text{ID}_2_i := \text{sillside}_{i,1} \]
Element ID

\[ \text{LC}_2_i := \text{sillside}_{i,2} \]
Load case number

\[ \text{S}_3_i := \text{sillside}_{i,5} \cdot \text{lbf} \]
\[ \text{S}_4_i := \text{sillside}_{i,6} \cdot \text{lbf} \]
Picking End A Shear from data

\[ S_i := \sqrt{\left(\text{S}_3_i\right)^2 + \left(\text{S}_4_i\right)^2} \]
Combined End A Shear

\[ \text{P}_i := \text{sillside}_{i,7} \cdot \text{lbf} \]
Picking End A Tension from data

\[ \text{M}_i := \text{sillside}_{i,3} \cdot \text{in-lbf} \]
Picking Z Moment from data

\[ \text{L}_i := 4.981 \cdot \text{in} \]
Length of beam inside socket

\[ \text{mls}_\text{ratio}_i := \text{if} \left( S_i = 0, 1000, \frac{\text{M}_i}{\text{S}_i \cdot \text{L}_i} \right) \]
\[ \text{slm}_\text{ratio}_i := \text{if} \left( \text{M}_i = 0, 1000, \frac{\text{L}_i}{\text{M}_i} \right) \]
Calculated values are then:

\[ w_{1i} := \begin{cases} \frac{K_{1i} \cdot M_i}{(L_i)^2} & \text{if } |\text{slm}_{\text{ratio}_{i}}| \leq 1 \\ \frac{K_{1i} \cdot S_i}{L_i} & \text{otherwise} \end{cases} \]

\[ w_{2i} := \begin{cases} \frac{K_{2i} \cdot M_i}{(L_i)^2} & \text{if } |\text{slm}_{\text{ratio}_{i}}| \leq 1 \\ \frac{K_{2i} \cdot S_i}{L_i} & \text{otherwise} \end{cases} \]

\[ a_{i} := K_{ai} \cdot L_{i} \]

Max. shear

\[ S_{\text{max}_{i}} := \begin{cases} \frac{(-K_{s}i) \cdot M_i}{L_i} & \text{if } |\text{slm}_{\text{ratio}_{i}}| \leq 1 \\ -K_{2} \cdot S_{i} & \text{otherwise} \end{cases} \]

Max. Bending moment

\[ M_{\text{max}_{i}} := \begin{cases} K_{mi} \cdot M_{i} & \text{if } |\text{slm}_{\text{ratio}_{i}}| \leq 1 \\ K_{mi} \cdot S_{i} \cdot L_{i} & \text{otherwise} \end{cases} \]

Now check:

\[ S_{c_{i}} := \frac{w_{1i} - w_{2i}}{2} \cdot L_{i} \]

\[ M_{c_{i}} := \frac{(-w_{1i}) + 2 \cdot w_{2i}}{6} \cdot (L_{i})^2 \]

Percent error:

\[ S_{\text{percentdiff}_{i}} := \frac{S_{i} - S_{c_{i}}}{S_{i}} \]

\[ M_{\text{percentdiff}_{i}} := \frac{M_{i} - M_{c_{i}}}{M_{i}} \]
To view graph with a specific load case, assign \( j \) a value \( j := 744 \)

Beam and Socket Coefficients
Note if \( \text{abs}(SL/M) \leq 1 \), Ratio = \( SL/M \), otherwise Ratio = \( M/SL \).
For this specific load case,

\[ S_j = 4788 \text{ lbf} \]
\[ M_j = 16629 \text{ in-lbf} \]

\text{Max Shear:} \quad S_{\text{max},j} = -29607 \text{ lbf} \quad \text{Shear Check:} \quad S_{c,j} = 4788.3 \text{ lbf}

\text{Max moment:} \quad M_{\text{max},j} = 18764 \text{ in-lbf} \quad \text{Moment Check:} \quad M_j = 16629 \text{ in-lbf}

With percent error

\[ S_{\text{percentdiff},j} = 0\% \]
\[ M_{\text{percentdiff},j} = 0\% \]
Stresses

Total moment

Bending Tensile stress
\[ \sigma_i := \frac{M_{\max_i}}{S_z} \]
max(\(\sigma\)) = 3554.1 psi

Shear stress
\[ \tau_{soc_i} := \frac{S_{\max_i}}{A} \]
max(\(\tau_{soc}\)) = 4407.2 psi

Axial tension stress
\[ \sigma_{ai} := \frac{P_i}{A} \]
max(\(\sigma_{ai}\)) = 5306.49 psi

Stress Ratios

Axial (ult)
\[ R_a := \frac{\sigma_{a-\text{FSu}}}{\text{flu-ctu}} \]

Bending (ult)
\[ R_b := \frac{FS_u - \sigma}{\text{flu-ctu}} \]

Shear (ult)
\[ R_s := \frac{FS_u - \tau_{soc}}{\text{fsu-ctu}} \]

Axial (yld)
\[ R_{ay} := \frac{\sigma_{a-\text{FSy}}}{\text{fly-cty}} \]

Bending (yld)
\[ R_{by} := \frac{FS_y - \sigma}{\text{fly-cty}} \]

Shear(yld)
\[ R_{sy} := \frac{FS_y - \tau_{soc}}{\text{fly-cty}} \]

Margins of safety

Margin of safety ultimate
\[ MS_{2u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \]
\(\min(MS_{2u}) = 3.33\)

Margin of safety yield
\[ MS_{2y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\(\min(MS_{2y}) = 3.84\)
Reference - Beam and Socket Margin of Safety - Sill Joint Side - Moment Z

See below for the ultimate minimum margin of safety with element and load case information:

\[
\text{output1} := \text{augment}\left(\text{ID2, LC2, MS2u}\right) \quad \text{sorted} := \text{csort}\left(\text{output1, 3}\right)
\]

\[
\begin{pmatrix}
\text{sorted}^T
\end{pmatrix}
= (1101 \ 1016 \ 3.33)
\]

Based upon the output of SORT function above, it reads:

- Element ID = 1101
- Load ID = 1016
- \(\text{MS1u} = 3.33\)

See below for the yield minimum margin of safety with element and load case information:

\[
\text{output1} := \text{augment}\left(\text{ID2, LC2, MS2y}\right) \quad \text{sorted} := \text{csort}\left(\text{output1, 3}\right)
\]

\[
\begin{pmatrix}
\text{sorted}^T
\end{pmatrix}
= (1101 \ 1016 \ 3.84)
\]

Based upon the output of SORT function above, it reads:

- Element ID = 1101
- Load ID = 1016
- \(\text{MS1y} = 3.84\)
Beam and Socket Analysis: Upper Vacuum Case Joint Side

The following loop stacks element IDs 1103, 1106, 1107, and 1110 so that the data can be used only on the Sill Joint side of the beam element. The loop below takes the original data from the "loads" database and pulls out only the data for element IDs 1103, 1106, 1107, and 1110. This includes loads and moments from beam end A and B, although only end A loads and moments are used for the beam and socket analysis.

\[
\text{rows(load)} = 2304 \quad \text{cols(load)} = 16
\]

\[
vcsidedefinition := \begin{align*}
    k &\leftarrow 0 \\
    \text{for } i &\in 1..\text{rows(load)} \\
    \text{if } \text{load}_i,1 = 1103 &\lor \text{load}_i,1 = 1106 &\lor \text{load}_i,1 = 1107 &\lor \text{load}_i,1 = 1110 \\
    k &\leftarrow k + 1 \\
    \text{newdata}^{(\psi)} &\leftarrow (\text{load}^T)^{(\psi)} \\
    \text{newdata} &\leftarrow 
\end{align*}
\]
Beam and Socket Analysis: Upper Vacuum Case Joint Side (Moment about Y)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

![Diagram of Beam and Socket Analysis](image)

\[ S_{\text{side}} \]

\[ M_{\text{side}} \]

\[ L \]

\[ b=2a \]

\[ W2 \]

\[ W1 \]

\[ S \]

\[ M_{\text{max}} \]

\[ S_{\text{max}} \]

\[ P_{\text{side}} \]

\[ L_{\text{side}} = 4.860 \text{ in} \]

\[ mls_{\text{ratio}}_{i} := \begin{cases} 0, & S_{i} \leq 0, 1000, \\ \frac{M_{i}}{S_{i}L_{i}}, & \text{otherwise} \end{cases} \]

\[ slm_{\text{ratio}}_{i} := \begin{cases} 0, & M_{i} \leq 0, 1000, \\ \frac{L_{i}}{M_{i}}, & \text{otherwise} \end{cases} \]
Calculated values are then:

\[
w_{1i} := \begin{cases} 
\frac{K_{1i} \cdot M_{1i}}{L_{i}^2} & \text{if } |\text{slm} \_\text{ratio}_{1i}| \leq 1 \\
\frac{K_{1i} \cdot S_{1i}}{L_{i}} & \text{otherwise}
\end{cases}
\]

\[
w_{2i} := \begin{cases} 
\frac{K_{2i} \cdot M_{1i}}{L_{i}^2} & \text{if } |\text{slm} \_\text{ratio}_{2i}| \leq 1 \\
\frac{K_{2i} \cdot S_{1i}}{L_{i}} & \text{otherwise}
\end{cases}
\]

\[
a_{i} := K_{i} \cdot L_{i}
\]

Max. shear

\[
S_{\text{max}i} := \begin{cases} 
\frac{(-K_{s}) \cdot M_{i}}{L_{i}} & \text{if } |\text{slm} \_\text{ratio}_{1i}| \leq 1 \\
-K_{2i} \cdot S_{1i} & \text{otherwise}
\end{cases}
\]

Max. Bending moment

\[
M_{\text{max}i} := \begin{cases} 
K_{m} \cdot M_{i} & \text{if } |\text{slm} \_\text{ratio}_{1i}| \leq 1 \\
K_{m} \cdot S_{i} \cdot L_{i} & \text{otherwise}
\end{cases}
\]

Now check:

\[
S_{i} := \frac{w_{1i} - w_{2i}}{2} \cdot L_{i}
\]

\[
M_{i} := \frac{(-w_{1i}) + 2 \cdot w_{2i}}{6} \cdot (L_{i})^2
\]

Percent error:

\[
S_{\text{percentdiff}i} := \frac{S_{i} - S_{ci}}{S_{i}}
\]

\[
M_{\text{percentdiff}i} := \frac{M_{i} - M_{ci}}{M_{i}}
\]
To view graph with a specific load case, assign \( j \) a value \( j = 61 \)

Beam and Socket Coefficients
Note if \( \text{abs}(S\ell/M) \leq 1 \), \( \text{Ratio} = S\ell/M \), otherwise \( \text{Ratio} = M/S\ell \).
For this specific load case,

\[ S_j = 2175 \text{ lbf} \]
\[ M_j = -84529 \text{ in-lbf} \]

Max Shear: \[ S_{\text{max}j} = 25219 \text{ lbf} \]  
Shear Check: \[ S_cj = 2174.5 \text{ lbf} \]

Max moment: \[ M_{\text{max}j} = -84529 \text{ in-lbf} \]  
Moment Check: \[ M_j = -84529 \text{ in-lbf} \]

With percent error
\[ S_{\text{percentdiff}j} = -0 \% \]
\[ M_{\text{percentdiff}j} = 0 \% \]
Stresses

Total moment

Bending Tensile stress
\[ \sigma_i := \frac{M_{\text{max}}}{S_y} \quad \text{max}(\sigma) = 7706.3 \text{ psi} \]

Shear stress
\[ \tau_{soc_i} := \frac{S_{\text{max}}}{A} \quad \text{max}(\tau_{soc}) = 5534.8 \text{ psi} \]

Axial tension stress
\[ \sigma_{ai} := \frac{P_i}{A} \quad \text{max}(\sigma_a) = 5186.067 \text{ psi} \]

Stress Ratios

Axial (ult)
\[ R_a := \frac{\sigma_a \cdot F_{Su}}{f_{tu} \cdot c_{tu}} \]

Bending (ult)
\[ R_b := \frac{F_{Su} \cdot \sigma}{f_{tu} \cdot c_{tu}} \]

Shear (ult)
\[ R_s := \frac{F_{Su} \cdot \tau_{soc}}{f_{su} \cdot c_{tu}} \]

Axial (yld)
\[ R_{ay} := \frac{\sigma_a \cdot F_{Sy}}{f_{ty} \cdot c_{ty}} \]

Bending (yld)
\[ R_{by} := \frac{F_{Sy} \cdot \sigma}{f_{ty} \cdot c_{ty}} \]

Shear(yld)
\[ R_{sy} := \frac{F_{Sy} \cdot \tau_{soc}}{f_{sy} \cdot c_{ty}} \]

Margins of safety

Margin of safety ultimate
\[ MS_{3u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \quad \text{min}(MS_{3u}) = 1.28 \]

Margin of safety yield
\[ MS_{3y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad \text{min}(MS_{3y}) = 1.73 \]
**Reference - Beam and Socket Margin of Safety - Upper Vacuum Case Joint Side - Moment Y**

See below for the ultimate minimum margin of safety with element and load case information:

\[
\text{output1 := augment(ID3, LC3, MS3u)} \quad \text{sorted := csort(output1, 3)}
\]

\[
\left( \text{sorted}^T \right)^T = (1103 \ 4016 \ 1.28)
\]

Based upon the output of the SORT function above, it reads:

- **Element ID** = 1103
- **Load ID** = 4016
- **MS1u** = 1.28

See below for the yield minimum margin of safety with element and load case information:

\[
\text{output1 := augment(ID3, LC3, MS3y)} \quad \text{sorted := csort(output1, 3)}
\]

\[
\left( \text{sorted}^T \right)^T = (1103 \ 4016 \ 1.73)
\]

Based upon the output of the SORT function above, it reads:

- **Element ID** = 1103
- **Load ID** = 4016
- **MS1y** = 1.73
Beam and Socket Analysis: Upper Vacuum Case Joint Side (Moment about Z)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[
S_i := \sqrt{(S7a_i)^2 + (S8a_i)^2} \quad \text{Combined End A Shear}
\]

\[
P_i := \text{Picking End A Tension from data}
\]

\[
L_i := 4.860 \text{-in} \quad \text{Length of beam inside socket}
\]

\[
\text{mls}_\text{ratio}_i := \text{if} \left\{ S_i = 0, 1000, \frac{M_i}{S_i L_i} \right\} \quad \text{slm}_\text{ratio}_i := \text{if} \left\{ M_i = 0, 1000, \frac{L_i}{S_i M_i} \right\}
\]
Calculated values are then:

\[ w_1 := \begin{cases} \frac{K_1 \cdot M_i}{(L_i)^2} & \text{if } |\text{slm_ratio}_i| \leq 1 \\ \frac{K_1 \cdot S_i}{L_i} & \text{otherwise} \end{cases} \]

\[ w_2 := \begin{cases} \frac{K_2 \cdot M_i}{(L_i)^2} & \text{if } |\text{slm_ratio}_i| \leq 1 \\ \frac{K_2 \cdot S_i}{L_i} & \text{otherwise} \end{cases} \]

\[ a_i := K_a \cdot L_i \]

Max. shear

\[ S_{\text{max}_i} := \begin{cases} \frac{(-K_a) \cdot M_i}{L_i} & \text{if } |\text{slm_ratio}_i| \leq 1 \\ -K_2 \cdot S_i & \text{otherwise} \end{cases} \]

Max. Bending moment

\[ M_{\text{max}_i} := \begin{cases} K_m \cdot M_i & \text{if } |\text{slm_ratio}_i| \leq 1 \\ K_m \cdot S_i \cdot L_i & \text{otherwise} \end{cases} \]

Now check:

\[ S_{\text{ci}} := \frac{w_1_i - w_2_i}{2} \]

\[ M_{\text{ci}} := \frac{\left(-w_1_i + 2 \cdot w_2_i\right)}{6} \left(\frac{L_i}{2}\right)^2 \]

Percent error:

\[ S_{\text{percentdiff}_i} := \frac{S_i - S_{\text{ci}}}{S_i} \]

\[ M_{\text{percentdiff}_i} := \frac{M_i - M_{\text{ci}}}{M_i} \]
To view graph with a specific load case, assign \( j \) a value: \( j := 573 \)

Beam and Socket Coefficients
Note if \( \text{abs}(SL/M) \leq 1 \), Ratio = SL/M, otherwise Ratio = M/SL.
For this specific load case,

\[ S_j = 1863 \text{ lbf} \]

\[ M_j = -10461 \text{ in-lbf} \]

Max Shear: \[ S_{\text{max}} = 2853 \text{ lbf} \]  
Shear Check: \[ S_c = 1862.7 \text{ lbf} \]

Max moment: \[ M_{\text{max}} = -10461 \text{ in-lbf} \]  
Moment Check: \[ M_j = -10461 \text{ in-lbf} \]

With percent error

\[ S_{\text{percentdiff}} = -0\% \]
\[ M_{\text{percentdiff}} = -0\% \]

---

Actual Shear and Moment Distribution Inside Socket
Stresses

Total moment

Bending Tensile stress
\[ \sigma_i = \frac{M_{\text{max}i}}{S_z} \]
\[ \text{max}(\sigma) = 2894.4 \text{ psi} \]

Shear stress
\[ \tau_{\text{soc}i} = \frac{S_{\text{max}i}}{A} \]
\[ \text{max}(\tau_{\text{soc}}) = 3419.6 \text{ psi} \]

Axial tension stress
\[ \sigma_{ai} = \frac{P_i}{A} \]
\[ \text{max}(\sigma_a) = 5186.067 \text{ psi} \]

Stress Ratios

Axial (ult)
\[ R_a := \frac{\sigma_a F_{\text{Su}}}{\text{ftu-ctu}} \]

Bending (ult)
\[ R_b := \frac{F_{\text{Su}} \cdot \sigma}{\text{ftu-ctu}} \]

Shear (ult)
\[ R_s := \frac{F_{\text{Su}} \cdot \tau_{\text{soc}}}{\text{fsu-ctu}} \]

Axial (yld)
\[ R_{ay} := \frac{\sigma_a F_{\text{Sy}}}{\text{fty-cty}} \]

Bending (yld)
\[ R_{by} := \frac{F_{\text{Sy}} \cdot \sigma}{\text{fty-cty}} \]

Shear(yld)
\[ R_{sy} := \frac{F_{\text{Sy}} \cdot \tau_{\text{soc}}}{\text{fly-cty}} \]

Margins of safety

Margin of safety ultimate
\[ MS_{4u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \]
\[ \text{min}(MS_{4u}) = 3.89 \]

Margin of safety yield
\[ MS_{4y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\[ \text{min}(MS_{4y}) = 4.43 \]
Reference - Beam and Socket Margin of Safety - Upper Vacuum Case Joint Side - Moment Z

See below for the ultimate minimum margin of safety with element and load case information:

\[ \left( \begin{array}{c} \text{sorted}^T \end{array} \right)^T = (1103 \quad 1016 \quad 3.89) \]

Based upon the output of SORT function above, it reads:

- Element ID = 1103
- Load ID = 1016
- MS1u = 3.89

See below for the yield minimum margin of safety with element and load case information:

\[ \left( \begin{array}{c} \text{sorted}^T \end{array} \right)^T = (1103 \quad 1016 \quad 4.43) \]

Based upon the output of SORT function above, it reads:

- Element ID = 1103
- Load ID = 1016
- MS1y = 4.43

Summary of Minimum Margin of Safety:

The ultimate minimum margin of safety is 1.28 and occurs in the beam and socket analysis for the upper vacuum case side (Moment about Y). See page 2.1.2 - 28.

The yield minimum margin of safety is 1.73 and occurs in the beam and socket analysis for the upper vacuum case side (Moment about Y). See page 2.1.2 - 28.
2.1.3 Sill Joint
SUMMARY OF CRITICAL MARGINS OF SAFETY

Note:
1) A = Axial, S = Shear, B = Buckling, Bg = Bending
2) In structural analysis, factors of safety are 1.4, 1.1 and 1.0 for ultimate, yield and fail-safe loads, respectively
3) Margin of Safety that is greater than 5.0 is defined as High M.S.
4) U = Ultimate, Y = Yield, F = Fail-Safe
5) Allowables includes temperature red. factors of 0.92 and 0.98 for ultimate and yield, respectively

<table>
<thead>
<tr>
<th>Part Information</th>
<th>Structural Analysis</th>
</tr>
</thead>
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<tr>
<td>Member</td>
<td>DWG. No.</td>
</tr>
<tr>
<td>Sill Joint</td>
<td>SDG39135730</td>
</tr>
</tbody>
</table>
1. Introduction:

The picture shows the finite element model of the USS One of the four Sill Joints

This picture shows the finite element model of one of the sill joints.
2. Method:

- Four joints are modeled.
- These joints are meshed as CHEXA, CPENTA, CQUAD4, and CTRIA3 elements in FEMAP V.8.1.
- Material used is 7050-T7451 AL plate, BMS 7-323C.
- RSSCON elements are applied in connecting plate to solid elements.
- The joints are imported into USS-11-02 model.
- CBUSH and RBE elements are used to connect the joints to USS.
- The entire AMS-02 model is analyzed by using MSC/NASTRAN V.2001.
3. Model Information:

a. The NASTRAN data file is at: /hsm/vbulsara/ams2/silljnt

b. The model check of the Sill Joint is performed. The results below show that the FEA math model is correct.

i. For matrix KGG:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.325338E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.422667E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.424255E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>2.664973E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.564759E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>4.169498E-08</td>
<td>PASS</td>
</tr>
</tbody>
</table>

SOME POSSIBLE REASONS MAY LEAD TO THE FAILURE:
1. CELASI ELEMENTS CONNECTING TO ONLY ONE GRID POINT;
2. CELASI ELEMENTS CONNECTING TO NON-COINCIDENT POINTS;
3. CELASI ELEMENTS CONNECTING TO NON-COLINEAR DOF;
4. IMPROPERLY DEFINED DMIG MATRICES;

ii. For matrix KNN:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.105031E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.213717E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.563264E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>7.065958E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>6.315909E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>7.459586E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

SOME POSSIBLE REASONS MAY LEAD TO THE FAILURE:
1. MULTIPOINT CONSTRAINT EQUATIONS WHICH DO NOT SATISFY RIGID-BODY MOTION;
2. RBE3 ELEMENTS FOR WHICH THE INDEPENDENT DEGREE-OF-FREEDOM CANNOT DESCRIBE ALL POSSIBLE RIGID-BODY MOTIONS.

iii. For matrix KFF:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.105031E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.213717E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.563264E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>7.065958E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>6.315909E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>7.459586E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

SOME POSSIBLE REASONS MAY LEAD TO THE FAILURE:
1. CONSTRAINTS WHICH PREVENT RIGID-BODY MOTION.
3. Model Information: (Cont'd)

iv. Eigenvalue Summary: First six modes are zero; transition modes are well separated.

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>ORDER</th>
<th>REAL EIGENVALUES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-7.63E-06</td>
<td>2.76E-03</td>
<td>4.40E-04</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-4.62E-06</td>
<td>2.15E-03</td>
<td>3.42E-04</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-2.27E-06</td>
<td>1.51E-03</td>
<td>2.40E-04</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>-8.74E-07</td>
<td>9.35E-04</td>
<td>1.49E-04</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>7.03E-08</td>
<td>2.65E-04</td>
<td>4.22E-05</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>4.15E-06</td>
<td>2.04E-03</td>
<td>3.24E-04</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>1.32E+08</td>
<td>1.15E+00</td>
<td>1.83E+00</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1.47E+08</td>
<td>1.21E+04</td>
<td>1.93E+04</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>2.08E+08</td>
<td>1.44E+04</td>
<td>2.29E+04</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>2.46E+08</td>
<td>1.57E+04</td>
<td>2.49E+04</td>
</tr>
</tbody>
</table>

v. Weight Summary: (Total weight = 386.0886 * MASS = 386.0886x0.2173418= 83.9lbf)

The weight of an individual sill joint from the CAD model is 58.76 lbf. The weight of an individual sill joint from the finite element model is 52.88 lbf. The output from the weight generator above includes extraneous parts with the sill joint.
See Appendix C12 for the 6-02 loads model vs. 11-02 loads model strap verification.

### Table 1. STRAP FORCES FROM LOAD MODEL 6-02

<table>
<thead>
<tr>
<th>Load Case</th>
<th>2015</th>
<th>2016</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>90001</td>
<td>5346.9</td>
<td>5386.8</td>
<td>1025.7</td>
<td>1007.9</td>
</tr>
<tr>
<td>90002</td>
<td>4412</td>
<td>4264.9</td>
<td>8913</td>
<td>1759.9</td>
</tr>
<tr>
<td>90003</td>
<td>192.9</td>
<td>188.3</td>
<td>3573.5</td>
<td>3573.5</td>
</tr>
<tr>
<td>90004</td>
<td>197.2</td>
<td>182.4</td>
<td>3568.5</td>
<td>3568.5</td>
</tr>
<tr>
<td>90005</td>
<td>593.7</td>
<td>575.3</td>
<td>4696.5</td>
<td>4696.5</td>
</tr>
<tr>
<td>90006</td>
<td>12295.2</td>
<td>12375.3</td>
<td>12375.3</td>
<td>12375.3</td>
</tr>
<tr>
<td>90007</td>
<td>1545.1</td>
<td>1545.1</td>
<td>1417</td>
<td>1417</td>
</tr>
<tr>
<td>90008</td>
<td>7521</td>
<td>7239.2</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>90009</td>
<td>15838.8</td>
<td>16557.1</td>
<td>14639.5</td>
<td>14639.5</td>
</tr>
<tr>
<td>9011</td>
<td>59612</td>
<td>6675.2</td>
<td>2727.1</td>
<td>2727.1</td>
</tr>
<tr>
<td>9013</td>
<td>15443.8</td>
<td>17762.2</td>
<td>1417</td>
<td>1417</td>
</tr>
<tr>
<td>9014</td>
<td>12675.1</td>
<td>12423.4</td>
<td>1630.2</td>
<td>1630.2</td>
</tr>
<tr>
<td>9015</td>
<td>6956.1</td>
<td>5752.5</td>
<td>1623</td>
<td>1623</td>
</tr>
<tr>
<td>9016</td>
<td>12022.6</td>
<td>1216.2</td>
<td>1477</td>
<td>1477</td>
</tr>
</tbody>
</table>

### Table 2. STRAP FORCES FROM SILL JOINT MODEL

<table>
<thead>
<tr>
<th>Load Case</th>
<th>2015</th>
<th>2016</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>90001</td>
<td>3.3</td>
<td>0.7</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>90002</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>90003</td>
<td>0.1</td>
<td>0.1</td>
<td>10</td>
<td>5.0</td>
</tr>
<tr>
<td>90004</td>
<td>0.8</td>
<td>0.5</td>
<td>2.0</td>
<td>0.1</td>
</tr>
<tr>
<td>90005</td>
<td>2.5</td>
<td>4.5</td>
<td>12</td>
<td>4.0</td>
</tr>
<tr>
<td>90006</td>
<td>0.7</td>
<td>0.5</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>90007</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>90008</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>90009</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>9010</td>
<td>0.2</td>
<td>0.1</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>9011</td>
<td>0.7</td>
<td>0.4</td>
<td>2.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

### Table 3. PERCENT DIFFERENCE OF STRAP FORCES BETWEEN LOAD MODEL AND STRAP-PORT MODEL

<table>
<thead>
<tr>
<th>Load Case</th>
<th>2015</th>
<th>2016</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>90001</td>
<td>0.7</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>90002</td>
<td>3.3</td>
<td>0.8</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>90003</td>
<td>0.1</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>90004</td>
<td>0.0</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>90005</td>
<td>2.5</td>
<td>3.3</td>
<td>4.4</td>
<td>5.5</td>
</tr>
<tr>
<td>90006</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>90007</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>90008</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>90009</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>9010</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>9011</td>
<td>2.7</td>
<td>13</td>
<td>0.7</td>
<td>3.2</td>
</tr>
<tr>
<td>9012</td>
<td>3.4</td>
<td>0.2</td>
<td>0.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>
3. Model Information:  
(Cont'd)  
c. Additional model checks are based on the Trunnion loads. These loads in the Sill Joint model for each load case are closely matched with those in the loads model. Table 1 shows the results of the comparision done between these loads.

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>TRUNNION FORCES (lbs)</th>
<th>Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>From Load Model</td>
</tr>
<tr>
<td>1</td>
<td>2015</td>
<td>-23011.3</td>
<td>75527.3</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>-44496.3</td>
<td>28599.1</td>
</tr>
<tr>
<td>3</td>
<td>2015</td>
<td>0.0</td>
<td>-1292.5</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>0.0</td>
<td>-5324.2</td>
</tr>
<tr>
<td>5</td>
<td>2015</td>
<td>0.0</td>
<td>-30002.7</td>
</tr>
<tr>
<td>1</td>
<td>2016</td>
<td>-37455.2</td>
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</tr>
<tr>
<td>2</td>
<td>2016</td>
<td>-30049.1</td>
<td>29120.0</td>
</tr>
<tr>
<td>3</td>
<td>2016</td>
<td>0.0</td>
<td>-720.9</td>
</tr>
<tr>
<td>4</td>
<td>2016</td>
<td>0.0</td>
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</tr>
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<td>2016</td>
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</tr>
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</tr>
<tr>
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</tr>
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<td>2020</td>
<td>0.0</td>
<td>-38208.1</td>
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<td>-49506.2</td>
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<td>1053</td>
<td>36414.5</td>
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<tr>
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<td>1053</td>
<td>0.0</td>
<td>-919.6</td>
</tr>
<tr>
<td>4</td>
<td>1053</td>
<td>0.0</td>
<td>9127.6</td>
</tr>
</tbody>
</table>

**Table 1:** Check of the Trunnion Loads
4. Load and Constraint:

The entire AMS-02 math model is constrained at five Trunnion locations whose GRID IDs are 1 and 2 with DOF(1 and 3), 3 and 4 with DOF(3), and 5 with DOF(2).

All 128 load cases under the launch and landing situations were investigated in order to identify the worst result.

5. Result:

Material Properties: 7050-T7451 AL plate, BMS 7-323C

\[ F_{tu} := 66000 \text{ psi} \]
\[ F_{ty} := 56000 \text{ psi} \]
\[ F_{su} := 44000 \text{ psi} \]

Factor of Safety,

\[ F_{Su} := 1.4 \quad F_{Sy} := 1.1 \]

Temperature Ranges per Appendix C2:

Launch (40F to 120F)
Abort Landing (40F to 150F)
Nominal Landing (-78F to 101F)

Temperature reduction factor at 150°F,

\[ \gamma_u := 0.88 \quad \gamma_y := 0.95 \]

(Ref. MIL-HDBK-5J, Figure 3.7.4.2.1)
5. Result:

   ii. For the Sill Joints:

Maximum Von-Mises, principal, and shear stresses are selected from 128 load cases for the Sill Joints. NASPOST V.2.1 is used to sort out stresses within the load cases.

The finite element models of the lower vc joints are comprised of 4 different types of elements:
1. Solid, Brick 8
2. Solid, Wedge 6
3. Plate, Quad 4
4. Plate, Tria3

Those elements that had at least one node involved in an RBE or RSSCON connection were not considered in the margin of safety calculation. Also, unusually high bearing stresses were compared to hand calculations from a beam in socket analysis. The following maximum stresses were found in the solid hex elements:

\[
\sigma_{uy} := 27294.27 \text{ psi} \quad (Load \ Case \ 2016, \ Element \ 215327, \ See \ Appendix \ A16-15)
\]

\[
\sigma_{uu} := 26689.19 \text{ psi} \quad (Load \ Case \ 2016, \ Element \ 215327, \ See \ Appendix \ A16-15)
\]

\[
\sigma_{us} := 15060.02 \text{ psi} \quad (Load \ Case \ 2016, \ Element \ 215327, \ See \ Appendix \ A16-15)
\]

Margins of Safety,

\[
yield \quad MS_y := \frac{F_y \cdot \gamma_y}{FS_y \cdot \sigma_{uy}} - 1 \quad MS_y = 0.77
\]

\[
ultimate \quad MS_u := \frac{F_u \cdot \gamma_u}{FS_u \cdot \sigma_{uu}} - 1 \quad MS_u = 0.55
\]

\[
shear \quad MS_s := \frac{F_u \cdot \gamma_u}{FS_u \cdot \sigma_{us}} - 1 \quad MS_s = 0.84
\]
Element 215327 is located on the inside surface of the trunnion hole

Maximum von-Mises Stress

Minimum Principal Stress
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brent Dyer</td>
<td>02/22/06</td>
<td>silljnt.mcd</td>
</tr>
<tr>
<td>Checked By</td>
<td>C. Bala</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Engineering and Science Contract Group  
Structural Analysis Section  

Title: USS-02 Sill Joint

Maximum Shear Stress

2.1.3-12 ESCG-4005-05-AMS-0039
High concentrated stresses at the RBE and RSSCON elements were ignored. High stresses due to the Sill trunnion bearing against the Sill Joint socket were also ignored. Therefore, a beam and socket analysis was performed to compare the bearing stress at the outer Sill face to the minimum principle stress from the Sill Joint analysis.

Material: 7050-T7451 Al Plate (Ref. MIL-HDBK-5J, table 3.7.4.0 (b1))

Fbrua := 107·10³ psi

Fbrya := 84·10³ psi

Ultimate Bearing Allowable

Yield Bearing Allowable

**Beam and Socket analysis**

Vertical load at primary trunnion

\[ F_z := 74247 \text{ lbf} \]

Ref. AMS-02 model 6-02 Load Case 2016

Horizontal load at primary trunnion

\[ F_x := 36249.7 \text{ lbf} \]

Max. resultant load

\[ P_r := \sqrt{F_z^2 + F_x^2} \]

\[ P_r = 82623.59 \text{ lbf} \]

Treated as a Beam in a Socket, as per SMM, Memo 41a

Resultant shear Load

\[ S := P_r \]

\[ S = 82624 \text{ lbf} \]

Moment at edge of sill joint

\[ M := 0 \]

\[ M = 0 \text{ in-lbf} \]

Length of overlap

\[ L := 6.5 \text{ in} \]

\[ \text{sln_ratio} := \begin{cases} 1000.000 & M = 0, 1000, \frac{S}{M} \\ 0.000 & S = 0, 1000, \frac{M}{S \cdot L} \end{cases} \]

Rational for Width of Sill Joint

\[ W := 2b \]

\[ W_2 := \text{Width of Sill Joint} \]

\[ W_1 := \text{Width of Sill Joint} \]
Beam and Socket Coefficients
Note if abs(SL/M) <= 1, Ratio = SL/M, otherwise Ratio = M/SL.

Coefficients are:

\[ \begin{align*}
    K_a &= 0.33 \\
    K_s &= 0.35 \\
    K_m &= 0.15 \\
    K_1 &= 4 \\
    K_2 &= 2
\end{align*} \]
Calculated values are then:

\[ w_1 := \begin{cases} \frac{K_1 \cdot M}{L^2} & \text{if } |\text{slm\_ratio}| \leq 1 \\ \frac{K_1 \cdot S}{L} & \text{otherwise} \end{cases} \quad w_1 = 50845.3 \text{ lbf/in} \]

\[ w_2 := \begin{cases} \frac{K_2 \cdot M}{L^2} & \text{if } |\text{slm\_ratio}| \leq 1 \\ \frac{K_2 \cdot S}{L} & \text{otherwise} \end{cases} \quad w_2 = 25422.6 \text{ lbf/in} \]

\[ a := K_a \cdot L \quad a = 2.14 \text{ in} \]

Max. shear \[ S_{\text{max}} := \begin{cases} -\frac{K_s \cdot M}{L} & \text{if } |\text{slm\_ratio}| \leq 1 \\ -K_s \cdot S & \text{otherwise} \end{cases} \quad S_{\text{max}} = -28649.1 \text{ lbf} \]

Max. Bending moment \[ M_{\text{max}} := \begin{cases} K_m \cdot M & \text{if } |\text{slm\_ratio}| \leq 1 \\ K_m \cdot S \cdot L & \text{otherwise} \end{cases} \quad M_{\text{max}} = 79144.7 \text{ in-lbf} \]

Now check:

\[ S_c := \frac{w_1 - w_2}{2} \cdot L \quad S_c = 82623.6 \text{ lbf} \]

\[ M_c := -\frac{w_1 + 2 \cdot w_2}{6} \cdot L^2 \quad M_c = 0 \text{ in-lbf} \]

Percent error:

\[ S_{\text{percentdiff}} := \frac{S - S_c}{S} \quad S_{\text{percentdiff}} = 0\% \]

\[ M_{\text{percentdiff}} := \frac{M - M_c}{M} \quad M_{\text{percentdiff}} = 0\% \]
Actual Shear and Moment Distribution Inside Socket
Sill Joint Bearing Stress Calculation

\[ c := L - a \quad c = 4.364 \text{ in} \]  
Loaded length along machined hole in Sill Joint (from outer face)

\[ ds_{\text{min}} := 3.2455 \text{ in} \]  
Minimum Diameter of machined hole in Sill Joint

\[ d := \frac{2}{3} \cdot c \quad d = 2.91 \text{ in} \]  
Bearing length along machined hole in Sill Joint (from outer face)

\[ A_{\text{br}} := d \cdot ds_{\text{min}} \quad A_{\text{br}} = 9.443 \text{ in}^2 \]  
Area in compression

\[ P_{\text{br}} := \frac{1}{2} \cdot |w1| \cdot c \quad P_{\text{br}} = 110954.4 \text{ lbf} \]  
Equivalent Compression Load

\[ \sigma_{\text{br}} := \frac{P_{\text{br}}}{A_{\text{br}}} \quad \sigma_{\text{br}} = 11749.8 \text{ psi} \]  
Bearing Stress

Margin of safety

\[ MS_{\text{brult}} := \frac{F_{\text{bru}} \cdot \gamma_u}{F_{\text{su}} \cdot \sigma_{\text{br}}} - 1 \quad MS_{\text{brult}} = 4.724 \]  
Margin of safety ultimate

\[ MS_{\text{bruyld}} := \frac{F_{\text{bry}} \cdot \gamma_y}{F_{\text{sy}} \cdot \sigma_{\text{br}}} - 1 \quad MS_{\text{bruyld}} = 5.174 \]  
Margin of safety yield

Summary of Sill Joint FEA analysis

Ref. AMS-02 model 6-02 Load Case 2016

\[ \sigma_{uu} := 26689.19 \text{ psi} \]  
Ultimate Stress (Load Case 2016, Element 215327, See p. 2.1.3 - 10)

\[ MS := 0.55 \]  
Ultimate Margin of Safety (Ftu used for ultimate allowable, see p. 2.1.3 - 10)

Conclusion

The bearing stress calculation results in a 44% decrease over the ultimate stress picked out of the FEA model. Notice the margin of safety for the bearing stress calculation uses a higher allowable for bearing.
2.1.4 Sill Pin
Sill Pin Analysis SDG39135731

There are two retaining sill pins, one on each side of the sill block. This prevents the sill trunnion from moving in the Y direction. The pins are made of custom 455 steel in the H1000 condition. The max. axial load in the Y direction is the friction load on the pin. Each pin will be in single shear. The Sill Pin analysis is performed three times, once for each of the following cases; launch, nominal landing, and abort landing.

Material Properties:

Material: Custom 455, H1000 bar AMS5617 (Ref. MIL-HDBK-5J, table 2.6.4.0 (b))

- \( F_{tu} := 200000 \text{ psi} \)
- \( F_{ty} := 185000 \text{ psi} \)
- \( F_{su} := 124000 \text{ psi} \)
- \( E_t := 28.9 \times 10^6 \text{ psi} \)
- \( \omega := 0.28 \frac{\text{lb}f}{\text{in}^3} \)

Temp. correction factor for ultimate: (Ref. MIL-HDBK-5J, fig.2.6.4.2.1 and Appendix C2)
- Launch Temperatures (40 to 120 F): \( c_{1tu} := 0.98 \)
- Abort Landing Temp. (40 to 150 F): \( c_{2tu} := 0.97 \)
- Nominal Landing Temp. (-78 to 101 F): \( c_{3tu} := 0.99 \)

Factor of safety, ultimate: \( F_{Su} := 1.40 \)
Factor of safety, yield: \( F_{Sy} := 1.10 \)

Geometry:

- Diameter of sill pin: \( D := 0.2470 \text{ in} \)
- Shear area of each pin: \( A_s := \frac{\pi D^2}{4} \)
  \( A_s = 0.04792 \text{ in}^2 \)

Loads:
(Ref. section 2.1.5 - Sill Trunnion and Appendix A2 for NASPOST sort)

Launch Case:
- Vertical load at primary trunnion: \( F_{zl} := 35897.98 \text{ lbf} \)
  (Ref.AMS-02, loads model 2-04, Load case 1016, element ID 1, data file: maxtrunnionforces1000.lis)
- Horizontal load at primary trunnion: \( F_{xl} := 27569.3 \text{ lbf} \)
- Max. resultant load: \( Prl := \sqrt{F_{zl}^2 + F_{xl}^2} \)
  \( Prl = 45263 \text{ lbf} \)
- Friction load (10% of load): \( P_{fl} := Prl \times 0.100 \)
  \( P_{fl} = 4526.3 \text{ lbf} \)
Abort Landing Case:

Vertical load at primary trunnion \( F_{za} = 42137.67 \text{ lbf} \) (Ref.AMS-02, loads model 2-04, Load case 2016, element ID 1, data file: maxtrunnionforces2000.lis)

Horizontal load at primary trunnion \( F_{xa} = 9960.34 \text{ lbf} \)

Max.resultant load \( P_{ra} = \sqrt{F_{za}^2 + F_{xa}^2} \) \( P_{ra} = 43299 \text{ lbf} \)

Friction load (10% of load) \( P_{fa} = P_{ra} \cdot 0.100 \) \( P_{fa} = 4329.9 \text{ lbf} \)

Nominal Landing Case:

Vertical load at primary trunnion \( F_{zn} = 53777 \text{ lbf} \) (Ref.AMS-02, loads model 2-04, Load case 4016, element ID 1, data file: maxtrunnionforces4000.lis)

Horizontal load at primary trunnion \( F_{xn} = 14600 \text{ lbf} \)

Max.resultant load \( P_{rn} = \sqrt{F_{zn}^2 + F_{xn}^2} \) \( P_{rn} = 55724 \text{ lbf} \)

Friction load (10% of load) \( P_{fn} = P_{rn} \cdot 0.100 \) \( P_{fn} = 5572.4 \text{ lbf} \)

Shear Stress and Margin of Safety Calculations:

Launch Case:

Max. load in the Y direction \( P_{fl} = 4526 \text{ lbf} \)

Shear stress in each pin \( \tau_l := \frac{P_{fl}}{2 \cdot As} \) \( \tau_l = 47231 \text{ psi} \) (Note that the load is divided by 2 since there are 2 pins. each pin is in single shear)

Margin of safety \( M_{sl} := \frac{F_{su} \cdot c1tu}{\tau_l \cdot F_{su}} - 1 \) \( M_{sl} = 0.84 \)

Abort Landing Case:

Max. load in the Y direction \( P_{fa} = 4330 \text{ lbf} \)

Shear stress in each pin \( \tau_a := \frac{P_{fa}}{2 \cdot As} \) \( \tau_a = 45182 \text{ psi} \) (Note that the load is divided by 2 since there are 2 pins. each pin is in single shear)

Margin of safety \( M_{sa} := \frac{F_{su} \cdot c2tu}{\tau_a \cdot F_{su}} - 1 \) \( M_{sa} = 0.90 \)
Nominal Landing Case:

Max. load in the Y direction

\[ P_{fn} = 5572 \text{ lbf} \]

Shear stress in each pin

\[ \tau_n := \frac{P_{fn}}{2 \cdot A_s} \]

\[ \tau_n = 58147 \text{ psi} \]  
( Note that the load is divided by 2 since there are 2 pins. each pin is in single shear )

Margin of safety

\[ M_{Sn} := \frac{F_{su \cdot c3tu}}{\tau_n \cdot F_{Su}} - 1 \]

\[ M_{Sn} = 0.51 \]
2.1.5   Sill Trunnion
USS-02 Sill Trunnion Analysis

The objective of this analysis is to demonstrate the structural strength of the Sill Trunnion (SDG39135732). This analysis covers the primary and secondary trunnions, both are the same geometry except for the loads in the secondary trunnions are smaller than the primary trunnions. The difference in minimum temperature (for launch, abort landing, and nominal landing) can change the friction coefficient and therefore affects the axial load in the trunnion. The Sill Trunnion analysis is performed three times, once for each of the following cases; launch, nominal landing, and abort landing.
**Material Properties:**

Material: Custom 455, H1000 bar AMS5617  
(Ref. MIL-HDBK-5J, table 2.6.4.0 (b))

\[
\begin{align*}
F_{tu} &= 200 \cdot 10^{3} \text{psi} \\
F_{ty} &= 185 \cdot 10^{3} \text{psi} \\
F_{su} &= 124 \cdot 10^{3} \text{psi} \\
F_{bru} &= 409 \cdot 10^{3} \text{psi} \\
F_{bry} &= 343 \cdot 10^{3} \text{psi} \\
E_t &= 28.9 \cdot 10^{6} \text{psi} \\
\beta &= 0.28 \frac{\text{lbf}}{\text{in}^3} 
\end{align*}
\]

Temp. correction factor, ult & yield:  
(Ref. MIL-HDBK-5J, fig.2.6.4.2.1 and Appendix C2)

Launch Temperatures (40 to 120 F):  \(c_1t_u := 0.98\) \(c_1t_y := 0.98\)

Abort Landing Temp. (40 to 150 F):  \(c_2t_u := 0.97\) \(c_2t_y := 0.97\)

Nominal Landing Temp. (-78 to 101 F):  \(c_3t_u := 0.99\) \(c_3t_y := 0.99\)

Factor of safety, ultimate  \(F_{Su} := 1.40\)

Factor of safety, yield  \(F_{Sy} := 1.10\)

**Geometry:**

Section at edge of trunnion joint \(Y=89.0\)

Max. outer dia. of trunnion  \(d_{t\text{max}} := 3.2413\text{in}\)  
(Ref. drawing SDG39135732)

Min. outer diameter of trunnion  \(d_{t0} := 3.2395\text{in}\)

Inner diameter of trunnion at \(Y=89.0\)  \(d_{t89} := 1.90\text{in} + 0.005\text{in}\)  
\(d_{t89} = 1.905\text{in}\)

Area of cross-section  \(A_s := \frac{\frac{d_{t0}^2 - d_{t89}^2}{4}}{4}\)  
\(A_s = 5.392\text{in}^2\)

Moment of inertia  \(I_{s} := \frac{\frac{d_{t0}^4 - d_{t89}^4}{64}}{64}\)  
\(I_{s} = 4.76\text{in}^4\)

Section at \(Y=91.5\)

Inner diameter of trunnion at \(Y=91.5\)  \(d_{ti} := 2.62\text{in} + 0.005\text{in} \)  
\(d_{ti} = 2.625\text{in}\)  
(Ref. drawing SDG39135732)

Area of cross-section  \(A_{s1} := \frac{\frac{d_{t0}^2 - d_{ti}^2}{4}}{4}\)  
\(A_{s1} = 2.83\text{in}^2\)

Moment of inertia  \(I_{s1} := \frac{\frac{d_{t0}^4 - d_{ti}^4}{64}}{64}\)  
\(I_{s1} = 3.075\text{in}^4\)
Loads:
The following NASPOST results were sorted for maximum forces in the x and z-directions for all trunnions. The sill trunnions have element IDs 1, 2, 3, and 4 in loads model 2-04 (Ref. Appendix A2 for NASPOST sort):

### MAX MAG X AND Z LAUNCH TRUNNION FORCES ###

<table>
<thead>
<tr>
<th>ID</th>
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<th>FX</th>
<th>FY</th>
<th>FZ</th>
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<tr>
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<td>-2.756930E+04</td>
<td>0.000000E+00</td>
<td>3.589798E+04</td>
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<tr>
<td>2</td>
<td>1005</td>
<td>-3.181006E+04</td>
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<tr>
<td>3</td>
<td>1019</td>
<td>0.000000E+00</td>
<td>0.000000E+00</td>
<td>-2.870820E+04</td>
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<tr>
<td>4</td>
<td>1057</td>
<td>0.000000E+00</td>
<td>0.000000E+00</td>
<td>1.901807E+04</td>
</tr>
</tbody>
</table>

### MAX MAG X AND Z ABORT LANDING TRUNNION FORCES ###

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</thead>
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<td>0.000000E+00</td>
<td>2.806803E+04</td>
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<tr>
<td>3</td>
<td>2019</td>
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### MAX MAG Y AND Z NOMLANDING TRUNNION FORCES ###

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<td>0.000000E+00</td>
<td>0.000000E+00</td>
<td>3.591928E+04</td>
</tr>
</tbody>
</table>

Launch Case:

Vertical load at primary trunnion

\[ F_z = 35897.98 \text{ lbf} \]  
(Ref.AMS-02, loads model 2-04, Load case 1016, element ID 1, data file: maxtrunnionforces1000.lis)

Horizontal load at primary trunnion

\[ F_x = 27569.3 \text{ lbf} \]

Max. resultant load

\[ Pr = \sqrt{F_x^2 + F_z^2} \]

\[ Pr = 45263 \text{ lbf} \]
The tolerances between the sill trunnion and the sill joint are tight. Due to this tight tolerance, any side load transferred through the sill trunnion is reacted by the sill joint.

Moment arm from load to edge of sill plate
\[ d_2 := (94.0 \text{ in} - 89.0 \text{ in}) + 0.5 \text{ in} \]
\[ d_2 = 5.5 \text{ in} \]

(Ref. Appendix C6 for the 0.5" dynamic excursion)

Max. bending moment at edge of sill plate
\[ M_b := Pr \cdot d_2 \]
\[ M_b = 248946 \text{ in lbf} \]

Friction coefficient is assessed based on Figure 4.1.1.1-1 of NSTS-21000-IDD-ISS, Ref. Appendix C7.

\[ P := Pr \quad P = 45263 \text{ lbf} \]

\[ T := 40 \text{-deg} \quad \text{(It is conservative to use the minimum temperature (Ref. Appendix C2))} \]
Friction coefficient

\[ \text{Friction coefficient} = 0.100 \]

Friction load (10% of load)

\[ \text{Pf} := \text{Pr} \times \text{Pf} = 4526.3 \text{-lbf} \]

Friction moment

\[ \text{Mf} := \text{Pf} \times \frac{\text{d}t_{\text{max}}}{2} \]

\[ \text{Mf} = 7335.5 \text{-in\cdotlbf} \]

Total moment

\[ M := Mb + Mf \]

\[ M = 256281.6 \text{-in\cdotlbf} \]

Applied limit stress in shaft

\[ \sigma_l := \left( \frac{M \times \text{d}t_{\text{max}}}{2Is} \right) \]

\[ \sigma_l = 87264.2 \text{-psi} \]

Plastic bending allowable (Ref. NASA TM X-73305, sect B.4.5)

Section factor

Outer radius

\[ \text{ro} := \frac{d_{\text{to}}}{2} \quad \text{ro} = 1.62 \text{-in} \]

Inner radius

\[ \text{ri} := \frac{d_{\text{t}89}}{2} \quad \text{ri} = 0.953 \text{-in} \]

Area of semicircular segment

\[ \text{Ase} := \frac{u}{2} \left( \text{ro}^2 - \text{ri}^2 \right) \]

\[ \text{Ase} = 2.696 \text{-in}^2 \]

Distance of neutral axis from center line

\[ \text{ybar} := \frac{4}{3 \cdot u} \left( \frac{\text{ro}^3 - \text{ri}^3}{\text{ro}^2 - \text{ri}^2} \right) \]

\[ \text{ybar} = 0.837 \text{-in} \]

First moment of area

\[ Q := \text{Ase} \cdot \text{ybar} \]

\[ Q = 2.257 \text{-in}^3 \]
Distance of extreme fiber from centerline of shaft  
\[ c := \frac{\text{dtmax}}{2} \quad c = 1.621\text{-in} \]

Section factor  
\[ K := \frac{2 \cdot Q \cdot c}{I_s} \quad K = 1.537 \]

Allowable bending modulus of rupture ult.  
\[ \sigma_p := 301000\text{-psi} \]  
(Ref.NASA TM X-73305, sect B.4.5 fig. B4.5.2-7)

Allowable bending modulus of rupture yld.  
\[ \sigma_y := 210000\text{-psi} \]

Check

Section factor  
\[ K := \frac{1.698}{\frac{\left(\frac{3}{r_o} - \frac{3}{r_i}\right)}{\frac{4}{r_o^4} - \frac{4}{r_i^4}}} \quad K = 1.5364 \]  
(Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)

\[ f_{mu} := 200000\text{-psi} \quad f_{ou} := 192000\text{-psi} \]  
(Ref. Bruhn, table C3.2 page C3.11)

\[ f_{my} := 176000\text{-psi} \quad f_{oy} := 65000\text{-psi} \]

\[ F_{bu} := f_{mu} + f_{ou} \cdot (K - 1) \quad F_{bu} = 302996\text{-psi} \]  
(Ref. Bruhn page C3.3, equation 3)

\[ F_{by} := f_{my} + f_{oy} \cdot (K - 1) \quad F_{by} = 210868.4\text{-psi} \]  
(These numbers match the \( \sigma_p \) and \( \sigma_y \) closely)

Axial tension stress  
\[ a := \frac{P_f}{A_s} \quad a = 839\text{-psi} \]

Shear stress  
\[ y := \frac{P_r}{A_s} \quad y = 8394\text{-psi} \]

Stress ratios, Ultimate

Stress ratio in axial, ultimate  
\[ R_{au} := \frac{a \cdot F_{Su}}{F_{t u} \cdot c \cdot f_{tu}} \quad R_{au} = 0.006 \]

Stress ratio in bending, ultimate  
\[ R_{bu} := \frac{a \cdot F_{Su}}{F_{bu} \cdot c \cdot f_{tu}} \quad R_{bu} = 0.411 \]

Stress ratio in shear, ultimate  
\[ R_{su} := \frac{y \cdot F_{Su}}{F_{su} \cdot c \cdot f_{tu}} \quad R_{su} = 0.097 \]

Margin of safety ultimate  
\[ MS_{u} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \quad MS_{u} = 1.33 \]
Stress ratios, Yield

Stress ratio in axial, yield
Ray := \( \frac{a \cdot F_{Sy}}{F_{ty \cdot c1ty}} \)
Ray = 0.005

Stress ratio in bending, yield
Rby := \( \frac{d \cdot F_{Sy}}{F_{by \cdot c1ty}} \)
Rby = 0.465

Stress ratio in shear, yield
Rsy := \( \frac{y \cdot F_{Sy}}{0.5F_{ty \cdot c1ty}} \)
Rsy = 0.102

Margin of safety, yield
MSy := \( \frac{1}{\sqrt{(Ray + Rby)^2 + Rsy^2}} - 1 \)
MSy = 1.08

Check section at Y=91.5

Total Moment at Y=91.5
M1 := Pr \cdot (94.0\text{ in} - 91.5\text{ in} + 0.5\text{ in}) + Mf \quad M1 = 143124.3\text{ in}\cdot\text{lbf}
(Ref. Appendix C6 for the 0.5” dynamic excursion)

Applied limit stress in shaft
\( d_l := \left( \frac{M1 \cdot d_{max}}{2 \cdot I_{s1}} \right) \)
\( d_l = 75423.3\text{ psi} \)

Plastic bending allowable (Ref.NASA TM X-73305,sect B.4.5)

Section factor

Outer radius
ro := \( \frac{d_{to}}{2} \)
ro = 1.62 in

Inner radius
ri := \( \frac{d_{ti}}{2} \)
ri = 1.313 in

Area of semicircular segment
Ase := \( \frac{u}{2} \left( \frac{ro^2 - ri^2}{3} \right) \)
Ase = 1.415 in

Distance of neutral axis from center line
ybar := \( \frac{4}{3 \cdot u} \left( \frac{ro^3 - ri^3}{ro^2 - ri^2} \right) \)
ybar = 0.937 in

First moment of area
Q := Ase \cdot ybar \quad Q = 1.326 \text{ in}^3

Distance of extreme fiber from centerline of shaft
c := \( \frac{d_{max}}{2} \)
c = 1.62 in
### Structural Analysis Section

**Title**
USS-02 Sill Trunnion

**Section factor**
\[ K := \frac{2}{c} \frac{Q}{I_{s1}} \]

- **Allowable bending modulus of rupture ult.**
  \[ p_1 = 274000 \text{ psi} \]
  (Ref. NASA TM X-73305, sect B.4.5 fig. B4.5.2-7)

- **Allowable bending modulus of rupture yld.**
  \[ y_1 = 200000 \text{ psi} \]

**Check**

- **Section factor**
  \[ K := 1.698 \frac{r_0}{r_1} \left( \frac{r_0^3 - r_1^3}{r_0^4 - r_1^4} \right) \]
  \[ K = 1.3968 \]
  (Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)

- **fmu** := 200000-psi
- **fou** := 192000-psi
  (Ref. Bruhn, table C3.2 page C3.11)

- **fmy** := 176000-psi
- **foy** := 65000-psi

- **Fbu1** := **fmu** + **fou** \((K - 1)\)
  \[ Fbu1 = 276176.9 \text{ psi} \]
  (Ref. Bruhn page C3.3, equation 3)
  (These numbers match the \(a_p1\) and \(a_y1\) closely)

- **Fby1** := **fmy** + **foy** \((K - 1)\)
  \[ Fby1 = 201789.1 \text{ psi} \]

**Axial tension stress**
\[ a_1 := \frac{P}{A_{s1}} \]
\[ a_1 = 1599.2 \text{ psi} \]

**Shear stress**
\[ y_1 := \frac{P_r}{A_{s1}} \]
\[ y_1 = 15992 \text{ psi} \]

**Stress ratios, Ultimate**

- **Stress ratio in axial, ultimate**
  \[ Rau1 := \frac{a_1 \cdot \text{FSu}}{F_{tu \cdot c1tu}} \]
  \[ Rau = 0.006 \]

- **Stress ratio in bending, ultimate**
  \[ Rbu1 := \frac{a_1 \cdot \text{FSu}}{F_{bu1 \cdot c1tu}} \]
  \[ Rbu = 0.411 \]

- **Stress ratio in shear, ultimate**
  \[ Rsu1 := \frac{y_1 \cdot \text{FSu}}{F_{su \cdot c1tu}} \]
  \[ Rsu = 0.097 \]

**Margin of safety ultimate**
\[ MSu := \frac{1}{\sqrt{(Rau + Rbu)^2 + Rsu^2}} - 1 \]
\[ MSu = 1.26 \]

---

2.1.5-9 ESCG-4005-05-AMS-0039
Stress ratios, Yield

Stress ratio in axial, yield
\[
\text{Ray}_1 := \frac{a_1 \cdot F_{Sy}}{F_{ty} \cdot c_{1ty}} \quad \text{Ray}_1 = 0.01
\]

Stress ratio in bending, yield
\[
\text{Rby}_1 := \frac{b_1 \cdot F_{Sy}}{F_{by} \cdot c_{1ty}} \quad \text{Rby}_1 = 0.42
\]

Stress ratio in shear, yield
\[
\text{Rsy}_1 := \frac{y_1 \cdot F_{Sy}}{0.5 \cdot F_{ty} \cdot c_{1ty}} \quad \text{Rsy}_1 = 0.194
\]

Margin of safety yield
\[
\text{MSy} := \frac{1}{\sqrt{(\text{Ray}_1 + \text{Rby}_1)^2 + \text{Rsy}_1^2}} - 1 \quad \text{MSy} = 1.12
\]

Beam and Socket analysis - Launch Case
Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[ S := Pr \quad S = 45263 \cdot \text{lb} \]

\[ M := Mb + Mf \quad M = 256282 \cdot \text{in} \cdot \text{lb} \]

Length of overlap
\[ L := 6.5 \cdot \text{in} \]

\[ \text{slm}_\text{ratio} := \text{if} \left( M \neq 0, 1000, \frac{L}{M} \right) \quad \text{slm}_\text{ratio} = 1.148 \]

\[ \text{mls}_\text{ratio} := \text{if} \left( S \neq 0, 1000, \frac{M}{S \cdot L} \right) \quad \text{mls}_\text{ratio} = 0.871 \]
Beam and Socket Coefficients

Note if \( \text{abs} \left( \frac{SL}{M} \right) \leq 1 \), Ratio = \( \frac{SL}{M} \), otherwise Ratio = \( \frac{M}{SL} \).

Coefficients are:

\[
\begin{align*}
Ka &= 0.43 \\
Ks &= 1.64 \\
Km &= 0.95 \\
K1 &= 9.23 \\
K2 &= 7.23
\end{align*}
\]
Calculated values are then:

\[
w_1 := \begin{cases} \frac{K_1 \cdot M}{L^2} & \text{if } |\text{slm\_ratio}| \leq 1 \\ \frac{K_1 \cdot S}{L} & \text{otherwise} \end{cases}
\]

\[
w_1 = \frac{64249.1 \text{lbf}}{\text{in}}
\]

\[
w_2 := \begin{cases} \frac{K_2 \cdot M}{L^2} & \text{if } |\text{slm\_ratio}| \leq 1 \\ \frac{K_2 \cdot S}{L} & \text{otherwise} \end{cases}
\]

\[
w_2 = \frac{50322.1 \text{lbf}}{\text{in}}
\]

\[a := K_a \cdot L \quad a = 2.79 \text{in}
\]

Max. shear \(S_{\text{max}} := \begin{cases} -\frac{K_s \cdot M}{L} & \text{if } |\text{slm\_ratio}| \leq 1 \\ -K_s \cdot S & \text{otherwise} \end{cases}\)

\[S_{\text{max}} = -74174.3 \text{lbf}
\]

Max. Bending moment \(M_{\text{max}} := \begin{cases} K_m \cdot M & \text{if } |\text{slm\_ratio}| \leq 1 \\ K_m \cdot S \cdot L & \text{otherwise} \end{cases}\)

\[M_{\text{max}} = 280254.5 \text{in-lbf}
\]

Now check:

\[
Sc := \frac{w_1 - w_2}{2} \cdot L \\
Sc = 45262.9 \text{lbf}
\]

\[
Mc := -\frac{w_1 + 2 \cdot w_2}{6} \cdot L^2 \\
Mc = 256281.6 \text{in-lbf}
\]

Percent error:

\[
S_{\text{percentdiff}} := \frac{S - Sc}{S} \\
S_{\text{percentdiff}} = 0 \%
\]

\[
M_{\text{percentdiff}} := \frac{M - Mc}{M} \\
M_{\text{percentdiff}} = -0 \%
\]
Actual Shear and Moment Distribution Inside Socket

**Case 1: Max. bending moment at Y=88.075 - Launch Case**

Max. moment occurs at \( b = 2a \) from inner end

- \( b = 2 \cdot a \)
- \( b = 5.575 \text{ in} \)

**Shear**

- \( S = 0 \text{ lbf} \)

**Max. Bending moment**

- \( M_{\text{max}} = 280254.5 \text{ in lbf} \)

**Section properties** at 5.575 in from inner end \( y=88.075 \)

- Inner diameter of trunnion at \( y=88.075 \)
  - \( d_{8807} := 1.9 \text{ in} + 0.005 \text{ in} \)
  - \( d_{8807} = 1.905 \text{ in} \)

- **Area of cross-section at 88.075**
  - \( A_s := \frac{u \left( dt^{2} - dt_{8807}^{2} \right)}{4} \)
  - \( A_s = 5.392 \text{ in}^2 \)

- **Moment of inertia at 88.075**
  - \( I_s := \frac{u \left( dt^{4} - dt_{8807}^{4} \right)}{64} \)
  - \( I_s = 4.76 \text{ in}^4 \)
Section modulus

\[ S_1 := \frac{I_s}{d_{\text{max}}} \]

\[ S_1 = 2.937 \text{ in}^3 \]

Total moment

\[ M_{8807} := M_{\text{max}} \]

\[ M_{8807} = 280254.5 \text{ in lbf} \]

Combined Tensile stress

\[ =8807 := \frac{M_{8807}}{S_1} \]

\[ =8807 = 95427 \text{ psi} \]

Shear stress

\[ y_{8807} := \frac{S}{A_s} \]

\[ y_{8807} = 0 \text{ psi} \]

Stress Ratios

**Axial (ult)**

\[ R_{\text{au}} := \frac{a \cdot F_{S_u}}{F_{t u} \cdot c_{1 tu}} \]

\[ R_{\text{au}} = 0.006 \]

**Bending(ult)**

\[ R_{\text{bu}} := \frac{F_{S_u} \cdot =8807}{F_{b u} \cdot c_{1 tu}} \]

\[ R_{\text{bu}} = 0.450 \]

**Shear(ult)**

\[ R_{\text{su}} := \frac{F_{S_u} \cdot y_{8807}}{F_{s u} \cdot c_{1 tu}} \]

\[ R_{\text{su}} = 0.000 \]

**Axial (yld)**

\[ R_{\text{ay}} := \frac{a \cdot F_{S_y}}{F_{t y} \cdot c_{1 ty}} \]

\[ R_{\text{ay}} = 0.005 \]

**Bending(yld)**

\[ R_{\text{by}} := \frac{F_{S_y} \cdot =8807}{F_{b y} \cdot c_{1 ty}} \]

\[ R_{\text{by}} = 0.508 \]

**Shear(yld)**

\[ R_{\text{sy}} := \frac{F_{S_y} \cdot y_{8807}}{0.50 F_{t y} \cdot c_{1 ty}} \]

\[ R_{\text{sy}} = 0.000 \]

Margin of safety

**Margin of safety ultimate**

\[ M_{S_u} := \frac{1}{\sqrt{(R_{\text{au}} + R_{\text{bu}})^2 + R_{\text{su}}^2}} - 1 \]

\[ M_{S_u} = 1.19 \]

**Margin of safety yield**

\[ M_{S_y} := \frac{1}{\sqrt{(R_{\text{ay}} + R_{\text{by}})^2 + R_{\text{sy}}^2}} - 1 \]

\[ M_{S_y} = 0.949 \]
Case 2 Max. shear at Y=85.288 - Launch Case

When shear is maximum the bending moment is 0.41 of Mmax

Max. shear \( S_{\text{max}} = -74174\text{-lbf} \)

Bending moment \( M_s := 0.41\cdot M_{\text{max}} \quad M_s = 114904.3\text{-in-lbf} \)

Max. shear occurs at \( a \) from inner end \( a = 2.788\text{ in} \) \((Y=85.288)\)

Section properties at 2.788 in from inner end \( y=85.288 \) Max. shear location

inner diameter at \( Y=85.288 \) \( d_t 8528 := 1.9\text{-in} + 0.03\text{-in} \quad d_t 8528 = 1.93\text{-in} \)

Wall thickness at \( y=85.288 \) \( w_t 8528 := \frac{d_o - d_t 8528}{2} \quad w_t 8528 = 0.655\text{-in} \)

Area of cross-section at \( 85.288 \) \( A_s := \frac{u\cdot(d_o^2 - d_t 8528^2)}{4} \quad A_s = 5.317\text{-in}^2 \)

Moment of inertia at \( 85.288 \) \( I_s := \frac{u\cdot(d_o^4 - d_t 8528^4)}{64} \quad I_s = 4.725\text{-in}^4 \)

Section modulus \( S_1 := \frac{I_s}{d_{\text{max}}} \quad S_1 = 2.915\text{-in}^3 \)

Total moment \( M_{8528} := M_s \quad M_{8528} = 114904.3\text{-in-lbf} \)

Tensile stress \( \sigma_{8528} := \frac{M_{8528}}{S_1} \quad \sigma_{8528} = 39411.7\text{-psi} \)

Shear stress \( \tau_{8528} := \left( \frac{|S_{\text{max}}|}{A_s} \right) \quad \tau_{8528} = 13951.1\text{-psi} \)
<table>
<thead>
<tr>
<th>Stress Ratios</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial (ult)</td>
<td>$R_{au} := \frac{a \cdot FS_u}{F_{tu} \cdot c_{1u}}$</td>
<td>$R_{au} = 0.006$</td>
</tr>
<tr>
<td>Bending(ult)</td>
<td>$R_{bu} := \frac{FS_u \cdot 8528}{F_{bu} \cdot c_{1u}}$</td>
<td>$R_{bu} = 0.186$</td>
</tr>
<tr>
<td>Shear(ult)</td>
<td>$R_{su} := \frac{a \cdot FS_u \cdot y \cdot 8528}{FS_u \cdot c_{1u}}$</td>
<td>$R_{su} = 0.161$</td>
</tr>
<tr>
<td>Axial (yld)</td>
<td>$R_{ay} := \frac{a \cdot FS_y}{F_{ty} \cdot c_{1y}}$</td>
<td>$R_{ay} = 0.005$</td>
</tr>
<tr>
<td>Bending(yld)</td>
<td>$R_{by} := \frac{FS_y \cdot 8528}{F_{by} \cdot c_{1y}}$</td>
<td>$R_{by} = 0.21$</td>
</tr>
<tr>
<td>Shear(yld)</td>
<td>$R_{sy} := \frac{FS_y \cdot y \cdot 8528}{0.5 \cdot F_{ty} \cdot c_{1y}}$</td>
<td>$R_{sy} = 0.169$</td>
</tr>
</tbody>
</table>

**Margin of safety**

Margin of safety ultimate

$$MS_u := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \quad MS_u = 3$$

Margin of safety yield

$$MS_y := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad MS_y = 2.66$$

**Case 3**

**At edge of socket Y=89.0 - Launch Case**

**Moment**

$M_{890} := 0.82 \cdot M_{max}$  
$M_{890} = 229808.7$-in-lbf

**Shear**

$S_{890} := 0.75 \cdot S_{max}$  
$S_{890} = -55630.7$-lbf

**Section properties at y=89.0**

**Area of cross-section**

$$As := \frac{u \left( d_{to}^2 - d_{t89}^2 \right)}{4} \quad As = 5.392$-in$^2$$
Moment of Inertia

\[ I_s := \frac{u(d_{to}^4 - d_{89}^4)}{64} \quad I_s = 4.76 \text{ in}^4 \]

Section Modulus

\[ S_1 := \frac{I_s}{d_{\text{max}}} \quad S_1 = 2.937 \text{ in}^3 \]

Combined Bending Stress

\[ =890 := \frac{M_{890}}{S_1} \quad =890 = 78250.2 \text{ psi} \]

Shear Stress

\[ y_{890} := \frac{S_{890}}{A_s} \quad y_{890} = 10317.2 \text{ psi} \]

Stress Ratios

Axial (ult)

\[ R_{au} := \frac{a \cdot F_{Su}}{F_{tu} \cdot c_{1tu}} \quad R_{au} = 0.006 \]

Bending (ult)

\[ R_{bu} := \frac{F_{Su} \cdot =890}{F_{bu} \cdot c_{1tu}} \quad R_{bu} = 0.369 \]

Shear (ult)

\[ R_{s} := \frac{F_{Su} \cdot y_{890}}{F_{su} \cdot c_{1tu}} \quad R_{s} = 0.119 \]

Axial (yld)

\[ R_{ay} := \frac{a \cdot F_{Sy}}{F_{ty} \cdot c_{1ty}} \quad R_{ay} = 0.005 \]

Bending (yld)

\[ R_{by} := \frac{F_{Sy} \cdot =890}{F_{by} \cdot c_{1ty}} \quad R_{by} = 0.417 \]

Shear (yld)

\[ R_{sy} := \frac{F_{Sy} \cdot y_{890}}{0.50F_{ty} \cdot c_{1ty}} \quad R_{sy} = 0.125 \]

Margin of Safety

\[ MS_{ult} := \frac{1}{\sqrt{R_{bu}^2 + R_{s}^2}} - 1 \quad MS_{ult} = 1.58 \]

\[ MS_{yld} := \frac{1}{\sqrt{R_{by}^2 + R_{sy}^2}} - 1 \quad MS_{yld} = 1.3 \]
Abort Landing Case:

Vertical load at primary trunnion \( F_z := 42137.67 \text{ lbf} \) (Ref. AMS-02, loads model 2-04, Load case 2016, element ID 1, data file: maxtrunnionforces2000.lis)

Horizontal load at primary trunnion \( F_x := 9960.34 \text{ lbf} \)

Max. resultant load \( Pr := \sqrt{F_z^2 + F_x^2} \) \( Pr = 43299 \text{ lbf} \)

The tolerances between the sill trunnion and the sill joint are tight. Due to this tight tolerance, any side load transferred through the sill trunnion is reacted by the sill joint.

Moment arm from load to edge of sill plate \( d_2 := (94.0 \text{ in} - 89.0 \text{ in}) + 0.5 \text{ in} \) \( d_2 = 5.5 \text{ in} \) (Ref. Appendix C6 for the 0.5" dynamic excursion)

Max. bending moment at edge of sill plate \( Mb := Pr \cdot d_2 \) \( Mb = 238143.8 \text{ in-lbf} \)

Friction coefficient is assessed based on Figure 4.1.1.1-1 of NSTS-21000-IDD-ISS, Ref. Appendix C7.

\( P := Pr \) \( P = 43299 \text{ lbf} \)

\( T := 40 \text{ deg} \) (It is conservative to use the minimum temperature (Ref. Appendix C2))
Friction coefficient

Friction load (10% of load)

Friction moment

Total moment

Applied limit stress in shaft

\[ Ff := Pr \times \frac{d_{max}}{2} \]

\[ Mf := Pf \times \frac{d_{max}}{2} \]

\[ M := Mb + Mf \]

\[ d := \left( \frac{M \times d_{max}}{2 \times Is} \right) \]

\[ Ff = 4329.9 \text{ lbf} \]

\[ Mf = 7017.2 \text{ in-lbf} \]

\[ M = 245161 \text{ in-lbf} \]

\[ d = 83477.6 \text{ psi} \]
Plastic bending allowable  (Ref.NASA TM X-73305,sect B.4.5)

**Section factor**

Outer radius

\[ r_o := \frac{d_0}{2} \quad r_o = 1.62\text{-in} \]

Inner radius

\[ r_i := \frac{d_{89}}{2} \quad r_i = 0.953\text{-in} \]

Area of semicircular segment

\[ A_{se} := \frac{u}{2} \left( \frac{r_o^2 - r_i^2}{2} \right) \quad A_{se} = 2.696\text{-in}^2 \]

Distance of neutral axis from center line

\[ y_{bar} := \frac{4}{3} \cdot u \left( \frac{r_o^3 - r_i^3}{2 \cdot r_o^2 - r_i^2} \right) \quad y_{bar} = 0.837\text{-in} \]

First moment of area

\[ Q := A_{se} \cdot y_{bar} \quad Q = 2.257\text{-in}^3 \]

Distance of extreme fiber from centerline of shaft

\[ c := \frac{d_{\text{max}}}{2} \quad c = 1.621\text{-in} \]

Section factor

\[ K := \frac{2 \cdot Q \cdot c}{I_S} \quad K = 1.537 \]

Allowable bending modulus of rupture ult.  \[ p := 301000\text{-psi} \]

Allowable bending modulus of rupture yld.  \[ y := 210000\text{-psi} \]

**Check**

Section factor

\[ K := 1.698 \cdot \frac{r_o^3 - r_i^3}{r_o^4 - r_i^4} \quad K = 1.5364 \]

(Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)

\[ f_{mu} := 200000\text{-psi} \quad f_{ou} := 192000\text{-psi} \]

(Ref. Bruhn, table C3.2 page C3.11)

\[ f_{my} := 176000\text{-psi} \quad f_{oy} := 65000\text{-psi} \]

Fbu := f_{mu} + f_{ou} \cdot (K - 1) \quad Fbu = 302996\text{-psi} \quad (Ref. Bruhn page C3.3, equation 3)

Fby := f_{my} + f_{oy} \cdot (K - 1) \quad Fby = 210868.4\text{-psi} \quad (These numbers match the \sigma_p and \sigma_y closely)
Axial tension stress

$$\sigma_a := \frac{P_f}{A_s} \quad = 803 \text{ psi}$$

Shear stress

$$\tau_y := \frac{P_r}{A_s} \quad = 8030 \text{ psi}$$

Stress ratios, Ultimate

Stress ratio in axial, ultimate

$$R_{au} := \frac{\sigma_a}{F_{tu} \cdot c_{tu}} \quad R_{au} = 0.006$$

Stress ratio in bending, ultimate

$$R_{bu} := \frac{\sigma_b}{F_{bu} \cdot c_{tu}} \quad R_{bu} = 0.398$$

Stress ratio in shear, ultimate

$$R_{su} := \frac{\tau_y}{F_{su} \cdot c_{tu}} \quad R_{su} = 0.093$$

Margin of safety ultimate

$$M_{Su} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \quad M_{Su} = 1.41$$

Stress ratios, Yield

Stress ratio in axial, yield

$$R_{ay} := \frac{\sigma_a}{F_{ty} \cdot c_{ty}} \quad R_{ay} = 0.005$$

Stress ratio in bending, yield

$$R_{by} := \frac{\sigma_b}{F_{by} \cdot c_{ty}} \quad R_{by} = 0.449$$

Stress ratio in shear, yield

$$R_{sy} := \frac{\tau_y}{0.5F_{ty} \cdot c_{ty}} \quad R_{sy} = 0.098$$

Margin of safety, yield

$$M_{Sy} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad M_{Sy} = 1.15$$

Check section at Y=91.5

Total Moment at Y=91.5

$$M_1 := P_r \cdot (94.0 \text{ in} - 91.5 \text{ in} + 0.5 \text{ in}) + M_f \quad M_1 = 136913.8 \text{ in-lbf}$$

(Ref. Appendix C6 for the 0.5° dynamic excursion)

Applied limit stress in shaft

$$\sigma_l := \left( \frac{M_1 \cdot d_{max}}{2 \cdot I_s l} \right) \quad = \sigma_l = 72150.5 \text{ psi}$$
Plastic bending allowable (Ref. NASA TM X-73305, sect B.4.5)

**Section factor**

Outer radius
\[ r_o := \frac{d_o}{2} \quad r_o = 1.62 \text{\,in} \]

Inner radius
\[ r_i := \frac{d_i}{2} \quad r_i = 1.313 \text{\,in} \]

Area of semicircular segment
\[ A_s := \frac{u}{2} \left( r_o^2 - r_i^2 \right) \quad A_s = 1.415 \text{\,in}^2 \]

Distance of neutral axis from center line
\[ y_{bar} := \frac{\frac{4}{3} \cdot u \left( \frac{r_o^3}{r_o^2 - r_i^2} \right) - \frac{4}{3} \cdot u \left( \frac{r_i^3}{r_o^2 - r_i^2} \right)}{r_o^2 - r_i^2} \quad y_{bar} = 0.937 \text{\,in} \]

First moment of area
\[ Q := A_s \cdot y_{bar} \quad Q = 1.326 \text{\,in}^3 \]

Distance of extreme fiber from centerline of shaft
\[ c := \frac{d_{max}}{2} \quad c = 1.62 \text{\,in} \]

Section factor
\[ K := \frac{2 \cdot Q \cdot c}{I_{s1}} \quad K = 1.3972 \]

Allowable bending modulus of rupture ult.
\[ \sigma_{p1} := 274000 \text{\,psi} \quad (\text{Ref. NASA TM X-73305, sect B.4.5 fig. B4.5.2-7}) \]

Allowable bending modulus of rupture yld.
\[ \sigma_{y1} := 200000 \text{\,psi} \]

**Check**

Section factor
\[ K := 1.698 \cdot \frac{r_o \left( \frac{r_o^3}{r_o^4 - r_i^4} \right)}{r_i \left( \frac{r_o^3}{r_o^4 - r_i^4} \right)} \quad K = 1.3968 \quad (\text{Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6}) \]

\[ f_{mu} := 200000 \text{\,psi} \quad f_{ou} := 192000 \text{\,psi} \quad (\text{Ref. Bruhn, table C3.2 page C3.11}) \]

\[ f_{my} := 176000 \text{\,psi} \quad f_{oy} := 65000 \text{\,psi} \]

\[ F_{bu1} := f_{mu} + f_{ou} \cdot (K - 1) \quad F_{bu1} = 276176.9 \text{\,psi} \quad (\text{Ref. Bruhn page C3.3, equation 3}) \]

\[ F_{by1} := f_{my} + f_{oy} \cdot (K - 1) \quad F_{by1} = 201789.1 \text{\,psi} \]

\[ \sigma_{a1} := \frac{P_f}{A_{s1}} \quad \sigma_{a1} = 1529.8 \text{\,psi} \]

\[ \sigma_{y1} := \frac{P_r}{A_{s1}} \quad \sigma_{y1} = 15298 \text{\,psi} \]
Stress ratios, Ultimate

Stress ratio in axial, ultimate
\[ \text{Rau}_1 := \frac{a_1 \cdot F_{Su}}{F_{tu} \cdot c_{tu}} \quad \text{Rau} = 0.006 \]

Stress ratio in bending, ultimate
\[ \text{Rbu}_1 := \frac{11 \cdot F_{Su}}{F_{bu1} \cdot c_{tu}} \quad \text{Rbu} = 0.398 \]

Stress ratio in shear, ultimate
\[ \text{Rsu}_1 := \frac{y_1 \cdot F_{Su}}{F_{su} \cdot c_{tu}} \quad \text{Rsu} = 0.093 \]

Margin of safety ultimate
\[ \text{MSu} := \frac{1}{\sqrt{(\text{Rau}_1 + \text{Rbu}_1)^2 + \text{Rsu}_1^2}} - 1 \quad \text{MSu} = 1.34 \]

Stress ratios, Yield

Stress ratio in axial, yield
\[ \text{Ray}_1 := \frac{a_1 \cdot F_{Sy}}{F_{ty} \cdot c_{ty}} \quad \text{Ray} = 0.009 \]

Stress ratio in bending, yield
\[ \text{Rby}_1 := \frac{11 \cdot F_{Sy}}{F_{by1} \cdot c_{ty}} \quad \text{Rby} = 0.405 \]

Stress ratio in shear, yield
\[ \text{Rsy}_1 := \frac{y_1 \cdot F_{Sy}}{0.5 \cdot F_{ty} \cdot c_{ty}} \quad \text{Rsy} = 0.188 \]

Margin of safety yield
\[ \text{MSy} := \frac{1}{\sqrt{(\text{Ray}_1 + \text{Rby}_1)^2 + \text{Rsy}_1^2}} - 1 \quad \text{MSy} = 1.2 \]
**Beam and Socket analysis - Abort Landing Case**

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

S and M are respectively beam shear in lbf and moment in in-lbf at end of socket. W is unit loading in lbf/in.

**Resultant shear Load**

\[ S := Pr \]

\[ S = 43299 \text{-lbf} \]

**Moment at edge of sill joint**

\[ M := Mb + Mf \]

\[ M = 245161 \text{-in-lbf} \]

**Length of overlap**

\[ L := 6.5 \text{-in} \]

\[ \text{slm}_\text{ratio} := \frac{M = 0, 1000, S}{M} \]

\[ \text{slm}_\text{ratio} = 1.148 \]

\[ \text{mls}_\text{ratio} := \frac{S = 0, 1000, M}{S \cdot L} \]

\[ \text{mls}_\text{ratio} = 0.871 \]
Beam and Socket Coefficients
Note if abs(SL/M) <= 1, Ratio = SL/M, otherwise Ratio = M/SL.

Coefficients are:

Ka = 0.43  
Ks = 1.64  
Km = 0.95  
K1 = 9.23  
K2 = 7.23
Calculated values are then:

\[ w_1 := \begin{cases} \frac{K_1 \cdot M}{L^2} & \text{if } |\text{slm_ratio}| \leq 1 \\ \frac{K_1 \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ w_1 = 61461.2 \text{ lbf/in} \]

\[ w_2 := \begin{cases} \frac{K_2 \cdot M}{L^2} & \text{if } |\text{slm_ratio}| \leq 1 \\ \frac{K_2 \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ w_2 = 48138.5 \text{ lbf/in} \]

\[ a := K_a \cdot L \quad a = 2.79 \text{ in} \]

Max. shear

\[ S_{\text{max}} := \begin{cases} \frac{-K_s \cdot M}{L} & \text{if } |\text{slm_ratio}| \leq 1 \\ -K_s \cdot S & \text{otherwise} \end{cases} \]

\[ S_{\text{max}} = -70955.8 \text{ lbf} \]

Max. Bending moment

\[ M_{\text{max}} := \begin{cases} K_m \cdot M & \text{if } |\text{slm_ratio}| \leq 1 \\ K_m \cdot S \cdot L & \text{otherwise} \end{cases} \]

\[ M_{\text{max}} = 268093.7 \text{ in-lbf} \]

Now check:

\[ S_c := \frac{w_1 - w_2}{2} \cdot L \]

\[ S_c = 43298.9 \text{ lbf} \]

\[ M_c := -w_1 + \frac{2 \cdot w_2}{6} \cdot L^2 \]

\[ M_c = 245161 \text{ in-lbf} \]

Percent error:

\[ S_{\text{percentdiff}} := \frac{S - S_c}{S} \quad S_{\text{percentdiff}} = -0\% \]

\[ M_{\text{percentdiff}} := \frac{M - M_c}{M} \quad M_{\text{percentdiff}} = 0\% \]
**Case 1: Max. bending moment at Y=88.075 - Abort Landing Case**

Max. moment occurs at \( b=2a \) from inner end

\[ b := 2a \quad b = 5.575 \text{ in} \quad (Y=88.075) \]

Shear \( S := 0 \text{ lbf} \)  
Max. Bending moment \( M_{max} = 268093.7 \text{ in-lbf} \)

**Section properties at 5.575 in from inner end \( y=88.075 \)**

Inner diameter of trunnion at \( y=88.075 \)  
\[ d_{t8807} := 1.9 \text{ in} + 0.005 \text{ in} \quad d_{t8807} = 1.905 \text{ in} \]

Area of cross-section at 88.075  
\[ A_s := \frac{u \left( d_{t8807}^2 - d_{t8807}^2 \right)}{4} \quad A_s = 5.392 \text{ in}^2 \]

Moment of inertia at 88.075  
\[ I_s := \frac{u \left( d_{t8807}^4 - d_{t8807}^4 \right)}{64} \quad I_s = 4.76 \text{ in}^4 \]
Section modulus

\[ S_1 := \frac{\text{Is}}{\text{dtmax}^2} \quad \Rightarrow S_1 = 2.937 \text{in}^3 \]

Total moment

\[ M_{8807} := M_{\text{max}} \quad \Rightarrow M_{8807} = 268093.7 \text{in} \cdot \text{lbf} \]

Combined Tensile stress

\[ \sigma_{8807} := \frac{M_{8807}}{S_1} \quad \Rightarrow \sigma_{8807} = 91286.3 \text{psi} \]

Shear stress

\[ \tau_{8807} := \frac{S}{A_s} \quad \Rightarrow \tau_{8807} = 0 \text{psi} \]

Stress Ratios

Axial (ult)

\[ R_{\text{Au}} := \frac{\sigma_{\text{ult}}}{F_{\text{u}} \cdot c_{\text{2u}}} \quad \Rightarrow R_{\text{Au}} = 0.006 \]

Bending (ult)

\[ R_{\text{Bu}} := \frac{\sigma_{\text{ult}}}{F_{\text{b}} \cdot c_{\text{2u}}} \quad \Rightarrow R_{\text{Bu}} = 0.435 \]

Shear (ult)

\[ R_{\text{S}} := \frac{\tau_{\text{ult}}}{F_{\text{s}} \cdot c_{\text{2u}}} \quad \Rightarrow R_{\text{S}} = 0 \]

Axial (yld)

\[ R_{\text{Ay}} := \frac{\sigma_{\text{yld}}}{F_{\text{y}} \cdot c_{\text{2y}}} \quad \Rightarrow R_{\text{Ay}} = 0.005 \]

Bending (yld)

\[ R_{\text{By}} := \frac{\sigma_{\text{yld}}}{F_{\text{b}} \cdot c_{\text{2y}}} \quad \Rightarrow R_{\text{By}} = 0.491 \]

Shear (yld)

\[ R_{\text{Sy}} := \frac{\tau_{\text{yld}}}{0.50F_{\text{y}} \cdot c_{\text{2y}}} \quad \Rightarrow R_{\text{Sy}} = 0.000 \]

Margin of safety

Margin of safety ultimate

\[ MS_{u} := \frac{1}{\sqrt{(R_{\text{Au}} + R_{\text{Bu}})^2 + R_{\text{S}}^2}} - 1 \quad \Rightarrow MS_{u} = 1.22 \]

Margin of safety yield

\[ MS_{y} := \frac{1}{\sqrt{(R_{\text{Ay}} + R_{\text{By}})^2 + R_{\text{Sy}}^2}} - 1 \quad \Rightarrow MS_{y} = 1.017 \]
**Case 2 Max.shear at Y=85.288 - Abort Landing Case**

When shear is maximum the bending moment is 0.41 of Mmax

\[
\begin{align*}
\text{Max.shear} & \quad S_{\text{max}} = -70956 \text{-lbf} \\
\text{Bending moment} & \quad M_s := 0.41 \cdot M_{\text{max}} \quad M_s = 109918.4 \text{-in-lbf}
\end{align*}
\]

Max. shear occurs at \( a = 2.788 \text{-in} \) \((Y=85.288)\)

**Section properties** at 2.788 in from inner end \( y=85.288 \) Max.shear location

inner diameter at \( Y=85.288 \) \( d_t8528 := 1.93 \text{-in} + 0.03 \text{-in} \)

\( d_t8528 = 1.93 \text{-in} \)

Wall thickness at \( y=85.288 \) \( \omega t8528 := \frac{d_t0 - d_t8528}{2} \)

\( wt8528 = 0.655 \text{-in} \)

Area of cross-section at 85.288

\( A_s := \frac{u \left( d_t0^2 - d_t8528^2 \right)}{4} \)

\( A_s = 5.317 \text{-in}^2 \)

Moment of inertia at 85.288

\( I_s := \frac{u \left( d_t0^4 - d_t8528^4 \right)}{64} \)

\( I_s = 4.725 \text{-in}^4 \)

Section modulus

\( S1 := \frac{I_s}{d_{\text{max}}} \)

\( S1 = 2.915 \text{-in}^3 \)

Total moment

\( M_{8528} := M_s \)

\( M_{8528} = 109918.4 \text{-in-lbf} \)

Tensile stress

\( \sigma_{8528} := \frac{M_{8528}}{S1} \)

\( \sigma_{8528} = 37701.5 \text{-psi} \)

Shear stress

\( \gamma_{8528} := \left( \frac{|S_{\text{max}}|}{A_s} \right) \)

\( \gamma_{8528} = 13345.8 \text{-psi} \)
Stress Ratios

Axial (ult) \[ \text{Rau} := \frac{a \cdot F_{Su}}{F_{tu} \cdot c_{2tu}} \quad \text{Rau} = 0.006 \]

Bending (ult) \[ \text{Rbu} := \frac{F_{Su} \cdot 8528}{F_{bu} \cdot c_{2tu}} \quad \text{Rbu} = 0.18 \]

Shear (ult) \[ \text{Rsu} := \frac{F_{Su} \cdot y \cdot 8528}{F_{su} \cdot c_{2tu}} \quad \text{Rsu} = 0.155 \]

Axial (yld) \[ \text{Ray} := \frac{a \cdot F_{Sy}}{F_{ty} \cdot c_{2ty}} \quad \text{Ray} = 0.005 \]

Bending (yld) \[ \text{Rby} := \frac{F_{Sy} \cdot 8528}{F_{by} \cdot c_{2ty}} \quad \text{Rby} = 0.203 \]

Shear (yld) \[ \text{Rsy} := \frac{F_{Sy} \cdot y \cdot 8528}{0.50 F_{ty} \cdot c_{2ty}} \quad \text{Rsy} = 0.164 \]

Margin of safety

Margin of safety ultimate \[ \text{MSu} := \frac{1}{\sqrt{(\text{Rau} + \text{Rbu})^2 + \text{Rsu}^2}} - 1 \quad \text{MSu} = 3.13 \]

Margin of safety yield \[ \text{MSy} := \frac{1}{\sqrt{(\text{Ray} + \text{Rby})^2 + \text{Rsy}^2}} - 1 \quad \text{MSy} = 2.78 \]

Case 3  At edge of socket Y=89.0 - Abort Landing Case

Moment \[ \text{M890} := 0.82 \cdot M_{\text{max}} \quad \text{M890} = 219836.8 \text{ in-lbf} \]

Shear \[ \text{S890} := 0.75 \cdot S_{\text{max}} \quad \text{S890} = -53216.8 \text{ lbf} \]

Section properties at y=89.0

Area of cross-section \[ \text{As} := \frac{u \left( \text{dto}^2 - \text{dt89}^2 \right)}{4} \quad \text{As} = 5.392 \text{ in}^2 \]
Moment of inertia
\[ I_s := \frac{u(d_0^4 - dt^89^4)}{64} \]
\[ I_s = 4.76 \text{ in}^4 \]

Section modulus
\[ S1 := \frac{I_s}{d_{\text{max}}} \]
\[ S1 = 2.937 \text{ in}^3 \]

Combined bending stress
\[ =890 := \frac{M890}{S1} \]
\[ =890 = 74854.7 \text{ psi} \]

Shear stress
\[ y890 := \frac{S890}{As} \]
\[ y890 = 9869.5 \text{ psi} \]

**Stress Ratios**

**Axial (ult)**
\[ \text{Rau} := \frac{a \cdot F_Su}{F_{tu} \cdot c_{2tu}} \]
\[ \text{Rau} = 0.006 \]

**Bending (ult)**
\[ \text{Rbu} := \frac{F_{Su} \cdot =890}{F_{bu} \cdot c_{2tu}} \]
\[ \text{Rbu} = 0.357 \]

**Shear (ult)**
\[ \text{Rs} := \frac{F_{Su} \cdot y890}{F_{su} \cdot c_{2tu}} \]
\[ \text{Rs} = 0.115 \]

**Axial (yld)**
\[ \text{Ray} := \frac{a \cdot F_{Sy}}{F_{ty} \cdot c_{2ty}} \]
\[ \text{Ray} = 0.005 \]

**Bending (yld)**
\[ \text{Rby} := \frac{F_{Sy} \cdot =890}{F_{by} \cdot c_{2ty}} \]
\[ \text{Rby} = 0.403 \]

**Shear (yld)**
\[ \text{Rsy} := \frac{F_{Sy} \cdot y890}{0.50F_{ty} \cdot c_{2ty}} \]
\[ \text{Rsy} = 0.121 \]

**Margin of safety**
\[ \text{MSult} := \frac{1}{\sqrt{\text{Rbu}^2 + \text{Rs}^2}} - 1 \]
\[ \text{MSult} = 1.67 \]

\[ \text{MSyld} := \frac{1}{\sqrt{\text{Rby}^2 + \text{Rsy}^2}} - 1 \]
\[ \text{MSyld} = 1.38 \]
Nominal Landing Case:

Vertical load at primary trunnion \( F_z := 53776.54\text{-lbf} \) (Ref.AMS-02, loads model 2-04, Load case 4016, element ID 1, data file: maxtrunnionforces4000.lis)

Horizontal load at primary trunnion \( F_x := 14600.43\text{-lbf} \)

Max. resultant load 
\[
Pr := \sqrt{F_z^2 + F_x^2} \\
Pr = 55723\text{-lbf}
\]

The tolerances between the sill trunnion and the sill joint are tight. Due to this tight tolerance, any side load transferred through the sill trunnion is reacted by the sill joint.

Moment arm from load to edge of sill plate \( d_2 := (94.0\text{-in} - 89.0\text{-in}) + 0.5\text{-in} \) 
\( d_2 = 5.5\text{-in} \) (Ref. Appendix C6 for the 0.5” dynamic excursion)

Max. bending moment at edge of sill plate 
\[
Mb := Pr \times d_2 \\
Mb = 306478.3\text{-in\-lbf}
\]

Friction coefficient is assessed based on Figure 4.1.1.1-1 of NSTS-21000-IDD-ISS, Ref. Appendix C7.

\( P := Pr \) \( P = 55723\text{-lbf} \)

\( T := -56\text{-deg} \) (It is conservative to use the minimum temperature (Ref. Appendix C2) )
Friction coefficient

\[ \mu = 0.100 \]

Friction load (10% of load)

\[ P_f := P_r \cdot \mu \]

\[ P_f = 5572.3 \text{ lbf} \]

Friction moment

\[ M_f := P_f \cdot \frac{d_{\text{max}}}{2} \]

\[ M_f = 9030.8 \text{ in-lbf} \]

Total moment

\[ M := M_b + M_f \]

\[ M = 315509.1 \text{ in-lbf} \]

Applied limit stress in shaft

\[ \sigma_l := \frac{M \cdot d_{\text{max}}}{2 \cdot I_s} \]

\[ \sigma_l = 107431.3 \text{ psi} \]
Plastic bending allowable  
(Ref. NASA TM X-73305, sect B.4.5)

Section factor

Outer radius

\[ \text{ro} := \frac{\text{dto}}{2} \]
\[ \text{ro} = 1.62\text{ in} \]

Inner radius

\[ \text{ri} := \frac{\text{dt}89}{2} \]
\[ \text{ri} = 0.953\text{ in} \]

Area of semicircular segment

\[ \text{Ase} := \frac{u}{2} \left( \text{ro}^2 - \text{ri}^2 \right) \]
\[ \text{Ase} = 2.696\text{ in}^2 \]

Distance of neutral axis from center line

\[ \text{ybar} := \frac{4}{3\cdot u} \left( \frac{\text{ro}^3 - \text{ri}^3}{\text{ro}^2 - \text{ri}^2} \right) \]
\[ \text{ybar} = 0.837\text{ in} \]

First moment of area

\[ \text{Q} := \text{Ase}\cdot\text{ybar} \]
\[ \text{Q} = 2.257\text{ in}^3 \]

Distance of extreme fiber from centerline of shaft

\[ \text{c} := \frac{\text{dmax}}{2} \]
\[ \text{c} = 1.621\text{ in} \]

Section factor

\[ \text{K} := \frac{2\cdot \text{Q} \cdot \text{c}}{\text{Is}} \]
\[ \text{K} = 1.537 \]

Allowable bending modulus of rupture ult.

\[ \text{p} := 301000\text{ psi} \]
(Ref. NASA TM X-73305, sect B.4.5 fig. B4.5.5.2-7)

Allowable bending modulus of rupture yld.

\[ \text{y} := 210000\text{ psi} \]

Check

Section factor

\[ \text{K} := 1.698 \cdot \frac{\text{ro}^3}{\text{ro}^4 - \text{ri}^4} \]
\[ \text{K} = 1.5364 \]
(Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)

\[ \text{fmu} := 200000\text{ psi} \]
\[ \text{fou} := 192000\text{ psi} \]
(Ref. Bruhn, table C3.2 page C3.11)

\[ \text{fmy} := 176000\text{ psi} \]
\[ \text{foy} := 65000\text{ psi} \]

\[ \text{Fbu} := \text{fmu} + \text{fou} \cdot (\text{K} - 1) \]
\[ \text{Fbu} = 302996\text{ psi} \]
(Ref. Bruhn page C3.3, equation 3)

\[ \text{Fby} := \text{fmy} + \text{foy} \cdot (\text{K} - 1) \]
\[ \text{Fby} = 210868.4\text{ psi} \]
(These numbers match the \( \sigma_p \) and \( \sigma_y \) closely)
Axial tension stress
\[ a := \frac{P_f}{A_s} \]
\[ a = 1033 \text{-psi} \]

Shear stress
\[ y := \frac{P_r}{A_s} \]
\[ y = 1033 \text{-psi} \]

**Stress ratios, Ultimate**

Stress ratio in axial, ultimate
\[ R_{au} := \frac{a - F_{Su}}{F_{u} \cdot c_{3tu}} \]
\[ R_{au} = 0.007 \]

Stress ratio in bending, ultimate
\[ R_{bu} := \frac{a - I - F_{Su}}{F_{bu} \cdot c_{3tu}} \]
\[ R_{bu} = 0.501 \]

Stress ratio in shear, ultimate
\[ R_{su} := \frac{y \cdot F_{Su}}{F_{su} \cdot c_{3tu}} \]
\[ R_{su} = 0.118 \]

Margin of safety ultimate
\[ M_{Su} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \]
\[ M_{Su} = 0.92 \]

**Stress ratios, Yield**

Stress ratio in axial, yield
\[ R_{ay} := \frac{a - F_{Sy}}{F_{ty} \cdot c_{3ty}} \]
\[ R_{ay} = 0.006 \]

Stress ratio in bending, yield
\[ R_{by} := \frac{y \cdot F_{Sy}}{F_{by} \cdot c_{3ty}} \]
\[ R_{by} = 0.566 \]

Stress ratio in shear, yield
\[ R_{sy} := \frac{y \cdot F_{Sy}}{0.5 \cdot F_{ty} \cdot c_{3ty}} \]
\[ R_{sy} = 0.124 \]

Margin of safety, yield
\[ M_{Sy} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\[ M_{Sy} = 0.71 \]

**Check section at Y=91.5**

Total Moment at Y=91.5
\[ M_1 := P_r \cdot (94.0 \text{-in} - 91.5 \text{-in} + 0.5 \text{-in}) + M_f \]
\[ M_1 = 176200.8 \text{-in-lbf} \]

(Ref. Appendix C6 for the 0.5" dynamic excursion)

Applied limit stress in shaft
\[ a_1 := \left( \frac{M_1 \cdot d_{max}}{2 \cdot I_{s1}} \right) \]
\[ a_1 = 92853.9 \text{-psi} \]
Plastic bending allowable  (Ref.NASA TM X-73305,sect B.4.5)

Section factor

<table>
<thead>
<tr>
<th>Outer radius</th>
<th>( r_o := \frac{d_{to}}{2} )</th>
<th>( r_o = 1.62\text{-in} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius</td>
<td>( r_i := \frac{d_{ti}}{2} )</td>
<td>( r_i = 1.313\text{-in} )</td>
</tr>
<tr>
<td>Area of semicircular segment</td>
<td>( A_{se} := \frac{u}{2} \left( r_o^2 - r_i^2 \right) )</td>
<td>( A_{se} = 1.415\text{-in}^2 )</td>
</tr>
<tr>
<td>Distance of neutral axis from center line</td>
<td>( y_{bar} := \frac{4}{3} \cdot u \left( \frac{r_o^3 - r_i^3}{r_o^2 - r_i^2} \right) )</td>
<td>( y_{bar} = 0.937\text{-in} )</td>
</tr>
<tr>
<td>First moment of area</td>
<td>( Q := A_{se} \cdot y_{bar} )</td>
<td>( Q = 1.326\text{-in}^3 )</td>
</tr>
<tr>
<td>Distance of extreme fiber from centerline of shaft</td>
<td>( c := \frac{d_{tmax}}{2} )</td>
<td>( c = 1.62\text{-in} )</td>
</tr>
</tbody>
</table>

Section factor

\( K := \frac{2 \cdot Q \cdot c}{I_{s1}} \)

\( K = 1.3972 \)  

Allowable bending modulus of rupture ult. \( = p_1 := 274000\text{-psi} \)  
(Ref.NASA TM X-73305,sect B.4.5  
fig. B4.5.2-7)

Allowable bending modulus of rupture yld. \( = y_1 := 200000\text{-psi} \)

Check

<table>
<thead>
<tr>
<th>Section factor</th>
<th>( K := 1.698 \cdot \frac{r_o^3}{\left( \frac{r_o^4}{r_i^4} \right)} )</th>
<th>( K = 1.3968 )</th>
<th>(Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{mu} := 200000\text{-psi} )</td>
<td>( f_{ou} := 192000\text{-psi} )</td>
<td>(Ref. Bruhn, table C3.2 page C3.11)</td>
<td></td>
</tr>
<tr>
<td>( f_{my} := 176000\text{-psi} )</td>
<td>( f_{oy} := 65000\text{-psi} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_{bu1} := f_{mu} + f_{ou} \cdot (K - 1) )</td>
<td>( F_{bu1} = 276176.9\text{-psi} )</td>
<td>(Ref. Bruhn page C3.3, equation 3)</td>
<td></td>
</tr>
<tr>
<td>( F_{by1} := f_{my} + f_{oy} \cdot (K - 1) )</td>
<td>( F_{by1} = 201789.1\text{-psi} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial tension stress</td>
<td>( a_1 := \frac{P_{f}}{A_{s1}} )</td>
<td>( a_1 = 1968.8\text{-psi} )</td>
<td></td>
</tr>
<tr>
<td>Shear stress</td>
<td>( y_1 := \frac{P_{r}}{A_{s1}} )</td>
<td>( y_1 = 19688\text{-psi} )</td>
<td></td>
</tr>
</tbody>
</table>
Stress ratios, Ultimate

Stress ratio in axial, ultimate
\[ R_{au1} := \frac{a1 \cdot F_{Su}}{F_{tu} \cdot c_{3tu}} \quad R_{au1} = 0.014 \]

Stress ratio in bending, ultimate
\[ R_{bu1} := \frac{11 \cdot F_{Su}}{F_{bu1} \cdot c_{3tu}} \quad R_{bu1} = 0.475 \]

Stress ratio in shear, ultimate
\[ R_{su1} := \frac{y1 \cdot F_{Su}}{F_{su} \cdot c_{3tu}} \quad R_{su1} = 0.225 \]

Margin of safety ultimate
\[ MS_u := \frac{1}{\sqrt{(R_{au1} + R_{bu1})^2 + R_{su1}^2}} - 1 \quad MS_u = 0.86 \]

Stress ratios, Yield

Stress ratio in axial, yield
\[ R_{ay1} := \frac{a1 \cdot F_{Sy}}{F_{ty} \cdot c_{3ty}} \quad R_{ay1} = 0.012 \]

Stress ratio in bending, yield
\[ R_{by1} := \frac{11 \cdot F_{Sy}}{F_{by1} \cdot c_{3ty}} \quad R_{by1} = 0.511 \]

Stress ratio in shear, yield
\[ R_{sy1} := \frac{y1 \cdot F_{Sy}}{0.5 \cdot F_{ty} \cdot c_{3ty}} \quad R_{sy1} = 0.236 \]

Margin of safety yield
\[ MS_y := \frac{1}{\sqrt{(R_{ay1} + R_{by1})^2 + R_{sy1}^2}} - 1 \quad MS_y = 0.74 \]
### Beam and Socket analysis - Nominal Landing Case

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

**Resultant shear Load**  \( S := Pr \quad S = 55723\text{-lbf} 

**Moment at edge of sill joint**  \( M := M_b + M_f \quad M = 315509\text{-in-lbf} 

**Length of overlap**  \( L := 6.5\text{-in} 

\[
\text{slm\_ratio} := \text{if } \left( M \neq 0, 1000, \frac{L}{M} \right) \quad \text{slm\_ratio} = 1.148
\]

\[
\text{mls\_ratio} := \text{if } \left( S \neq 0, 1000, \frac{M}{S \cdot L} \right) \quad \text{mls\_ratio} = 0.871
\]
Beam and Socket Coefficients
Note if abs(SL/M) <= 1, Ratio = SL/M, otherwise Ratio = M/SL.

Coefficients are:

Ka = 0.43  Ks = 1.64  Km = 0.95
K1 = 9.23  K2 = 7.23
Calculated values are then:

\[
\begin{align*}
\text{w}_1 & := \begin{cases} \\
\frac{K_1 \cdot M}{L^2} & \text{if } \left| \text{slm\_ratio} \right| \leq 1 \\
\frac{K_1 \cdot S}{L} & \text{otherwise}
\end{cases} \\
& = 79097.3 \text{ lbf/in}
\end{align*}
\]

\[
\begin{align*}
\text{w}_2 & := \begin{cases} \\
\frac{K_2 \cdot M}{L^2} & \text{if } \left| \text{slm\_ratio} \right| \leq 1 \\
\frac{K_2 \cdot S}{L} & \text{otherwise}
\end{cases} \\
& = 61951.7 \text{ lbf/in}
\end{align*}
\]

\[
\begin{align*}
a & := K_a \cdot L \\
a & = 2.79 \text{ in}
\end{align*}
\]

\[
\begin{align*}
\text{Max. shear} & \quad \text{S}_{\text{max}} := \begin{cases} \\
\frac{-K_s \cdot M}{L} & \text{if } \left| \text{slm\_ratio} \right| \leq 1 \\
-K_s \cdot S & \text{otherwise}
\end{cases} \\
& = -91316.3 \text{ lbf}
\end{align*}
\]

\[
\begin{align*}
\text{Max. Bending moment} & \quad \text{M}_{\text{max}} := \begin{cases} \\
K_m \cdot M & \text{if } \left| \text{slm\_ratio} \right| \leq 1 \\
K_m \cdot S \cdot L & \text{otherwise}
\end{cases} \\
& = 345022.3 \text{ in-lbf}
\end{align*}
\]

Now check:

\[
\begin{align*}
\text{S}_{\text{c}} & := \frac{\text{w}_1 - \text{w}_2 \cdot L}{2} \\
& = 55723.3 \text{ lbf}
\end{align*}
\]

\[
\begin{align*}
\text{M}_{\text{c}} & := \frac{-\text{w}_1 + 2 \cdot \text{w}_2 \cdot L^2}{6} \\
& = 315509.1 \text{ in-lbf}
\end{align*}
\]

Percent error:

\[
\begin{align*}
\text{S\_percentdiff} & := \frac{S - \text{S}_{\text{c}}}{S} \\
& = 0 \% \\
\text{M\_percentdiff} & := \frac{M - \text{M}_{\text{c}}}{M} \\
& = -0 \%
\end{align*}
\]
Actual Shear and Moment Distribution Inside Socket

Case 1: Max. bending moment at Y=88.075 - Nominal Landing Case

Max. moment occurs at \( b=2a \) from inner end

Shear \( S := 0 \text{ lbf} \)  
Max. Bending moment \( M_{\text{max}} = 345022.3 \text{ in-lbf} \)

Section properties at 5.575 in from inner end \( y=88.075 \)

Inner diameter of trunnion at \( y=88.075 \) \( d_{t8807} := 1.9 \text{ in} + 0.005 \text{ in} \)  
\( d_{t8807} = 1.905 \text{ in} \)

Area of cross-section at 88.075 \( A_s := \frac{u(d_{t0}^2 - d_{t8807}^2)}{4} \)  
\( A_s = 5.392 \text{ in}^2 \)

Moment of inertia at 88.075 \( I_s := \frac{u(d_{t0}^4 - d_{t8807}^4)}{64} \)  
\( I_s = 4.76 \text{ in}^4 \)
### Section modulus

\[
S_1 := \frac{I_s}{d_{\text{max}}} \quad S_1 = 2.937 \text{ in}^3
\]

### Total moment

\[
M_{8807} := M_{\text{max}} \quad M_{8807} = 345022.3 \text{ in lbf}
\]

### Combined Tensile stress

\[
=8807 := \frac{M_{8807}}{S_1} \quad =8807 = 117480.5 \text{ psi}
\]

### Shear stress

\[
y_{8807} := \frac{S}{A_s} \quad y_{8807} = 0 \text{ psi}
\]

### Stress Ratios

- **Axial (ult)**
  \[
  R_a := \frac{-\alpha \cdot F_{su}}{F_{tu \cdot c3tu}} \quad R_a = 0.007
  \]

- **Bending (ult)**
  \[
  R_{bu} := \frac{F_{su} \cdot =8807}{F_{bu \cdot c3tu}} \quad R_{bu} = 0.548
  \]

- **Shear (ult)**
  \[
  R_{su} := \frac{F_{su} \cdot y_{8807}}{F_{su \cdot c3tu}} \quad R_{su} = 0
  \]

- **Axial (yld)**
  \[
  R_{ay} := \frac{-\alpha \cdot F_{sy}}{F_{ty \cdot c3ty}} \quad R_{ay} = 0.006
  \]

- **Bending (yld)**
  \[
  R_{by} := \frac{F_{sy} \cdot =8807}{F_{by \cdot c3ty}} \quad R_{by} = 0.619
  \]

- **Shear (yld)**
  \[
  R_{sy} := \frac{F_{sy} \cdot y_{8807}}{0.50 F_{ty \cdot c3ty}} \quad R_{sy} = 0.000
  \]

### Margin of safety

**Margin of safety ultimate**

\[
M_{Su} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \quad M_{Su} = 0.8
\]

**Margin of safety yield**

\[
M_{Sy} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad M_{Sy} = 0.599
\]
Case 2 Max. shear at Y=85.288 - Nominal Landing Case

When shear is maximum the bending moment is 0.41 of Mmax

Max. shear \( S_{\text{max}} = 91316\text{-lbf} \)

Bending moment \( M_s := 0.41 \cdot M_{\text{max}} \quad M_s = 141459.1\text{-in-lbf} \)

Max. shear occurs at \( a \) from inner end \( a = 2.788\text{-in} \quad (Y=85.288) \)

Section properties at 2.788 in from inner end \( Y=85.288 \) Max. shear location

inner diameter at \( Y=85.288 \) \( d_{t8528} := 1.9\text{-in} + 0.03\text{-in} \quad d_{t8528} = 1.93\text{-in} \)

Wall thickness at \( Y=85.288 \) \( w_{t8528} := \frac{d_{t0} - d_{t8528}}{2} \quad w_{t8528} = 0.655\text{-in} \)

Area of cross-section at 85.288 \( A_s := \frac{u \left( d_{t0}^2 - d_{t8528}^2 \right)}{4} \quad A_s = 5.317\text{-in}^2 \)

Moment of inertia at 85.288 \( I_s := \frac{u \left( d_{t0}^4 - d_{t8528}^4 \right)}{64} \quad I_s = 4.725\text{-in}^4 \)

Section modulus \( S_1 := \frac{I_s}{d_{\text{max}}} \quad S_1 = 2.915\text{-in}^3 \)

Total moment \( M_{8528} := M_s \quad M_{8528} = 141459.1\text{-in-lbf} \)

Tensile stress \( =_{8528} := \frac{M_{8528}}{S_1} \quad =_{8528} = 48519.8\text{-psi} \)

Shear stress \( y_{8528} := \left( \frac{\left| S_{\text{max}} \right|}{A_s} \right) \quad y_{8528} = 17175.3\text{-psi} \)
Stress Ratios

Axial (ult) \( R_{au} := \frac{a_{FSu}}{Ftu\cdot c3tu} \) \( R_{au} = 0.007 \)

Bending(ult) \( R_{bu} := \frac{FSu \cdot 8528}{Fbu\cdot c3tu} \) \( R_{bu} = 0.226 \)

Shear(ult) \( R_{su} := \frac{FSu \cdot y8528}{Fsuc\cdot c3tu} \) \( R_{su} = 0.196 \)

Axial (yld) \( R_{ay} := \frac{a_{FSy}}{Fty\cdot c3ty} \) \( R_{ay} = 0.006 \)

Bending(yld) \( R_{by} := \frac{FSy \cdot 8528}{Fby\cdot c3ty} \) \( R_{by} = 0.256 \)

Shear(yld) \( R_{sy} := \frac{FSy \cdot y8528}{0.50Fty\cdot c3ty} \) \( R_{sy} = 0.206 \)

Margin of safety

Margin of safety ultimate
\[ MS_{u} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \]
\[ MS_{u} = 2.28 \]

Margin of safety yield
\[ MS_{y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\[ MS_{y} = 2 \]

Case 3 At edge of socket \( Y = 89.0 \) - Nominal Landing Case

Moment \( M_{890} := 0.82 \cdot M_{max} \) \( M_{890} = 282918.3 \text{ in-lbf} \)

Shear \( S_{890} := 0.75 \cdot S_{max} \) \( S_{890} = -68487.2 \text{ lbf} \)

Section properties at \( y = 89.0 \)

Area of cross-section \[ A_s := \frac{u \cdot \left(d_{to}^2 - dt89^2\right)}{4} \]
\[ A_s = 5.392 \text{ in}^2 \]
Moment of inertia
\[ I_s := \frac{u(dto^4 - d89^4)}{64} \]
\[ I_s = 4.76 \text{ in}^4 \]

Section modulus
\[ S1 := \frac{I_s}{d_{max}} \]
\[ S1 = 2.937 \text{ in}^3 \]

Combined bending stress
\[ =890 := \frac{M890}{S1} \]
\[ =890 = 96334 \text{ psi} \]

Shear stress
\[ y890 := \frac{890}{As} \]
\[ y890 = 12701.6 \text{ psi} \]

Stress Ratios

Axial (ult)
\[ Rau := \frac{-a \times FSu}{Ftu \times c3tu} \]
\[ Rau = 0.007 \]

Bending(ult)
\[ Rb := \frac{FSu \times =890}{Fbu \times c3tu} \]
\[ Rb = 0.450 \]

Shear(ult)
\[ Rs := \frac{FSu \	imes y890}{Fsu \times c3tu} \]
\[ Rs = 0.145 \]

Axial (yld)
\[ Ray := \frac{-a \times FSy}{Fty \times c3ty} \]
\[ Ray = 0.006 \]

Bending(yld)
\[ Rby := \frac{FSy \times =890}{Fby \times c3ty} \]
\[ Rby = 0.508 \]

Shear(yld)
\[ Rsy := \frac{FSy \times y890}{0.50Fty \times c3ty} \]
\[ Rsy = 0.153 \]

Margin of safety
\[ MSult := \frac{1}{\sqrt{Rb^2 + Rs^2}} - 1 \]
\[ MSult = 1.12 \]

\[ MSyld := \frac{1}{\sqrt{Rby^2 + Rsy^2}} - 1 \]
\[ MSyld = 0.89 \]
2.1.6 Sill Plate (SDG39135733)
Sill Plate SDG39135733

The Sill Plate is classified as a non-structural component. The material of the Sill Plate is Al Alloy 6061-T651.
2.1.7 Lower Trunnion Bridge Beam Elbow
Margins of Safety

Table 2.1.7-1 Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Case</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135734</td>
<td>Bridge Beam Elbow, Lower Trunnion (in-between Sill Joint and Lower Trunnion Bridge Beam)</td>
<td>AL ALY 7050 T7451</td>
<td>2015</td>
<td>Tension</td>
<td>1.97 (u)</td>
<td>2.1.7-22</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. Boundary conditions are at five Trunnion locations.
3. 128 load cases of launch and off-nominal landing are applied.
4. $u =$ ultimate, $y =$ yield
Factors of Safety

The hardware is designed with a factor of safety of 1.1 and 1.4 for yield and ultimate, respectively. This is for both launch and landing load conditions.

Description of Structure

Figure 2.1.7-1 below shows the locations of four Bridge Beam Elbow Joints in AMS-02. The joints were machined out of 7050-T7451 Aluminum Alloy block. All four joints are identical. The upper part of each Joint is riveted to the Sill Joints. The lower part of the elbow is riveted to the Lower Trunnion Bridge Beam.

The model was then constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.1.7-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5.

* Note that in the above figure the Vacuum Case is not shown for clarity. With respect to the XY plane, Trunnion 3, 1, 2, and 4 are located in 1st, 2nd, 3rd, and 4th quadrants, respectively. Elbow joint numbering / referencing in this report are identical to the Trunnion numbers.
Description of Model

A FEM model was built of the Bridge Beam Elbow Joint using FEMAP. For each of the four joints:

1. 5340 Nodes, 4560 Elements (including the CBEAM and RBE2 elements that are technically not part of the Elbow Joint but used to model the Sill Joint and Bridge Beam interfaces).

2. Elbow joint modeled using 2618 CHEXA, 348 CPENTA, and 8 CTETRA solid elements along with 1558 CQUAD4, 14 CTRIA3 plate elements (4546 elements total).
   a. Solid-to-shell connections are established using RSSCON elements that were manually created.
   b. For the purpose of lowering the strain energy in the harmonic model checks, some RSSCON elements were replaced with equally weighted RBE3 elements at the grid point location that produced failure. These locations showed high ground check forces when RSSCON elements were used.
   c. Properties for the upper and lower elbow joint plate elements are identical yet have different IDs for no other reason than model organization.

3. The Sill Joint Interface (representative rivets and sheath):
   a. Elbow Joint is connected to Sill Joint sheath’s 4 CBEAM elements using 4 RBE2s whose independent node is at the properly located CBEAM element and whose dependent nodes are at the appropriate rivet locations.
   b. DOF 123 is transferred to the dependent nodes.
   c. 4 RBE2s representing 5 rows of rivets, for a total of 96 rivets at this connection location.
   d. The Sill Joint sheath is part of the Elbow Joint model imported into the detailed loads model with the interface being a single node. Technically speaking the Sill Joint sheath is not part of the Bridge Beam Elbow Joint; hence, it is not analyzed in this section.
   e. The material property for the Sill Joint sheath CBEAM elements has zero density because the mass was properly accounted for/adjusted in the loads model. The material and property was taken from the loads model with no changes to the ID.

4. The Bridge Beam Interface (representative rivets and insert):
   a. Elbow Joint is connected to Bridge Beam insert’s 3 CBEAM elements using 3 RBE2s whose independent node is at the properly located CBEAM element and whose dependent nodes are at the appropriate rivet locations.
   b. DOF 123 is transferred to the dependent nodes.
   c. 3 RBE2s representing 3 rows of rivets (staggered), for a total of 60 rivets at this connection location.
   d. The Bridge Beam insert is part of the Elbow Joint model imported into the detailed loads model with the interface being a single node. Technically speaking the Bridge Beam insert is not part of the Bridge Beam Elbow Joint; hence, it is not analyzed in this section.
   e. The material property for the Bridge Beam insert CBEAM elements has a density that was properly adjusted in the loads model. The material and property was taken from the loads model with no changes to the ID.
Table 2.1.7-2 shows the numbering scheme used for the Bridge Beam Elbow Joint. Node and element numbers include beam elements previously discussed.

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>PROP</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 1 2nd quadrant</td>
<td>13,020,001 – 13,021,120</td>
<td>13,021,123 – 13,025,340</td>
<td>1201 (top interface)</td>
<td>1573 (bottom interface)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13,020,001 – 13,024,560</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint 2 3rd quadrant</td>
<td>13,000,001 – 13,001,120</td>
<td>13,001,123 – 13,005,340</td>
<td>1208 (top interface)</td>
<td>1574 (bottom interface)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13,000,001 – 13,004,560</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint 3 1st quadrant</td>
<td>13,010,001 – 13,011,120</td>
<td>13,011,123 – 13,015,340</td>
<td>1215 (top interface)</td>
<td>1575 (bottom interface)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13,010,001 – 13,014,560</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint 4 4th quadrant</td>
<td>13,030,001 – 13,031,120</td>
<td>13,031,123 – 13,035,340</td>
<td>1222 (top interface)</td>
<td>1224 (bottom interface)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13,030,001 – 13,034,560</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 2.1.7-3 FEM Numbering Scheme for the Bridge Beam Elbow Joint Solid-to-Plate Element Connections

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>ELEM #</th>
</tr>
</thead>
</table>
| Joint 1 2nd quadrant | upper RSSCON 13,520,001 – 13,520,062, without 5,6,7,15,16,32,33,34,46,47  
  lower RSSCON 13,620,001 – 13,620,054, without 11,12,13,14,15  
  lower RSSCON (ribs outer elbow) 13,720,001 – 13,720,016, no exclusions  
  lower RSSCON (ribs inner elbow) 13,820,001 – 13,820,012, without 5,6  
  RBE3 elements located at previously discussed appropriate grid point 13,920,001 – 13,920,011  |
| Joint 2 3rd quadrant | upper RSSCON 13,500,001 – 13,500,062, without 46,47,61,62  
  13,500,047 and 13,500,061 are RBE3 elements at appropriate grid point  
  lower RSSCON 13,600,001 – 13,600,054, no exclusions  
  lower RSSCON (ribs outer elbow) 13,700,001 – 13,700,016, no exclusions  
  lower RSSCON (ribs inner elbow) 13,800,001 – 13,800,012, no exclusions  |
| Joint 3 1st quadrant | upper RSSCON 13,510,001 – 13,510,062, without 5,6,7,15,16,32,33,34,46,47  
  lower RSSCON 13,610,001 – 13,610,054, without 11,12,13,14,15  
  lower RSSCON (ribs outer elbow) 13,710,001 – 13,710,016, no exclusions  
  lower RSSCON (ribs inner elbow) 13,810,001 – 13,810,012, without 5,6  
  RBE3 elements located at previously discussed appropriate grid point 13,910,001 – 13,910,011  |
| Joint 4 4th quadrant | upper RSSCON 13,530,001 – 13,530,062, without 46,47,61,62  
  13,530,047 and 13,530,061 are RBE3 elements at appropriate grid point  
  lower RSSCON 13,630,001 – 13,630,054, no exclusions  
  lower RSSCON (ribs outer elbow) 13,730,001 – 13,730,016, no exclusions  
  lower RSSCON (ribs inner elbow) 13,830,001 – 13,830,012, no exclusions  |

* The shorthand nomenclature is such that 5 will imply 13,520,005 for joint 1. The shorthand number exists in the range given to the left of the set of shorthand numbers.

** See beginning of section entitled Description of Model.

Note the 10,000 offset from quadrant to quadrant. The 3rd quadrant was created first then copied (translation and/or rotation) to the other locations. The fact that more fixes were needed for the 1st and 2nd quadrant was eventually linked to precision and/or rounding using the Modify, Rotate By, Element command in FEMAP®.
Figure 2.1.7-2 shows the FE model of one of the Bridge Beam Elbow joints. All four joints in the model are identical. The component consists of an upper insert and lower sheath as well as a middle solid section of aluminum. The upper portion is inserted into the sill joint and the connection is made with rivets. The lower portion covers a portion of the lower trunnion bridge beam and the connection is also made with rivets. The rivets are represented in the model using RBE2 elements as shown in the lower left depiction of the joint in the figure. The independent node of said RBE2 elements is also on beam elements whose cross section is from the appropriate region of the sill joint and lower trunnion bridge beam. The solid to shell connections are made primarily with RSSCON elements shown in the lower right depiction in the figure with the exception of a few RBE3 replacements.
Model Checks

The weight of a single joint in the FEM model is 16.25lbs calculated using FEMAP®, while the more detailed CAD weight is 16.25lbs. This is the only model check performed solely on the bridge beam elbow joint.

For the entire USS model check see section 2.2.4.

The comparison of the strap loads in the load model and the detailed model was performed using randomly picked loads. Loads in both models closely matched. This information can be found in Appendix A17 – 2-06 Trunnion and Strap Force NASPOST Results (see Section 2.2.4 and 2.1.7).

Material and Temperature

The Bridge Beam Elbow joints are 7050-T7451 Aluminum Alloy. The material properties are taken from MMPDS-01. Temperature limits at the Bridge Beam Elbow Joints are provided by the Thermal Analysis Group. For launch conditions, the temperature range is between 40°F and 120°F. For nominal landing conditions, the temperature range is from -78°F to 101°F. For abort landing conditions, the temperature range is from 40°F to 150°F.
Analysis

MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02 version 2-06.

A total of 128 load cases were applied for launch and abort landing.

Loads across the top and bottom portion of the elbow joints were extracted from the FE model. These loads are used in calculations to find the critical stresses for the Bridge Beam Elbow Joints’ beam cross sections (top and bottom). The computed stresses are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy while taking into account temperature degradation effects. All margins of safety are positive. Since the beam cross sections show positive margins, the solid center section will also have positive margins.

Material Properties: 7050-T7451 AL ALY, BMS 7-323C
or AMS 4050

\[
F_{tu} := 66000 \text{psi} \quad \text{(MMPDS-01, Table 3.7.4.0(b1) for thickness of 5.001"-6.000")}
\]
\[
F_{ty} := 57000 \text{psi}
\]
\[
F_{su} := 43000 \text{psi}
\]

Factors of Safety, \( F_{Su} := 1.4 \) \( F_{Sy} := 1.1 \)

Temperature reduction factors, \( \gamma_u \) for Launch condition and \( \gamma_u \) for Abort Landing condition:

\[
\gamma_u^1 := 0.95 \quad \gamma_u^2 := 0.91
\]

Allowable stresses:

Launch:

\[
F_{tu1.a} := \gamma_u^1 F_{tu} \quad F_{tu1.a} = 62700 \text{psi}
\]
\[
F_{ty1.a} := \gamma_y^1 F_{ty} \quad F_{ty1.a} = 56430 \text{psi}
\]
\[
F_{su1.a} := \gamma_u^1 F_{su} \quad F_{su1.a} = 40850 \text{psi}
\]

Abort landing condition:

\[
F_{tu2.a} := \gamma_u^2 F_{tu} \quad F_{tu2.a} = 60060 \text{psi}
\]
\[
F_{ty2.a} := \gamma_y^2 F_{ty} \quad F_{ty2.a} = 55290 \text{psi}
\]
\[
F_{su2.a} := \gamma_u^2 F_{su} \quad F_{su2.a} = 39130 \text{psi}
\]
Goemetry: 5.938X5.938X.25 Tube (top-symmetric cross section)

\[
b_{\text{Top}} := 5.938 \text{ in} \quad d_{\text{Top}} := 5.938 \text{ in} \quad t_{\text{Top}} := .250 \text{ in} \quad c_{\text{Top}} := \frac{b_{\text{Top}}}{2}
\]

\[
A_{\text{Top}} := b_{\text{Top}} \cdot d_{\text{Top}} - (b_{\text{Top}} - 2 \cdot t_{\text{Top}}) \cdot (d_{\text{Top}} - 2 \cdot t_{\text{Top}})
\]

\[
I_{\text{Top}} := \frac{b_{\text{Top}} \cdot d_{\text{Top}}^3 - (b_{\text{Top}} - 2 \cdot t_{\text{Top}}) \cdot (d_{\text{Top}} - 2 \cdot t_{\text{Top}})^3}{12}
\]

Top cantilever distance to solid chunk of aluminum:
\[
d_{\text{CantT}} := 6.0 \text{ in}
\]

Goemetry: 5.5X5.5X.25 Tube (bottom-symmetric cross section if flanges ignored - conservative)

\[
b_{\text{Bot}} := 5.5 \text{ in} \quad d_{\text{Bot}} := 5.5 \text{ in} \quad t_{\text{Bot}} := .250 \text{ in} \quad c_{\text{Bot}} := \frac{b_{\text{Bot}}}{2}
\]

\[
A_{\text{Bot}} := b_{\text{Bot}} \cdot d_{\text{Bot}} - (b_{\text{Bot}} - 2 \cdot t_{\text{Bot}}) \cdot (d_{\text{Bot}} - 2 \cdot t_{\text{Bot}})
\]

\[
I_{\text{Bot}} := \frac{b_{\text{Bot}} \cdot d_{\text{Bot}}^3 - (b_{\text{Bot}} - 2 \cdot t_{\text{Bot}}) \cdot (d_{\text{Bot}} - 2 \cdot t_{\text{Bot}})^3}{12}
\]

Bottom cantilever distance to solid chunk of aluminum:
\[
d_{\text{CantB}} := 5.31349 \text{ in}
\]
Stresses for Launch (lower beam forces):

\[
\text{load} := \text{READPRN}(\text{"beamLoads.Bot.1k.txt"}) \quad i := 1.. \text{rows}(\text{load})
\]

Element ID: \(\text{ID} := \text{load}\)  
Load case number: \(\text{LC} := \text{load}\)

At end A of beam element:

\[
\begin{align*}
\text{Moment:} & \quad M_{1a} := \text{load} \cdot \text{in-lbf} \\
\text{Shear force:} & \quad V_{1a} := \text{load} \cdot \text{lbf} \\
\text{Axial force:} & \quad P_a := \text{load} \cdot \text{lbf} \\
\text{Total torque:} & \quad T_{oa} := \text{load} \cdot \text{in-lbf}
\end{align*}
\]

Total Bending:

\[
\begin{align*}
M_{yi} & := \left| -M_{2a} - V_{2a} \cdot \text{dCantB} \right| \\
M_{zi} & := \left| M_{1a} + V_{1a} \cdot \text{dCantB} \right|
\end{align*}
\]

Axial Stress:

Stresses on cross section:

Normal is direct axial plus bending: (Conservative)

\[
\sigma_i := \frac{P_a}{A_{Bot}} \quad \max(\sigma) = 7888\text{psi}
\]

\[
\sigma_b_i := \frac{M_{yi} \cdot c_{Bot}}{\text{IntBot}} + \frac{M_{zi} \cdot c_{Bot}}{\text{IntBot}} \quad \max(\sigma_b) = 3453\text{psi}
\]

\[
\sigma_i := \sigma_i + \sigma_b_i \quad \max(\sigma) = 10085\text{psi}
\]
Shear Stress:

Shear due to transverse loading:
\[
\tau_v := \sqrt{\left(\frac{V_{1a}}{A_{Bot}}\right)^2 + \left(\frac{V_{2a}}{A_{Bot}}\right)^2}
\]
\[
\max(\tau_v) = 407 \text{ psi}
\]

Shear due to torsion (conservative):
\[
\tau_t := \frac{|Toa|}{2t_{Bot}(b_{Bot} - t_{Bot}) - (d_{Bot} - t_{Bot})}
\]
\[
\max(\tau_t) = 1039 \text{ psi}
\]
tt from Roark's 6th, p352, Table 20, Case 16, Avg.

Shear stress

Combined shear:
\[
\tau_i := \tau_v + \tau_t
\]
\[
\max(\tau) = 1318 \text{ psi}
\]

Principal Stresses:
\[
\sigma_{p1,1} := \frac{\sigma_i}{2} + \left[\left(\frac{\sigma_i}{2}\right)^2 + (\tau_i)^2\right]^{1/2}
\]
\[
\max(\sigma_p) = 10188 \text{ psi}
\]
\[
\sigma_{p1,2} := \frac{\sigma_i}{2} - \left[\left(\frac{\sigma_i}{2}\right)^2 + (\tau_i)^2\right]^{1/2}
\]
\[
\min(\sigma_p) = -4131 \text{ psi}
\]

Maximum principal stress is:
\[
\sigma_{\text{max}} := \begin{cases} 
\sigma_{p1,1} & \text{if } |\sigma_{p1,1}| \geq |\sigma_{p1,2}| \\
\sigma_{p1,2} & \text{otherwise}
\end{cases}
\]

Von-Mises Stress:
\[
\sigma_{\text{vm}} := \sqrt{\sigma_{p1,1}^2 + \sigma_{p1,2}^2 - \sigma_{p,1} \cdot \sigma_{p,2}}
\]
\[
\max(\sigma_{\text{vm}}) = 10240 \text{ psi}
\]

Maximum shear:
\[
\tau_{\text{max}} := \frac{1}{4} \left(\sigma_i^2 + (\tau_i)^2\right)
\]
\[
\max(\tau_{\text{max}}) = 5146 \text{ psi}
\]
Margins of safety:

Ultimate

\[ MS_{u,i} := \begin{cases} \frac{F_{tu1,a}}{F_{Su}\cdot \sigma_{max}} - 1 & \text{if } \sigma_{max} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on element 1221, for load case 1016

\[ \text{info} := \left( \text{csort augment} \left( \text{ID, LC, MSu}, \frac{P_a}{1 \text{ lbf}}, \frac{V_{1a}}{1 \text{ lbf}}, \frac{V_{2a}}{1 \text{ in-} \text{lbf}}, \frac{Toa}{1 \text{ in-} \text{lbf}}, \frac{My}{1 \text{ in-} \text{lbf}}, \frac{Mz}{1 \text{ in-} \text{lbf}} \right), 3 \right)^T \]

\[ \text{info} = (1221 \ 1016 \ 3.4 \ 40763.95 \ -1097.19 \ -74.01 \ 11231.41 \ 3227.53 \ 17168.57) \]

Ultimate, shear

\[ MS_{su,i} := \begin{cases} \frac{F_{su1,a}}{F_{Su}\cdot \tau_{max}} - 1 & \text{if } \tau_{max} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on element 1221, for load case 1016

\[ \text{info} := \left( \text{csort augment} \left( \text{ID, LC, MSsu}, \frac{P_a}{1 \text{ lbf}}, \frac{V_{1a}}{1 \text{ lbf}}, \frac{V_{2a}}{1 \text{ in-} \text{lbf}}, \frac{Toa}{1 \text{ in-} \text{lbf}}, \frac{My}{1 \text{ in-} \text{lbf}}, \frac{Mz}{1 \text{ in-} \text{lbf}} \right), 3 \right)^T \]

\[ \text{info} = (1221 \ 1016 \ 4.67 \ 40763.95 \ -1097.19 \ -74.01 \ 11231.41 \ 3227.53 \ 17168.57) \]

Yield

(Using von-Mises)

\[ MS_{y,i} := \begin{cases} \frac{F_{ty1,a}}{F_{Sy}\cdot \sigma_{vm_i}} - 1 & \text{if } \sigma_{vm_i} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on element 1221, for load case 1016

\[ \text{info} := \left( \text{csort augment} \left( \text{ID, LC, MSy}, \frac{P_a}{1 \text{ lbf}}, \frac{V_{1a}}{1 \text{ lbf}}, \frac{V_{2a}}{1 \text{ in-} \text{lbf}}, \frac{Toa}{1 \text{ in-} \text{lbf}}, \frac{My}{1 \text{ in-} \text{lbf}}, \frac{Mz}{1 \text{ in-} \text{lbf}} \right), 3 \right)^T \]

\[ \text{info} = (1221 \ 1016 \ 4.01 \ 40763.95 \ -1097.19 \ -74.01 \ 11231.41 \ 3227.53 \ 17168.57) \]
Stresses for Launch (upper beam forces):

\[
\begin{align*}
\text{load} & := \text{READPRN} \ "\text{beamLoads.Top.1k.txt}" \\
\text{Node ID:} & \quad \text{ID} := \text{load}(1) \\
\text{Load case number:} & \quad \text{LC} := \text{load}(2)
\end{align*}
\]

+ MPC forces acting on the joint:

\[
\begin{align*}
\text{Moment:} & \quad \text{Mxmpc} := \text{load}(6) \cdot \text{in} \cdot \text{lbf} \quad \text{Mympc} := \text{load}(7) \cdot \text{in} \cdot \text{lbf} \\
\text{Shear force:} & \quad \text{Vx} := \text{load}(3) \cdot \text{lbf} \quad \text{Vy} := \text{load}(4) \cdot \text{lbf} \\
\text{Axial force:} & \quad \text{Pz} := \text{load}(5) \cdot \text{lbf}
\end{align*}
\]

Total Bending:

\[
\begin{align*}
\text{Mx}_i & := \left| \text{Mxmpc}_i - \text{Vy}_i \cdot \text{dCant} \right| \quad \max(\text{Mx}) = 61694\text{in} \cdot \text{lbf} \\
\text{My}_i & := \left| \text{Mympc}_i + \text{Vx}_i \cdot \text{dCant} \right| \quad \max(\text{My}) = 21524\text{in} \cdot \text{lbf}
\end{align*}
\]

Axial Stress:

Stresses on cross section:

Normal is direct axial plus bending: (Conservative)

\[
\begin{align*}
\text{Tension:} & \quad \sigma_t := \frac{\text{Pz}_i}{\text{ATop}} \quad \max(\sigma_t) = 5279\text{psi} \\
\text{Bending:} & \quad \sigma_b := \frac{\text{Mx}_i \cdot \text{cTop}}{\text{IntTop}} + \frac{\text{My}_i \cdot \text{cTop}}{\text{IntTop}} \quad \max(\sigma_b) = 7898\text{psi} \\
\text{Tension plus bending:} & \quad \sigma_i := \sigma_t + \sigma_b \quad \max(\sigma) = 11427\text{psi}
\end{align*}
\]
Shear Stress:

Shear due to transverse loading:
\[ \tau_i := \sqrt{\left( \frac{Vx_i}{ATop} \right)^2 + \left( \frac{Vy_i}{ATop} \right)^2} \]
\[ \max(\tau) = 5025 \text{psi} \]

Shear due to torsion (conservative):
\[ \tau_i := \frac{|Tz_i|}{2tTop \cdot (bTop - tTop) \cdot (dTop - tTop)} \]
\[ \max(\tau) = 967 \text{psi} \]

Equation from Roark’s 6th, p352, Table 20, Case 16, Avg. Shear stress

Combined shear:
\[ \tau_i := \tau v_i + \tau t_i \]
\[ \max(\tau) = 5610 \text{psi} \]

Principal Stresses:
\[ \sigma p_{i,1} := \frac{\sigma_i}{2} + \left[ \left( \frac{\sigma_i}{2} \right)^2 + (\tau_i)^2 \right]^{\frac{1}{2}} \]
\[ \max(\sigma p) = 12830 \text{psi} \]

\[ \sigma p_{i,2} := \frac{\sigma_i}{2} - \left[ \left( \frac{\sigma_i}{2} \right)^2 + (\tau_i)^2 \right]^{\frac{1}{2}} \]
\[ \min(\sigma p) = -2657 \text{psi} \]

Most principal stress is:
\[ \sigma_{\max} := \begin{cases} \sigma p_{i,1} & \text{if } |\sigma p_{i,1}| \geq |\sigma p_{i,2}| \\ \sigma p_{i,2} & \text{otherwise} \end{cases} \]

Von-Mises Stress:
\[ \sigma vm_i := \sqrt{\left( \sigma p_{i,1} \right)^2 + \left( \sigma p_{i,2} \right)^2 - \sigma p_{i,1} \cdot \sigma p_{i,2}} \]
\[ \max(\sigma vm) = 13586 \text{psi} \]

Maximum shear:
\[ \tau_{\max} := \frac{1}{\sqrt{4}} \left( \frac{\sigma_i^2}{2} + (\tau_i)^2 \right) \]
\[ \max(\tau_{\max}) = 7276 \text{psi} \]
Margins of safety:

Ultimate

\[ MS_{u,i} := \begin{cases} \left( \frac{F_{tu1,a}}{FS_u \cdot \sigma_{\max}} \right) - 1 & \text{if } \sigma_{\max} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on node 1215, for load case 1019

\[ \text{info} = (1215 \ 1019 \ 2.49 \ -22360.58 \ -1385.22 \ -22666.66 \ -4043.62 \ 56924.24 \ 20662.32) \]

Ultimate, shear

\[ MS_{su,i} := \begin{cases} \left( \frac{F_{su1,a}}{FS_{u} \cdot \sigma_{\max}} \right) - 1 & \text{if } \sigma_{\max} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on node 1201, for load case 1015

\[ \text{info} = (1201 \ 1015 \ 3.01 \ 30026.48 \ -1038.87 \ 28565.73 \ 8828.72 \ 35295.12 \ 6935.2) \]

Yield (using von-Mises)

\[ MS_{y,i} := \begin{cases} \left( \frac{F_{ty1,a}}{FS_{y} \cdot \sigma_{vm_i}} \right) - 1 & \text{if } \sigma_{vm_i} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on node 1215, for load case 1019

\[ \text{info} = (1215 \ 1019 \ 2.78 \ -22360.58 \ -1385.22 \ -22666.66 \ -4043.62 \ 56924.24 \ 20662.32) \]
Stresses for Abort (lower beam forces):

\[
\text{load} := \text{READPRN}("\text{beamLoads.Bot.2k.tex}\}) \quad \text{\textit{i := 1.. rows(load)}}
\]

Element ID: \( \text{ID := load}^{(1)} \)
Load case number: \( \text{LC := load}^{(2)} \)

+ At end A of beam element:

\[
\begin{align*}
\text{Moment:} & \quad M1_{a} := \text{load}^{(3)}\text{-in\text{-}lbf} \\
& \quad M2_{a} := \text{load}^{(4)}\text{-in\text{-}lbf} \\
\text{Shear force:} & \quad V1_{a} := \text{load}^{(5)}\text{-lbf} \\
& \quad V2_{a} := \text{load}^{(6)}\text{-lbf} \\
\text{Axial force:} & \quad Pa := \text{load}^{(7)}\text{-lbf} \\
& \quad \text{Total torque:} \quad Toa := \text{load}^{(8)}\text{-in\text{-}lbf}
\end{align*}
\]

Total Bending:

\[
\begin{align*}
M_y_{i} & := \left| -M2_{a_{i}} - V2_{a_{i}} \cdot \text{dCant}_B \right| \quad \max(M_y) = 23413\text{in\text{-}lbf} \\
M_z_{i} & := \left| M1_{a_{i}} + V1_{a_{i}} \cdot \text{dCant}_B \right| \quad \max(M_z) = 16697\text{in\text{-}lbf}
\end{align*}
\]

Axial Stress:

Stresses on cross section:

Normal is direct axial plus bending: (Conservative)

Tension:

\[
\sigma_{t_{i}} := \frac{Pa_{i}}{ABot} \quad \max(\sigma_t) = 5279\text{psi}
\]

Bending:

\[
\sigma_{b_{i}} := \frac{M_{y_{i}} \cdot \text{cBot}}{\text{IntBot}} + \frac{M_{z_{i}} \cdot \text{cBot}}{\text{IntBot}} \quad \max(\sigma_b) = 7898\text{psi}
\]

Tension plus bending:

\[
\sigma_{i} := \sigma_{t_{i}} + \sigma_{b_{i}} \quad \max(\sigma) = 11427.2\text{psi}
\]
Shear Stress:

Shear due to transverse loading:
\[ \tau_v := \sqrt{\left( \frac{V_1 a}{A_{Bot}} \right)^2 + \left( \frac{V_2 a}{A_{Bot}} \right)^2} \quad \text{max}(\tau_v) = 298 \text{psi} \]

Shear due to torsion (conservative):
\[ \tau_t := \frac{|Toa_i|}{2t_{Bot}(b_{Bot} - t_{Bot})(d_{Bot} - t_{Bot})} \quad \text{max}(\tau_t) = 480 \text{psi} \]

\( \tau_t \) from Roark’s 6th, p352, Table 20, Case 16, Avg.

Shear stress

Combined shear:
\[ \tau_i := \tau_v + \tau_t \quad \text{max}(\tau) = 674 \text{psi} \]

Principal Stresses:
\[ \sigma_{pi,1} := \frac{\sigma_i}{2} + \left[ \left( \frac{\sigma_i}{2} \right)^2 + \left( \tau_i \right)^2 \right]^{1/2} \quad \text{max}(\sigma_p) = 11390 \text{psi} \]

\[ \sigma_{pi,2} := \frac{\sigma_i}{2} - \left[ \left( \frac{\sigma_i}{2} \right)^2 + \left( \tau_i \right)^2 \right]^{1/2} \quad \text{min}(\sigma_p) = -3024 \text{psi} \]

Maximum principal stress is:
\[ \sigma_{max} := \begin{cases} \sigma_{pi,1} & \text{if } |\sigma_{pi,1}| \geq |\sigma_{pi,2}| \\ |\sigma_{pi,2}| & \text{otherwise} \end{cases} \]

Von-Mises Stress:
\[ \sigma_{vm} := \sqrt{\left( \sigma_{pi,1} \right)^2 + \left( \sigma_{pi,2} \right)^2 - \sigma_{pi,1} \cdot \sigma_{pi,2}} \quad \text{max}(\sigma_{vm}) = 11401 \text{psi} \]

Maximum shear:
\[ \tau_{max} := \frac{1}{4} \left( \frac{\sigma_i}{2} \right)^2 + \left( \tau_i \right)^2 \quad \text{max}(\tau_{max}) = 5706 \text{psi} \]
Margins of safety:

Ultimate

\[
MSu_{i} := \left( \frac{F_{tu,a}}{FS_{u} \cdot \sigma_{\max}} \right) - 1 \quad \text{if} \quad \sigma_{\max} \neq 0 \text{ psi} \quad \min(\text{MSu}) = 2.77
\]

```
10000 \quad \text{otherwise}
```

Minimum margin occurs on element 1221, for load case 2016

```
info := \left( \begin{array}{c}
\text{Csor} \left( \begin{array}{c}
\text{augment} \left( \begin{array}{cccc}
\text{ID}, \text{LC}, \text{MSu}, \frac{P_{a}}{1 \text{-lbf}}, \frac{V_{1a}}{1 \text{-lbf}}, \frac{V_{2a}}{1 \text{-lbf}}, \frac{Toa}{1 \text{-in-lbf}}, \frac{My}{1 \text{-in-lbf}}, \frac{Mz}{1 \text{-in-lbf}}
\end{array} \right) \end{array} \right) \end{array} \right)_{1}^{T}
\end{array}
```

```
info = (1221 2016 2.77 47589.96 -723.31 617.85 4485.55 10244.24 9993.11)
```

Ultimate, shear

\[
MSsu_{i} := \left( \frac{F_{su,a}}{FS_{u} \cdot \tau_{\max}} \right) - 1 \quad \text{if} \quad \tau_{\max} \neq 0 \text{ psi} \quad \min(\text{MSsu}) = 3.9
\]

```
10000 \quad \text{otherwise}
```

Minimum margin occurs on element 1221, for load case 2016

```
info := \left( \begin{array}{c}
\text{Csor} \left( \begin{array}{c}
\text{augment} \left( \begin{array}{cccc}
\text{ID}, \text{LC}, \text{MSsu}, \frac{P_{a}}{1 \text{-lbf}}, \frac{V_{1a}}{1 \text{-lbf}}, \frac{V_{2a}}{1 \text{-lbf}}, \frac{Toa}{1 \text{-in-lbf}}, \frac{My}{1 \text{-in-lbf}}, \frac{Mz}{1 \text{-in-lbf}}
\end{array} \right) \end{array} \right) \end{array} \right)_{1}^{T}
\end{array}
```

```
info = (1221 2016 3.9 47589.96 -723.31 617.85 4485.55 10244.24 9993.11)
```

Yield (using von-Mises)

\[
MSy_{i} := \left( \frac{F_{ty,a}}{FS_{y} \cdot \sigma_{vm}} \right) - 1 \quad \text{if} \quad \sigma_{vm} \neq 0 \text{ psi} \quad \min(\text{MSy}) = 3.41
\]

```
10000 \quad \text{otherwise}
```

Minimum margin occurs on element 1221, for load case 2016

```
info := \left( \begin{array}{c}
\text{Csor} \left( \begin{array}{c}
\text{augment} \left( \begin{array}{cccc}
\text{ID}, \text{LC}, \text{MSy}, \frac{P_{a}}{1 \text{-lbf}}, \frac{V_{1a}}{1 \text{-lbf}}, \frac{V_{2a}}{1 \text{-lbf}}, \frac{Toa}{1 \text{-in-lbf}}, \frac{My}{1 \text{-in-lbf}}, \frac{Mz}{1 \text{-in-lbf}}
\end{array} \right) \end{array} \right) \end{array} \right)_{1}^{T}
\end{array}
```

```
info = (1221 2016 3.41 47589.96 -723.31 617.85 4485.55 10244.24 9993.11)
```
Stresses for Abort (upper beam forces):

load := READPRN("beamLoads.Top.2k.txt") 
ii := 1.. rows(load)

Node ID: 
ID := load(i)
Load case number: 
LC := load(2)

+ MPC forces acting on the joint:

Moment:
Mxmpc := load(i) · in-lbf
Mympc := load(i) · in-lbf

Shear force:
Vx := load(i) · lbf
Vy := load(i) · lbf

Axial force:
Pz := load(i) · lbf

Total Bending:

Mx := |Mxmpc_i - Vy_i · dCantT|
max(Mx) = 60233in·lbf

My := |Mympc_i + Vx_i · dCantT|
max(My) = 16873in·lbf

Axial Stress:

Stresses on cross section:

Normal is direct axial plus bending: (Conservative)

Tension:

σt := Pz_i / ATop 
max(σt) = 6067psi

Bending:

σb := |Mx_i · cTop / IntTop| + |My_i · cTop / IntTop| 
max(σb) = 6704psi

Tension plus bending:

σ := σt + σb 
max(σ) = 11908psi
Shear Stress:

Shear due to transverse loading:
\[ \tau_i := \sqrt{\left(\frac{Vx_i}{ATop}\right)^2 + \left(\frac{Vy_i}{ATop}\right)^2} \quad \text{max}(\tau) = 5937 \text{psi} \]

Shear due to torsion (conservative):
\[ \tau_i := \frac{|Tz_i|}{2 \cdot t_{Top} \cdot (b_{Top} - t_{Top}) \cdot (d_{Top} - t_{Top})} \quad \text{max}(\tau) = 572 \text{psi} \]

tt from Roark’s 6th, p352, Table 20, Case 16, Avg.
Shear stress

Combined shear:
\[ \tau_i := \tau v_i + \tau t_i \quad \text{max}(\tau) = 6111 \text{psi} \]

Principal Stresses:
\[ \sigma p_{i,1} := \frac{\sigma_i}{2} + \left[\left(\frac{\sigma_i}{2}\right)^2 + (\tau_i)^2\right]^{1/2} \quad \text{max}(\sigma p) = 14423 \text{psi} \]
\[ \sigma p_{i,2} := \frac{\sigma_i}{2} - \left[\left(\frac{\sigma_i}{2}\right)^2 + (\tau_i)^2\right]^{1/2} \quad \text{min}(\sigma p) = -2604 \text{psi} \]

Maximum principal stress is:
\[ \sigma_{\text{max}} := \begin{cases} \sigma p_{i,1} & \text{if } |\sigma p_{i,1}| \geq |\sigma p_{i,2}| \\ \sigma p_{i,2} & \text{otherwise} \end{cases} \]

Von-Mises Stress:
\[ \sigma v_m := \sqrt{\left(\frac{\sigma p_{i,1}}{2}\right)^2 + \left(\sigma p_{i,2}\right)^2 - \frac{1}{2} \cdot \sigma p_{i,1} \cdot \sigma p_{i,2}} \quad \text{max}(\sigma v m) = 15832 \text{psi} \]

Maximum shear:
\[ \tau_{\text{max}} := \frac{1}{4} \left(\frac{\tau i}{2}\right)^2 + (\tau t)^2 \quad \text{max}(\tau_{\text{max}}) = 8474 \text{psi} \]
Margins of safety:

Ultimate

\[ MSu_{i} := \begin{cases} \frac{F_{tu2.a}}{FS_{u} \cdot \sigma_{max}} - 1 & \text{if } \sigma_{max} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on element 1201, for load case 2015

\[ \text{info} := \left( \text{csort} \left( \text{augment} \left( ID, LC, MSu, \frac{Pz}{1 \text{-lbf}}, \frac{Vx}{1 \text{-lbf}}, \frac{Vy}{1 \text{-lbf}}, \frac{Tz}{1 \text{-in-lbf}}, \frac{Mx}{1 \text{-in-lbf}}, \frac{My}{1 \text{-in-lbf}} \right), 3 \right) \right)^T \]

\[ \text{info} = (1201, 2015, 1.97, 34510.16, -560.21, 33767.12, 1393.29, 56594.78, 3859.31) \]

Ultimate, shear

\[ MSu_{i} := \begin{cases} \frac{F_{su2.a}}{FS_{u} \cdot \tau_{max}} - 1 & \text{if } \tau_{max} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on node 1201, for load case 2016

\[ \text{info} := \left( \text{csort} \left( \text{augment} \left( ID, LC, MSu, \frac{Pz}{1 \text{-lbf}}, \frac{Vx}{1 \text{-lbf}}, \frac{Vy}{1 \text{-lbf}}, \frac{Tz}{1 \text{-in-lbf}}, \frac{Mx}{1 \text{-in-lbf}}, \frac{My}{1 \text{-in-lbf}} \right), 3 \right) \right)^T \]

\[ \text{info} = (1201, 2016, 2.3, 34114.51, -767.79, 33316.2, 4087.13, 56333.2, 3103.02) \]

Yield (using von-Mises)

\[ MSy_{i} := \begin{cases} \frac{F_{ty2.a}}{FS_{y} \cdot \sigma_{vmi}} - 1 & \text{if } \sigma_{vmi} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

Minimum margin occurs on node 1201, for load case 2015

\[ \text{info} := \left( \text{csort} \left( \text{augment} \left( ID, LC, MSy, \frac{Pz}{1 \text{-lbf}}, \frac{Vx}{1 \text{-lbf}}, \frac{Vy}{1 \text{-lbf}}, \frac{Tz}{1 \text{-in-lbf}}, \frac{Mx}{1 \text{-in-lbf}}, \frac{My}{1 \text{-in-lbf}} \right), 3 \right) \right)^T \]

\[ \text{info} = (1201, 2015, 2.17, 34510.16, -560.21, 33767.12, 1393.29, 56594.78, 3859.31) \]
2.1.8 Lower Trunnion Bridge Beam Assembly
Lower Trunnion Bridge Beam

Buckling Analysis:

Since part is a slender beam with compressive loads, buckling is critical.

In Finite Element Model of USS-02 version 2-04 shown in Figure 2.1.8-1, Lower Trunnion Bridge Beam includes Element Ids of 1201-1203, 1204-1206, 1207-1209, and 1210-1212. These elements has Property Id of 1007.

Figure 2.1.8-1: Lower Trunnion Bridge Beam shown in 2-04 Loads Model
Factor of Safety, ultimate: \( F_{Su} = 1.4 \)

Factor of Safety, yield: \( F_{Sy} = 1.1 \)

Material: AL 7075-T73511

(Ref. MIL-HDBK-5J, Table 3.7.6.0\(\text{g}_2\), Thickness: 0.250-0.499)

Compressive modulus, \( E_c = 10700000 \text{ psi} \)

Ultimate tensile strength, \( f_{tu} = 68000 \text{ psi} \)

Tensile yield strength, \( f_{ty} = 57000 \text{ psi} \)

Compression yield strength, \( f_{cy} = 60000 \text{ psi} \)

Ultimate shear strength, \( f_{su} = 38000 \text{ psi} \)

Temperature correction factor, ultimate: \( c_{tu} = 0.94 \)

Temperature correction factor, yield: \( c_{ty} = 0.96 \)

Temperature correction factor, \( E_c \): \( c_{cc} = 0.98 \)

Maximum Temperature occurs during abort landing

Temperature correction factor, ultimate: \( T_{max} = 150\text{ deg} \)

Section: 4.938" x 4.938" x 0.3125" Tube (Ref. Dwg# SDG39135735)
Shape Factor, \( f := 1.22 \)  

Supported length, \( L := 40.50\,\text{in} \)  

Properties of cross-section:  
\( \text{(Ref. Table 2.1.8-1)} \)  

Width, \( \text{Dy} := 4.938\,\text{in} \)  
Area, \( A := 5.782\,\text{in}^2 \)  

For torsional calculation, use:  
\( \text{Dytor} := 4.938\,\text{in} \)  
\( \text{Moment of Inertia, } I_y := 20.712\,\text{in}^4 \)  

Depth, \( \text{Dz} := 4.938\,\text{in} \)  
\( I_z := 20.712\,\text{in}^4 \)  

For torsional calculation, use:  
\( \text{Dztor} := 4.938\,\text{in} \)  

Thickness, \( t := 0.3125\,\text{in} \)  
\( Q_y := 5.022\,\text{in}^3 \)  
\( Q_z := 5.022\,\text{in}^3 \)  

Define:  
\( b := 2\cdot t \)
Table 2.1.8-1a: Property about Y-Y axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Az</th>
<th>Az^2</th>
<th>icy</th>
<th>ly'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9380</td>
<td>0.3125</td>
<td>1.5431</td>
<td>4.7818</td>
<td>7.3788</td>
<td>35.2838</td>
<td>0.0126</td>
<td>35.2963</td>
</tr>
<tr>
<td>2</td>
<td>0.3125</td>
<td>4.3130</td>
<td>1.3478</td>
<td>2.4690</td>
<td>3.3277</td>
<td>8.2162</td>
<td>2.0893</td>
<td>10.3055</td>
</tr>
<tr>
<td>3</td>
<td>4.9380</td>
<td>0.3125</td>
<td>1.5431</td>
<td>0.1563</td>
<td>0.2411</td>
<td>0.0377</td>
<td>0.0126</td>
<td>0.0502</td>
</tr>
<tr>
<td>4</td>
<td>0.3125</td>
<td>4.3130</td>
<td>1.3478</td>
<td>2.4690</td>
<td>3.3277</td>
<td>8.2162</td>
<td>2.0893</td>
<td>10.3055</td>
</tr>
</tbody>
</table>

Sum: 

<table>
<thead>
<tr>
<th>A</th>
<th>z_bar</th>
<th>Iyy</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.782</td>
<td>2.469</td>
<td>20.712</td>
</tr>
</tbody>
</table>

\[ z_{\text{bar}} = 2.469 \]
\[ I_{yy} = 20.712 \]

Table 2.1.8-1b: Property about Z-Z axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>y</th>
<th>Ay</th>
<th>Ay^2</th>
<th>lcz</th>
<th>lzz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3125</td>
<td>4.9380</td>
<td>1.5431</td>
<td>2.4690</td>
<td>3.8100</td>
<td>9.4068</td>
<td>3.1356</td>
<td>12.5424</td>
</tr>
<tr>
<td>2</td>
<td>4.3130</td>
<td>0.3125</td>
<td>1.3478</td>
<td>4.7818</td>
<td>6.4449</td>
<td>30.8179</td>
<td>0.0110</td>
<td>30.8289</td>
</tr>
<tr>
<td>3</td>
<td>0.3125</td>
<td>4.9380</td>
<td>1.5431</td>
<td>2.4690</td>
<td>3.8100</td>
<td>9.4068</td>
<td>3.1356</td>
<td>12.5424</td>
</tr>
<tr>
<td>4</td>
<td>4.3130</td>
<td>0.3125</td>
<td>1.3478</td>
<td>0.1563</td>
<td>0.2106</td>
<td>0.0329</td>
<td>0.0110</td>
<td>0.0439</td>
</tr>
</tbody>
</table>

Sum: 

<table>
<thead>
<tr>
<th>A</th>
<th>y_bar</th>
<th>Izz</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.782</td>
<td>2.469</td>
<td>20.712</td>
</tr>
</tbody>
</table>

\[ y_{\text{bar}} = 2.469 \]
\[ I_{zz} = 20.712 \]

Table 2.1.8-1c: First Moment about Y-Y axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Qyy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9380</td>
<td>0.3125</td>
<td>1.5431</td>
<td>2.3128</td>
<td>3.5689</td>
</tr>
<tr>
<td>2</td>
<td>0.3125</td>
<td>2.1565</td>
<td>0.67390625</td>
<td>1.2345</td>
<td>0.9525</td>
</tr>
<tr>
<td>4</td>
<td>0.3125</td>
<td>2.1565</td>
<td>0.67390625</td>
<td>1.0783</td>
<td>0.7266</td>
</tr>
</tbody>
</table>

Sum: 

\[ Q_{yy} = 5.022 \]

Table 2.1.8-1d: First Moment about Z-Z axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>y</th>
<th>Qzz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3125</td>
<td>2.4690</td>
<td>0.7715625</td>
<td>1.2345</td>
<td>0.9525</td>
</tr>
<tr>
<td>2</td>
<td>4.3130</td>
<td>0.3125</td>
<td>1.3478125</td>
<td>2.3128</td>
<td>3.1172</td>
</tr>
<tr>
<td>3</td>
<td>0.3125</td>
<td>2.4690</td>
<td>0.7715625</td>
<td>1.2345</td>
<td>0.9525</td>
</tr>
</tbody>
</table>

Sum: 

\[ Q_{zz} = 5.022 \]
Section modulus, \[ Sy := \frac{I_y}{\frac{1}{2} \cdot D_z} \quad Sy = 8.389 \text{ in}^3 \]

\[ Sz := \frac{I_z}{\frac{1}{2} \cdot D_y} \quad Sz = 8.389 \text{ in}^3 \]

Torsional constant / distance, \[ JoR := 2 \cdot t \cdot (Dztor - t) \cdot (Dytor - t) \quad JoR = 13.372 \text{ in}^3 \]

Radii of gyration, \[ ry := \sqrt{\frac{I_y}{A}} \quad ry = 1.893 \text{ in} \]

\[ rz := \sqrt{\frac{I_z}{A}} \quad rz = 1.893 \text{ in} \]

Fixity coefficient, \( K := 1.2 \quad (\text{Ref. Structural Engineering Handbook, 4th Edition, Figure 5, p.8-10}) \)

Slenderness ratios, \[ SRy := \frac{K \cdot L}{ry} \quad SRy = 25.678 \]

\[ SRz := \frac{K \cdot L}{rz} \quad SRz = 25.678 \]

Constants depending upon the mechanical properties of the material from Ref. Structural Engineering Handbook, 4th Edition, Formulas 5a-c, p.11-6:

\[ Bc := f_{cy} \cdot cty \cdot \left[ 1 + \left( \frac{f_{cy} \cdot cty}{2250000 \cdot \text{psi}} \right)^{\frac{1}{2}} \right] \quad Bc = 66816 \text{ psi} \]

\[ Dc := \frac{Bc}{10 \left( \frac{Bc}{Ec \cdot cec} \right)^{\frac{1}{2}}} \quad Dc = 533 \text{ psi} \]

\[ Cc := 0.41 \cdot \frac{2 \cdot Bc}{3 \cdot Dc} \quad Cc = 34.242 \]
Compression allowables:

\[
F_{cy} := \begin{cases} 
B_c - D_c \cdot SR_y & \text{if } SR_y \leq C_c \\
Ec \cdot cec \left( \frac{\pi}{SR_y} \right)^2 & \text{otherwise}
\end{cases}
\]
\[F_{cy} = 53120 \text{ psi}\]

\[
F_{cz} := \begin{cases} 
B_c - D_c \cdot SR_z & \text{if } SR_z \leq C_c \\
Ec \cdot cec \left( \frac{\pi}{SR_z} \right)^2 & \text{otherwise}
\end{cases}
\]
\[F_{cz} = 53120 \text{ psi}\]

(Note: FSu is used below for moment magnification due to eccentricities.)

\[
F_{ey} := \frac{102000000 \text{ psi}}{FSu \cdot SR_y^2}
\]
\[F_{ey} = 110495 \text{ psi}\]

\[
F_{ez} := \frac{102000000 \text{ psi}}{FSu \cdot SR_z^2}
\]
\[F_{ez} = 110495 \text{ psi}\]

Ultimate shear allowables:

\[
V_{ulty} := \frac{fsu \cdot ctu \cdot I_z \cdot b}{Q_z}
\]
\[V_{ulty} = 92074 \text{ lbf}\]

\[
V_{ultz} := \frac{fsu \cdot ctu \cdot I_y \cdot b}{Q_y}
\]
\[V_{ultz} = 92074 \text{ lbf}\]

Ultimate torsion allowable:

\[T_{ult} := fsu \cdot ctu \cdot JoR\]
\[T_{ult} = 477649 \text{ in-lbf}\]

Axial tensile allowable:

\[P_{t} := ftu \cdot ctu \cdot A\]
\[P_{t} = 369585 \text{ lbf}\]

Axial compression allowable:

\[
P_{cr} := \begin{cases} 
Fcz \cdot A & \text{if } Fcy \geq Fcz \\
Fcy \cdot A & \text{otherwise}
\end{cases}
\]
\[P_{cr} = 307142 \text{ lbf}\]

Ultimate bending allowables:

\[
M_{ulty} := Sy \cdot \left[ ftu \cdot ctu + (f - 1) \cdot fty \cdot cty \right]
\]
\[M_{ulty} = 637201 \text{ in-lbf}\]

\[
M_{ultz} := Sz \cdot \left[ ftu \cdot ctu + (f - 1) \cdot fty \cdot cty \right]
\]
\[M_{ultz} = 637201 \text{ in-lbf}\]

Combined bending and axial allowables:

\[
P_{ey} := Fey \cdot A
\]
\[P_{ey} = 638883 \text{ lbf}\]

\[
P_{ez} := Fez \cdot A
\]
\[P_{ez} = 638883 \text{ lbf}\]
Input for NASPOST was taken from 192 punch files in three different folders:

/hsm/bsommer/ams/nonlin/1000/2-04
/hsm/bsommer/ams/nonlin/2000/2-04
/hsm/bsommer/ams/nonlin/4000/2-04

MathCAD will read in all the load data from "ltbb.txt" for the calculations below.

\[
\text{load} := \text{READPRN}("ltbb.txt") \quad i := 1..\text{rows(load)}
\]

**Element ID:** ID := load\(\{1\}\) \quad **Load case number:** LC := load\(\{2\}\)

+ At end A of beam element:

**Moment:** M1a := load\(\{3\}\) \(\text{in} \cdot \text{lbf}\) \quad M2a := load\(\{4\}\) \(\text{in} \cdot \text{lbf}\)

**Shear force:** V1a := load\(\{5\}\) \(\text{lbf}\) \quad V2a := load\(\{6\}\) \(\text{lbf}\)

**Axial force:** Pa := load\(\{7\}\) \(\text{lbf}\)

**Total torque:** Toa := load\(\{8\}\) \(\text{in} \cdot \text{lbf}\)

**Warp torque:** Warpa := load\(\{9\}\) \(\text{in} \cdot \text{lbf}\)

+ At end B of beam element:

**Moment:** M1b := load\(\{10\}\) \(\text{in} \cdot \text{lbf}\) \quad M2b := load\(\{11\}\) \(\text{in} \cdot \text{lbf}\)

**Shear force:** V1b := load\(\{12\}\) \(\text{lbf}\) \quad V2b := load\(\{13\}\) \(\text{lbf}\)

**Axial force:** Pb := load\(\{14\}\) \(\text{lbf}\)

**Total torque:** Tob := load\(\{15\}\) \(\text{in} \cdot \text{lbf}\)

**Warp torque:** Warpb := load\(\{16\}\) \(\text{in} \cdot \text{lbf}\)
Modify end torque by subtracting warping torque:

\[ T_{ai} := \text{Toa}_{ai} - \text{Warp}_{ai} \]
\[ T_{bi} := \text{Tob}_{bi} - \text{Warp}_{bi} \]

Shear ratios:

\[ \text{RS}_{ai} := \frac{V_{1a_{i}}}{V_{ulty}} + \frac{V_{2a_{i}}}{V_{ultz}} + \frac{T_{ai}}{T_{ult}} \]
\[ \text{RS}_{bi} := \frac{V_{1b_{i}}}{V_{ulty}} + \frac{V_{2b_{i}}}{V_{ultz}} + \frac{T_{bi}}{T_{ult}} \]

Tensile ratio at end A:

\[ \text{RT}_{ai} := \frac{\text{Pa}_{i}}{\text{Pc}_{r}} + \frac{\text{M2}_{a_{i}}}{\text{Mul}_{ty}} + \frac{\text{M1}_{a_{i}}}{\text{Mul}_{tz}} \]
\[ \text{RT}_{ai} = \frac{\text{Pa}_{i}}{\text{Pc}_{r}} + \frac{\text{M2}_{a_{i}}}{\text{Mul}_{ty}} \cdot \frac{1}{\text{Pc}_{r} - \text{P}_{ey}} + \frac{\text{M1}_{a_{i}}}{\text{Mul}_{tz}} \cdot \frac{1}{\text{Pc}_{r} - \text{P}_{ez}} \]
\[ \text{if } P_{a_{i}} \geq 0 \text{-lb} \]
\[ \text{otherwise} \]

Tensile ratio at end B:

\[ \text{RT}_{bi} := \frac{\text{Pb}_{i}}{\text{Pc}_{r}} + \frac{\text{M2}_{b_{i}}}{\text{Mul}_{ty}} + \frac{\text{M1}_{b_{i}}}{\text{Mul}_{tz}} \]
\[ \text{RT}_{bi} = \frac{\text{Pb}_{i}}{\text{Pc}_{r}} + \frac{\text{M2}_{b_{i}}}{\text{Mul}_{ty}} \cdot \frac{1}{\text{Pc}_{r} - \text{P}_{ey}} + \frac{\text{M1}_{b_{i}}}{\text{Mul}_{tz}} \cdot \frac{1}{\text{Pc}_{r} - \text{P}_{ez}} \]
\[ \text{if } P_{b_{i}} \geq 0 \text{-lb} \]
\[ \text{otherwise} \]

Combined Ratios:

\[ \text{RATIO}_{ai} := \sqrt{\left( \text{RT}_{ai} \right)^{2} + \left( \text{RS}_{ai} \right)^{2}} \]
\[ \text{RATIO}_{bi} := \sqrt{\left( \text{RT}_{bi} \right)^{2} + \left( \text{RS}_{bi} \right)^{2}} \]

\[ \text{RATIO}_{i} := \text{if } \left( \text{RATIO}_{ai} \geq \text{RATIO}_{bi}, \text{RATIO}_{ai}, \text{RATIO}_{bi} \right) \]

Margin of Safety:

\[ \text{MS}_{i} := \frac{1}{\text{RATIO}_{i} \cdot F_{Su}} - 1 \]
\[ \min(\text{MS}) = 1.42 \]
Reference - Buckling Margin of Safety

The worst load case that yielded minimum margin of safety is shown below:

$$\text{output} := \text{augment}(\text{ID}, \text{LC}, \text{MS}) \quad \text{sorted} := \text{csort}(\text{output}, 3)$$

$$\left(\begin{array}{c} \text{sorted} T \end{array}\right)^T = (1203 \quad 4016 \quad 1.42)$$

Based upon the output of SORT function above, it reads:

- **Element ID** = 1203
- **Load ID** = 4016
- **MS** = 1.42

Beam and Socket Analysis: Lower Trunnion Bridge Beam Elbow Side

The following loop stacks element IDs 1201, 1204, 1207, and 1210 so that the data can be used only on the Elbow side of the beam element. The loop below takes the original data from the "loads" database and pulls out only the data for element IDs 1201, 1204, 1207, and 1210. This includes loads and moments from beam end A and B, although only end A loads and moments are used for the beam and socket analysis.

$$\text{rows(load)} = 2304 \quad \text{cols(load)} = 16$$

$$\text{elbowside} := \begin{cases} k \leftarrow 0 \\ \text{for}\ i \in 1..\text{rows(load)} \\ \quad \text{if}\ \text{load}_{i,1} = 1201 \lor \text{load}_{i,1} = 1204 \lor \text{load}_{i,1} = 1207 \lor \text{load}_{i,1} = 1210 \\ \quad k \leftarrow k + 1 \\ \quad \text{newdata}^T \leftarrow \left(\text{load}^T\right)^T \\ \end{cases}$$
Beam and Socket Analysis: Lower Trunnion Bridge Beam Elbow Side (Moment about Y)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[ S \text{ and } M \text{ are respectively beam shear in lbf and moment in in-lbf at end of socket. } W \text{ is unit loading in lbf/in.} \]

\[ i := 1 \text{ rows(elbowside)} \quad \text{rows(elbowside)} = 768 \]

\[ \text{ID1}_i := \text{elbowside}_{i,1} \quad \text{Element ID} \]

\[ \text{LC1}_i := \text{elbowside}_{i,2} \quad \text{Load case number} \]

\[ S1a_i := \text{elbowside}_{i,5} \text{lbf} \quad S2a_i := \text{elbowside}_{i,6} \text{lbf} \quad \text{Picking End A Shear from data} \]

\[ S_i := \sqrt{(S1a_i)^2 + (S2a_i)^2} \quad \text{Combined End A Shear} \]

\[ P_i := \text{elbowside}_{i,7} \text{lbf} \quad \text{Picking End A Tension from data} \]

\[ M_i := \text{elbowside}_{i,4} \text{in-lbf} \quad \text{Picking Y Moment from data} \]

\[ L_i := 4.465 \text{in} \quad \text{Length of beam inside socket} \]

\[ \text{mls}_\text{ratio}_i := \begin{cases} 0, & \text{if } S_i = 0, 1000, \frac{M_i}{S_i \cdot L_i} \end{cases} \]

\[ \text{slm}_\text{ratio}_i := \begin{cases} 0, & \text{if } M_i = 0, 1000, \frac{L_i}{M_i} \end{cases} \]
Calculated values are then:

\[
\begin{align*}
\text{w}_1_i & := \begin{cases} 
\frac{K1_i \cdot M_i}{(L_i)^2} & \text{if } |slm\_ratio_i| \leq 1 \\
\frac{K1_i \cdot S_i}{L_i} & \text{otherwise}
\end{cases} \\
\text{w}_2_i & := \begin{cases} 
\frac{K2_i \cdot M_i}{(L_i)^2} & \text{if } |slm\_ratio_i| \leq 1 \\
\frac{K2_i \cdot S_i}{L_i} & \text{otherwise}
\end{cases}
\end{align*}
\]

\[
a_i := K_a \cdot L_i
\]

Max. shear \[
\text{Smax}_i := \begin{cases} 
\frac{(-Ks)_i \cdot M_i}{L_i} & \text{if } |slm\_ratio_i| \leq 1 \\
-K2_i \cdot S_i & \text{otherwise}
\end{cases}
\]

Max. Bending moment \[
\text{Mmax}_i := \begin{cases} 
Km_i \cdot M_i & \text{if } |slm\_ratio_i| \leq 1 \\
Km_i \cdot S_i \cdot L_i & \text{otherwise}
\end{cases}
\]

Now check:

\[
\text{Sc}_i := \frac{w_1_i - w_2_i}{2} \cdot L_i
\]

\[
\text{Mc}_i := \frac{(-w1)_i + 2 \cdot w_2_i}{6} \cdot L_i^2
\]

Percent error:

\[
\text{S\_percentdiff}_i := \frac{S_i - \text{Sc}_i}{S_i}
\]

\[
\text{M\_percentdiff}_i := \frac{M_i - \text{Mc}_i}{M_i}
\]
To view graph with a specific load case, assign \( j \) a value: \( j := 569 \)

Beam and Socket Coefficients
Note if \( \text{abs}(SL/M) <= 1 \), Ratio = SL/M, otherwise Ratio = M/SL.
For this specific load case,

\[ S_j = 965 \text{ lbf} \]
\[ M_j = 41177 \text{ in-lbf} \]

Max Shear: \[ S_{\text{max}}_j = -13960 \text{ lbf} \]

Shear Check: \[ S_c j = 965.1 \text{ lbf} \]

Max moment: \[ M_{\text{max}}_j = 41177 \text{ in-lbf} \]

Moment Check: \[ M_j = 41177 \text{ in-lbf} \]

With percent error

\[ S_{\text{percentdiff}}_j = -0 \% \]
\[ M_{\text{percentdiff}}_j = 0 \% \]

Actual Shear and Moment Distribution Inside Socket
Stresses

Total moment

Bending Tensile stress

\[ \sigma_i := \frac{M_{\text{max}i}}{S_y} \quad \text{max}(\sigma) = 5993.6 \text{ psi} \]

Shear stress

\[ \tau_{soc_i} := \frac{S_{\text{max}i}}{A} \quad \text{max}(\tau_{soc}) = 2959.5 \text{ psi} \]

Axial tension stress

\[ \sigma_{ai} := \frac{P_i}{A} \quad \text{max}(\sigma_a) = 10287.8 \text{ psi} \]

Stress Ratios

Axial (ult)

\[ R_a := \frac{\sigma_a - F_{S_u}}{f_t - c_t} \]

Bending (ult)

\[ R_b := \frac{F_{S_u} \cdot \sigma}{f_t - c_t} \]

Shear (ult)

\[ R_s := \frac{F_{S_u} \cdot \tau_{soc}}{f_{u} - c_t} \]

Axial (yld)

\[ R_{ay} := \frac{\sigma_a - F_{S_y}}{f_t - c_y} \]

Bending (yld)

\[ R_{by} := \frac{F_{S_y} \cdot \sigma}{f_t - c_y} \]

Shear(yld)

\[ R_{sy} := \frac{F_{S_y} \cdot \tau_{soc}}{f_{y} - c_y} \]

Margins of safety

Margin of safety ultimate

\[ MS_{1u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \quad \text{min}(MS_{1u}) = 1.87 \]

Margin of safety yield

\[ MS_{1y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad \text{min}(MS_{1y}) = 2.22 \]
Reference - Beam and Socket Margin of Safety - Lower Trunnion Bridge Beam Elbow Side - Moment Y

See below for the ultimate minimum margin of safety with element and load case information:

\[
\begin{align*}
\text{output1} & := \text{augment}(\text{ID1}, \text{LC1}, \text{MS1u}) \\
\text{\left(\text{sorted}\right)^T} & = (1201 \quad 4016 \quad 1.87)
\end{align*}
\]

Based upon the output of SORT function above, it reads:

Element ID = 1201

Load ID = 4016

MS1u = 1.87

See below for the yield minimum margin of safety with element and load case information:

\[
\begin{align*}
\text{output1} & := \text{augment}(\text{ID1}, \text{LC1}, \text{MS1y}) \\
\text{\left(\text{sorted}\right)^T} & = (1201 \quad 4016 \quad 2.22)
\end{align*}
\]

Based upon the output of SORT function above, it reads:

Element ID = 1201

Load ID = 4016

MS1y = 2.22
**Beam and Socket Analysis: Lower Trunnion Bridge Beam Elbow Side (Moment about Z)**

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[
S_i = \sqrt{\left(S_{3ai_i}\right)^2 + \left(S_{4ai_i}\right)^2}
\]

Combined End A Shear

\[
P_i = S_{3ai_i}
\]

Picking End A Shear from data

\[
P_i = S_{4ai_i}
\]

Picking End A Tension from data

\[
M_i = S_{1i} L_i
\]

Picking Z Moment from data

\[
L_i = 4.465\text{ in}
\]

Length of beam inside socket

\[
\text{mls}_\text{ratio}_{i} = \begin{cases} 
0, 1000, \frac{M_i}{S_i} 
\end{cases} 
\]

\[
\text{slm}_\text{ratio}_{i} = \begin{cases} 
0, 1000, \frac{L_i}{M_i} 
\end{cases} 
\]
Calculated values are then:

\[
\begin{align*}
\text{w}_1 &= \begin{cases} 
\frac{K_1 \cdot M_i}{\left(L_i\right)^2} & \text{if } \left|\text{slm\_ratio}_i\right| \leq 1 \\
\frac{K_1 \cdot S_i}{L_i} & \text{otherwise}
\end{cases} \\
\text{w}_2 &= \begin{cases} 
\frac{K_2 \cdot M_i}{\left(L_i\right)^2} & \text{if } \left|\text{slm\_ratio}_i\right| \leq 1 \\
\frac{K_2 \cdot S_i}{L_i} & \text{otherwise}
\end{cases}
\end{align*}
\]

\[a_i := K_1 \cdot L_i\]

Max. shear \[\text{S}_\text{max} := \begin{cases} 
\frac{(-K_s) \cdot M_i}{L_i} & \text{if } \left|\text{slm\_ratio}_i\right| \leq 1 \\
-K_2 \cdot S_i & \text{otherwise}
\end{cases}\]

Max. Bending moment \[\text{M}_\text{max} := \begin{cases} 
K_m \cdot M_i & \text{if } \left|\text{slm\_ratio}_i\right| \leq 1 \\
K_m \cdot S_i \cdot L_i & \text{otherwise}
\end{cases}\]

Now check: \[\text{S}_c := \frac{w_1 - w_2}{2} \cdot L_i\]

\[\text{M}_c := \frac{(-w_1) + 2 \cdot w_2}{6} \cdot \left(L_i\right)^2\]

Percent error: \[\text{S\_percentdiff} := \frac{S_i - S_c_i}{S_i}\]

\[\text{M\_percentdiff} := \frac{M_i - Mc_i}{M_i}\]
To view graph with a specific load case, assign \( j \) a value \( j := 573 \)

Beam and Socket Coefficients
Note if \( \text{abs}(SL/M) \leq 1 \), \( \text{Ratio} = SL/M \), otherwise \( \text{Ratio} = M/SL \).
For this specific load case,

\[ S_j = 1143 \text{ lbf} \]

\[ M_j = -1923 \text{ in-lbf} \]

Max Shear: \( S_{\text{max},j} = 298 \text{ lbf} \)  
Shear Check: \( S_c = 1143.3 \text{ lbf} \)

Max moment: \( M_{\text{max},j} = 0 \text{ in-lbf} \)  
Moment Check: \( M_j = -1923 \text{ in-lbf} \)

With percent error

\[ S_{\text{percentdiff},j} = 0 \% \]
\[ M_{\text{percentdiff},j} = -0 \% \]

Actual Shear and Moment Distribution Inside Socket
Stresses

Total moment

Bending Tensile stress
\[ \sigma_{i} := \frac{M_{\text{max}}}{S_z} \]
\[ \text{max}(\sigma) = 1775.1 \text{ psi} \]

Shear stress
\[ \tau_{\text{soc}} := \frac{S_{\text{max}}}{A} \]
\[ \text{max}(\tau_{\text{soc}}) = 1978.2 \text{ psi} \]

Axial tension stress
\[ \sigma_{a} := \frac{P_{i}}{A} \]
\[ \text{max}(\sigma_{a}) = 10287.8 \text{ psi} \]

Stress Ratios

Axial (ult)
\[ R_{a} := \frac{\sigma_{a} \cdot F_{S\text{u}}}{\text{ftu-ctu}} \]

Bending (ult)
\[ R_{b} := \frac{F_{S\text{u}} \cdot \sigma}{\text{ftu-ctu}} \]

Shear (ult)
\[ R_{s} := \frac{F_{S\text{u}} \cdot \tau_{\text{soc}}}{\text{fsu-ctu}} \]

Axial (yld)
\[ R_{ay} := \frac{\sigma_{a} \cdot F_{S\text{y}}}{\text{fty-cty}} \]

Bending (yld)
\[ R_{by} := \frac{F_{S\text{y}} \cdot \sigma}{\text{fty-cty}} \]

Shear(yld)
\[ R_{sy} := \frac{F_{S\text{y}} \cdot \tau_{\text{soc}}}{\text{fty-cty}} \]

Margins of safety

Margin of safety ultimate
\[ MS_{2u} := \frac{1}{\sqrt{(R_{a} + R_{b})^{2} + R_{s}^{2}}} - 1 \]
\[ \text{min}(MS_{2u}) = 3.14 \]

Margin of safety yield
\[ MS_{2y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^{2} + R_{sy}^{2}}} - 1 \]
\[ \text{min}(MS_{2y}) = 3.52 \]
Reference - Beam and Socket Margin of Safety - Lower Trunnion Bridge Beam Elbow Side - Moment Z

See below for the ultimate minimum margin of safety with element and load case information:

output1 := augment(ID2, LC2, MS2u) sorted := csort(output1, 3)

\[
\begin{pmatrix}
\text{sorted} & \text{T} \\
\end{pmatrix} = (1201 \quad 4015 \quad 3.14)
\]

Based upon the output of SORT function above, it reads:

Element ID = 1201

Load ID = 4015

MS1u = 3.14

See below for the yield minimum margin of safety with element and load case information:

output1 := augment(ID2, LC2, MS2y) sorted := csort(output1, 3)

\[
\begin{pmatrix}
\text{sorted} & \text{T} \\
\end{pmatrix} = (1201 \quad 4015 \quad 3.52)
\]

Based upon the output of SORT function above, it reads:

Element ID = 1201

Load ID = 4015

MS1y = 3.52
Beam and Socket Analysis: Lower Vacuum Case Joint Side

The following loop stacks element IDs 1203, 1206, 1209, and 1212 so that the data can be used only on the Vacuum Case side of the beam element. The loop below takes the original data from the "loads" database and pulls out only the data for element IDs 1203, 1206, 1209, and 1212. This includes loads and moments from beam end A and B, although only end A loads and moments are used for the beam and socket analysis.

rows(load) = 2304  cols(load) = 16

\[ \text{lvcside := } \begin{align*}
  & k \leftarrow 0 \\
  & \text{for } i \in 1..\text{rows(load)} \\
  & \quad \text{if load}_{i,1} = 1203 \lor \text{load}_{i,1} = 1206 \lor \text{load}_{i,1} = 1209 \lor \text{load}_{i,1} = 1212 \\
  & \quad \quad k \leftarrow k + 1 \\
  & \quad \quad \text{newdata} \leftarrow (\text{load}^T)^{\psi} \\
  & \quad \quad \text{newdata}^T
\end{align*} \]
Beam and Socket Analysis: Lower Vacuum Case Joint Side (Moment about Y)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[ S_i \] and \[ M_i \] are respectively beam shear in lbf and moment in in-lbf at end of socket. \( W \) is unit loading in lbf/in.

\[ i := 1 \ldots \text{rows(lvcsid)} \]
\[ \text{rows(lvcsid)} = 768 \]

\[ \text{ID3}_i := \text{lvcsid}_{i, 1} \quad \text{Element ID} \]

\[ \text{LC3}_i := \text{lvcsid}_{i, 2} \quad \text{Load case number} \]

\[ \text{S5a}_i := \text{lvcsid}_{i, 5} \cdot \text{lbf} \quad \text{S6a}_i := \text{lvcsid}_{i, 6} \cdot \text{lbf} \]

\[ \text{Picking End A Shear from data} \]

\[ S_i := \sqrt{(S5a_i)^2 + (S6a_i)^2} \quad \text{Combined End A Shear} \]

\[ P_i := \text{lvcsid}_{i, 7} \cdot \text{lbf} \quad \text{Picking End A Tension from data} \]

\[ M_i := \text{lvcsid}_{i, 4} \cdot \text{in-lbf} \quad \text{Picking Y Moment from data} \]

\[ L_i := 4.465 \cdot \text{in} \quad \text{Length of beam inside socket} \]

\[ \text{mls}_\text{ratio}_i := \begin{cases} 0, 1000, \frac{M_i}{S_i \cdot L_i} \\
0, 1000, \frac{S_i}{L_i} 
\end{cases} \]

\[ \text{slm}_\text{ratio}_i := \begin{cases} 0, 1000, \frac{L_i}{M_i} \\
0, 1000, \frac{M_i}{S_i} 
\end{cases} \]
Calculated values are then:

\[
w_1 := \begin{cases} 
  \frac{K_1 \cdot M_1}{(L_i)^2} & \text{if } |\text{slm}_\text{ratio}_i| \leq 1 \\
  \frac{K_1 \cdot S_1}{L_i} & \text{otherwise}
\end{cases}
\]

\[
w_2 := \begin{cases} 
  \frac{K_2 \cdot M_1}{(L_i)^2} & \text{if } |\text{slm}_\text{ratio}_i| \leq 1 \\
  \frac{K_2 \cdot S_1}{L_i} & \text{otherwise}
\end{cases}
\]

\[
a_i := K_i \cdot L_i
\]

Max. shear

\[
S_{\text{max}} := \begin{cases} 
  \frac{(-K_1) \cdot M_1}{L_i} & \text{if } |\text{slm}_\text{ratio}_i| \leq 1 \\
  -K_2 \cdot S_i & \text{otherwise}
\end{cases}
\]

Max. Bending moment

\[
M_{\text{max}} := \begin{cases} 
  K_m \cdot M_i & \text{if } |\text{slm}_\text{ratio}_i| \leq 1 \\
  K_m \cdot S_i \cdot L_i & \text{otherwise}
\end{cases}
\]

Now check:

\[
S_c := \frac{w_1 - w_2}{2} \cdot L_i
\]

\[
M_c := \frac{(-w_1) + 2 \cdot w_2}{6} \cdot (L_i)^2
\]

Percent error:

\[
S_{\text{percentdiff}} := \frac{S_i - S_c}{S_i}
\]

\[
M_{\text{percentdiff}} := \frac{M_i - M_c}{M_i}
\]
To view graph with a specific load case, assign j a value \( j := 740 \)

Beam and Socket Coefficients
Note if \( \text{abs}(SL/M) \leq 1 \), Ratio = SL/M, otherwise Ratio = M/SL.
For this specific load case,

\[ S_j = 3726 \text{lbf} \]
\[ M_j = -37400 \text{in-lbf} \]

Max Shear: \[ S_{\text{max}} = 11558 \text{lbf} \]

Shear Check: \[ S_c = 3725.9 \text{lbf} \]

Max moment: \[ M_{\text{max}} = -37400 \text{in-lbf} \]

Moment Check: \[ M_j = -37400 \text{in-lbf} \]

With percent error

\[ S_{\text{percentdiff}} = 0\% \]
\[ M_{\text{percentdiff}} = 0\% \]
Stresses

Total moment

Bending Tensile stress
\[ \sigma_i := \frac{M_{\text{max}}}{S_y} \]
\[ \text{max}(\sigma) = 6234.4 \text{ psi} \]

Shear stress
\[ \tau_{\text{soc}} := \frac{S_{\text{max}}}{A} \]
\[ \text{max}(\tau_{\text{soc}}) = 3211.7 \text{ psi} \]

Axial tension stress
\[ \sigma_{a_i} := \frac{P_i}{A} \]
\[ \text{max}(\sigma_{a}) = 9771.2 \text{ psi} \]

Stress Ratios

Axial (ult)
\[ R_a := \frac{\sigma_a \cdot F_{\text{Su}}}{f_{\text{tu}} \cdot c_{\text{tu}}} \]

Bending (ult)
\[ R_b := \frac{F_{\text{Su}} \cdot \sigma}{f_{\text{tu}} \cdot c_{\text{tu}}} \]

Shear (ult)
\[ R_s := \frac{F_{\text{Su}} \cdot \tau_{\text{soc}}}{f_{\text{su}} \cdot c_{\text{tu}}} \]

Axial (yld)
\[ R_{ay} := \frac{\sigma_a \cdot F_{\text{Sy}}}{f_{\text{ty}} \cdot c_{\text{ty}}} \]

Bending (yld)
\[ R_{by} := \frac{F_{\text{Sy}} \cdot \sigma}{f_{\text{ty}} \cdot c_{\text{ty}}} \]

Shear (yld)
\[ R_{sy} := \frac{F_{\text{Sy}} \cdot \tau_{\text{soc}}}{f_{\text{ty}} \cdot c_{\text{ty}}} \]

Margins of safety

Margin of safety ultimate
\[ \text{MS3u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \]
\[ \text{min}(\text{MS3u}) = 2.15 \]

Margin of safety yield
\[ \text{MS3y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\[ \text{min}(\text{MS3y}) = 2.64 \]
Reference - Beam and Socket Margin of Safety - Lower Vacuum Case Joint Side - Moment Y

See below for the ultimate minimum margin of safety with element and load case information:

\[ \text{output1} := \text{augment(ID3,LC3,MS3u)} \quad \text{sorted} := \text{csort(output1,3)} \]

\[
\begin{pmatrix}
\text{sorted}^T
\end{pmatrix}^T = (1203 \quad 4031 \quad 2.15)
\]

Based upon the output of SORT function above, it reads:

Element ID = 1203

Load ID = 4031

MS1u = 2.15

See below for the yield minimum margin of safety with element and load case information:

\[ \text{output1} := \text{augment(ID3,LC3,MS3y)} \quad \text{sorted} := \text{csort(output1,3)} \]

\[
\begin{pmatrix}
\text{sorted}^T
\end{pmatrix}^T = (1203 \quad 4031 \quad 2.64)
\]

Based upon the output of SORT function above, it reads:

Element ID = 1203

Load ID = 4031

MS1y = 2.64
Beam and Socket Analysis: Lower Vacuum Case Joint Side (Moment about Z)

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

\[ S_1 = \sqrt{(S7_{ai})^2 + (S8_{ai})^2} \]

Combined End A Shear

\[ P_i = lvcside_{i,7} \cdot \text{lbf} \]

Picking End A Tension from data

\[ M_i = lvcside_{i,3} \cdot \text{in.\bf} \]

Picking Z Moment from data

\[ L_i = 4.465 \cdot \text{in} \]

Length of beam inside socket

\[ \text{mls\_ratio}_i = \begin{cases} 0, & \text{if } S_i = 0, 1000, \frac{M_i}{S_i \cdot L_i} \\ \text{slm\_ratio}_i, & \text{if } M_i = 0, 1000, \frac{L_i}{M_i} \end{cases} \]
Calculated values are then:

\[
\begin{align*}
  w_1_i &= \begin{cases} 
    \frac{K_1 \cdot M_i}{L_i^2} & \text{if } |slm\_ratio_i| \leq 1 \\
    \frac{K_1 \cdot S_i}{L_i} & \text{otherwise}
  \end{cases} \\
  w_2_i &= \begin{cases} 
    \frac{K_2 \cdot M_i}{L_i^2} & \text{if } |slm\_ratio_i| \leq 1 \\
    \frac{K_2 \cdot S_i}{L_i} & \text{otherwise}
  \end{cases}
\end{align*}
\]

\[
a_i := \frac{K_a \cdot L_i}{L_i}
\]

Max. shear
\[
S_{\text{max} i} := \begin{cases} 
    \frac{(-K_s) \cdot M_i}{L_i^2} & \text{if } |slm\_ratio_i| \leq 1 \\
    -\frac{K_2 \cdot S_i}{L_i} & \text{otherwise}
  \end{cases}
\]

Max. Bending moment
\[
M_{\text{max} i} := \begin{cases} 
    \frac{K_m \cdot M_i}{L_i} & \text{if } |slm\_ratio_i| \leq 1 \\
    \frac{K_m \cdot S_i \cdot L_i}{L_i} & \text{otherwise}
  \end{cases}
\]

Now check:
\[
\begin{align*}
  S_{c i} &= \frac{w_1_i - w_2_i}{2} \cdot L_i \\
  M_{c i} &= \frac{(-w_1)_i + 2 \cdot w_2_i}{6} \cdot L_i^2
\end{align*}
\]

Percent error:
\[
\begin{align*}
  S_{\text{percentdiff} i} &= \frac{S_i - S_{c i}}{S_i} \\
  M_{\text{percentdiff} i} &= \frac{M_i - M_{c i}}{M_i}
\end{align*}
\]
To view graph with a specific load case, assign j a value $j := 633$

**Beam and Socket Coefficients**

Note if $|SL/M| \leq 1$, Ratio = $SL/M$, otherwise Ratio = $M/SL$. 

---

2.1.8-32 
ESCG-4005-05-AMS-0039
For this specific load case,

\[ S_j = 4161 \text{ lbf} \]

\[ M_j = -40202 \text{ in-lbf} \]

Max Shear: \[ S_{\text{max}} = 12404 \text{ lbf} \]

Shear Check: \[ S_c = 4161.4 \text{ lbf} \]

Max moment: \[ M_{\text{max}} = -40202 \text{ in-lbf} \]

Moment Check: \[ M_j = -40202 \text{ in-lbf} \]

With percent error

\[ S_{\text{percentdiff}} = 0\% \]

\[ M_{\text{percentdiff}} = -0\% \]
**Stresses**

Total moment

**Bending Tensile stress**
\[ \sigma_i := \frac{M_{\text{max}i}}{S_z} \]
\[ \text{max}(\sigma) = 5394.4 \text{ psi} \]

**Shear stress**
\[ \tau_{\text{soc}i} := \frac{S_{\text{max}i}}{A} \]
\[ \text{max}(\tau_{\text{soc}}) = 2959.8 \text{ psi} \]

**Axial tension stress**
\[ \sigma_{ai} := \frac{P_i}{A} \]
\[ \text{max}(\sigma_a) = 9771.2 \text{ psi} \]

**Stress Ratios**

**Axial (ult)**
\[ R_a := \frac{\sigma_a \cdot F_{Su}}{\text{ftu-ctu}} \]

**Bending (ult)**
\[ R_b := \frac{F_{Su} \cdot \sigma}{\text{ftu-ctu}} \]

**Shear (ult)**
\[ R_s := \frac{F_{Su} \cdot \tau_{\text{soc}}}{\text{fsu-ctu}} \]

**Axial (yld)**
\[ R_{ay} := \frac{\sigma_a \cdot F_{Sy}}{\text{fty-cty}} \]

**Bending (yld)**
\[ R_{by} := \frac{F_{Sy} \cdot \sigma}{\text{fty-cty}} \]

**Shear(yld)**
\[ R_{sy} := \frac{F_{Sy} \cdot \tau_{\text{soc}}}{\text{fty-cty}} \]

**Margins of safety**

**Margin of safety ultimate**
\[ MS_{4u} := \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1 \]
\[ \text{min}(MS_{4u}) = 2.13 \]

**Margin of safety yield**
\[ MS_{4y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]
\[ \text{min}(MS_{4y}) = 2.55 \]
Reference - Beam and Socket Margin of Safety - Lower Vacuum Case Joint Side - Moment Z

See below for the ultimate minimum margin of safety with element and load case information:

\[
\begin{pmatrix}
\text{sorted}^T \\
(1) \end{pmatrix} = (1212 \ 4057 \ 2.13)
\]

Based upon the output of SORT function above, it reads:

- Element ID = 1212
- Load ID = 4057
- MS1u = 2.13

See below for the yield minimum margin of safety with element and load case information:

\[
\begin{pmatrix}
\text{sorted}^T \\
(1) \end{pmatrix} = (1212 \ 4057 \ 2.55)
\]

Based upon the output of SORT function above, it reads:

- Element ID = 1212
- Load ID = 4057
- MS1y = 2.55

Summary of Minimum Margin of Safety:

The ultimate minimum margin of safety is 1.42 and occurs in the buckling analysis. See page 2.1.8 - 9.

The yield minimum margin of safety is 2.22 and occurs in the beam and socket analysis for the lower trunnion bridge beam elbow side (Moment about Y). See page 2.1.8 - 15.
2.1.9 Lower Vacuum Case Interface Joint
Margins of Safety

Table 2.1.9-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135737</td>
<td>Interface Joint Assembly, Lower VC, Lower USS-02 Assembly</td>
<td>AL ALY 7050-T7451</td>
<td>Landing</td>
<td>Max Prin. Stress</td>
<td>0.06 (u)</td>
<td>2.1.9-13</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. Boundary condition is at five Trunnion locations.
3. All 192 load cases of Launch and Landing are applied.
4. u = ultimate, y = yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing.

Description of Structure

Figure 2.1.9-2 below shows the locations of four Lower VC Joints in AMS-02. The Joints were machined out of 7050-T7451 Aluminum Alloy plate. One part of a Joint was riveted to Lower Trunnion Bridge. One was bolted to Lower Angle Tube. One was bolted to Lower TOF Strut. And one was bolted to Interface Plate in Vacuum Case.

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built of the Lower VC Joint hardware using FEMAP.

1. Parts were mainly modeled as CHEXA and CPENTA solid elements.
2. At the bolt holes, RBE2 rigid elements with DOF’s 1, 2 & 3 are represented.
3. The interface between Lower Trunnion Bridge and the Tube Section are represented by RBE2 rigid elements with DOF’s 1, 2 & 3.
4. The interfaces of Vacuum Case, Lower Angle Beam, and Lower TOF to the Lower VC Joints are represented by RBE2 rigid elements with DOF’s 1.

Figure 2.1.9-3 : View 1 - FEMAP Model of Lower VC Joint
The model was then constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.1.9-2), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5.

All 192 load cases for Launch and Landing were applied. MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02 version 2-04.

Solid stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in all four Lower VC Joints.

Table below shows detail of model inputs.

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>PROP</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 1</td>
<td>500,001 - 515,504</td>
<td>500,001 - 511,332</td>
<td>200001 - solid</td>
<td>200001 - 7050-T7451</td>
</tr>
<tr>
<td>Joint 2</td>
<td>200,001 - 215,504</td>
<td>200,001 - 211,332</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint 3</td>
<td>300,001 - 315,504</td>
<td>300,001 - 311,332</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint 4</td>
<td>600,001 - 615,504</td>
<td>600,001 - 611,332</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
--------- ------------- ---------
1 1.103060E-08 PASS
2 2.298996E-08 PASS
3 4.454561E-07 PASS
4 4.764726E-06 PASS
5 3.137545E-08 PASS
6 2.111139E-06 PASS

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
--------- ------------- ---------
1 1.103060E-08 PASS
2 2.298996E-08 PASS
3 4.454561E-07 PASS
4 4.764726E-06 PASS
5 3.137545E-08 PASS
6 2.111139E-06 PASS

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN+AUTO (N+AUTOSPC-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
--------- ------------- ---------
1 1.103060E-08 PASS
2 2.298996E-08 PASS
3 4.454561E-07 PASS
4 4.764726E-06 PASS
5 3.137545E-08 PASS
6 2.111139E-06 PASS
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.103060E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.298996E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>4.454561E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>4.764726E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.137545E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.111139E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 2.1.9-3: Eigenvalue Summary of Lower VC Joint Model

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.08E-05</td>
<td>3.29E-03</td>
<td>5.23E-04</td>
<td>1.00E+00</td>
<td>-1.08E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-5.16E-06</td>
<td>2.27E-03</td>
<td>3.62E-04</td>
<td>1.00E+00</td>
<td>-5.16E-06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4.63E-07</td>
<td>6.80E-04</td>
<td>1.08E-04</td>
<td>1.00E+00</td>
<td>4.63E-07</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2.99E-06</td>
<td>1.73E-03</td>
<td>2.75E-04</td>
<td>1.00E+00</td>
<td>2.99E-06</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>5.30E-06</td>
<td>2.30E-03</td>
<td>3.67E-04</td>
<td>1.00E+00</td>
<td>5.30E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>7.86E-06</td>
<td>2.80E-03</td>
<td>4.46E-04</td>
<td>1.00E+00</td>
<td>7.86E-06</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>1.84E+07</td>
<td>4.29E+03</td>
<td>6.83E+02</td>
<td>1.00E+00</td>
<td>1.84E+07</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>4.61E+07</td>
<td>6.79E+03</td>
<td>1.08E+03</td>
<td>1.00E+00</td>
<td>4.61E+07</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>6.05E+07</td>
<td>7.78E+03</td>
<td>1.24E+03</td>
<td>1.00E+00</td>
<td>6.05E+07</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>6.21E+07</td>
<td>7.88E+03</td>
<td>1.25E+03</td>
<td>1.00E+00</td>
<td>6.21E+07</td>
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Additional check is comparison of the strap loads between the load model and the detail model. The loads are picked randomly. Loads in both models are closely matched.
### Table 2.1.9-4: Strap Loads (lbf) in Load Model 2-04

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<td>9044.1</td>
<td>3929.6</td>
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<tr>
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<td>2245.6</td>
<td>1605.7</td>
<td>6899.0</td>
<td>1013.3</td>
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<td>1670.6</td>
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<td>2100.1</td>
<td>7849.4</td>
<td>479.6</td>
<td>947.1</td>
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### Table 2.1.9-5: Strap Loads (lbf) in Lower VC Joint

<table>
<thead>
<tr>
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<th>90004</th>
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<tr>
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Table 2.1.9-6 : Load Differences (lbf) between Two Models

<table>
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<td>0.5</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Note:  1. Negative sign in Table 2.1.9-6 means load in Detail model greater than in Load model.
Material and Temperature

The Lower VC Joints are 7050-T7451 Aluminum Alloy. Material properties of 7050-T7451 are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5H. Temperature limits at the interface of Lower USS to Upper USS are provided by the Thermal Analysis Group. For Launch condition, the temperature of 120°F is applied. For Landing condition, the temperature of 161°F is applied.

Analysis

The critical stresses for Lower VC Joints are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. All margins of safety are positive.
CHECK OF LOWER VACUUM CASE JOINTS

Material Properties : 7050-T7451 AL ALY, BMS 7-323C or AMS 4050

\[ F_{tu} := 67000 \text{psi} \]

\[ F_{ty} := 57000 \text{psi} \]

\[ F_{su} := 43000 \text{psi} \]

Factors of Safety,

\[ F_{Su1} := 1.4 \quad F_{Su2} := 1.1 \]

Temperature reduction factors,

\( \gamma_u \)

\( \gamma_y \)

\( + \) At 120°F for Launch condition:

\[ \gamma_{u1} := 0.95 \]

\[ \gamma_{y1} := 0.99 \]

\( + \) At 161°F for Landing condition:

\[ \gamma_{u2} := 0.90 \]

\[ \gamma_{y2} := 0.96 \]

Allowable stresses:

\( + \) For Launch condition:

\[ F_{tu1,a} := \gamma_{u1} F_{tu} \]

\[ F_{tu1,a} = 63650 \text{ psi} \]

\[ F_{ty1,a} := \gamma_{y1} F_{ty} \]

\[ F_{ty1,a} = 56430 \text{ psi} \]

\[ F_{su1,a} := \gamma_{u1} F_{su} \]

\[ F_{su1,a} = 40850 \text{ psi} \]

\( + \) For Landing condition:

\[ F_{tu2,a} := \gamma_{u2} F_{tu} \]

\[ F_{tu2,a} = 60300 \text{ psi} \]

\[ F_{ty2,a} := \gamma_{y2} F_{ty} \]

\[ F_{ty2,a} = 54720 \text{ psi} \]

\[ F_{su2,a} := \gamma_{u2} F_{su} \]

\[ F_{su2,a} = 38700 \text{ psi} \]
Maximum Von-Mises, principal, and shear stresses of solid elements are selected from 192 load cases for Launch and Landing. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

+ For Launch condition: (Stress contour plot shown in Figure 2.1.9-5)

\[ \sigma_{uu1.\text{max}} := 27441 \text{ psi} \quad LC# 1016, ELEM# 506475 \quad \text{(see p.A6-3)} \]

\[ \sigma_{uy1.\text{max}} := 27865 \text{ psi} \quad LC# 1016, ELEM# 506474 \quad \text{(see p.A6-3)} \]

\[ \sigma_{us1.\text{max}} := 15199 \text{ psi} \quad LC# 1016; ELEM# 505774 \quad \text{(see p.A6-4)} \]

+ For Landing condition: (Stress contour plot shown in Figure 2.1.9-6)

\[ \sigma_{uu2.\text{max}} := 40690 \text{ psi} \quad LC# 4016; ELEM# 506475 \quad \text{(see p.A6-8)} \]

\[ \sigma_{uy2.\text{max}} := 42302 \text{ psi} \quad LC# 4016; ELEM# 505774 \quad \text{(see p.A6-8)} \]

\[ \sigma_{us2.\text{max}} := 24295 \text{ psi} \quad LC# 4016; ELEM# 505774 \quad \text{(see p.A6-9)} \]
Margins of Safety,

+ For Launch condition:

\[ MS_{u1} := \frac{F_{u1.a}}{F_{u1} \cdot \sigma_{uu1.max}} - 1 \quad MS_{u1} = 0.66 \]
\[ MS_{y1} := \frac{F_{y1.a}}{F_{y1} \cdot \sigma_{uy1.max}} - 1 \quad MS_{y1} = 0.84 \]
\[ MS_{s1} := \frac{F_{s1.a}}{F_{s1} \cdot \sigma_{us1.max}} - 1 \quad MS_{s1} = 0.92 \]

+ For Landing condition:

\[ MS_{u2} := \frac{F_{u2.a}}{F_{u2} \cdot \sigma_{uu2.max}} - 1 \quad MS_{u2} = 0.06 \]
\[ MS_{y2} := \frac{F_{y2.a}}{F_{y2} \cdot \sigma_{uy2.max}} - 1 \quad MS_{y2} = 0.18 \]
\[ MS_{s2} := \frac{F_{s2.a}}{F_{s2} \cdot \sigma_{us2.max}} - 1 \quad MS_{s2} = 0.14 \]
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<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Peter Hoang</td>
<td>06/06/05</td>
<td>lvcj.mcd</td>
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<td>Checked By</td>
<td>John Krejci</td>
<td>06/21/05</td>
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</table>

**Engineering and Science Contract Group**

**Structural Analysis Section**

**Title**: AMS-02 LOWER VACUUM CASE INTERFACE JOINT

![Stress Contour Plot of Lower VC Joint in Launch Condition](image)

**Figure 2.1.9-5**: Stress Contour Plot of Lower VC Joint in Launch Condition

2.1.9-14

ESCG-4005-05-AMS-0039
Figure 2.1.9-6: Stress Contour Plot of Lower VC Joint in Landing Condition
2.1.10  Sill Bracket
2.1.11 Sill Tube
COMPONENT: USS-02 Sill Tube, SDG39135739

MARGIN OF SAFETY SUMMARY:

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<tr>
<th>Part</th>
<th>Part Number</th>
<th>Material</th>
<th>Element ID</th>
<th>Subcase</th>
<th>MS</th>
<th>Failure Mode</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
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<td>SDG39135739-301</td>
<td>7075-T73511</td>
<td>1703</td>
<td>1032</td>
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<td>2.1.11-7</td>
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</tbody>
</table>

INTRODUCTION:

The Sill Tube is fabricated from 4" x 4" x 0.25" thick 7075-T73511 aluminum square tubing. Two Sill Tubes are located on the USS-02 assembly, one on the port side, and one on the starboard side. The tubes are riveted to the Sill Bracket on the forward end, and to the Diagonal Sill Bracket on the aft end as shown in Figure 1.

LOADS:

Applied loads to the Sill Tube have been calculated using the 2-04 loads model. The Sill Tube is represented by four CBEAM elements in the loads model: elements 1701 and 1702 on the -y side of the assembly and elements 1703 and 1704 on the +y side. Using NASPOST, three forces and three moments were calculated at each end of the beam elements and output to the file "silltube.lis". For analysis, the NASGRO output file was stripped of all headers and the reformatted file "SillTube.txt" is imported into MathCAD for analysis.

FACTORS OF SAFETY

A factor of safety of 1.4 is used on ultimate and 1.1 on yield.
PART: Sill Tube, SDG39135739-301

ANALYSIS: Combined Tension/Compression, Bending and Shear Analysis (Includes Buckling)

FACTORS OF SAFETY:

\[ SF_u := 1.4 \quad SF_y := 1.1 \quad \text{(Ultimate and Yield Factors of Safety)} \]

MATERIAL PROPERTIES: 7075-T73511 Aluminum, 0.250”-0.499 Thick Extrusion @150F per MMPDS-01

Thermal properties have been derated relative to the maximum temperature of 150F taken from Appendix C2

\[ E_c := 0.98 \times 10700 \text{ ksi} \quad E_c = 10486 \text{ ksi} \quad \text{(Compressive Modulus of Elasticity)} \]
\[ F_{tu} := 0.93 \times 68 \text{ ksi} \quad F_{tu} = 63.24 \text{ ksi} \quad \text{(Ultimate Tensile Strength)} \]
\[ F_{ty} := 0.95 \times 57 \text{ ksi} \quad F_{ty} = 54.15 \text{ ksi} \quad \text{(Tensile Yield Strength)} \]
\[ F_{cy} := 0.96 \times 60 \text{ ksi} \quad F_{cy} = 57.6 \text{ ksi} \quad \text{(Compressive Yield Strength)} \]
\[ F_{su} := 0.99 \times 38 \text{ ksi} \quad F_{su} = 37.62 \text{ ksi} \quad \text{(Ultimate Shear Strength)} \]

PART GEOMETRY:

\[ L := 52.3 \text{ in} \quad \text{(Tube Length)} \]
\[ D_y := 4 \text{ in} \quad \text{(Tube Height)} \]
\[ D_z := 4 \text{ in} \quad \text{(Tube Width)} \]
\[ t := 0.25 \text{ in} \quad \text{(Wall Thickness)} \]
\[ A := (D_y \cdot D_z) - [(D_y - 2t) \cdot (D_z - 2t)] \]
\[ A = 3.75 \text{ in}^2 \quad \text{(Cross Sectional Area)} \]
\[ I_y := \frac{1}{12} \cdot D_y \cdot D_z^3 - \frac{1}{12} \cdot (D_y - 2t) \cdot (D_z - 2t)^3 \]
\[ I_y = 8.828 \text{ in}^4 \quad \text{(Moment of Inertia about Y)} \]
\[ I_z := I_y \quad \text{(Moment of Inertia about Z)} \]
\[ Q_y := D_z \cdot t \left( \frac{D_z}{2} - \frac{t}{2} \right) + t \left( \frac{D_z}{2} - t \right)^2 \]
\[ Q_y = 2.641 \text{ in}^3 \quad \text{(First Moment of Area at Y-Y)} \]
\[ Q_z := Q_y \quad Q_z = 2.641 \text{ in}^3 \quad \text{(First Moment of Area at Z-Z)} \]
Stress Analysis for Sill Tube

\[ S_y := \frac{I_y}{5 \cdot D_z} \quad S_y = 4.414 \text{ in}^3 \quad \text{(Section Modulus about Y-Y)} \]

\[ S_z := \frac{I_x}{5 \cdot D_y} \quad S_z = 4.414 \text{ in}^3 \quad \text{(Section Modulus about Z-Z)} \]

\[ J_t := 2 \cdot t \cdot (D_z - t) \cdot (D_y - t) \quad J_t = 7.031 \text{ in}^3 \quad \text{(Torsional Constant, Ref Roark, 7th Edition, Table 10.1, Case 16)} \]

\[ R_y := \frac{I_y}{\sqrt{A}} \quad R_y = 1.534 \text{ in} \quad \text{(Radius of Gyration about Y)} \]

\[ R_z := \frac{I_z}{\sqrt{A}} \quad R_z = 1.534 \text{ in} \quad \text{(Radius of Gyration about Z)} \]

\[ K ::= 1.0 \quad \text{(Effective Length Factor for Column, assuming a pin ended beam. Ref Structural Engineering Handbook, 4th Edition, Figure 5, pg. 8-10)} \]

\[ SR_y ::= \frac{K \cdot L}{R_y} \quad SR_y = 34.087 \quad \text{(Slenderness Ratio, Y)} \]

\[ SR_z ::= \frac{K \cdot L}{R_z} \quad SR_z = 34.087 \quad \text{(Slenderness Ratio, Z)} \]

**CALCULATE ALLOWABLE LOADS:**

The following constants are calculated per the *Structural Engineering Handbook, 4th Edition*, Formulas 5a-c, pg. 11-6 in order to calculate the allowable compressive stresses for the beam.

\[ B_c ::= \frac{F_{cy}}{1 + \sqrt{\frac{F_{cy}}{2250 \text{ ksi}}}} \quad B_c = 66.816 \text{ ksi} \]

\[ D_c ::= \frac{B_c}{10} \left( \frac{B_c}{E_c} \right) \quad D_c = 0.533 \text{ ksi} \]

\[ C_c ::= 0.41 \frac{2-B_c}{3-D_c} \quad C_c = 34.242 \]
The allowable compressive loads are calculated using the above constants to approximate the tangent-modulus column formula if the slenderness ratio is less than the constant $C_c$. Otherwise, the allowable is calculated using the Euler column formula.

$$F_{cy} := \begin{cases} B_c - D_c SR_y & \text{if } SR_y \leq C_c \\ E_c \left( \frac{\pi}{SR_y} \right)^2 & \text{otherwise} \end{cases} \quad F_{cy} = 48.636 \text{ ksi} \quad (\text{Allowable Compressive Stress Based on Slenderness Ratio about Y})$$

$$F_{cz} := \begin{cases} B_c - D_c SR_z & \text{if } SR_z \leq C_c \\ E_c \left( \frac{\pi}{SR_z} \right)^2 & \text{otherwise} \end{cases} \quad F_{cz} = 48.636 \text{ ksi} \quad (\text{Allowable Compressive Stress Based on Slenderness Ratio about Z})$$

$$P_{cr} := \min(F_{ex} A, F_{cy} A) \quad P_{cr} = 182384.22 \text{ lbf} \quad (\text{Allowable Compressive Axial Load})$$

$$P_t := F_{tu} A \quad P_t = 237150 \text{ lbf} \quad (\text{Allowable Tensile Load})$$

The allowable shear load is calculated per *Roarks Formulas for Stress and Strain*, Seventh Edition, Eq 8.1-2:

$$\tau = \frac{V \cdot A \cdot dy}{I \cdot b} \quad \text{where: } b := 2t \quad \text{and} \quad A \cdot dy = Q \quad \text{is the first moment of area of the section}$$

Therefore, the maximum allowable shear load is:

$$V_{uy} := F_{su} \frac{I_y b}{Q_x} \quad V_{uy} = 62885.503 \text{ lbf} \quad (\text{Allowable Shear Load in Y})$$

$$V_{uz} := F_{su} \frac{I_y b}{Q_x} \quad V_{uz} = 62885.503 \text{ lbf} \quad (\text{Allowable Shear Load in Z})$$

The allowable torsional load is calculated per *Roarks Formulas for Stress and Strain*, Seventh Edition, Table 10.1, Case 16

$$\tau_{avg} = \frac{T}{2t \cdot (D_y - t) \cdot (D_z - t)} \quad \text{where } J_r \text{ has previously been defined as } J_r := 2 \cdot t \cdot (D_y - t) \cdot (D_z - t)$$

Therefore, the maximum allowable torsional load is:

$$T_u := F_{su} J_r \quad T_u = 264515.625 \text{ in-lbf} \quad (\text{Allowable Torsion Load})$$
Allowable bending loads are calculated using the shape factor (f) which is defined for various cross sections in *Structural Engineering Handbook*, 4th Edition, Table 7, pg.11-15:

\[
f := 1.22 \quad \text{(Shape Factor for Hollow Rectangular Tube)}
\]

\[
M_{uy} := S_y [F_u + (f - 1) F_{ly}] \quad M_{uy} = 331730.039 \text{ in-lbf} \quad \text{(Allowable Bending Moment about Y)}
\]

\[
M_{uz} := S_z [F_u + (f - 1) F_{ly}] \quad M_{uz} = 331730.039 \text{ in-lbf} \quad \text{(Allowable Bending Moment about Z)}
\]

In order to calculate a combined Bending and Axial margin of safety, the following factors are calculated per the *Structural Engineering Handbook*, 4th Edition, pg.11-25.

\[
F_{ey} := \frac{102000 - \text{ksi}}{S_{fu \cdot SR_y}^2} \quad F_{ey} = 62.706 \text{ ksi}
\]

\[
F_{ez} := \frac{102000 - \text{ksi}}{S_{fu \cdot SR_z}^2} \quad F_{ez} = 62.706 \text{ ksi}
\]

\[
P_{ey} := F_{ey} \cdot A \quad P_{ey} = 235145.803 \text{ lbf}
\]

\[
P_{ez} := F_{ez} \cdot A \quad P_{ez} = 235145.803 \text{ lbf}
\]

**IMPORT LOADS:**

NASPOST was used to output all element loads for the Sill Tube into a file named "silltube.lis". This file is located at /hsm/bsommer/ams/naspost/uss/2-04/. The file "SillTube.txt" was generated from the NASPOST output with the headers and formatting removed.

\[
\text{load} := \text{READPRN}("SillTube.txt") \quad i := 1 .. \text{rows(load)}
\]

\[
\begin{array}{ll}
\text{ID} & := \text{load}^{(1)} \quad (Element \ ID) \\
M_{1a} & := \text{load}^{(3)} \cdot \text{in-lbf} \quad M_{1b} := \text{load}^{(9)} \cdot \text{in-lbf} \quad (Moment \ About \ Element \ Z \ Axis \ at \ Ends \ A \ and \ B) \\
M_{2a} & := \text{load}^{(4)} \cdot \text{in-lbf} \quad M_{2b} := \text{load}^{(10)} \cdot \text{in-lbf} \quad (Moment \ About \ Element \ Y \ Axis \ at \ Ends \ A \ and \ B) \\
V_{1a} & := \text{load}^{(6)} \cdot \text{lbf} \quad V_{1b} := \text{load}^{(11)} \cdot \text{lbf} \quad (Shear \ Force \ in \ Element \ Y \ Direction \ at \ Ends \ A \ and \ B) \\
V_{2a} & := \text{load}^{(6)} \cdot \text{lbf} \quad V_{2b} := \text{load}^{(12)} \cdot \text{lbf} \quad (Shear \ Force \ in \ Element \ Z \ Direction \ at \ Ends \ A \ and \ B) \\
P_a & := \text{load}^{(7)} \cdot \text{lbf} \quad P_b := \text{load}^{(13)} \cdot \text{lbf} \quad (Axial \ Load \ at \ Ends \ A \ and \ B) \\
T & := \text{load}^{(8)} \cdot \text{in-lbf} \quad (Total \ Torque)
\end{array}
\]
CALCULATE COMBINED MARGINS OF SAFETY:

$$RS_a := \frac{V_{1a}}{V_{uy}} + \frac{V_{2a}}{V_{uz}} + \frac{T_i}{T_u} \quad \text{(Shear Ratio at End A)}$$

$$RS_b := \frac{V_{1b}}{V_{uy}} + \frac{V_{2b}}{V_{uz}} + \frac{T_i}{T_u} \quad \text{(Shear Ratio at End B)}$$

$$RT_a := \left| \frac{P_a}{P_{cr}} \right| + \frac{|M_{2a}|}{M_{uy}} + \frac{|M_{1a}|}{M_{uz}} \quad \text{if } P_a \geq 0\text{-lbf}$$

$$RT_a := \left| \frac{P_a}{P_{cr}} \right| + \frac{|M_{2a}|}{M_{uy}} \cdot \frac{1}{1 - \frac{|P_a|}{P_{ey}}} + \frac{|M_{1a}|}{M_{uz}} \cdot \frac{1}{1 - \frac{|P_a|}{P_{ex}}} \quad \text{otherwise} \quad \text{(Tensile Ratio at End A)}$$

$$RT_b := \left| \frac{P_b}{P_{cr}} \right| + \frac{|M_{2b}|}{M_{uy}} + \frac{|M_{1b}|}{M_{uz}} \quad \text{if } P_b \geq 0\text{-lbf}$$

$$RT_b := \left| \frac{P_b}{P_{cr}} \right| + \frac{|M_{2b}|}{M_{uy}} \cdot \frac{1}{1 - \frac{|P_b|}{P_{ey}}} + \frac{|M_{1b}|}{M_{uz}} \cdot \frac{1}{1 - \frac{|P_b|}{P_{ex}}} \quad \text{otherwise} \quad \text{(Tensile Ratio at End B)}$$

$$RATIO_a := \sqrt{\left( RT_a \right)^2 + \left( RS_a \right)^2}$$

$$RATIO_b := \sqrt{\left( RT_b \right)^2 + \left( RS_b \right)^2}$$

$$RATIO_i := \min \left( RATIO_a, RATIO_b \right)$$

$$MS_i := \frac{1}{RATIO_i \cdot SF_u} - 1 \quad \text{...Minimum Combined Margin of Safety}$$

DETERMINE WORST LOAD CASE AND ELEMENT:

cases := augment(ID, LC, MS) \quad \text{sorted_cases := csort(cases, 3)}$$

$$\begin{pmatrix} 1703 \\ 1032 \\ 4.267 \end{pmatrix} \quad \text{(Element ID)}$$

$$\begin{pmatrix} 1032 \\ 4.267 \end{pmatrix} \quad \text{(Load Case)}$$

$$\begin{pmatrix} 4.267 \end{pmatrix} \quad \text{(Margin of Safety)}$$
2.1.12 Diagonal Sill Bracket
COMPONENT:  USS-02 Diagonal Sill Bracket, SDG39135740

MINIMUM MARGINS OF SAFETY:

<table>
<thead>
<tr>
<th>PART</th>
<th>Material</th>
<th>Elem ID</th>
<th>Subcase</th>
<th>MSu</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diag. Sill Bracket</td>
<td>Al 7050-T7451</td>
<td>1721</td>
<td>1032</td>
<td>0.411</td>
<td>2.1.12-13</td>
</tr>
</tbody>
</table>

INTRODUCTION:
The Diagonal Sill Bracket is connected to the Sill Tube and Diagonal Strut at one end and to the Sill Joint at the other end. Figure 1 highlights these components which are on the Upper USS-02 Assembly. The diagonal sill bracket, which is manufactured from Al Aly 7050-T7451 6" plate, is riveted to the Sill Tube and bolted to the Sill Joint. There is an integrally machined clevis on the diagonal sill joint to attach the diagonal strut by a clevis pin.

LOADS:
Loads to the Diagonal Sill Bracket have been taken from the NASPOST output from the 2-04 loads model. The original NASPOST results (located at /hsm/bsommer/ams/naspost/uss/2-04/diagsillbracket.lis) have been re-formatted to remove headers and create a reformatted file (diagsillbracket_mc.txt) for import into MathCAD.

ANALYSIS METHOD:
The loads obtained from the Loads Model are applied to the diagonal sill bracket using classical hand calculation methods. The bracket will be checked at two cross sections.

FACTORs OF SAFETY
A factor of safety of 1.4 is used on ultimate and 1.1 on yield. The temperature reduction factor at 140 def F is 0.92 for ultimate and 0.97 for yield.

Figure 1: Diagonal Sill Bracket
Figure 2. Upper USS-02 Assembly
PART: Diagonal Sill Bracket, at Section A-A

ANALYSIS: Shear & Bending, Launch/ Landing Loads

FACTORS OF SAFETY:

\[ SF_u := 1.4 \quad SF_y := 1.1 \]  
(Ultimate and Yield Factors of Safety)

MATERIAL PROPERTIES: 7050-T7451 Aluminum, 5"-6" Thick Plate @150F per MMPDS-01

\[ TD_u := 92\% \quad TD_y := 97\% \]  
(Ultimate and Yield Thermal Degradation Factors)

\[ F_{tu} := TD_u \cdot 66\text{ksi} \quad F_{ty} := TD_y \cdot 57\text{ksi} \quad F_{su} := TD_u \cdot 43\text{ksi} \]  
(Ultimate Tensile Strength)

\[ F_{ty} := TD_y \cdot 57\text{ksi} \quad F_{sy} := TD_y \cdot 55.29\text{ksi} \]  
(Tensile Yield Strength)

\[ F_{su} := TD_u \cdot 43\text{ksi} \quad F_{sy} := TD_y \cdot 39.56\text{ksi} \]  
(Ultimate Shear Strength)

PART GEOMETRY: (At Section A-A)

\[ b := 4.562\text{in} \quad (\text{Section Width}) \]
\[ b_1 := 3\text{in} \quad (\text{Tube Bore Width}) \]
\[ h := 4.562\text{in} \quad (\text{Section Height}) \]
\[ h_1 := 3.25\text{in} \quad (\text{Tube Bore Height}) \]

\[ A_{aa} := b \cdot h - b_1 \cdot h_1 \]

\[ A_{aa} = 11.062\text{in}^2 \]  
(Cross Sectional Area at A-A)

\[ I_{aa,y} := \frac{1}{12} \left( b \cdot h^3 - b_1 \cdot h_1^3 \right) \]

\[ I_{aa,y} = 27.512\text{in}^4 \]  
(Moment of Inertia about Y at Section A-A)

\[ I_{aa,z} := \frac{1}{12} \left( h \cdot b^3 - h_1 \cdot b_1^3 \right) \]

\[ I_{aa,z} = 28.782\text{in}^4 \]  
(Moment of Inertia about Z at Section A-A)
LOADS

 Loads to the Diagonal Sill Bracket at section A-A are taken from the NASPOST output found in /hsm/bsommer/ams/naspost/uss/2-04/diagsillbracket.lis. This output has been reformatted for import into MathCAD in the file diagsillbracket.mc.txt. Section A-A of the bracket corresponds to side A of beam elements 1721 and 1722 as shown below.

```
Load := READPRN("diagsillbracket_mc.txt")
Sorted_Loads := csort(Load, 1)  (Sort Loads by Element ID)
ncases := 192   (Number of Load Cases)
nelem := 8     (Number of Elements in Matrix)
r1 := 6·ncases + 1 (First Row of Data for Element 1721)
r2 := nelem·ncases (Last Row of Data for Element 1722)
Load_{aa} := submatrix(Sorted_Loads, r1, r2, 1, cols(Load))  
i := 1 .. rows(Load_{aa})
ID := Load_{aa}^{(1)} (Element ID)
M_{1a} := Load_{aa}^{(3)}·in-lbf (Moment about Z axis at end A)
V_{1a} := Load_{aa}^{(5)}·lbf (Shear in Y direction at end A)
P_a := Load_{aa}^{(7)}·lbf (Tensile Load)
M_{2a} := Load_{aa}^{(4)}·in-lbf (Moment about Y axis at end A)
V_{2a} := Load_{aa}^{(6)}·lbf (Shear in Z direction at end A)
T_a := Load_{aa}^{(8)}·in-lbf (Torsional Load)
```

Diagonal Sill Bracket (-y side)  
Diagonal Sill Bracket (+y side)
STRESS AND MARGINS OF SAFETY AT SECTION A-A

\[
\sigma_{a_i} := \frac{P_{1i}}{A_{aa}} + \frac{M_{2a_i}}{2 \cdot I_{aa \cdot y}} + \frac{M_{1a_i} \cdot b}{2 \cdot I_{aa \cdot z}} \quad \text{max}(\sigma_a) = 24844.959 \text{ psi} \quad (\text{Maximum Tensile Stress})
\]

\[
\tau_{a1_i} := \frac{\sqrt{(V_{1a_i})^2 + (V_{2a_i})^2}}{A_{aa}} \quad \text{max}(\tau_{a1}) = 1873.409 \text{ psi} \quad (\text{Maximum Shear Stress due to Transverse Load})
\]

\[
\tau_{a2_i} := \frac{T_{ai}}{2 \cdot \left(\frac{h - h_1}{2}\right) \cdot b_1 \cdot h_1} \quad \text{max}(\tau_{a2}) = 126.407 \text{ psi} \quad (\text{Maximum Shear Stress due to Torsional Load, Ref. Roark, 7th Edition, Table 10.1, Case 16})
\]

\[
\tau_{a_i} := \tau_{a1_i} + \tau_{a2_i} \quad \text{max}(\tau_a) = 1990.279 \text{ psi} \quad (\text{Combined Shear Stress})
\]

\[
\sigma_{\max_{p1_i}} := \frac{\sigma_{a_i}}{2} + \frac{\left(\frac{\sigma_{a_i}}{2}\right)^2 + (\tau_{a_i})^2}{\sqrt{2}} \quad \text{max}(\sigma_{\max_{p1}}) = 25003.386 \text{ psi} \quad (\text{Maximum Principal Stress})
\]

\[
\sigma_{\min_{p1_i}} := \frac{\sigma_{a_i}}{2} - \frac{\left(\frac{\sigma_{a_i}}{2}\right)^2 + (\tau_{a_i})^2}{\sqrt{2}} \quad \text{min}(\sigma_{\min_{p1}}) = -158.783 \text{ psi} \quad (\text{Minimum Principal Stress})
\]

\[
\sigma_{\text{vmi}} := \sqrt{\left(\frac{\sigma_a}{2}\right)^2 + (3 \cdot \tau_{a_i})^2} \quad \text{max}(\sigma_{\text{vmi}}) = 25552.356 \text{ psi} \quad (\text{Maximum Von Mises Stress, Ref. Bruhn, Section C1.17, Eq 32})
\]

\[
\tau_{\max_{i}} := \sqrt{\left(\frac{\sigma_a}{2}\right)^2 + (\tau_{a_i})^2} \quad \text{max}(\tau_{\max_{i}}) = 12580.906 \text{ psi} \quad (\text{Maximum Shear Stress})
\]

\[
\text{MS}_{ui} := \frac{F_{iu}}{SF_{u} \cdot \sigma_{\max_{p1_i}}} - 1 \quad \text{min}(\text{MS}_{ui}) = 0.735 \quad \ldots \text{Minimum Ultimate Margin of Safety}
\]

\[
\text{MS}_{yi} := \frac{F_{iy}}{SF_{y} \cdot \sigma_{\text{vmi}}} - 1 \quad \text{min}(\text{MS}_{yi}) = 0.967 \quad \ldots \text{Minimum Yield Margin of Safety}
\]

\[
\text{MS}_{si} := \frac{F_{su}}{SF_{u} \cdot \tau_{\max_{i}}} - 1 \quad \text{min}(\text{MS}_{si}) = 1.246 \quad \ldots \text{Minimum Shear Margin of Safety}
\]

DETERMINE WORST LOAD CASE AND ELEMENT:

\[
\text{cases} := \text{augment(ID, LC, MS_{u})} \quad \text{sorted_cases} := \text{csort(cases, 3)}
\]

\[
\left(\text{sorted_cases}^T\right)^{(1)} = \begin{bmatrix}
1721 \\
1032 \\
0.735
\end{bmatrix} \quad (\text{Element ID})
\]

\[
\begin{bmatrix}
(\text{Load Case}) \\
(\text{Margin of Safety})
\end{bmatrix}
\]

2.1.12-6
PART: Diagonal Sill Bracket, at Section B-B

ANALYSIS: Shear & Bending, Launch/ Landing Loads

FACTORS OF SAFETY:

\[ SF_u := 1.4 \quad SF_y := 1.1 \quad (\text{Ultimate and Yield Factors of Safety}) \]

MATERIAL PROPERTIES: 7050-T7451 Aluminum, 5”-6” Thick Plate @150F per MMPDS-01

\[ TD_u := 92\% \quad TD_y := 97\% \quad (\text{Ultimate and Yield Thermal Degradation Factors}) \]
\[ F_{tu} := TD_u \cdot 66-ksi \quad F_{ty} := TD_y \cdot 57-ksi \quad (\text{Ultimate Tensile Strength}) \]
\[ F_{ty} := TD_y \cdot 57-ksi \quad F_{su} := TD_u \cdot 43-ksi \quad (\text{Tensile Yield Strength}) \]
\[ F_{su} := TD_u \cdot 43-ksi \quad (\text{Ultimate Shear Strength}) \]

PART GEOMETRY: (At Section B-B)

\[ b := 4.562\text{-in} \quad (\text{Flange Width}) \]
\[ d := 3\text{-in} \quad (\text{Web Height}) \]
\[ t_w := .812\text{-in} \quad (\text{Web Thickness}) \]
\[ t := \frac{4.562\text{-in} - d}{2} \quad (\text{Flange Thickness}) \]
\[ h := 4.562\text{ in} \quad (\text{Beam Height}) \]
\[ A_{bb} := 2 \cdot b \cdot t + t_w \cdot d \quad (\text{Cross Sectional Area at B-B}) \]
\[ A_{bb} = 9.562 \text{ in}^2 \]
\[ I_{bb,y} := \frac{b^3 \cdot t}{6} + \frac{t_w^3 \cdot d}{12} \quad (\text{Moment of Inertia about Y at Section B-B}) \]
\[ I_{bb,y} = 12.492 \text{ in}^4 \]
\[ I_{bb,z} := \frac{b \cdot (d + 2t)^3}{12} - \frac{(b - t_w) \cdot d^3}{12} \quad (\text{Moment of Inertia about Z at Section B-B}) \]
\[ I_{bb,z} = 27.657 \text{ in}^4 \]
\[ J := \frac{1}{3} \left( b \cdot t^3 + b \cdot t^3 + d \cdot t_w^3 \right) \quad (\text{Torsional Constant at Section B-B, Ref Bruhn, A6-6}) \]
\[ J = 1.984 \text{ in}^4 \]
LOADS

Loads to the Diagonal Sill Bracket at section B-B are taken from the NASPOST output found in /hsm/bsommer/ams/naspost/uss/2-04/diagsillbracket.lis. This output has been reformatted for import into MathCAD in the file diagsillbracket_mc.txt. Section B-B of the bracket corresponds to side B of beam elements 1721 and 1722 as shown below.

```
Load := READPRN("diagsillbracket_mc.txt")
Sorted_Loads := csort(Load, 1)  (Sort Loads by Element ID)
ncases := 192  (Number of Load Cases)
nelem := 8  (Number of Elements in Matrix)
r1 := 6·ncases + 1  (First Row of Data for Element 1721)
r2 := nelem·ncases  (Last Row of Data for Element 1722)
Loadbb := submatrix(Sorted_Loads, r1, r2, 1, cols(Load))
ID := Loadbb^1  (Element ID)
M1b := Loadbb^9·in·lbf  (Moment about Z axis at end B)
V1b := Loadbb^11·lbf  (Shear in Y direction at end B)
Pb := Loadbb^13·lbf  (Tensile Load)
Li := 1..rows(Loadbb)
LC := Loadbb^2  (Load Case)
M2b := Loadbb^10·in·lbf  (Moment about Y axis at end B)
V2b := Loadbb^12·lbf  (Shear in Z direction at end B)
Tb := Loadbb^14·in·lbf  (Torsional Load)
```
STRESS AND MARGINS OF SAFETY AT SECTION B-B

\[
\sigma_{bi} = \frac{P_{bi}}{A_{bb}} + \frac{M_{2bi}}{2 \cdot I_{bb,y}} + \frac{M_{1bi}}{2 \cdot I_{bb,z}} \quad \text{max}(\sigma_b) = 23963.424 \text{ psi} \quad \text{(Maximum Tensile Stress)}
\]

\[
\tau_{b1i} = \sqrt{\left(\frac{V_{1bi}}{A_{bb}}\right)^2 + \left(\frac{V_{2bi}}{A_{bb}}\right)^2} \quad \text{max}(\tau_{b1}) = 2167.298 \text{ psi} \quad \text{(Maximum Shear Stress due to Transverse Load)}
\]

\[
\tau_{b2i} = \frac{3}{J} \cdot \max(t,t_w) \quad \text{max}(\tau_{b2}) = 1985.173 \text{ psi} \quad \text{(Maximum Shear Stress due to Torsional Load, Ref. Bruhn, Section A6.6)}
\]

\[
\tau_{bi} = \tau_{b1i} + \tau_{b2i} \quad \text{max}(\tau_{b}) = 4002.692 \text{ psi} \quad \text{(Combined Shear Stress)}
\]

\[
\sigma_{\text{max}_p}_{i} = \frac{\sigma_{bi}}{2} + \sqrt{\left(\frac{\sigma_{bi}}{2}\right)^2 + (\tau_{bi})^2} \quad \text{max}(\sigma_{\text{max}_p}) = 24614.328 \text{ psi} \quad \text{(Maximum Principal Stress)}
\]

\[
\sigma_{\text{min}_p}_{i} = \frac{\sigma_{bi}}{2} - \sqrt{\left(\frac{\sigma_{bi}}{2}\right)^2 + (\tau_{bi})^2} \quad \text{min}(\sigma_{\text{min}_p}) = -684.656 \text{ psi} \quad \text{(Minimum Principal Stress)}
\]

\[
\sigma_{vmi} = \sqrt{\left(\frac{\sigma_{bi}}{2}\right)^2 + (3 \cdot \tau_{bi})^2} \quad \text{max}(\sigma_{vm}) = 26803.724 \text{ psi} \quad \text{(Maximum Von Mises Stress, Ref. Bruhn, Section C1.17, Eq 32)}
\]

\[
\tau_{\text{max}} = \sqrt{\left(\frac{\sigma_{bi}}{2}\right)^2 + (3 \cdot \tau_{bi})^2} \quad \text{max}(\tau_{\text{max}}) = 12632.616 \text{ psi} \quad \text{(Maximum Shear Stress)}
\]

\[
\text{MS}_{ui} := \frac{F_{iu}}{\sigma_{\text{max}_p}_{i}} - 1 \quad \text{min}(\text{MS}_{u}) = 0.762 \quad \text{... Minimum Ultimate Margin of Safety}
\]

\[
\text{MS}_{yi} := \frac{F_{iy}}{\sigma_{vmi}} - 1 \quad \text{min}(\text{MS}_{y}) = 0.875 \quad \text{... Minimum Yield Margin of Safety}
\]

\[
\text{MS}_{si} := \frac{F_{su}}{\tau_{\text{max}_i}} - 1 \quad \text{min}(\text{MS}_{s}) = 1.237 \quad \text{... Minimum Shear Margin of Safety}
\]

DETERMINE WORST LOAD CASE AND ELEMENT:

\[
\text{cases} := \text{augment}([\text{ID}, \text{LC}, \text{MS}_{u}]) \quad \text{sorted_cases} := \text{sort}([\text{cases}, 3])
\]

\[
\begin{pmatrix}
1721 \\
1032 \\
0.762
\end{pmatrix}
\quad \text{(Element ID)}
\]

\[
\begin{pmatrix}
1721 \\
1032 \\
0.762
\end{pmatrix}
\quad \text{(Load Case)}
\]

\[
\begin{pmatrix}
1721 \\
1032 \\
0.762
\end{pmatrix}
\quad \text{(Margin of Safety)}
\]
PART: Diagonal Sill Bracket, at Diagonal Strut Clevis

ANALYSIS: Lug Analysis, Launch/ Landing Loads

FACTORS OF SAFETY:

$$SF_u := 1.4 \quad SF_y := 1.1$$  (Ultimate and Yield Factors of Safety)

MATERIAL PROPERTIES: 7050-T7451 Aluminum, 5"-6" Thick Plate @150F per MMPDS-01

$$TD_u := 92\% \quad TD_y := 97\%$$  (Ultimate and Yield Thermal Degradation Factors)

$$F_{tu} := TD_u \cdot 66\text{ksi} \quad F_{tu} = 60.72\text{ksi}$$  (Ultimate Tensile Strength)

$$F_{ty} := TD_y \cdot 57\text{ksi} \quad F_{ty} = 55.29\text{ksi}$$  (Tensile Yield Strength)

$$F_{su} := TD_u \cdot 43\text{ksi} \quad F_{su} = 39.56\text{ksi}$$  (Ultimate Shear Strength)

PART GEOMETRY:

$$D := 1.005\text{in}$$  (Diameter of Hole)

$$e := 5.56\text{in} - 4.026\text{in} \quad e = 1.534\text{in}$$  (Edge Distance)

$$t := 1\text{in}$$  (Thickness of Lug)

$$W := 2\cdot1.75\text{in} \quad W = 3.5\text{in}$$  (Width of Lug)

Shape Ratios:

$$\frac{e}{D} = 1.526 \quad \frac{D}{t} = 1.005 \quad \frac{W}{D} = 3.483$$

$$A_{br} := D \cdot t \quad A_{br} = 1.005\text{in}^2$$  (Bearing Area)

$$A_{t} := (W - D) \cdot t \quad A_{t} = 2.495\text{in}^2$$  (Tensile Area)

$$\alpha := 69.69\text{deg}$$  (Angle of Applied Force)

LOADS:

Loads to the diagonal strut clevis are taken from the 2-04 loads model. The Diagonal Struts are represented by two CBEAM elements in the loads model: elements 1801 and 1803. Since the strut includes rod end bearings at each end, loads to the strut act in the axial direction only. Using NASPOST, the finite element results were sorted to determine the maximum axial load in the struts which was found to be 34052.7 lbf. NASPOST output files are located in the files "diagstrutlaunch.lis", "diagstrutlanding.lis", and "diagstrutabortlanding.lis" in the folder /hsm/bsommer/ams/naspost/uss/2-04/.

$$P := 34052.7\text{lbf}$$  (Total Applied Load to Joint)

$$P_{axial} := \frac{P}{2} \cdot \cos(\alpha) \quad P_{axial} = 5909.835\text{lbf}$$  (Axial Load per lug)

$$P_{transverse} := \frac{P}{2} \cdot \sin(\alpha) \quad P_{transverse} = 15967.794\text{lbf}$$  (Transverse Load per lug)
CALCULATE ALLOWABLE LOADS (Axial Load Component):

From *Astronautics Structures Manual*, Figure B.2.1.0-3, using: \[
\frac{e}{D} = 1.526 \quad \frac{D}{t} = 1.005
\]
\[K_{br} := 1.45\]
\[P_{bru} := K_{br} F_{tu} \cdot A_{br} \quad P_{bru} = 88484.22 \text{ lbf} \quad \text{(Ultimate Bearing Load)}\]

From *Astronautics Structures Manual*, Figure B.2.1.0-4, Curve 4, using: \[
\frac{W}{D} = 3.483
\]
\[K_{t} := 0.77\]
\[P_{tu} := K_{t} F_{tu} \cdot A_{t} \quad P_{tu} = 116652.228 \text{ lbf} \quad \text{(Ultimate Tensile Load)}\]

From *Astronautics Structures Manual*, Figure B.2.1.0-5, using: \[
\frac{e}{D} = 1.526
\]
\[K_{bry} := 1.53\]
\[P_{bry} := K_{bry} A_{br} F_{ty} \quad P_{bry} = 85016.668 \text{ lbf} \quad \text{(Yield Bearing Load)}\]

COMPUTE ULTIMATE & YIELD LOAD RATIOS (actual/allowable)

using smaller of $P_{tu}$ and $P_{bru}$ for ultimate:
\[
R_{bru} := \begin{cases} \frac{SF_{u} \cdot P_{axial}}{P_{tu}} & \text{if } P_{tu} < P_{bru} \\ \frac{SF_{u} \cdot P_{axial}}{P_{bru}} & \text{otherwise} \end{cases} \
R_{bru} = 0.094
\]

for yield:
\[
R_{bry} := \frac{SF_{y} \cdot P_{axial}}{P_{bry}} \
R_{bry} = 0.076
\]
CALCULATE ALLOWABLE LOADS (Transverse Load Component):

$\beta := 45^\circ$ deg

Calculate lug section areas:

$A_1 := t \cdot \frac{W - D \sin(\beta)}{2}$  
$A_1 = 1.395 \text{ in}^2$

$A_2 := t \cdot \frac{W - D}{2}$  
$A_2 = 1.247 \text{ in}^2$

$A_3 := t \cdot \left( e - \frac{D}{2} \right)$  
$A_3 = 1.032 \text{ in}^2$

$A_4 := t \cdot \frac{W - D \sin(\beta)}{2}$  
$A_4 = 1.395 \text{ in}^2$

Areas of Lug for Calculating Shape Parameter

Calculate the weighted average area:

$A_{avg} := \frac{6}{\frac{1}{A_1} + \frac{1}{A_2} + \frac{1}{A_3} + \frac{1}{A_4}}$  
$A_{avg} = 1.293 \text{ in}^2$

From above, the bearing area is:

$A_{br} = 1.005 \text{ in}^2$

The shape parameter is:

$\frac{A_{avg}}{A_{br}} = 1.287$

From Astronautics Structures Manual, Figure B.2.2.0-4, curve 8, using:

$K_{bru} := 0.53$  
$P_{bru} := K_{bru} \cdot F_{tu} \cdot A_{br}$  
$P_{bru} = 32342.508 \text{ lbf} \quad (\text{Ultimate Transverse Bearing Load})$

From Astronautics Structures Manual, Figure B.2.2.0-4, using:

$K_{tbry} := 1.26$  
$P_{tbry} := K_{tbry} \cdot F_{ty} \cdot A_{br}$  
$P_{tbry} = 70013.727 \text{ lbf} \quad (\text{Yield Transverse Bearing Load})$

COMPUTE ULTIMATE & YIELD LOAD RATIOS (actual/allowable)

ultimate:

$R_{thru} := \frac{SF_{u} \cdot P_{transverse}}{P_{bru}}$  
$R_{thru} = 0.691$

yield:

$R_{thry} := \frac{SF_{y} \cdot P_{transverse}}{P_{tbry}}$  
$R_{thry} = 0.251$
### Stress Analysis for Diagonal Sill Bracket

CALCULATE COMBINED MARGINS OF SAFETY: Ref *Astronautics Structures Manual*, section B2.3.0:

\[
MS_u := \left( R_{bru}^{1.6} + R_{vhru}^{1.6} \right)^{0.625} - 1 \quad \text{MS}_u = 0.411 \\
MS_y := \left( R_{bry}^{1.6} + R_{vhr}^{1.6} \right)^{0.625} - 1 \quad \text{MS}_y = 2.654
\]

... Margin of Safety on Combined Ultimate

... Margin of Safety on Combined Yield
CALCULATE STRESS AND MARGIN OF SAFETY AT SECTION A-A

PART GEOMETRY:

- \( t_{lug} := 2 \cdot t \)  
  \( t_{lug} = 2 \text{ in} \)  
  (Thickness of Section A-A, Two Lugs)

- \( w := 8 \cdot \text{in} \)  
  (Section Width)

- \( S := \frac{t_{lug} \cdot w^2}{6} \)  
  \( S = 21.333 \text{ in}^3 \)  
  (Section Modulus)

- \( A := t_{lug} \cdot w \)  
  \( A = 16 \text{ in}^2 \)  
  (Cross Sectional Area)

- \( d_1 := 4.026 \cdot \text{in} - \frac{4.562}{2} \cdot \text{in} \)  
  \( d_1 = 1.745 \text{ in} \)  
  (Distance From Load to Section A-A)

LOADS, STRESSES, AND MARGINS OF SAFETY:

- \( P_{pin\text{-}axial} := 2 \cdot P_{axial} \)  
  \( P_{pin\text{-}axial} = 11820 \text{ lbf} \)  
  (Axial Load at Section A-A)

- \( P_{pin\text{-}transverse} := 2 \cdot P_{transverse} \)  
  \( P_{pin\text{-}transverse} = 31936 \text{ lbf} \)  
  (Transverse Load at Section A-A)

- \( M := P_{pin\text{-}transverse} \cdot d_1 \)  
  \( M = 55728 \text{ in}\cdot\text{lbf} \)  
  (Bending Moment)

- \( \sigma := \frac{M}{S} + \frac{P_{pin\text{-}axial}}{A} \)  
  \( \sigma = 3351 \text{ psi} \)  
  (Normal Stress, Bending + Axial)

- \( \tau := \frac{P_{pin\text{-}transverse}}{A} \)  
  \( \tau = 1996 \text{ psi} \)  
  (Shear Stress)

- \( MS_u := \frac{F_{tu}}{SF_u \cdot \sigma} - 1 \)  
  \( MS_u = 11.943 \)  
  ... Ultimate Margin of Safety at Section A-A

- \( MS_y := \frac{F_{ty}}{SF_y \cdot \sigma} - 1 \)  
  \( MS_y = 14 \)  
  ... Yield Margin of Safety at Section A-A

- \( MS_s := \frac{F_{su}}{SF_u \cdot \tau} - 1 \)  
  \( MS_s = 13.157 \)  
  ... Shear Margin of Safety at Section A-A
### PART: Diagonal Sill Bracket, SDG39135740

### ANALYSIS: Diagonal Sill Bracket to Sill Joint Fastener Hole

### FACTORS OF SAFETY:

<table>
<thead>
<tr>
<th>SF\textsubscript{u}</th>
<th>SF\textsubscript{y}</th>
<th>(Ultimate and Yield Factors of Safety)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FF</th>
<th>(Fitting Factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td></td>
</tr>
</tbody>
</table>

### MATERIAL PROPERTIES: 7050-T7451 Aluminum, 6" Thick Plate per MMPDS-01

<table>
<thead>
<tr>
<th>TD\textsubscript{u}</th>
<th>TD\textsubscript{y}</th>
<th>(Temperature Degradation Factors, Ultimate and Yield @140 F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>0.97</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FS\textsubscript{u}</th>
<th>FS\textsubscript{y}</th>
<th>(Ultimate Shear Strength)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD\textsubscript{u} \cdot 44 ksi</td>
<td>FS\textsubscript{y} = 40.48 ksi</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FB\textsubscript{ru}</th>
<th>FB\textsubscript{ry}</th>
<th>(Ultimate Bearing Strength, e/D=1.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD\textsubscript{u} \cdot 103 ksi</td>
<td>FB\textsubscript{ry} = 94.76 ksi</td>
<td></td>
</tr>
</tbody>
</table>

### LOADS: Worst case shear and tensile loads are taken from the fastener analysis in Section 2.4.1.5.

```plaintext
file := "output_forces_diagsillbrack_r2_launch.txt"
data := READPRN(file)
```

Tensile loads are contained in the third column of the matrix and shear loads are contained in the fourth.

\[
P := \max(data^3) \text{ lbf}
V := \max(data^4) \text{ lbf}
\]

\[
P = 12428.59 \text{ lbf} \quad (\text{Maximum Fastener Tensile Load}) 
V = 2111.781 \text{ lbf} \quad (\text{Maximum Fastener Shear Load})
\]

### PART GEOMETRY

<table>
<thead>
<tr>
<th>t</th>
<th>1.0-in</th>
<th>(Flange Thickness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.5-in</td>
<td>(Min Edge Distance)</td>
</tr>
<tr>
<td>D</td>
<td>0.539-in</td>
<td>(Hole Diameter)</td>
</tr>
</tbody>
</table>

\[
e = 0.28 \quad \text{D} 
\]

<table>
<thead>
<tr>
<th>Dw</th>
<th>0.875-in</th>
<th>(Washer OD)</th>
</tr>
</thead>
</table>

\[
A_{sto} := 2 \cdot t \left( e - \frac{D}{2} \right) 
A_{sto} = 0.461 \text{ in}^2 \quad (\text{Shear Tear-Out Area})
\]

\[
A_{brg} := t \cdot D 
A_{brg} = 0.539 \text{ in}^2 \quad (\text{Bearing Area})
\]

\[
A_{spt} := \frac{D + Dw}{2} \cdot \pi \cdot t 
A_{spt} = 2.221 \text{ in}^2 \quad (\text{Shear Pull-Thru Area})
\]

2.1.12-15
STRESS ANALYSIS:

The Sill Bracket will be checked for bearing strength, shear pull-thru, and shear tear-thru.

![Shear Tear-Out](image1)

![Bearing](image2)

![Shear Pull-Thru](image3)

\[
\tau_{sto} := \frac{V}{A_{sto}} \quad \tau_{sto} = 4.581 \text{ ksi} \quad \text{(Shear Tear-Out Stress)}
\]

\[
\tau_{spt} := \frac{P}{A_{spt}} \quad \tau_{spt} = 5.596 \text{ ksi} \quad \text{(Shear Pull-Thru Stress)}
\]

\[
\sigma_{brg} := \frac{V}{A_{brg}} \quad \sigma_{brg} = 3.918 \text{ ksi} \quad \text{(Bearing Stress)}
\]

Since the ratio of e/D is less than 1.5, adjust bearing strength allowables:

\[
F_{bru} := F_{bru}\left(\frac{e}{D} - .5\right) \quad F_{bru} = 40.524 \text{ ksi} \quad \text{(Ultimate Bearing Strength, e/D=1.5)}
\]

\[
F_{bry} := F_{bry}\left(\frac{e}{D} - .5\right) \quad F_{bry} = 34.43 \text{ ksi} \quad \text{(Bearing Yield Strength, e/D=1.5)}
\]

\[
MS_{sto} := \frac{F_{su}}{\tau_{sto}SF_uFF} - 1 \quad MS_{sto} = 4.489 \quad \text{..Margin of Safety on Shear Tear-Out}
\]

\[
MS_{spt} := \frac{F_{su}}{\tau_{spt}SF_uFF} - 1 \quad MS_{spt} = 3.493 \quad \text{..Margin of Safety on Shear Pull-Thru}
\]

\[
MS_{bru} := \frac{F_{bru}}{\sigma_{brg}SF_uFF} - 1 \quad MS_{bru} = 5.424 \quad \text{..Margin of Safety on Ultimate Bearing Strength}
\]

\[
MS_{bry} := \frac{F_{bry}}{\sigma_{brg}SF_yFF} - 1 \quad MS_{bry} = 5.947 \quad \text{(Margin of Safety on Shear Tear-Out)}
\]
2.1.13 Diagonal Strut Assy
2.1.13.1 Diagonal Strut Tube
**INTRODUCTION:**

The Diagonal Strut Tube is one component in the Diagonal Strut Assembly (SEG39135741-301). The assembly is made up of the Diagonal Strut Tube (SDG39135742-001), two Endfittings (SDG39135743-001/-003) which are riveted to the strut tube, and two Rod End Bearings (SDG39135745-801/-803) which thread into the Endfittings. The Diagonal Strut Tube is fabricated from 4" OD x 3.5" ID 6061-T6511 aluminum round tubing. Two Diagonal Struts are incorporated in the USS-02 assembly, one each on the port and starboard sides.

**LOADS:**

Applied loads to the Diagonal Strut Tube have been calculated using the 2-04 loads model. The Diagonal Struts are represented by two CBEAM elements in the loads model: elements 1801 and 1803. Since the strut includes rod end bearings at each end, loads to the strut act in the axial direction only. Using NASPOST, the finite element results were sorted to determine the maximum axial load in the struts which was found to be 34052.7 lbf. NASPOST output files are located in the files "diagstrutlaunch.lis", "diagstrutlanding.lis", and "diagstrutabortlanding.lis" in the folder /hsm/bsomer/ams/naspost/uss/2-04/.

**FACTORS OF SAFETY**

A factor of safety of 1.4 is used on ultimate and 1.1 on yield.

---

**Figure 2.1.13.1-1: Upper USS-02 Assembly**

2.1.13.1-2
PART: Diagonal Strut Tube, SDG39135742-001

ANALYSIS: Tension/Compression Analysis (Includes Buckling)

FACTORS OF SAFETY:

\[SF_u := 1.4 \quad SF_y := 1.1\]  
(Ultimate and Yield Factors of Safety)

MATERIAL PROPERTIES: 6061-T6511 Aluminum, 0.250"-0.499 Thick Extrusion @150°F per MMPDS-01

Thermal properties have been derated relative to the maximum temperature of 150°F taken from Appendix C2

\[E_c := 99\% \cdot 10100\text{-ksi} \quad E_c = 9999\text{ksi} \]  
(Compressive Modulus of Elasticity)

\[F_{tu} := 94\% \cdot 37\text{-ksi} \quad F_{tu} = 34.78\text{ksi} \]  
(Ultimate Tensile Strength)

\[F_{cy} := 95\% \cdot 34\text{-ksi} \quad F_{cy} = 32.3\text{ksi} \]  
(Compressive Yield Strength)

PART GEOMETRY:

\[L := 31.43\text{-in} \]  
(Tube Length)

\[D_0 := 3.944\text{-in} \]  
(Minimum Tube OD)

\[D_i := 3.53\text{-in} \]  
(Maximum Tube ID)

\[t := 0.5 \left(D_0 - D_i\right) \]  
(Minimum Wall Thickness)

\[A := \frac{\pi}{4} \left(D_0^2 - D_i^2\right) \]  
(Cross Sectional Area)

\[A = 2.43\text{in}^2 \]  

\[I := \frac{\pi}{64} \left(D_0^4 - D_i^4\right) \]  
(Moment of Inertia)

\[I = 4.255\text{in}^4 \]  

\[R := \sqrt{\frac{I}{A}} \]  
(Radius of Gyration)

\[R = 1.323\text{in} \]  

\[K := 1.0 \]  
(Effective Length Factor for Column, assuming a pin ended beam. Ref Structural Engineering Handbook, 4th Edition, Figure 5, pg. 8-10)

\[SR := \frac{K \cdot L}{R} \]  
(Slenderness Ratio)

\[SR = 23.752 \]  

2.1.13.1-3
CALCULATE ALLOWABLE LOADS:

The following constants are calculated per the *Structural Engineering Handbook, 4th Edition*, Formulas 5a-c, pg. 11-6 in order to calculate the allowable compressive stresses for the beam.

\[ B_c := F_{cy} \left( 1 + \sqrt{\frac{F_{cy}}{2250 \text{ ksi}}} \right) \quad B_c = 36.17 \text{ ksi} \]

\[ D_c := \frac{B_c}{10} \sqrt{\frac{B_c}{E_c}} \quad D_c = 0.218 \text{ ksi} \]

\[ C_c := 0.41 \frac{2-B_c}{3D_c} \quad C_c = 45.446 \]

The allowable compressive loads are calculated using the above constants to approximate the tangent-modulus column formula if the slenderness ratio is less than the constant \( C_c \). Otherwise, the allowable is calculated using the Euler column formula.

\[ F_c := \begin{cases} B_c - D_c \cdot \text{SR} & \text{if } \text{SR} \leq C_c \\ E_c \left( \frac{\pi}{\text{SR}} \right)^2 & \text{otherwise} \end{cases} \quad F_c = 31.003 \text{ ksi} \quad (\text{Allowable Compressive Stress Based on Slenderness Ratio}) \]

\[ P_{cr} := F_c \cdot A \quad P_{cr} = 75343.54 \text{ lbf} \quad (\text{Allowable Compressive Axial Load}) \]

\[ P_t := F_{tu} \cdot A \quad P_t = 84522.61 \text{ lbf} \quad (\text{Allowable Tensile Load}) \]

LOADS:

NASPOST was used to output worst case element loads for the Diagonal Strut Tube during launch, landing and abort landing. Three files were generated: "diagstrutlaunch.lis", "diagstrutlanding.lis", and "diagstrutabortlanding.lis" and are located in the folder /hsm/bsommer/ams/naspost/uss/2-04/. Analysis will be performed using the maximum axial load found in any load case.

\[ P_{\text{max\_launch}} := 34052.77 \cdot \text{lbf} \quad (\text{Worst Case Axial Load in Strut, Launch Cases, Element ID 1803, Subcase 1032}) \]

\[ P_{\text{max\_landing}} := -22696.79 \cdot \text{lbf} \quad (\text{Worst Case Axial Load in Strut, Landing Cases, Element ID 1803, Subcase 4045}) \]

\[ P_{\text{max\_abort}} := -14987.22 \cdot \text{lbf} \quad (\text{Worst Case Axial Load in Strut, Abort Landing Cases, Element ID 1803, Subcase 2045}) \]

\[ P_a := \max(P_{\text{max\_launch}}, P_{\text{max\_landing}}, P_{\text{max\_abort}}) \quad P_a = 34052.77 \text{ lbf} \quad (\text{Maximum Axial Load}) \]
MARGINS OF SAFETY:

The part will be checked assuming the maximum axial load acts in both the tensile and compressive directions in order to determine the minimum margin of safety

\[
MS_{\text{tens}} := \frac{P_t}{P_a SF_u} - 1 \quad MS_{\text{tens}} = 0.773
\]

\[
MS_{\text{comp}} := \frac{P_{\text{cr}}}{P_a SF_u} - 1 \quad MS_{\text{comp}} = 0.58
\]

\[
MS := \min(\text{MS}_{\text{tens}}, \text{MS}_{\text{comp}}) \quad MS = 0.58 \quad \text{...Margin of Safety}
\]
2.1.13.2 Diagonal Strut Endfitting
COMPONENT: USS-02 Diagonal Strut Endfitting, SDG39135743-001,-003

MARGIN OF SAFETY SUMMARY:

<table>
<thead>
<tr>
<th>Part</th>
<th>Part Number</th>
<th>Material</th>
<th>MS</th>
<th>Failure Mode</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagonal Strut Endfitting</td>
<td>SDG39135743-001,-003</td>
<td>7075-T7351</td>
<td>0.58</td>
<td>Thread Shear</td>
<td>2.1.13.2-5</td>
</tr>
</tbody>
</table>

INTRODUCTION:

The Diagonal Strut Endfitting is one component in the Diagonal Strut Assembly (SEG39135741-301). The assembly is made up of the Diagonal Strut Tube (SDG39135742-001), two Endfittings (SDG39135743-001/-003) which are riveted to the strut tube, and two Rod End Bearings (SDG39135745-801/-803) which thread into the Endfittings. The Diagonal Strut Tube is fabricated from 4" OD x 3.5" ID 6061-T6511 aluminum round tubing. Two Diagonal Struts are incorporated in the USS-02 assembly, one each on the port and starboard sides. This analysis will address the thread shear at the interface with the Rod End Bearings. Analysis of the rivet holes and tension across the net section is addressed in the rivet analysis in Section 2.5.1.5.

LOADS:

Applied loads to the Diagonal Strut Endfitting have been calculated using the 2-04 loads model. The Diagonal Struts are represented by two CBEAM elements in the loads model: elements 1801 and 1803. Since the strut includes rod end bearings at each end, loads to the strut act in the axial direction only. Using NASPOST, the finite element results were sorted to determine the maximum axial load in the struts which was found to be 34052.7 lbf. NASPOST output files are located in the files "diagstrutlaunch.lis", "diagstrutlanding.lis", and "diagstrutabortlanding.lis" in the folder /hsm/bsommer/ams/naspost/uss/2-04/.

TEMPERATURE:

Temperatures of the diagonal strut are taken from Appendix C, Table C2-2 for Launch (120F), Landing (101F), and Abort Landing (150F). Margins of safety for each flight event are calculated using appropriate material thermal degradation.

FACTORS OF SAFETY

A factor of safety of 1.4 is used on ultimate and 1.1 on yield.
**PART:** Diagonal Strut Endfitting, SDG39135743-001,-003

**ANALYSIS:** Thread Shear

**FACTORS OF SAFETY:**

\[
SF_u := 1.4 \quad SF_y := 1.1 \quad \text{(Ultimate and Yield Factors of Safety)}
\]

**MATERIAL PROPERTIES:** 7075-T73511 Aluminum Bar, per MMPDS-01, Table 3.7.6.0(g)

Thermal degradation factors for launch, landing and abort landing are applied to the margin of safety calculations

\[
TD_{\text{launch}} := 96.5\% \quad \text{(Temperature Degradation @120F - Launch)}
\]

\[
TD_{\text{landing}} := 98\% \quad \text{(Temperature Degradation @101F - Landing)}
\]

\[
TD_{\text{abort}} := 94\% \quad \text{(Temperature Degradation @150F - Abort Landing)}
\]

\[
F_u := 58 \text{ksi} \quad F_u = 58 \text{ksi} \quad \text{(Ultimate Tensile Strength)}
\]

\[
F_{su} := 37 \text{ksi} \quad F_{su} = 37 \text{ksi} \quad \text{(Ultimate Shear Strength)}
\]

**PART GEOMETRY:**

\[
d_p := 1.1959 \text{ in} \quad \text{(Pitch Diameter of 1.25-12UNJF Thread)}
\]

\[
l_{\text{max}} := 2.5 \text{ in} \quad \text{(Thread Depth in Endfitting)}
\]

Figure 2.1.13.2-2: Diagonal Strut Endfitting
Calculate Thread Engagement of Rod End Bearing

\[ l_r := 5.51 \text{ in} \quad (\text{Length of Rod End Bearing}) \]

\[ d_r := 2.78 \text{ in} \quad (\text{Outer Diameter of Rod End Race}) \]

\[ l_i := 2.94 \text{ in} \quad (\text{Length from Center of Rod End to Endfitting}) \]

\[ \text{tol} := 0.06 \text{ in} \quad (\text{Tolerance on Thread Engagement}) \]

\[ \text{L}\text{thread} := \left( l_r - \frac{d_r}{2} \right) - l_i - \text{tol} \quad \text{L}\text{thread} = 1.12 \text{ in} \quad (\text{Minimum Thread Engagement Length}) \]

\[ A_{\text{thd}} := \frac{\pi \cdot \text{L}\text{thread} \cdot d_p}{2} \quad A_{\text{thd}} = 2.104 \text{ in}^2 \quad (\text{Thread Shear Area}) \]
LOADS:

NASPOST was used to output worst case element loads for the Diagonal Strut Tube during launch, landing and abort landing. Three files were generated: “diagstrutlaunch.lis”, “diagstrutlanding.lis”, and “diagstrutabortlanding.lis” and are located in the folder /hsm/bsommer/ams/naspost/uss/2-04/. Analysis will be performed using the maximum axial load found in any load case.

\[
P_{\text{max\_launch}} := 34052.77 \text{lbf} \quad \text{(Worst Case Axial Load in Strut, Launch Cases, Element ID 1803, Subcase 1032)}
\]

\[
P_{\text{max\_landing}} := -22696.79 \text{lbf} \quad \text{(Worst Case Axial Load in Strut, Landing Cases, Element ID 1803, Subcase 4045)}
\]

\[
P_{\text{max\_abort}} := -14987.22 \text{lbf} \quad \text{(Worst Case Axial Load in Strut, Abort Landing Cases, Element ID 1803, Subcase 2045)}
\]

STRESS AND MARGIN OF SAFETY:

\[
\tau_{\text{launch}} := \frac{P_{\text{max\_launch}}}{A_{\text{thd}}} \quad \tau_{\text{launch}} = 16185.26 \text{ psi} \quad \text{(Thread Shear Stress, Launch)}
\]

\[
\tau_{\text{landing}} := \frac{P_{\text{max\_landing}}}{A_{\text{thd}}} \quad \tau_{\text{landing}} = 10787.77 \text{ psi} \quad \text{(Thread Shear Stress, Landing)}
\]

\[
\tau_{\text{abort}} := \frac{P_{\text{max\_abort}}}{A_{\text{thd}}} \quad \tau_{\text{abort}} = 7123.416 \text{ psi} \quad \text{(Thread Shear Stress, Abort Landing)}
\]

\[
M_{S_{\text{launch}}} := \frac{F_{su\cdot TD_{\text{launch}}}}{\tau_{\text{launch}} \cdot SF_{u}} - 1 \quad M_{S_{\text{launch}}} = 0.58 \quad \text{...Margin of Safety on Thread Shear, Launch}
\]

\[
M_{S_{\text{landing}}} := \frac{F_{su\cdot TD_{\text{landing}}}}{\tau_{\text{landing}} \cdot SF_{u}} - 1 \quad M_{S_{\text{landing}}} = 1.4 \quad \text{...Margin of Safety on Thread Shear, Landing}
\]

\[
M_{S_{\text{abort}}} := \frac{F_{su\cdot TD_{\text{abort}}}}{\tau_{\text{abort}} \cdot SF_{u}} - 1 \quad M_{S_{\text{abort}}} = 2.49 \quad \text{...Margin of Safety on Thread Shear, Abort Landing}
\]

\[
M_{S} := \min(M_{S_{\text{launch}}}, M_{S_{\text{landing}}}, M_{S_{\text{abort}}}) \quad M_{S} = 0.58 \quad \text{...Minimum Margin of Safety}
\]
2.1.13.3 Rod-end Bearing
Analysis of diagonal strut rod-end bearing:

Diagonal Sill Bracket

Clevis Pin

Rod-End Bearing

Diagonal Strut Assembly

Rod End Bearing - SDG39135745

Diagonal Strut Assembly (View shown on diagonal sill bracket side) - SEG39135741

Vacuum Case
Clevis Plate

Diagonal Strut Assembly (View shown on vacuum case side) - SEG39135741
Description of Rod End Bearing:
Thread Size: 1.2500-12UNJF-3A

\[
N := \frac{1}{12} \text{ in}
\]

Rod-End Bearing Part No. SWRKMLH-16-516 (Left Hand Thread),
SWRKM-16-516 (Right Hand Thread) (Ref. Southwest Products Co. Spec)

Altered Item Part No. SDG39135745-801 (Right Hand Thread)
SDG39135745-803 (Left Hand Thread)

\[
d_t := 1.1959 \text{ in} \quad \text{pitch diameter of threads}
\]

Diagonal Strut Assembly SEG39135741

Note: Referenced dimension of 42.55" in drawing SEG39135741 equals a thread engagement of 1.185". Analysis will allow for .50" of linear adjustment in addition to the length of 42.55". See below. (See section 2.1.13.2 for the endfitting analysis.)

Referenced thread engagement length:

length of rod end \( lr := 5.51 \text{ in} \)

Outer diameter of rod-end race \( dr := 2.78 \text{ in} \)

length from endfitting to endfitting \( le := 36.68 \text{ in} \)

length between the center of rod-end to rod-end \( lrc := 42.55 \text{ in} \)

Referenced thread engagement length

\[
Lr := \left( \frac{lr - dr}{2} \right) - \frac{lrc - le}{2} \quad Lr = 1.185 \text{ in}
\]
Adjusted thread engagement length:

Additional linear adjustment \( l_a := .50 \text{-in} \)

Number of turns \( \frac{l_a}{L} = 6 \)

Length of thread engagement inside of endfitting \( L = 0.685 \text{ in} \)

Area of thread shear \( A_s = 1.287 \text{ in}^2 \)

Material Properties:

Rod-End Body - CRES 15-5PH Stainless Steel, 1025 cond. (Ref. Mil-HDBK-5J, table 2.6.7.0 (b))

\( F_{tu} := 155000 \text{-psi} \) \( F_{su} := 97000 \text{-psi} \)

Rod-End Ball - 13-8Mo (AMS5629) (Ref. Mil-HDBK-5J, table 2.6.6.0 (b))

\( P_{ult} := 80300 \text{lbf} \) (Ultimate Static Load Allowable from MIL-B-81935/1B or SAE-AS81935/1)

Factors of Safety:

\( F_{Su} := 1.4 \) Ultimate Factor of Safety \( F_{Sy} := 1.1 \) Yield Factor of Safety

\( FF := 1.15 \) Fitting Factor of Safety

Temperature Input:

Maximum Temperature \( \text{temp}_{\text{max}} := 150 \text{-deg} \) (Abort Landing Temperature, Ref. Appendix C2)

Temperature Correction Factor \( c := .96 \) (For CRES 15-5PH and 13-8Mo)

Load Input:

\( R_{maxaxial} := 34052.77 \text{-lbf} \) (max axial load from load case 1032 of USS-02, loads model 2-04, element ID 1803, Ref. Appendix 12)

Rod-End Body Margin of Safety:

\[
\text{Margin of Safety} \quad MS_{ult} := \frac{P_{ult} \cdot c}{FF \cdot F_{Su} \cdot R_{maxaxial}} - 1 \quad MS_{ult} = 0.406
\]
Rod-End Ball Margin of Safety:

Margin of Safety

$$MS_{bru} := \frac{P_{ult} \cdot c}{FF \cdot F_{Su} \cdot R_{maxaxial}} - 1$$

$$MS_{bru} = 0.406$$

Rod-End Threads Margin of Safety:

Shear Stress of pulled-out threads

$$\tau := \frac{R_{maxaxial}}{A_s}$$

$$\tau = 26463.491 \text{ psi}$$

Margin of Safety

$$MS := \frac{F_{su} \cdot c}{FF \cdot F_{Su} \cdot \tau} - 1$$

$$MS = 1.186$$
2.1.14 Clevis Pin
Clevis Pin, SDG39135744

The Clevis Pin analysis is performed in the following report sections. The analysis covers the Clevis Pin for the Diagonal Sill Bracket on the Upper USS-02 Assembly and the Clevis Pin for the Clevis Plate on the Upper USS-02 Assembly.

<table>
<thead>
<tr>
<th>2.1.14.1</th>
<th>Clevis Pin (Sill Tube Side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.14.2</td>
<td>Clevis Pin (Vacuum Case Side)</td>
</tr>
</tbody>
</table>
2.1.14.1 Clevis Pin (Sill Tube Side)
Check USS clevis pin stresses:

This analysis covers the clevis pin for the diagonal sill bracket on the upper USS-02 assembly. Reference drawing SDG39135744 for pin details.

Reference section 2.1.12 Diagonal Sill Bracket for the lug analysis.

Temperature Input:

- Maximum Temperature: Temp\_max:= 150\text{deg} \quad \text{(Abort Landing Temperature, Ref. Appendix C2)}

Material Properties of Pin:

- Custom 455 H1000, AMS5617 
- Temperature Correction Factor: cp := .97
- Tensile allowable, ultimate: Ftu\_pin := 200000\text{-cp-psi} 
  \quad \text{Ftu\_pin} = 194000\text{psi}
- Tensile allowable, yield: Fty\_pin := 185000\text{-cp-psi} 
  \quad \text{Fty\_pin} = 179450\text{psi}

Material Properties of Lug:

- 7050-T7451, BMS 7 323-C, 5.75 in thick 
- Temperature Correction Factor: cl := .92
- Tensile allowable, ultimate Ftu\_lug := 66000cl\text{-psi} 
  \quad \text{Ftu\_lug} = 60720\text{psi}
- Shear allowable Fsu\_lug := 43000cl\text{-psi} 
  \quad \text{Fsu\_lug} = 39560\text{psi}

Factor of Safety:

- Ultimate Factor of Safety: FSu := 1.4 \quad \text{(Since the stress check is on combined bending and shear, there is no yield check.)}
**Load Inputs:**

Applied force: \( P := 34052.77 \text{ lbf} \)  
*This load is the max axial load from AMS 2-04 model, load case 1032*

*Ref Appendix A12.*

**Geometry:**

Distance from centerline to outside of lug: \( e := (5.56 - 4.026) \text{-in} \) \( e = 1.534 \text{ in} \)

Diameter of pin \( D_p := 0.9976 \text{-in} \)

Thickness of one lug: \( t := 1.0 \text{-in} \)

Diameter of lug hole: \( D := 1.005 \text{-in} \)

Outer Radius of lug: \( W := 3.5 \text{-in} \)

Bearing area (Lug hole): \( \text{Abr} := D \cdot t \) \( \text{Abr} = 1.005 \text{ in}^2 \)

Tensile area (Lug): \( \text{At} := (W - D) \cdot t \) \( \text{At} = 2.495 \text{ in}^2 \)

**Check Pin Bending Stress:**

Thickness of rod-end ball: \( t_2 := 1.375 \text{-in} \)

*(For \( t_2 \) reference SAE-AS81935, Table 1)*

Depth of two lugs: \( d_{lug} := 3.46 \text{-in} \)

Gap is: \( g := \frac{d_{lug} - 2 \cdot t - t_2}{2} \)

\( g = 0.0425 \text{ in} \)

Calculate ratios:

\( \frac{e}{D} = 1.526 \)

\( \frac{D}{t} = 1.005 \)

\( \frac{W}{D} = 3.483 \)
**Ultimate Allowable Loads:**

From AERONAUTICS STRUCTURES MANUAL, FIG B.2.1.0-3  \( K_{br} := 1.49 \)

Ultimate load for shear bearing is therefore: \( P_{bru} := K_{br} \cdot F_{tu\_lug} \cdot A_{br} \) \( P_{bru} = 90925 \text{ lbf} \)

From AERONAUTICS STRUCTURES MANUAL, FIG B.2.1.0-4, CURVE 4  \( K_{t} := 0.77 \)

Ultimate load for tension is therefore: \( P_{tu} := K_{t} \cdot F_{tu\_lug} \cdot A_{t} \) \( P_{tu} = 116652 \text{ lbf} \)

From AERONAUTICS STRUCTURES MANUAL, B2.1.0-6

\[
r := \left( \frac{c}{D} \right) - \frac{1}{2} \left( \frac{D}{t_2} \right)^2
\]

\( r = 0.75 \)

\[
\text{Pumin} := \begin{cases} P_{tu} & \text{if } P_{tu} \leq P_{bru} \\ P_{bru} & \text{otherwise} \end{cases}
\]

\( \text{Pumin} = 90925 \text{ lbf} \)

\[ \frac{\text{Pumin}}{A_{br} \cdot F_{tu\_lug}} = 1.49 \]

From AERONAUTICS STRUCTURES MANUAL, Figure B 2.1.0-6  \( \gamma := .74 \)

Calculate the moment arm "b" \( b := \frac{1}{2} + g + \gamma \left( \frac{t_2}{4} \right) \) \( b = 0.797 \text{ in} \)

Maximum pin bending moment is: \( M_{max} := P \cdot \frac{b}{2} \) \( M_{max} = 13568 \text{ in\cdotlbf} \)

Maximum Shear on the pin is: \( P = 34052.77 \text{ lbf} \)

**Section Properties:**

Cross section of the pin (bolt) is a circle.

Diameter: \( d := D_p \) \( d = 0.9976 \text{ in} \)

Area is: \( \text{Area} := \left( \frac{\pi}{4} \right) \cdot (d^2) \)

\( \text{Area} = 0.782 \text{ in}^2 \)
Distance from centroid to outer fiber:

\[ z_c := \frac{d}{2} \quad z_c = 0.499 \text{ in} \]

\[ c_z := z_c \quad c_z = 0.499 \text{ in} \]

Moments of inertia about centroid:

\[ I_y := \left( \frac{\pi}{64} \right) d^4 \quad I_y = 0.049 \text{ in}^4 \]

**Stresses on cross section:**

Bending stress is:

\[ \sigma := \frac{M_{\text{max}} \cdot c_z}{I_y} \quad \sigma = 139201 \text{ psi} \]

Shear stress is:

\[ \tau := \frac{P}{\text{Area}} \quad \tau = 43566 \text{ psi} \]

Find Modulus of Rupture of pin to check bending (Ref. Bruhn, C4.16, figure C4.11)

Assume D/t=2 for solid pin.

\[ F_{\text{rup}} := 330000-\text{cp-psi} \quad F_{\text{rup}} = 320100 \text{ psi} \]

**Margins of safety:**

Stress ratios

Bending

\[ R_b := \frac{\sigma \cdot F_{\text{Su}}}{F_{\text{rup}}} \quad R_b = 0.609 \]

Shear

\[ R_s := \frac{\tau \cdot F_{\text{Su}}}{F_{\text{Su, pin}}} \quad R_s = 0.507 \]

Margins of safety:

\[ M_{\text{Su}} := \frac{1}{\sqrt{R_b^2 + R_s^2}} - 1 \quad M_{\text{Su}} = 0.262 \]
2.1.14.2 Clevis Pin (Vacuum Case Side)
Check VC clevis pin stresses:

This analysis covers the clevis pin for the Clevis Plate on the upper USS-02 assembly. Reference drawing SDG39135744-003 for pin details.

Reference section 3.8 Clevis Plate for the lug analysis.

Temperature Input:

Maximum Temperature: \(\text{Temp}_{\text{max}} = 150 \, \text{deg} \) (Abort Landing Temperature, Ref. Appendix C2)

Material Properties of Pin: Custom 455 H1000, AMS5617 (Ref. MIL-HDBK-5J, table 2.6.4.0 (b) and figure 2.6.4.1.1)

Temperature Correction Factor: \(\text{cp} = 0.97\)

Tensile allowable, ultimate: \(\text{Ftu}_{\text{pin}} := 200000\, \text{cp-psi}\)
\[\text{Ftu}_{\text{pin}} = 1.94 \times 10^5 \, \text{psi}\]

Shear allowable: \(\text{Fsu}_{\text{pin}} := 124000\, \text{cp-psi}\)
\[\text{Fsu}_{\text{pin}} = 1.203 \times 10^5 \, \text{psi}\]

Tensile allowable, yield: \(\text{Fty}_{\text{pin}} := 185000\, \text{cp-psi}\)
\[\text{Fty}_{\text{pin}} = 1.795 \times 10^5 \, \text{psi}\]
**Factor of Safety:**
Ultimate Factor of Safety: \( F_{Su} := 1.4 \)  
(Since the stress check is on combined bending and shear, there is no yield check.)

**Load Inputs:**
Angle of applied force: \( \alpha := 54.0\,\text{deg} \)  
(Ref. CAD Model)

Applied force: \( P := 34052.77\,\text{lbf} \)  
*This load is the max axial load from AMS 2-04 model, load case 1032.*
Check Pin Bending Stress:

Pin Diameter: \( D := 0.9976 \text{ in} \)

Thickness of clevis plate: \( t_1 := 0.5 \text{ in} \)

Thickness of Rod-End Bearing: \( t_2 := 1.38 \text{ in} \)

Depth of lug is: \( d_{lug} := 2.455 \text{ in} \)

Gap is: \[
g = \frac{d_{lug} - 2t_1 - t_2}{2}
\]

\( g = 0.0375 \text{ in} \)
From AERONAUTICS STRUCTURES MANUAL, Figure B 2.1.0-6  \( \gamma := 1.0 \) (conservative)

Calculate the moment arm "b" \( b := \frac{t_1}{2} + g + \gamma \left( \frac{t_2}{4} \right) \)  
\( b = 0.633 \text{ in} \)

Applied force: \( P = 3.405 \times 10^4 \text{lbf} \)

Maximum pin bending moment is: \( M_{\text{max}} := \frac{P \cdot b}{2} \)  
\( M_{\text{max}} = 10769 \text{ in-lbf} \)

Shear on the pin is: \( F_z := \frac{P}{2} \)  
\( F_z = 17026 \text{ lbf} \)

**Section Properties:**

Cross section of the pin (bolt) is a circle.

Diameter: \( d := D \)

Area: \( A := \left( \frac{\pi}{4} \right) \left( d^2 \right) \)  
\( A = 0.782 \text{ in}^2 \)

Distance to centroid is:
\( y_c := \frac{d}{2} \)  
\( y_c = 0.499 \text{ in} \)
\( z_c := \frac{d}{2} \)  
\( z_c = 0.499 \text{ in} \)

Distance from centroid to outer fiber:
\( c_y := y_c \)  
\( c_y = 0.499 \text{ in} \)
\( c_z := z_c \)  
\( c_z = 0.499 \text{ in} \)

Moments of inertia about centroid:
\( I_y := \left( \frac{\pi}{64} \right) \left( d^4 \right) \)  
\( I_y = 0.049 \text{ in}^4 \)
\( I_z := I_y \)  
\( I_z = 0.049 \text{ in}^4 \)
Stresses on cross section:

Bending stress is:

\[ \sigma := \frac{|M_{\text{max}}| \cdot cz}{I_y} \]

\[ \sigma = 110488 \text{ psi} \]

Shear stress is:

\[ \tau := \frac{F_z}{A} \]

\[ \tau = 21783 \text{ psi} \]

Find Modulus of Rupture of pin to check bending

From Bruhn, C4.16, for D/t=2 (solid pin), figure C4.11

Frup := 330000 \text{ cp psi}

Frup := 320100 \text{ psi}

Margins of safety:

Stress ratios

Bending

\[ R_b := \frac{\sigma \cdot F_{\text{Su}}}{F_{\text{rup}}} \]

\[ R_b = 0.483 \]

Shear

\[ R_s := \frac{\tau \cdot F_{\text{Su}}}{F_{\text{Su}_{\text{pin}}}} \]

\[ R_s = 0.254 \]

Margins of safety:

\[ M_{\text{Su}} := \frac{1}{\sqrt{R_b^2 + R_s^2}} - 1 \]

\[ M_{\text{Su}} = 0.832 \]
2.1.15  WIF Adapter Bracket
WIF ADAPTER PLATE STRENGTH ANALYSIS

Drawings no.: SDG39135747

Units used: in, lbf

The objective of this analysis is to demonstrate the structural strength of the WIF ADAPTER PLATE. The WIF adapter plate is mounted on the sill tube to support the WIF socket.

![WIF Adapter Plate](image)

a). WIF adapter plate

![Location of WIF adapter plate](image)

b). Location of WIF adapter plate

Figure 2.1.15-1 WIF Adapter Plate
Load

Per CARD JSC-33499, WIF Socket is subjected to 4200 in-lbf (bending moment), 4200 in-lbf (torsional moment), 274 (shear force), and 274 lbf (axial force).

Figure 2.1.15-2 WIF Socket and WIF Adapter Plate

<table>
<thead>
<tr>
<th>Load case 1</th>
<th>Load case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x := 274 \text{ lbf}$</td>
<td>$F_x := 274 \text{ lbf}$</td>
</tr>
<tr>
<td>$F_y := 274 \text{ lbf}$</td>
<td>$F_z := 274 \text{ lbf}$</td>
</tr>
<tr>
<td>$M_x := 4200 \text{ in-lbf}$</td>
<td>$M_x := 4200 \text{ in-lbf}$</td>
</tr>
<tr>
<td>$M_z := 4200 \text{ in-lbf}$</td>
<td>$M_y := 4200 \text{ in-lbf}$</td>
</tr>
<tr>
<td>Axial force</td>
<td>Axial force</td>
</tr>
<tr>
<td>Shear force</td>
<td>Shear force</td>
</tr>
<tr>
<td>Torsion moment</td>
<td>Torsion moment</td>
</tr>
<tr>
<td>Bending moment</td>
<td>Bending moment</td>
</tr>
</tbody>
</table>
The finite element model (FEM) of the WIF adapter plate and sill tube is created using I-DEAS (file name: WIF-adapter-plate.dat). In the finite element model, shell elements are used. The SPC restraints in all degrees of freedom are applied to the attachment locations where the sill tube is fixed. The bolts connecting the plate to the sill tube are modeled as bush elements. The center of the WIF Socket is modeled as a nodal point and connected to the WIF adapter plate with a rigid element. Forces and moments are applied to the center of the WIF Socket. The analysis was performed using NASTRAN. An overview of the FEM is shown in Figure 2.1.15-3.

Figure 2.1.15-3  Finite Element Model
The Free-Free normal modes analysis was performed. The finite element model obtains six rigid body modes. Results showed that the finite element model passes the stiffness energy check.

RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-03
DIRECTION        STRAIN ENERGY        PASS/FAIL
---------        -------------        ---------
1               1.327280E-07          PASS
2               8.003553E-10          PASS
3               2.095476E-09          PASS
4               5.859583E-07          PASS
5               2.740852E-06          PASS
6               1.775559E-07          PASS

RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-03
DIRECTION        STRAIN ENERGY        PASS/FAIL
---------        -------------        ---------
1               1.180597E-07          PASS
2               1.461012E-08          PASS
3               1.600711E-09          PASS
4               2.781626E-07          PASS
5               2.788014E-06          PASS
6               1.577424E-07          PASS

RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-03
DIRECTION        STRAIN ENERGY        PASS/FAIL
---------        -------------        ---------
1               1.180597E-07          PASS
2               1.461012E-08          PASS
3               1.600711E-09          PASS
4               2.781626E-07          PASS
5               2.788014E-06          PASS
6               1.577424E-07          PASS

The first 10 frequencies obtained from the Free-Free normal modes analysis are listed as below:

1 3.62E-04
2 4.87E-04
3 6.88E-04
4 8.15E-04
5 1.06E-03
6 2.12E-03
7 7.49E+02
8 1.51E+03
9 1.64E+03
10 2.28E+03
The finite element static analysis results show that maximum principal stress for the load case 1 is 13.8 ksi as shown in Figure 2.1.15-4 (a) and that for the load case 2 is 8.55 ksi as shown in Figure 2.1.15-4 (b).

Fig. 2.1.15-4  Maximum principal stress contours
The finite element static analysis results show that Von mises stress for the load case 1 is 12.5ksi as shown in Figure 2.1.15-5 (a) and that for the load case 2 is 7.74ksi as shown in Figure 2.1.15-5(b).

Fig. 2.1.15-5  Von Mises stress contours
The finite element static analysis results show that maximum shear stress for the load case 1 is 6.97 ksi as shown in Figure 2.1.15-6 (a) and that for the load case 2 is 4.27 ksi as shown in Figure 2.1.15-6(b).

Fig. 2.1.15-6 Maximum shear stress contours
The finite element static analysis results show that minimum principal stress for the load case 1 is -13.9ksi as shown in Figure 2.1.15-7 (a) and that for the load case 2 is -8.40ksi as shown in Figure 2.1.15-7(b).

Fig. 2.1.15-7 Minimum principal stress contours

2.1.15-9 ESCG-4005-05-AMS-0039
The following max. stresses were retrieved from the NASPOST-processing of FE model data (see 2.1.15-11 & 2.1.15-12):

\[ S_1 := 13771 \text{ psi} \quad \text{(Max. Principal stress)} \]
\[ \sigma_{eq} := 12581 \text{ psi} \quad \text{(Von Mises stress)} \]
\[ \tau_{max} := 6967 \text{ psi} \quad \text{(Max shear)} \]
\[ S_3 := -13933 \text{ psi} \quad \text{(Min. Principal stress)} \]

Material mechanical properties

Material: 6061-T651 AL ALY (SAE-AMS-QQ-A-250/11). From MIL -HDBK-5J page 3-265, Table 3.6.2.0(b2) (.6 thickness):

Tensile strength, ultimate: \( F_{tu} := 42000 \text{ psi} \)

Tensile strength, yield: \( F_{ty} := 35000 \text{ psi} \)

Compressive strength, yield: \( F_{cy} := 35000 \text{ psi} \)

Shear strength, ultimate: \( F_{su} := 27000 \text{ psi} \)

Factors of Safety and Design Factors:

\( F_{Sy} := 1.25 \quad \text{Yield factor of safety} \)

\( F_{Su} := 2.0 \quad \text{Ultimate factor of safety} \)

The Expected temperature range is -50 to +140F (Ref. Appendix C2). 96% temperature de-rating is applied for on-orbit operation.

Margin of safety against yield failure:

\[ M_{Sy} := \frac{F_{ty} \cdot 0.96}{F_{Sy} \sigma_{eq}} - 1 \]
\[ M_{Sy} = 1.137 \]

Margin of safety against ultimate failure:

\[ M_{Su} := \frac{F_{tu} \cdot 0.96}{F_{Su} S_3} - 1 \]
\[ M_{Su} = 0.447 \]

Margin of safety against ultimate failure (shear):

\[ M_{Sus} := \frac{F_{su} \cdot 0.96}{F_{Su} \tau_{max}} - 1 \]
\[ M_{Sus} = 0.86 \]
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*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

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<td>-9.094947E-13</td>
<td>-1.371934E+04</td>
<td>1.371934E+04</td>
</tr>
</tbody>
</table>

### ¶
### SOIT VAR = MAXABS(VON-MISES-TOP,VON-MISES-BOT);OPT=12
### PRINT 9 13 17; NCASES = 2;
### HEADING = 'WIF BRACKET : VON-MISIS STRESS'

+++ WIF BRACKET : VON-MISES STRESS +++

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>VON-MISES-TOP</th>
<th>VON-MISES-BOT</th>
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<tr>
<td>50256</td>
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### ¶
### SOIT VAR = MAXABS(MAX-SHEAR-TOP,MAX-SHEAR-BOT);OPT=12
### PRINT 10 14 16; NCASES = 2;
### HEADING = 'WIF BRACKET : SHEAR STRESS'
<table>
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<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>MAX-SHEAR.TOP</th>
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<tr>
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<td>6.029441E+03</td>
<td>6.05671E+03</td>
<td>6.05671E+03</td>
</tr>
</tbody>
</table>

###  
### **EXIT**
2.2 Lower USS-02 Assembly
2.2.1 Primary Centerbody Box Joint
Table 1 Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135759</td>
<td>Lower Center Body Assembly</td>
<td>7050-T7451 Al. Aly.</td>
<td>Landing</td>
<td>Tension</td>
<td>0.18 (Ult)</td>
<td>2.2.1 - 14</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Factor of Safety is 1.4 for Ultimate and 1.1 for Yield
The Stress Analysis of the Lower Center Body Assembly

1. Introduction of the Lower Center Body Assemblies

The four Lower Center Body Assemblies are the major structural joints in the lower USS-02. They are connected to 4x4x0.25 tubes to form the Lower Center Body Assemblies. The Lower Center Body Assemblies provide attachment to the Electromagnetic Calorimeter (ECAL), Ring Imaging Chernokov Counter (RICH) and the Struts for the Lower Time of Flight (LTOF).

The Keel Assembly is bolted to two of the Lower Center Body Assemblies because it is offset to the minus X-axis side of AMS-02. The Payload Attach System (PAS) is also attached to the Lower Center Body Assemblies. Two of the Lower Center Body Assemblies on Keel side are shown in Figure 2.2.1-1.
Figure 2.2.1-1  Lower Center Body Assemblies and AMS-02 Structure
The Lower Center Body Assembly consists of the Lower Centerbody Joint (SDG39135759-5760) and Lower Angle Beam Flange(SDG39135767-001). The Lower Centerbody Joint and Lower Angle Beam Flange are put together using bolt connection. The Lower Center Body Assembly is shown in Figure 2.2.1-2.
The Lower Centerbody joints with and without the Keel Connection are shown in Figure 2.2.1-3.

Figure 2.2.1-3a. Lower Centerbody Joint with the Keel Connection

Figure 2.2.1-3b. Lower Centerbody Joint with no keel connection
2. **Method Used to Perform the Stress Analysis of the Lower Center Body Assemblies**

The FEA math models of the Lower Center Body Assembly were made using FEMAP software. The FEA models of the Lower Center Body Assembly consist of the CQUAD4, CTRIA3, and also RBE’s of SPC/MPC. After completion, the models of the Lower Center Body Assembly were connected to the USS-02 FEA model using RBE’s. The solutions of the FEA math models of the Lower Center Body Assemblies were obtained from running NASTRAN 2000. The modifications, design changes, and engineering judgments were made based on these solutions.

3. **FEA models of the Lower Center Body Assembly and Assumptions**

When the FEA models of the Lower Center Body Assembly are put into the USS-02 model, we assume the USS02 FEA math model is correct. All the boundary conditions including the constraints and loading cases are also modeled correctly. The stress analysis of the Lower Center Body Assembly only focuses on the FEA models of the Lower Center Body Assembly. The picture below is showing the FEA models of the Lower Center Body Assembly are embedded into the USS-02 FEA model.

The NASTRAN data file of the Lower Center Body Assembly is put under the directory: /hsm/swang/ams02/centerbody-model, and named as ”wholecenter-stress.dat”

![Figure 2.2.1-4 Center body Assembly FEA models embedded into the USS02 FEA model](image-url)
A partial view of the FEA models for the Lower Center Body Assembly connected to the USS02 FEA model is shown in Figure 2.2.1-5.

![Partial view of FEA models for Lower Center Body Assembly in USS-02](image)

Figure 2.2.1-5 Partial view of FEA models for Lower Center Body Assembly in USS-02

4. **FEA model check of the Lower Center Body Assembly**

   a. **Model check of the Lower Angle Beam Flange**

The model check was individually performed for the Lower Angle Beam Flange of the Lower Center Body Assembly using NASTRAN 2000. The results of the KGG, KNN, KFF and Six Rigid Body Modes are listed below.

<table>
<thead>
<tr>
<th>Output From Grid Point Weight Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASS AXIS</td>
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<td>X</td>
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<td>Y</td>
</tr>
<tr>
<td>Z</td>
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<td>* -2.895216E-03</td>
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<tr>
<td>I(Q)</td>
</tr>
<tr>
<td>* 1.013771E-01</td>
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<tr>
<td>* 1.090683E-01</td>
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<tr>
<td>* 1.011621E-01</td>
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<tr>
<td>Q</td>
</tr>
<tr>
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<tr>
<td>* -7.093208E-01</td>
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<td>* -3.954015E-02</td>
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</table>
### RESULTS OF RIGID BODY CHECKS OF MATRIX KGG

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.510480E-07</td>
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<td>2</td>
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### RESULTS OF RIGID BODY CHECKS OF MATRIX KNN

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<th>DIRECTION</th>
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<tr>
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<td>1.491906E-07</td>
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<tr>
<td>3</td>
<td>2.395882E-07</td>
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<tr>
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### RESULTS OF RIGID BODY CHECKS OF MATRIX KFF

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</table>

### REAL EIGENVALUES

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<tr>
<th>MODE</th>
<th>EXTRAC</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES GENERALIZED</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
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</thead>
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<td>1.172649E+03</td>
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</tr>
</tbody>
</table>
b. Model check of the Lower Centerbody Joint with no keel

The model check was individually performed for the Lower Centerbody Joint with no keel connection using NASTRAN 97. The results of the KGG, KNN, KAA and Six Rigid Body Modes are listed below.

Output From Grid Point Weight Generator

<table>
<thead>
<tr>
<th>MASS AXIS</th>
<th>MASS</th>
<th>X-C.G.</th>
<th>Y-C.G.</th>
<th>Z-C.G.</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Z</td>
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<td>2.494448E+01</td>
<td>-2.483113E+01</td>
<td>0.000000E+00</td>
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</table>

I(S)

* 1.473682E+00 -5.220714E-01 -4.203794E-02 *
* -5.220714E-01  1.419779E+00  2.709832E-02 *
* -4.203794E-02  2.709832E-02  2.446938E+00 *

I(Q)

* 1.969206E+00 *
* 9.224145E-01 *
* 2.448779E+00 *

Q

* -7.240968E-01  6.885488E-01  3.980378E-02 *
* -6.892588E-01 -7.244894E-01 -6.125023E-03 *
*  2.462004E-02 -3.187021E-02  9.991887E-01 *

STIFFNESS MATRIX KGG 6 X 6

4.4895D-08 1.8070D-08 1.0160D-08 8.8238D-07 -2.8194D-06 1.8149D-06
-1.5505D-08 -2.3805D-07 -1.3890D-08 -1.2884D-05  1.0476D-06  -6.1494D-06
2.7868D-08 1.7052D-09 2.2182D-07  5.0413D-06  -7.4311D-06  7.8437D-07
3.5303D-06 1.2570D-05  2.2657D-03 -5.6532D-06 -1.8535D-04

STIFFNESS MATRIX KNN 6 X 6

4.4681D-08 4.9654D-09 1.1801D-09 3.2292D-07 -2.7184D-06  1.4605D-06
-2.6351D-08 -2.4155D-07 -1.8722D-08 -1.2899D-05  1.7935D-06 -6.3091D-06
2.0846D-08 -1.6132D-09  2.3241D-07  -5.6707D-06  -7.7592D-06  5.1567D-07

2.2.1 - 10 ESCG-4005-05-AMS-0039
STIFFNESS MATRIX KAA 6 X 6

\[
\begin{pmatrix}
4.6481D-08 & 4.9654D-09 & 1.1801D-09 & 3.2292D-07 & -2.7184D-06 & 1.4605D-06 \\
-2.6351D-08 & -2.4155D-07 & -1.8722D-08 & -1.2899D-05 & 1.7935D-06 & -2.7184D-06 \\
2.0846D-08 & 1.5132D-07 & -1.2375D-05 & -7.6955D-06 & -5.707D-06 & 5.1576D-07 \\
2.7137D-06 & -1.1236D-06 & -4.793D-06 & 1.5835D-04 & -6.3091D-06 & 6.8071D-05 \\
-1.2195D-06 & -4.3725D-06 & -8.3048D-06 & 2.4403D-04 & 6.6075D-05 & 1.1716D-04 \\
\end{pmatrix}
\]

REAL EIGENVALUES

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE RADIANS</th>
<th>CYCLES GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
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<tbody>
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</tr>
</tbody>
</table>

c. Model check for the Lower Centerbody Joint with keel

The model check was individually performed for the Lower Centerbody Joint with keel connection using NASTRAN 97. The results of the KGG, KNN, KAA and Six Rigid Body Modes are listed below.

OUTPUT FROM GRID POINT WEIGHT GENERATOR

<table>
<thead>
<tr>
<th>MASS AXIS SYSTEM (S)</th>
<th>MASS X-C.G.</th>
<th>Y-C.G.</th>
<th>Z-C.G.</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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</tbody>
</table>

I(S) * 1.553620E+00 4.588256E-01 8.878412E-02 *
* 4.588256E-01 1.596962E+00 8.578976E-03 *
* 8.878412E-02 8.578976E-03 2.677803E+00 *

I(Q) * 2.029985E+00 *
* 2.685599E+00 *
* 1.112802E+00 *

Q * 6.831037E-01 9.032679E-02 7.247140E-01 *
* -7.254732E-01 -3.022486E+00 6.875865E-01 *
* 8.401186E-02 -9.954534E-01 4.488296E-02 *

2.2.1 - 11 ESCG-4005-05-AMS-0039
STRESS ANALYSIS OF LOWER CENTERBODY Assembly - Alpha Magnetic Spectrometer (AMS)-02

MATRIX KGG (6 X 6)

\[
\begin{pmatrix}
-1.1503D-07 & -5.0282D-08 & -5.0778D-09 & -2.8176D-06 & 6.3442D-06 & -1.3897D-06 \\
-7.9346D-09 & 8.1724D-08 & -2.2117D-08 & 5.1243D-06 & 3.7126D-06 & -4.0628D-06 \\
\end{pmatrix}
\]

MATRIX KNN (6 X 6)

\[
\begin{pmatrix}
-6.9589D-08 & 8.0780D-08 & -2.0137D-08 & 5.0534D-06 & 3.2127D-06 & -3.8736D-06 \\
-1.6619D-09 & -3.9210D-08 & -5.2602D-08 & -5.1020D-07 & -1.3928D-06 & 1.1901D-06 \\
-4.8954D-06 & 1.1577D-06 & -3.3970D-06 & 1.5164D-04 & 1.7424D-04 & -1.6063D-04 \\
\end{pmatrix}
\]

MATRIX KAA (6 X 6)

\[
\begin{pmatrix}
-6.9589D-08 & 8.0780D-08 & -2.0137D-08 & 5.0534D-06 & 3.2127D-06 & -3.8736D-06 \\
-1.6619D-09 & -3.9210D-08 & -5.2602D-08 & -5.1020D-07 & -1.3928D-06 & 1.1901D-06 \\
-4.8954D-06 & 1.1577D-06 & -3.3970D-06 & 1.5164D-04 & 1.7424D-04 & -1.6063D-04 \\
\end{pmatrix}
\]

**REAL EIGENVALUES**

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
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<td>1.050724E+04</td>
<td>1.672279E+03</td>
<td>1.000000E+00</td>
</tr>
</tbody>
</table>
The results of the model checks show that the FEA models of the Lower Center Body Assembly are correct because the underlined translation values of each matrix are close to zero. The first six modes are also close to zero and transition modes are well separated.

The NASTRAN data files used for the model check are put under the directory:
/hsm/swang/ams02/checkmodel/ckcentbody

5. Loads and Constraints.

The FEA models of the Lower Center Body assembly are connected with the USS-02 FEA models using RBE’s and CBUSH elements. The entire AMS02 FEA model is constrained at the five Trunnion locations.

A number of load cases under the launch, landing and thermal conditions were investigated in order to identify the worst load cases. The NASTRAN data files of the load cases are within the directories below. The Load Factors of the load cases are applied at the C.G. of the entire AMS02 FEA model when running NASTRAN. The combined Load Factors are taken from Table 4.1 of Page 16 in AMS02 Structural Verification Plan for STS and ISS (JSC-28792, Rev.B).

In the directory: /hsm/swang/ams02/nonlin/centerbody-new/1000, the data files are for launch condition named from R1001.dat to R1064.dat.

In the directory: /hsm/swang/ams02/nonlin/centerbody-new/2000, the data files are for landing condition named from R2001.dat to R2064.dat.

In the directory: /hsm/swang/ams02/nonlin/centerbody-new/4000, the data files are for thermal condition named from R4001.dat to R4064.dat.

6. Maximum Stresses and Calculation for the Margins of Safety

The maximum stresses of the elements and the relative worst Load Cases are listed in Table2. The maximum stresses were sorted out from the pch data files of the load cases using the NASPOST. The sorted-out data files for the load cases are attached in Appendix A5. The f06 files of the load cases are used to perform the post-processing of the FEA models of the Lower Center Body Assembly. The f06 and pch files of NASTRAN for the FEA models of the Lower Center Body Assembly are put under directory below.

/hsm/swang/ams02/nonlin/centerbody-new/1000/2-03, and on February 2003.
Table 2. Maximum Stresses and the Elements with Worst Load Cases

<table>
<thead>
<tr>
<th>Ele ID</th>
<th>Ele Types</th>
<th>Load Case</th>
<th>Max-PRINV (Top)</th>
<th>Von-MISES (Top)</th>
<th>Max-Shear (Top)</th>
<th>Max-PRINV (Bot)</th>
<th>Von-MISES (Bot)</th>
<th>Max-Shear (Bot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6101530</td>
<td>QUAD4</td>
<td>4015</td>
<td>3.8607E+04</td>
<td>3.7449E+04</td>
<td>1.9304E+04</td>
<td>3.1242E+04</td>
<td>3.1530E+04</td>
<td>1.5905E+04</td>
</tr>
<tr>
<td>6103019</td>
<td>QUAD4</td>
<td>2058</td>
<td>3.323E+04</td>
<td>3.3150E+04</td>
<td>1.6619E+04</td>
<td>3.8815E+04</td>
<td>3.7491E+04</td>
<td>1.9407E+04</td>
</tr>
<tr>
<td>6104879</td>
<td>QUAD4</td>
<td>4037</td>
<td>7.2760E-12</td>
<td>3.8206E+04</td>
<td>1.9327E+04</td>
<td>-3.6380E-12</td>
<td>3.7980E+04</td>
<td>1.9334E+04</td>
</tr>
<tr>
<td>6101879</td>
<td>QUAD4</td>
<td>2015</td>
<td>3.8033E+04</td>
<td>3.6220E+04</td>
<td>1.9016E+04</td>
<td>3.7187E+04</td>
<td>3.8259E+04</td>
<td>1.9623E+04</td>
</tr>
<tr>
<td>6104879</td>
<td>QUAD4</td>
<td>4037</td>
<td>-3.8654E+04</td>
<td>3.8206E+04</td>
<td>1.9327E+04</td>
<td>-3.8669E+04</td>
<td>3.7980E+04</td>
<td>1.9334E+04</td>
</tr>
<tr>
<td>6104879</td>
<td>QUAD4</td>
<td>2037</td>
<td>-3.8635E+04</td>
<td>3.8190E+04</td>
<td>1.9317E+04</td>
<td>-3.8676E+04</td>
<td>3.7986E+04</td>
<td>1.9338E+04</td>
</tr>
</tbody>
</table>

Based on Table 2, the following maximum stresses will be used to perform the margin calculation of the stress analysis for the Lower Center Body Assembly.

\[ \sigma_t = 38815 \text{ psi} \quad (\text{max. tensile at R2058, Ele 6103019, Max-prin Page A5 - 3}) \]

\[ \sigma_y = 38259 \text{ psi} \quad (\text{max. yield at R2015, Ele 6101879, Von-MISES on Page A5 - 4}) \]

\[ \tau_s = 19623 \text{ psi} \quad (\text{max. shear at R2015, Ele 6101879, Max-Shear on Page A5 - 5}) \]

Lower Center Body Assembly, **7050-T7451** Al. Aly. (AMS 4050)

\[
\begin{align*}
F_{tu} &:= 70000 \text{ psi} & \text{ultimate tensile strength} \\
F_{ty} &:= 60000 \text{ psi} & \text{tensile yield strength} \\
F_{su} &:= 43000 \text{ psi} & \text{shear strength} \\
\eta_{u} &:= 0.92 & \text{(ultimate thermal factor at 140 F)} \\
\eta_{y} &:= 0.98 & \text{(yield thermal factor at 140 F)}
\end{align*}
\]

**Margins of Safety**

\[
\begin{align*}
\text{Ultimate} & \quad M_{Su} := \frac{\eta_{u} \cdot F_{tu}}{\sigma_t \cdot F_{su}} - 1 & MSu = 0.185 \\
\text{Yield} & \quad M_{Sy} := \frac{\eta_{y} \cdot F_{ty}}{\sigma_y \cdot F_{su}} - 1 & MSy = 0.397 \\
\text{Shear} & \quad M_{Ss} := \frac{\eta_{u} \cdot F_{su}}{\tau_s \cdot F_{su}} - 1 & MSs = 0.44
\end{align*}
\]
6. **Locations of the Maximum Stresses in the Lower Center Body Assembly**

a. **Locations of the Elements with the Maximum Stresses**

The Figure 2.2.1-6 below shows the FEA models of the Center Body Assembly isolated from the USS-02 FEA models. The locations of the elements with high stresses are also indicated in Figure 2.2.1-6.

![Figure 2.2.1-6 Locations of the Elements with the Maximum Stresses](image-url)
b. Locations of the Maximum Stresses

Figure 2.2.1-7a. Location of the Maximum Tensile Stress on the Plate Element

Figure 2.2.1-7b. Location of the Maximum Yield Stress on the Plate Element
Figure 1.2.2.7c.  Location of the Maximum Shear Stress on the Plate Element
c. Locations of the Elements with Artificial High Stresses

The RBE’s elements are used to make the connections between the plate elements and solid elements in the Lower Angle Beam Flange FEA model. The stresses of the solid elements at the connections are artificially high due to the applications of the RBE’s. On the other hand, the high stresses are due to that the model can not simulate the connection with a radius. Therefore, the high stresses on the solid elements will not be used to perform the stress analysis.

The pictures below show the artificial high stresses due to the RBE’s connections.

![Diagram showing high stress distributed on concentrated area with RBE's connection](image1.png)

![Diagram showing plate elements, solid elements, and RBE's elements](image2.png)

Figure 2.2.1-8   Locations of the Elements with Artificial High Stresses
2.2.2 Secondary Centerbody Box Joint
The stress analysis of Secondary Centerbody Box Joint was covered in the previous Section 2.2.1.
2.2.3 EMC Box Tube
EMC BOX TUBE

Since part is a slender beam with compressive loads, buckling is critical.

In Finite Element Model of USS-02 version 2-04 shown in Figure 2.2.3-1, EMC Box Tube includes Element Ids of 1501-1517. These elements has Property Id of 1004.

![EMC Box Tube Diagram](image)

Figure 2.2.3-1: EMC Box Tube shown in Lower uss2-04 Model
Factor of Safety, \( FS := 1.4 \)

Material: AL 7075-T73511 \( (\text{Ref. MIL-HDBK-5H, Table 3.7.4.0(g)}, p.3-361; \text{Thickness: 0.250-0.499}) \)

- Compressive modulus, \( Ec := 10700000\text{-psi} \)
- Ultimate tensile strength, \( ftu := 68000\text{-psi} \)
- Tensile yield strength, \( fty := 57000\text{-psi} \)
- Compression yield strength, \( fcy := 57000\text{-psi} \)
- Ultimate shear strength, \( fsu := 37000\text{-psi} \)

Section: 4.0" x 4.0" x 0.25" Tube \( (\text{Ref. Dwg# SDG39135761, Section-A-A}) \)
Shape Factor, \( f := 1.22 \) 


Supported length, \( L := 35.62 \text{ in} \)  

(Between two Centerbody Joints)

Width, \( D_y := 4.0 \text{ in} \)

For torsional calculation, use: \( D_{ytor} := 4.0 \text{ in} \)

Depth, \( D_z := 4.0 \text{ in} \)

For torsional calculation, use: \( D_{ztor} := 4.0 \text{ in} \)

Thickness, \( t := 0.25 \text{ in} \)

Define: \( b := 2t \)

Properties of cross-section: 

(Ref. *Table 2.2.3-1*)

Area, \( A := 3.75 \text{ in}^2 \)

Moment of Inertia, \( I_y := 8.828 \text{ in}^4 \)

\( I_z := 8.828 \text{ in}^4 \)

First moments, \( Q_y := 2.641 \text{ in}^3 \)

\( Q_z := 2.641 \text{ in}^3 \)

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Az</th>
<th>Az^2</th>
<th>Icy</th>
<th>Iy'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.250</td>
<td>4.000</td>
<td>1.000</td>
<td>2.000</td>
<td>4.000</td>
<td>1.333</td>
<td>5.333</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3.500</td>
<td>0.250</td>
<td>0.875</td>
<td>3.875</td>
<td>3.391</td>
<td>13.139</td>
<td>0.005</td>
<td>13.143</td>
</tr>
<tr>
<td>3</td>
<td>0.250</td>
<td>4.000</td>
<td>1.000</td>
<td>2.000</td>
<td>4.000</td>
<td>1.333</td>
<td>5.333</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3.500</td>
<td>0.250</td>
<td>0.875</td>
<td>0.125</td>
<td>0.109</td>
<td>0.014</td>
<td>0.005</td>
<td>0.018</td>
</tr>
<tr>
<td>Sum</td>
<td>3.750</td>
<td></td>
<td>7.500</td>
<td></td>
<td>23.828</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( z_{bar} = 2.000 \)

\( I_{yy} = 8.828 \)
Table 2.2.3-1b: Property about Z-Z axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>y</th>
<th>Ay</th>
<th>Ay^2</th>
<th>Icz</th>
<th>Iz'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.000</td>
<td>0.250</td>
<td>1.000</td>
<td>0.125</td>
<td>0.125</td>
<td>0.016</td>
<td>0.005</td>
<td>0.021</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>3.500</td>
<td>0.875</td>
<td>2.000</td>
<td>1.750</td>
<td>3.500</td>
<td>0.893</td>
<td>4.393</td>
</tr>
<tr>
<td>3</td>
<td>4.000</td>
<td>0.250</td>
<td>1.000</td>
<td>3.875</td>
<td>3.875</td>
<td>15.016</td>
<td>0.005</td>
<td>15.021</td>
</tr>
<tr>
<td>4</td>
<td>0.250</td>
<td>3.500</td>
<td>0.875</td>
<td>2.000</td>
<td>1.750</td>
<td>3.500</td>
<td>0.893</td>
<td>4.393</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>3.750</td>
<td>7.500</td>
<td></td>
<td></td>
<td></td>
<td>23.828</td>
</tr>
</tbody>
</table>

\[y_{\text{bar}} = 2.000\]
\[I_{zz} = 8.828\]

Table 2.2.3-1c: First Moment about Y-Y axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Qyy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.250</td>
<td>2.000</td>
<td>0.500</td>
<td>1.000</td>
<td>0.500</td>
</tr>
<tr>
<td>2</td>
<td>3.500</td>
<td>0.250</td>
<td>0.875</td>
<td>1.875</td>
<td>1.641</td>
</tr>
<tr>
<td>3</td>
<td>0.250</td>
<td>2.000</td>
<td>0.500</td>
<td>1.000</td>
<td>0.500</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Qyy = 2.641</td>
</tr>
</tbody>
</table>

Table 2.2.3-1d: First Moment about Z-Z axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>y</th>
<th>Qzz</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.000</td>
<td>0.250</td>
<td>1.000</td>
<td>1.875</td>
<td>1.875</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>1.750</td>
<td>0.438</td>
<td>0.875</td>
<td>0.383</td>
</tr>
<tr>
<td>4</td>
<td>0.250</td>
<td>1.750</td>
<td>0.438</td>
<td>0.875</td>
<td>0.383</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Qzz = 2.641</td>
</tr>
</tbody>
</table>

2.2.3-5  ESCG-4005-05-AMS-0039
USS-02 EMC BOX TUBE

Section modulus,

\[ S_y := \frac{l_y}{\frac{1}{2} \cdot D_z} \]

\[ S_y = 4.414 \text{ in}^3 \]

\[ S_z := \frac{l_z}{\frac{1}{2} \cdot D_y} \]

\[ S_z = 4.414 \text{ in}^3 \]

Torsional constant / distance,

\[ J_o R := 2 \cdot t \cdot (D_z t) \cdot (D_y t) \]

\[ J_o R = 7.031 \text{ in}^3 \]

Radii of gyration,

\[ r_y := \sqrt{\frac{I_y}{A}} \]

\[ r_y = 1.534 \text{ in} \]

\[ r_z := \sqrt{\frac{I_z}{A}} \]

\[ r_z = 1.534 \text{ in} \]

Fixity coefficient,

\[ K := 0.8 \]

(Ref. Structural Engineering Handbook, 4th Edition, Figure 5, p.8-10)

Slenderness ratios,

\[ S_R y := \frac{K \cdot L}{r_y} \]

\[ S_R y = 18.572 \]

\[ S_R z := \frac{K \cdot L}{r_z} \]

\[ S_R z = 18.572 \]

Constants depending upon the mechanical properties of the material from Ref. Structural Engineering Handbook, 4th Edition, Formulas 5a-c, p.11-6:

\[ B_c := f_{c y} \left[ 1 + \left( \frac{f_{c y}}{2250000 \text{ psi}} \right)^\frac{1}{2} \right] \]

\[ B_c = 66072 \text{ psi} \]

\[ D_c := \frac{B_c}{10} \left( \frac{B_c}{E_c} \right)^\frac{1}{2} \]

\[ D_c = 519 \text{ psi} \]

\[ C_c := 0.41 \cdot \frac{2 \cdot B_c}{3 \cdot D_c} \]

\[ C_c = 34.784 \]
Compression allowables:

\[
F_{cy} := \begin{cases} 
  B_c - D_c \cdot S_{Ry} & \text{if } S_{Ry} \leq C_c \\
  \frac{E_c \left( \frac{\pi}{S_{Ry}} \right)^2}{4} & \text{otherwise}
\end{cases} 
\]

\[
F_{cz} := \begin{cases} 
  B_c - D_c \cdot S_{Rz} & \text{if } S_{Rz} \leq C_c \\
  \frac{E_c \left( \frac{\pi}{S_{Rz}} \right)^2}{4} & \text{otherwise}
\end{cases} 
\]


\[
F_{ey} := \frac{102000000 \text{ psi}}{F_S \cdot S_{Ry}^2} \quad F_{ey} = 211220 \text{ psi}
\]

\[
F_{ez} := \frac{102000000 \text{ psi}}{F_S \cdot S_{Rz}^2} \quad F_{ez} = 211220 \text{ psi}
\]

Ultimate shear allowables:

\[
V_{ulty} := \text{fsu} \cdot \frac{I_z \cdot b}{Q_z} \quad V_{ulty} = 61839 \text{ lbf}
\]

\[
V_{ultz} := \text{fsu} \cdot \frac{I_y \cdot b}{Q_y} \quad V_{ultz} = 61839 \text{ lbf}
\]

Ultimate torsion allowable:

\[
T_{ult} := \text{fsu} \cdot J_o R \quad T_{ult} = 260156 \text{ in-lbf}
\]

Axial tensile allowable:

\[
P_t := \text{ftu} \cdot A \quad P_t = 255000 \text{ lbf}
\]

Axial compression allowable:

\[
P_{cr} := \begin{cases} 
  F_{cz} \cdot A & \text{if } F_{cy} \geq F_{cz} \\
  F_{cy} \cdot A & \text{otherwise}
\end{cases} \quad P_{cr} = 211611 \text{ lbf}
\]

Ultimate bending allowables:

\[
M_{ulty} := S_y \cdot \left[ \text{ftu} + (f - 1) \cdot f_{ty} \right] \quad M_{ulty} = 355504 \text{ in-lbf}
\]

\[
M_{ultz} := S_z \cdot \left[ \text{ftu} + (f - 1) \cdot f_{ty} \right] \quad M_{ultz} = 355504 \text{ in-lbf}
\]

Combined bending and axial allowables:

\[
P_{ey} := F_{ey} \cdot A \quad P_{ey} = 792076 \text{ lbf}
\]

\[
P_{ez} := F_{ez} \cdot A \quad P_{ez} = 792076 \text{ lbf}
\]
NASPOST was used to list all element loads of Lower Angle Beams in the file named "emc.lis". The file is located at /hsm/phoang/ams2/uss/bklg. Input for NASPOST was taken from 192 punch files in three different folders:

/hsm/bsommer/ams/nonlin/1000/2-04
/hsm/bsommer/ams/nonlin/2000/2-04
/hsm/bsommer/ams/nonlin/4000/2-04

File "emc.txt" was generated from "emc.lis" by removing all texts and comments. MathCAD will read in all datum from "emc.txt" for the calculation below.

```math
load := READPRN("emc.txt") 
1 := 1 .. rows(load)

Element ID: ID := load(1)
Load case number: LC := load(2)

+ At end A of beam element:

Moment: M1a := load(3) \cdot \text{in-lbf} M2a := load(4) \cdot \text{in-lbf}
Shear force: V1a := load(5) \cdot \text{lbf} V2a := load(6) \cdot \text{lbf}
Axial force: Pa := load(7) \cdot \text{lbf}
Total torque: Toa := load(8) \cdot \text{in-lbf}
Warp torque: Warpa := load(9) \cdot \text{in-lbf}

+ At end B of beam element:

Moment: M1b := load(10) \cdot \text{in-lbf} M2b := load(11) \cdot \text{in-lbf}
Shear force: V1b := load(12) \cdot \text{lbf} V2b := load(13) \cdot \text{lbf}
Axial force: Pb := load(14) \cdot \text{lbf}
Total torque: Tob := load(15) \cdot \text{in-lbf}
Warp torque: Warpb := load(16) \cdot \text{in-lbf}
```
Modify end torque by subtracting warping torque:

\[ T_{a_i} := |Toa_i| - |Warp_{a_i}| \]
\[ T_{b_i} := |Tob_i| - |Warp_{b_i}| \]

Shear ratios:

\[ RS_{a_i} := \frac{|V_{1a_i}|}{V_{ult}} + \frac{|V_{2a_i}|}{V_{ult}} + \frac{T_{a_i}}{T_{ult}} \]
\[ RS_{b_i} := \frac{|V_{1b_i}|}{V_{ult}} + \frac{|V_{2b_i}|}{V_{ult}} + \frac{T_{b_i}}{T_{ult}} \]

Tensile ratio at end A:

\[ RT_{a_i} := \frac{|Pa_i|}{Pt} + \frac{|M_{2a_i}|}{M_{ult}} + \frac{|M_{1a_i}|}{M_{ult}} \]
\[ \text{if } Pa_i \geq 0 \text{-lbf} \]
\[ \frac{|Pa_i|}{P_{cr}} + \frac{|M_{2a_i}|}{M_{ult}} \left(1 - \frac{|Pa_i|}{P_{ey}}\right) + \frac{|M_{1a_i}|}{M_{ult}} \left(1 - \frac{|Pa_i|}{P_{ez}}\right) \]
\[ \text{otherwise} \]

Tensile ratio at end B:

\[ RT_{b_i} := \frac{|Pb_i|}{Pt} + \frac{|M_{2b_i}|}{M_{ult}} + \frac{|M_{1b_i}|}{M_{ult}} \]
\[ \text{if } Pb_i \geq 0 \text{-lbf} \]
\[ \frac{|Pb_i|}{P_{cr}} + \frac{|M_{2b_i}|}{M_{ult}} \left(1 - \frac{|Pb_i|}{P_{ey}}\right) + \frac{|M_{1b_i}|}{M_{ult}} \left(1 - \frac{|Pb_i|}{P_{ez}}\right) \]
\[ \text{otherwise} \]

Combined Ratios:

\[ \text{RATIO}_{a_i} := \sqrt{(RT_{a_i})^2 + (RS_{a_i})^2} \]
\[ \text{RATIO}_{b_i} := \sqrt{(RT_{b_i})^2 + (RS_{b_i})^2} \]
\[ \text{RATIO}_{i} := \text{if } \left(\text{RATIO}_{a_i} \geq \text{RATIO}_{b_i}, \text{RATIO}_{a_i}, \text{RATIO}_{b_i}\right) \]

Margin of Safety:

\[ MS_i := \frac{1}{\text{RATIO}_i \cdot FS} - 1 \]
\[ \text{min}(MS) = 1.76 \]
The worst load case that yielded minimum margin of safety is shown below:

\[
\text{output} := \text{augment}(\text{ID}, \text{LC}, \text{MS}) \quad \text{sorted} := \text{csort}(\text{output}, 3)
\]

\[
\left(\text{sorted}^T\right)\left(\text{ID}\right)^T = (1513 \quad 1024 \quad 1.76)
\]

Based upon the output of submatrix function above, it reads:

Element ID = 1513

Load ID = 1024

MS = 1.76
2.2.4 Lower USS to Upper USS Joint
Margins of Safety

Table 2.2.4-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135762</td>
<td>Lower USS-02 to Upper USS-02 Joint</td>
<td>AL ALY 7050-T7451</td>
<td>Launch</td>
<td>Max Prin. Stress</td>
<td>1.15 (u)</td>
<td>2.2.4-16</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. Boundary conditions are at five Trunnion locations.
3. 128 load cases for Launch and Abort Landing are applied.
4. u = ultimate, y = yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Abort Landing.

Description of Structure

Figure 2.2.4-1 below shows the locations of four AMS-02 Lower USS to Upper USS Joints in loads model 2-06. The Joints were machined out of 7050-T7451 Aluminum Alloy plate. One end of the Joint is riveted to the Lower Angle Beam. The other end is bolted to the Lower Vacuum Case Joint.

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built for four Lower USS to Upper USS joints using FEMAP.

1. Joints were modeled as CHEXA, CPENTA, and CQUAD4 elements. The CHEXA and CPENTA elements represent the solid section and flat plate. The CQUAD4 elements represent the square tube cross-section.
2. RSSCON elements were used to attach the CQUAD4 elements to the CHEXA elements.
3. RBE3 elements were used in the corners of the attachments between CQUAD4 elements and CHEXA elements.
4. At the bolt holes, RBE2 rigid elements with DOF’s 1, 2, & 3 are represented.
5. The interface between the Lower USS to Upper USS joint and the Lower Vacuum Case joint are represented by RBE2 rigid elements with DOF’s 1.
6. At the shear pin hole, RBE2 rigid elements with DOF’s 2 & 3 are represented.
7. Each row of rivets is represented by a single RBE2 rigid element with DOF’s 1, 2, & 3.
8. The interfaces of the Lower USS to Upper USS Joints and Lower Angle Beams are represented by RBE2 rigid elements with DOF’s 1, 2, & 3.
9. CBEAM elements were modeled to represent the Lower Angle Beams.

Figure 2.2.4-2: View 1 - FEMAP Model of Lower USS to Upper USS Joint
The model was then constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.2.4-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5.

A total of 128 load cases for Launch and Abort Landing were applied. MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02 version 2-06.

Due to the small geometry and the amount of rigid constraints on each end of the joint, hand calculations are performed for the square tube cross-section and flat plate section. Beam and CBUSH loads were recovered and used in the hand calculations.

Table below shows detail of model inputs.
Table 2.2.4-2 – Inputs of Finite Element Model of Lower USS to Upper USS Joints

<table>
<thead>
<tr>
<th>Description</th>
<th>Node #</th>
<th>CHEXA/CPENTA</th>
<th>CQUAD4</th>
<th>CBEAM</th>
<th>RSSCON</th>
<th>RBE2</th>
<th>RBE3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 1</td>
<td>14200001 - 14208002</td>
<td>14200001 - 14205488</td>
<td>14207001 - 14208488</td>
<td>14209101 - 14209001 - 14209148 - 14208002</td>
<td>14209162</td>
<td>14209170</td>
<td></td>
</tr>
<tr>
<td>Joint 2</td>
<td>14210001 - 14218002</td>
<td>14210001 - 14215488</td>
<td>14217001 - 14218488</td>
<td>14219101 - 14219001 - 14219148 - 14218002</td>
<td>14219162</td>
<td>14219170</td>
<td></td>
</tr>
<tr>
<td>Joint 3</td>
<td>14220001 - 14228002</td>
<td>14220001 - 14225488</td>
<td>14227001 - 14228488</td>
<td>14229101 - 14229001 - 14229148 - 14228002</td>
<td>14229162</td>
<td>14229170</td>
<td></td>
</tr>
<tr>
<td>Joint 4</td>
<td>14230001 - 14238002</td>
<td>14230001 - 14235488</td>
<td>14237001 - 14238488</td>
<td>14239101 - 14239001 - 14239148 - 14238002</td>
<td>14239162</td>
<td>14239170</td>
<td></td>
</tr>
</tbody>
</table>

The CBEAM elements have property ID 1040 and material ID 1006. The CQUAD4 elements have property ID 14200001 and material ID 14200001. The CHEXA and CPENTA elements have property ID 14200002 and material ID 14200001.
Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below for the USS detail model. The KGG, KNN and KFF matrices all pass with low strain energies. Reference file, checkams-v1.f06, for additional information.

*** USER INFORMATION MESSAGE 7570 (GPWG1D) RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW: PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.367707E-06</td>
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</tr>
<tr>
<td>2</td>
<td>6.774038E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.557411E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>4.438838E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.103632E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>5.481726E-04</td>
<td>PASS</td>
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</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D) RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW: PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000E-02

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<td>1</td>
<td>1.824517E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.342224E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>2.343345E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>4.275563E-04</td>
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<td>2.288010E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>8.717927E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D) RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW: PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000E-02

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<tbody>
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<td>PASS</td>
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<tr>
<td>2</td>
<td>1.342224E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>2.343345E-06</td>
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<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>8.717927E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>
RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1(A-SET) FOLLOW:

PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
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<tbody>
<tr>
<td>1</td>
<td>1.824517E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.342224E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>2.343345E-06</td>
<td>PASS</td>
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<tr>
<td>4</td>
<td>4.275563E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>2.288010E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>8.717927E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

**Table 2.2.4-3 : Eigenvalue Summary of Lower USS to Upper USS Joint Detail Model**

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4.12E-08</td>
<td>2.03E-04</td>
<td>3.23E-05</td>
<td>1.00E+00</td>
<td>4.12E-08</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2.23E-07</td>
<td>4.73E-04</td>
<td>7.52E-05</td>
<td>1.00E+00</td>
<td>2.23E-07</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2.92E-07</td>
<td>5.40E-04</td>
<td>8.60E-05</td>
<td>1.00E+00</td>
<td>2.92E-07</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>9.49E-07</td>
<td>9.74E-04</td>
<td>1.55E-04</td>
<td>1.00E+00</td>
<td>9.49E-07</td>
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<tr>
<td>5</td>
<td>5</td>
<td>1.28E-06</td>
<td>1.13E-03</td>
<td>1.80E-04</td>
<td>1.00E+00</td>
<td>1.28E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2.13E-06</td>
<td>1.46E-03</td>
<td>2.32E-04</td>
<td>1.00E+00</td>
<td>2.13E-06</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>6.90E+02</td>
<td>2.63E+01</td>
<td>4.18E+00</td>
<td>1.00E+00</td>
<td>6.90E+02</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1.03E+03</td>
<td>3.21E+01</td>
<td>5.10E+00</td>
<td>1.00E+00</td>
<td>1.03E+03</td>
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<tr>
<td>9</td>
<td>9</td>
<td>1.03E+03</td>
<td>3.22E+01</td>
<td>5.12E+00</td>
<td>1.00E+00</td>
<td>1.03E+03</td>
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<tr>
<td>10</td>
<td>10</td>
<td>1.12E+03</td>
<td>3.35E+01</td>
<td>5.32E+00</td>
<td>1.00E+00</td>
<td>1.12E+03</td>
</tr>
</tbody>
</table>

Additional checks are comparisons of the strap loads and trunnion loads between the 2-06 loads model and the detail model. Loads in both models are closely matched.
The table below shows the top 20 strap load differences between the 2-06 loads model and the detailed model for the Lower USS to Upper USS Joint and the Bridge Beam Elbow Joints. The loads from both models are normalized by dividing by the highest load in the 2-06 loads model. A percent difference is then taken from these normalized loads. See Appendix A17 for more information on the strap load comparison. The NASPOST output files for the 2-06 loads model and detail model are strapforcescase.lis and strapforces_detail.lis, respectively.

Table 2.2.4-4 : Strap Load Differences (lbf) between Two Models

<table>
<thead>
<tr>
<th>Element ID#</th>
<th>Load Case</th>
<th>2-06 Loads Model</th>
<th>Detail Model</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>90006</td>
<td>2013</td>
<td>1.000</td>
<td>0.995</td>
<td>0.486</td>
</tr>
<tr>
<td>90006</td>
<td>2009</td>
<td>0.997</td>
<td>0.992</td>
<td>0.435</td>
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<tr>
<td>90014</td>
<td>2048</td>
<td>0.984</td>
<td>0.984</td>
<td>0.039</td>
</tr>
<tr>
<td>90014</td>
<td>2044</td>
<td>0.982</td>
<td>0.987</td>
<td>0.444</td>
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<tr>
<td>90002</td>
<td>2026</td>
<td>0.976</td>
<td>0.975</td>
<td>0.136</td>
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<tr>
<td>90010</td>
<td>2059</td>
<td>0.975</td>
<td>0.976</td>
<td>0.089</td>
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<tr>
<td>90010</td>
<td>2063</td>
<td>0.961</td>
<td>0.959</td>
<td>0.176</td>
</tr>
<tr>
<td>90002</td>
<td>2030</td>
<td>0.958</td>
<td>0.949</td>
<td>0.931</td>
</tr>
<tr>
<td>90011</td>
<td>1002</td>
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<td>0.932</td>
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</tr>
<tr>
<td>90015</td>
<td>1021</td>
<td>0.942</td>
<td>0.963</td>
<td>2.263</td>
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<tr>
<td>90013</td>
<td>1027</td>
<td>0.926</td>
<td>0.932</td>
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<td>90013</td>
<td>1025</td>
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<td>0.924</td>
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<tr>
<td>90009</td>
<td>1014</td>
<td>0.921</td>
<td>0.898</td>
<td>2.573</td>
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<tr>
<td>90009</td>
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<tr>
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<td>0.901</td>
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<td>90006</td>
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<td>0.885</td>
<td>0.885</td>
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<tr>
<td>90002</td>
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<td>0.878</td>
<td>0.877</td>
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</table>
The table below shows the top 20 trunnion load differences between the 2-06 loads model and the detailed model for the Lower USS to Upper USS Joint and the Bridge Beam Elbow Joints. The loads from both models are normalized by dividing by the highest load in the 2-06 loads model. A percent difference is then taken from these normalized loads. See Appendix A17 for more information on the trunnion load comparison. The NASPOST output files for the 2-06 loads model and detail model are trunnionforces.lis and trunnionforces_detail.lis, respectively.

Table 2.2.4-5 : Trunnion Load Differences (lbf) between Two Models

<table>
<thead>
<tr>
<th>Element ID#</th>
<th>Load Case</th>
<th>2-06 Loads Model</th>
<th>Detail Model</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
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<td>0.995</td>
<td>0.500</td>
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<tr>
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Material and Temperature

The Lower USS to Upper USS Joints are 7050-T7451 aluminum alloy. Material properties of 7050-T7451 are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5H. Temperature limits at the interface of Lower USS to Upper USS are provided by the Thermal Analysis Group. See Appendix C2 for temperature data. For Launch condition, the temperature of 120°F is applied. For Abort Landing condition, the temperature of 150°F is applied.

Analysis

Due to the small geometry and the amount of rigid constraints on each end of the joint, hand calculations are performed for the square tube cross-section and flat plate section. Beam and CBUSH loads were recovered and used in the hand calculations.
Geometry and Cross Sectional Properties:

**Tube Section 4X4X.25:**

- \( b := 4.0 \text{ in} \) \hspace{1cm} \text{Height of Tube}
- \( d := 4.0 \text{ in} \) \hspace{1cm} \text{Width of Tube}
- \( t := 0.250 \text{ in} \) \hspace{1cm} \text{Wall Thickness of Tube}

<table>
<thead>
<tr>
<th>Portion</th>
<th>( b )</th>
<th>( d )</th>
<th>( A )</th>
<th>( z )</th>
<th>( Az )</th>
<th>( Az^2 )</th>
<th>( I_{cy} )</th>
<th>( I_{y'} )</th>
</tr>
</thead>
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<td>3.8750</td>
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<td>1.0000</td>
<td>0.1250</td>
<td>0.1250</td>
<td>0.0156</td>
<td>0.0052</td>
<td>0.0208</td>
</tr>
<tr>
<td>4</td>
<td>0.2500</td>
<td>3.5000</td>
<td>0.8750</td>
<td>2.0000</td>
<td>1.7500</td>
<td>3.5000</td>
<td>0.8932</td>
<td>4.3932</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>( A = 3.750 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- \( z_{bar} = 2.000 \) \hspace{1cm} \text{Area}
- \( I_{yy} = 8.828 \) \hspace{1cm} \text{Moment of Interia}
- \( c := 2.0 \text{ in} \) \hspace{1cm} \text{Distance of outer extreme fiber for square tube section}

**Plate Section:**

- \( h := 7.250 \text{ in} \) \hspace{1cm} \text{Height of plate}
- \( k := 7.189 \text{ in} \) \hspace{1cm} \text{Width of plate}
- \( \text{thick} := 0.750 \text{ in} \) \hspace{1cm} \text{Thickness of Plate}

\( A_1 := h \times \text{thick} = 5.437 \text{ in}^2 \) \hspace{1cm} \text{Area along cross section 1-1}

\( A_2 := k \times \text{thick} = 5.392 \text{ in}^2 \) \hspace{1cm} \text{Area along cross section 2-2}

Moments of Interia for cross sections 1-1 and 2-2:

\( I_{z1} := \frac{h \times \text{thick}^3}{12} \) \hspace{1cm} \( I_{z1} = 0.255 \text{ in}^4 \)

\( I_{y1} := \frac{\text{thick} \times h^3}{12} \) \hspace{1cm} \( I_{y1} = 23.817 \text{ in}^4 \)

\( I_{y2} := \frac{k \times \text{thick}^3}{12} \) \hspace{1cm} \( I_{y2} = 0.253 \text{ in}^4 \)

\( I_{x1} := \frac{\text{thick} \times k^3}{12} \) \hspace{1cm} \( I_{x1} = 23.221 \text{ in}^4 \)
Factor of Safety, Material Properties, and Temperature Data:

Material Properties: 7050-T7451 AL ALY, BMS 7-323C or AMS 4050 (Boeing Material Specification, BMS 7-323C, Table 1 & MIL-HDBK-5H, Table 3.7.3.0(b1) for thickness of 5.001"-6.000")

\[
\begin{align*}
F_{tu} & := 66000 \text{ psi} \\
F_{ty} & := 57000 \text{ psi} \\
F_{su} & := 43000 \text{ psi}
\end{align*}
\]

Factors of Safety, \( \gamma_u := 1.4 \quad \gamma_y := 1.1 \)

Temperature reduction factors, (Ref. MIL-HDBK-5H, Figure 3.7.3.2.1)

+ At 120°F for Launch condition: + At 150°F for Abort Landing condition:

\[
\begin{align*}
\gamma_{u1} & := 0.95 \\
\gamma_{y1} & := 0.99 \\
\gamma_{u2} & := 0.91 \\
\gamma_{y2} & := 0.97
\end{align*}
\]

Allowable stresses:

+ For Launch condition: + For Landing condition:

\[
\begin{align*}
F_{tu1.a} & := \gamma_{u1} F_{tu} \\
F_{tu1.a} & = 62700 \text{ psi} \\
F_{ty1.a} & := \gamma_{y1} F_{ty} \\
F_{ty1.a} & = 56430 \text{ psi} \\
F_{su1.a} & := \gamma_{u1} F_{su} \\
F_{su1.a} & = 40850 \text{ psi}
\end{align*}
\]

\[
\begin{align*}
F_{tu2.a} & := \gamma_{u2} F_{tu} \\
F_{tu2.a} & = 60060 \text{ psi} \\
F_{ty2.a} & := \gamma_{y2} F_{ty} \\
F_{ty2.a} & = 55290 \text{ psi} \\
F_{su2.a} & := \gamma_{u2} F_{su} \\
F_{su2.a} & = 39130 \text{ psi}
\end{align*}
\]
Analysis of Square Tube Cross Section (Launch):

**Loads from 2-06 detailed loads model, launch case**

```plaintext
load := READPRN("lab_1000.txt") i := 1 .. rows(load)

Element ID: ID := load(1) Load case number: LC := load(2)

+ At end A of beam element:

![Diagram of beam with labels](image)

Moment: 
Mya := load(3) \cdot \text{in} \cdot \text{lbf} 
Mza := load(4) \cdot \text{in} \cdot \text{lbf}

Shear force: 
Fy := load(5) \cdot \text{lbf} 
Fz := load(6) \cdot \text{lbf}

Axial force: 
Fx := load(7) \cdot \text{lbf} 
Total torque: Tor := load(8) \cdot \text{in} \cdot \text{lbf}

Cant := 5.38 \cdot \text{in} 
Cantilevered Distance from Beam End

Mya := Mya + Fz \cdot \text{Cant} 
Total Moment about y

Mza := Mza + Fy \cdot \text{Cant} 
Total Moment about z
```
Analysis of Square Tube Cross Section (Launch):

Normal is direct axial plus bending: (Conservatively)  
(Ref. Stress, Strain, And Structural Matrices, p. 764)

\[
\sigma_i := \frac{F_{x,i}}{\text{Area}} + \left| \frac{M_{y,i}}{\text{Int} \cdot c} \right| + \left| \frac{M_{z,i}}{\text{Int} \cdot c} \right| \quad \max(\sigma) = 20021.8 \text{ psi}
\]

(This \( \sigma_i \) gives the least MS)

Since the normal and shear stresses are not applied at the same location, the simplified calculation for the combined shear stress is as follows:

Shear due to transverse loading
\[
\tau_{v,i} := \sqrt{\left( \frac{F_{y,i}}{\text{Area}} \right)^2 + \left( \frac{F_{z,i}}{\text{Area}} \right)^2} \quad \max(\tau_v) = 1807.1 \text{ psi}
\]

Shear due to torsion (conservatively):
\[
\tau_{t,i} := \frac{T_{o,i}}{2 \cdot t \cdot (b - t) \cdot (d - t)} \quad \max(\tau_t) = 2669.2 \text{ psi}
\]

Combined shear:
\[
\tau_i := \tau_{v,i} + \tau_{t,i} \quad \max(\tau) = 4168 \text{ psi}
\]

Principal Stresses:
\[
\sigma_{p,1,i} := \frac{\sigma_i}{2} + \left[ \left( \frac{\sigma_i}{2} \right)^2 + \left( \tau_i \right)^2 \right]^{1/2} \quad \max(\sigma_p) = 20854.8 \text{ psi}
\]
\[
\sigma_{p,2,i} := \frac{\sigma_i}{2} - \left[ \left( \frac{\sigma_i}{2} \right)^2 + \left( \tau_i \right)^2 \right]^{1/2} \quad \min(\sigma_p) = -1362 \text{ psi}
\]

Maximum principal stress is:
\[
\sigma_{\max,i} := \begin{cases} 
\sigma_{p,1,i} & \text{if } |\sigma_{p,1,i}| \geq |\sigma_{p,2,i}| \\
\sigma_{p,2,i} & \text{otherwise}
\end{cases}
\]

Von-Mises Stress:
\[
\sigma_{vm,i} := \sqrt{\left( \sigma_{p,1,i} \right)^2 + \left( \sigma_{p,2,i} \right)^2 - \sigma_{p,1,i} \cdot \sigma_{p,2,i}} \quad \max(\sigma_{vm}) = 21283.5 \text{ psi}
\]

Maximum shear:
\[
\tau_{\max,i} := \frac{1}{4} \left( \sigma_i \right)^2 + \left( \tau_i \right)^2 \quad \max(\tau_{\max}) = 10843.9 \text{ psi}
\]
Margins of safety for Square Tube Cross Section (Launch):

Ultimate

\[ \text{MSu}_i := \begin{cases} \frac{F_{u1,a}}{F_{Su-\sigma_{max}}_i} - 1 & \text{if } \sigma_{max}_i \neq 0 \text{-psi} \\ 10000 & \text{otherwise} \end{cases} \]

min(\text{MSu}) = 1.15

\[
\begin{array}{cccccc}
\text{ID} & \text{LC} & \text{MSu} & \text{Mya} & \text{Mza} & \text{Fx} \\
1028 & 1608 & 1.15 & -51065.76 & -12014.9 & 940.8 \\
\end{array}
\]

The minimum margin of safety of 1.15 occurs on element ID 1608 and load case 1028 along with the following moments and forces: (Mya) -51065.76, (Mza) -12014.9, (Fy) 940.8, (Fz) -5541.2, and (Fx) 21490.3.

Ultimate, shear

\[ \text{MSu}_i := \begin{cases} \frac{F_{su1,a}}{F_{Su-\tau_{max}}_i} - 1 & \text{if } \tau_{max}_i \neq 0 \text{-psi} \\ 10000 & \text{otherwise} \end{cases} \]

min(\text{MSu}) = 1.69

\[
\begin{array}{cccccc}
\text{ID} & \text{LC} & \text{MSu} & \text{Mya} & \text{Mza} & \text{Fx} \\
1028 & 1608 & 1.69 & -51065.76 & -12014.9 & 940.8 \\
\end{array}
\]

Yield (using von-Mises)

\[ \text{MSy}_i := \begin{cases} \frac{F_{ty1,a}}{F_{Sy-\sigma_{vm}}_i} - 1 & \text{if } \sigma_{vm}_i \neq 0 \text{-psi} \\ 10000 & \text{otherwise} \end{cases} \]

min(\text{MSy}) = 1.41

\[
\begin{array}{cccccc}
\text{ID} & \text{LC} & \text{MSy} & \text{Mya} & \text{Mza} & \text{Fx} \\
1028 & 1608 & 1.41 & -51065.76 & -12014.9 & 940.8 \\
\end{array}
\]
Analysis of Square Tube Cross Section (Abort Landing):

**Loads from 2-06 detailed loads model, abort landing case**

```plaintext
load := READPRN("lab_2000.txt")
i := 1 .. rows(load)

Element ID: ID := load(1)
Load case number: LC := load(2)

+ At end A of beam element:

| Moment:   | Mya := load(3) \cdot \text{in}-\text{lbf} | Mza := load(4) \cdot \text{in}-\text{lbf} |
| Shear force: | Fy := load(5) \cdot \text{lbf} | Fz := load(6) \cdot \text{lbf} |
| Axial force: | Fx := load(7) \cdot \text{lbf} | Total torque: Tor := load(8) \cdot \text{in}-\text{lbf} |

Cant := 5.38\cdot\text{in}
Cantilevered Distance from Beam End
Mya := Mya + Fz\cdot\text{Cant}
Total Moment about y
Mza := Mza + Fy\cdot\text{Cant}
Total Moment about z
```

2.2.4 - 17
Analysis of Square Tube Cross Section (Abort Landing):

Normal is direct axial plus bending: (Conservatively) (Ref. Stress, Strain, And Structural Matrices, p. 764)

\[
\sigma_i := \frac{F_{x_i}}{\text{Area}} + \frac{M_{y_i}c}{\text{Int}} + \frac{M_{z_i}c}{\text{Int}} \\
\max(\sigma) = 18816.5 \text{ psi}
\]

(This \(\sigma_i\) gives the least MS)

Since the normal and shear stresses are not applied at the same location, the simplified calculation for the combined shear stress is as follows:

Shear due to transverse loading

\[
\tau_{v_i} := \sqrt{\left(\frac{F_{y_i}}{\text{Area}}\right)^2 + \left(\frac{F_{z_i}}{\text{Area}}\right)^2} \\
\max(\tau_v) = 1633.8 \text{ psi}
\]

Shear due to torsion (conservatively):

\[
\tau_{t_i} := \frac{\text{Tor}_{i}}{2t \cdot (b - t) \cdot (d - t)} \\
\max(\tau_t) = 2238.7 \text{ psi}
\]

Combined shear:

\[
\tau_i := \tau_{v_i} + \tau_{t_i} \\
\max(\tau) = 3540.8 \text{ psi}
\]

Principal Stresses:

\[
\sigma_{p_{i,1}} = \frac{\sigma_i}{2} + \left(\frac{\sigma_i}{2}\right)^2 + \left(\tau_i\right)^2 \\
\max(\sigma_p) = 18823.1 \text{ psi}
\]

\[
\sigma_{p_{i,2}} = \frac{\sigma_i}{2} - \left(\frac{\sigma_i}{2}\right)^2 + \left(\tau_i\right)^2 \\
\min(\sigma_p) = -1070.1 \text{ psi}
\]

Maximum principal stress is:

\[
\sigma_{\max_i} := \begin{cases} 
\sigma_{p_{i,1}} & \text{if } \sigma_{p_{i,1}} \geq \sigma_{p_{i,2}} \\
\sigma_{p_{i,2}} & \text{otherwise}
\end{cases}
\]

Von-Mises Stress:

\[
\sigma_{vm_i} := \sqrt{\left(\sigma_{p_{i,1}}\right)^2 + \left(\sigma_{p_{i,2}}\right)^2 - \sigma_{p_{i,1}} \cdot \sigma_{p_{i,2}}} \\
\max(\sigma_{vm}) = 18826.4 \text{ psi}
\]

Maximum shear:

\[
\tau_{\max_i} := \frac{1}{4} \left(\sigma_i\right)^2 + \left(\tau_i\right)^2 \\
\max(\tau_{\max}) = 9414.8 \text{ psi}
\]
Margins of safety for Square Tube Cross Section (Abort Landing):

Ultimate

\[ \text{MS}_{\text{u,i}} := \left( \frac{F_{\text{u1,a}}}{FS_{\text{u}}, \sigma_{\text{max,i}}} \right) - 1 \quad \text{if } \sigma_{\text{max,i}} \neq 0 \text{-psi} \]

\[ \min(\text{MS}_{\text{u}}) = 1.38 \]

\[ \text{output1} := \text{augment}\left( \text{ID, LC, MS}_{\text{u}}, \frac{\text{My}_a}{\text{in-lbf}}, \frac{\text{M}_z}{\text{in-lbf}}, \frac{F_y}{\text{lbf}}, \frac{F_z}{\text{lbf}}, \frac{F_x}{\text{lbf}} \right) \]

\[ \text{sorted} := \text{csort(output1, 3)} \]

\[ \left( \text{sorted}^T \right)^{(i)^T} = (1603 \ 2015 \ 1.38 \ 6083.15 \ 53499.69 \ 3915.5 \ 4712.5 \ 19942) \]

The minimum margin of safety of 1.38 occurs on element ID 1603 and load case 2015 along with the following moments and forces: (Mya) 6083.2, (Mza) 53499.7, (Fy) 3915.5, (Fz) 4712.5, and (Fx) 19942.

Ultimate, shear

\[ \text{MS}_{\text{su,i}} := \left( \frac{F_{\text{su1,a}}}{FS_{\text{u}}, \tau_{\text{max,i}}} \right) - 1 \quad \text{if } \tau_{\text{max,i}} \neq 0 \text{-psi} \]

\[ \min(\text{MS}_{\text{su}}) = 2.1 \]

\[ \text{output2} := \text{augment}\left( \text{ID, LC, MS}_{\text{su}}, \frac{\text{My}_a}{\text{in-lbf}}, \frac{\text{M}_z}{\text{in-lbf}}, \frac{F_y}{\text{lbf}}, \frac{F_z}{\text{lbf}}, \frac{F_x}{\text{lbf}} \right) \]

\[ \text{sorted} := \text{csort(output2, 3)} \]

\[ \left( \text{sorted}^T \right)^{(i)^T} = (1603 \ 2015 \ 2.1 \ 6083.15 \ 53499.69 \ 3915.5 \ 4712.5 \ 19942) \]

Yield (using von-Mises)

\[ \text{MS}_{\text{y,i}} := \left( \frac{F_{\text{y1,a}}}{FS_{\text{y}}, \sigma_{\text{vm,i}}} \right) - 1 \quad \text{if } \sigma_{\text{vm,i}} \neq 0 \text{-psi} \]

\[ \min(\text{MS}_{\text{y}}) = 1.72 \]

\[ \text{output3} := \text{augment}\left( \text{ID, LC, MS}_{\text{y}}, \frac{\text{My}_a}{\text{in-lbf}}, \frac{\text{M}_z}{\text{in-lbf}}, \frac{F_y}{\text{lbf}}, \frac{F_z}{\text{lbf}}, \frac{F_x}{\text{lbf}} \right) \]

\[ \text{sorted} := \text{csort(output3, 3)} \]

\[ \left( \text{sorted}^T \right)^{(i)^T} = (1603 \ 2015 \ 1.72 \ 6083.15 \ 53499.69 \ 3915.5 \ 4712.5 \ 19942) \]
Stress Analysis of Plate Section:

The loads on the cbush elements from the detailed loads model 2-06 are used to analyze the plate section. The Mz and My moments are coupled out in order to find the tensile stress in the side and top flange of the plate section. (cross section 1-1 and 2-2) The Mx moment is coupled out in order to find the shear stress in the side and top flange of the plate section. (cross section 1-1 and 2-2) See below.

![Diagram of plate section with stress analysis](image)

**Figure 2.2.4 -1 Dimensions and Bolt Locations**

Basic Dimensions:

\[
\begin{align*}
  r_1 &:= \begin{bmatrix} 0 \\ 2.75 \\ 2.5 \end{bmatrix} \text{ in} \\
  r_2 &:= 2.75 \text{ in} \quad \text{Dimension along side flange from center of shear pin hole to centerline of bolt holes} \\
  r_3 &:= 2.5 \text{ in} \quad \text{Dimension along top flange from shear pin hole to centerline of bolt holes} \\
  dy &:= .750 \text{ in} \quad \text{Dimension from center line of bolt holes along side flange to solid section (1-1)} \\
  dz &:= .338 \text{ in} \quad \text{Dimension from center line of bolt holes along top flange to solid section (2-2)} 
\end{align*}
\]

(Ref. CAD Model)
Loads from 2-06 detailed loads model, launch case

data := READPRN("cbush_launch.txt")

\[ j := 1 \text{ to } \text{rows(data)} \]

Axial Load \[ F_x := \text{data}_{j,3} \text{ lb} \]

Torsion \[ M_x := \text{data}_{j,6} \text{ in} \cdot \text{lb} \]

Shear in Y axis \[ F_y := \text{data}_{j,4} \text{ lb} \]

Moment about Y axis \[ M_y := \text{data}_{j,7} \text{ in} \cdot \text{lb} \]

Shear in Z axis \[ F_z := \text{data}_{j,5} \text{ lb} \]

Moment about Z axis \[ M_z := \text{data}_{j,8} \text{ in} \cdot \text{lb} \]

Element Identification \[ \text{ID} := \text{data}_{j,1} \]

Load Case Number \[ \text{LC} := \text{data}_{j,2} \]

\[ c_2 := \frac{\text{thick}}{2} \]

\[ c_2 = 0.375 \text{ in} \]

Distance of outer extreme fiber for plate section

Tension Stress for Section 1-1 (Mz Couple)

\[ \text{Fx}_{\text{nor}} := \frac{|F_{x,j}|}{4} \]

Fx Normal Force (The number 4 represents the four quadrants on the plate. Bolt numbers 1, 4, and 6 form a quadrant of the plate. See figure 2.2.4 -1.)

\[ F_{mz} := \frac{|M_{z,j}|}{r_2^2} \]

Force due to Mz couple

\[ F_{t\text{en}1,j} := F_{x\text{nor},j} + F_{mz,j} \]

\[ \max(F_{t\text{en}1}) = 12389.3 \text{ lb} \]

Total Force

\[ M_{z1,j} := F_{t\text{en}1,j} \cdot dy \]

Total Mz moment on plate along solid section (cross section 1-1)

\[ \sigma_{z1} := \frac{M_{z1,j} \cdot c_2}{I_{z1}} \]

\[ \max(\sigma_{z1}) = 13671 \text{ psi} \]

(Stress along solid section (cross section 1-1))
Tension Stress for Section 2-2 (My Couple)

\[ F_{x,\text{nor}} := \frac{|F_x|}{4} \]

Fx Normal Force (The number 4 represents the four quadrants on the plate. Bolt numbers 1, 2, and 3 form a quadrant of the plate. See figure 2.2.4 - 1.)

\[ F_{M,y} := \frac{|M_{y,j}|}{r_3^2} \]

Force due to My couple

\[ F_{\text{ten2}} := F_{x,\text{nor}} + F_{M,y} \]

max \( F_{\text{ten2}} = 10231.3 \text{ lbf} \) Total Force

\[ M_{2,j} := F_{\text{ten2}} \cdot dz \]

Total My moment on plate along solid section (cross section 2-2)

\[ \sigma_{y2,j} := \frac{M_{2,j} \cdot c^2}{I_{y2}} \]

max \( \sigma_{y2} = 5131.1 \text{ psi} \) (Stress along solid section (cross section 2-2))

Combined Corner Tensile Stress

\[ \sigma_{yz,j} := \sqrt{(\sigma_{z1,j})^2 + (\sigma_{y2,j})^2} \]

max \( \sigma_{yz} = 13981.7 \text{ psi} \)

Shear Forces for Section 1-1 (Mx Couple)

\[ F_{z,\text{nor}} := \frac{|F_z|}{2} \]

Fz Normal Force (The two side flanges of the plate section shear along the solid section. See following picture.)

\[ F_{M,x} := \frac{|M_{x,j}|}{r_2^2} \]

Force due to Mx couple

\[ F_{sh1} := F_{z,\text{nor}} + F_{M,x} \]

max \( F_{sh1} = 20275.5 \text{ lbf} \) Total Force

\[ \tau_{x1,j} := \frac{F_{sh1,j}}{A_1} \]

max \( \tau_{x1} = 3728.8 \text{ psi} \) (Stress along solid section (cross section 1-1))
Shear Forces for Section 2-2 (Mx Couple)

\[ F_{\text{nor}} := \left| F_y \right| \]
Fy Normal Force (The top flange of the plate section shears along the top solid section. See following picture.)

\[ F_{\text{mx}2} := \frac{M_x}{t_s^2} \]
Force due to Mx couple

\[ F_{\text{sh}2} := F_{\text{nor}} + F_{\text{mx}2} \]
\[ \max(F_{\text{sh}2}) = 18515.6 \text{ lbf} \]
Total Force

\[ \tau_{\text{x}2} := \frac{F_{\text{sh}2}}{A_2} \]
\[ \max(\tau_{\text{x}2}) = 3434.1 \text{ psi} \]
(Stress along solid section (cross section 1-1))

Combined Corner Shear Stress

\[ \tau_{\text{x}} := \sqrt{\left(\tau_{\text{x}1}\right)^2 + \left(\tau_{\text{x}2}\right)^2} \]
\[ \max(\tau_{\text{x}}) = 5049 \text{ psi} \]

Margins of Safety for Plate Section (Launch):

**Tension Ultimate:**

\[ M_{\text{Stenu}} := \frac{F_{tu1.a}}{F_{\text{Su} \cdot \sigma_{yz,j}}} \]
\[ \min(M_{\text{Stenu}}) = 3.2 \]

**Tension Yield:**

\[ M_{\text{Steny}} := \frac{F_{ty1.a}}{F_{\text{Sy} \cdot \sigma_{yz,j}}} \]
\[ \min(M_{\text{Steny}}) = 3.67 \]

**Shear Ultimate:**

\[ M_{\text{Sh}} := \frac{F_{su1.a}}{F_{\text{Su} \cdot \tau_{x,j}}} \]
\[ \min(M_{\text{Sh}}) = 5.78 \]

The minimum margin of safety of 3.2 occurs on element ID 66042 and load case 1037 along with the following moments and forces: 
(Fx) 5236.8, (Fy) 14701.3, (Fz) 13246.8, (Mx) 59801.5, (My) -12666.4, and (Mz) -49926.8.
Loads from 2-06 detailed loads model, abort landing case

data := READPRN("cbush_abort.txt")

j := 1 .. rows(data)

Axial Load
Fx := data[j,3] lbf

Torsion
Mx := data[j,6] in-lbf

Shear in Y axis
Fy := data[j,4] lbf

Moment about Y axis
My := data[j,7] in-lbf

Shear in Z axis
Fz := data[j,5] lbf

Moment about Z axis
Mz := data[j,8] in-lbf

Element Identification
ID := data[j,1]

Load Case Number
LC := data[j,2]

c2 := \frac{\text{thick}}{2} = 0.375 \text{ in} \quad \text{Distance of outer extreme fiber for plate section}

Tension Stress for Section 1-1 (Mz Couple)

\( F_{x_{\text{nor}}} := \frac{F_x}{4} \) \quad \text{Fx Normal Force (The number 4 represents the four quadrants on the plate. Bolt numbers 1, 4, and 6 form a quadrant of the plate. See figure 2.2.4-1.)}

\( F_{mz} := \frac{|M_z|}{r_2^2} \) \quad \text{Force due to Mz couple}

\( F_{ten1} := F_{x_{\text{nor}}} + F_{mz} \) \quad \text{max}(F_{ten1}) = 11023.9 \text{ lbf} \quad \text{Total Force}

\( M_{z1} := F_{ten1} \cdot dy \) \quad \text{Total Mz moment on plate along solid section (cross section 1-1)}

\( \sigma_{z1} := \frac{M_{z1} \cdot c_2}{I_{z1}} \) \quad \text{max}(\sigma_{z1}) = 12164.3 \text{ psi} \quad \text{(Stress along solid section (cross section 1-1))}
Tension Stress for Section 2-2 (My Couple)

\[ F_{x\text{nor}} := \frac{F_x}{4} \]
Fx Normal Force (The number 4 represents the four quadrants on the plate. Bolt numbers 1, 2, and 3 form a quadrant of the plate. See figure 2.2.4-1.)

\[ F_{my} := \frac{M_y}{r_3^2} \]
Force due to My couple

\[ F_{ten2} := F_{x\text{nor}} + F_{my} \]
\[ \text{max}(F_{ten2}) = 9520.7 \text{ lbf} \]
Total Force

\[ M_{y2} := F_{ten2} \cdot dz \]
Total My moment on plate along solid section (cross section 2-2)

\[ \sigma_{y2} := \frac{M_{y2} \cdot c_2}{I_{y2}} \]
\[ \text{max}(\sigma_{y2}) = 4774.7 \text{ psi} \]
(Stress along solid section (cross section 2-2))

Combined Corner Tensile Stress

\[ \sigma_{yz} := \sqrt{\left(\sigma_{z1}\right)^2 + \left(\sigma_{y2}\right)^2} \]
\[ \text{max}(\sigma_{yz}) = 12734.5 \text{ psi} \]

Shear Forces for Section 1-1 (Mx Couple)

\[ F_{z\text{nor}} := \frac{F_z}{2} \]
Fz Normal Force (The two side flanges of the plate section shear along the solid section. See following picture.)

\[ F_{mx1} := \frac{M_x}{r_2^2} \]
Force due to Mx couple

\[ F_{sh1} := F_{z\text{nor}} + F_{mx1} \]
\[ \text{max}(F_{sh1}) = 18847.4 \text{ lbf} \]
Total Force

\[ \tau_{x1} := \frac{F_{sh1}}{A_1} \]
\[ \text{max}(\tau_{x1}) = 3466.2 \text{ psi} \]
(Stress along solid section (cross section 1-1))
Shear Forces for Section 2-2 (Mx Couple)

\[ F_{ynor, j} := \left| F_y \right| \]
\( F_{ynor} \) Normal Force (The top flange of the plate section shears along the top solid section. See following picture.)

\[ F_{mx2, j} := \frac{M_{x, j}}{r_3^2} \]
Force due to Mx couple

\[ F_{sh2, j} := F_{ynor, j} + F_{mx2, j} \]
\( \max(F_{sh2}) = 18320.2 \text{ lbf} \)
Total Force

\[ \tau_{x2, j} := \frac{F_{sh2, j}}{A_2} \]
\( \max(\tau_{x2}) = 3397.8 \text{ psi} \) (Stress along solid section (cross section 1-1))

Combined Corner Shear Stress

\[ \tau_x := \sqrt{\left(\tau_{x1, j}\right)^2 + \left(\tau_{x2, j}\right)^2} \]
\( \max(\tau_x) = 4853.8 \text{ psi} \)

Margins of Safety for Plate Section (Abort Landing):

Tension Ultimate:
\[ M_{Stenu, j} := \frac{F_{tu1, a}}{F_{Su-\sigma yz, j}} \]
\( \min(M_{Stenu}) = 3.52 \)

Tension Yield:
\[ M_{Steny, j} := \frac{F_{ty1, a}}{F_{Sy-\sigma yz, j}} \]
\( \min(M_{Steny}) = 4.03 \)

Shear Ultimate:
\[ M_{Sh, j} := \frac{F_{su1, a}}{F_{Su-\tau x, j}} \]
\( \min(M_{Sh}) = 6.01 \)

The minimum margin of safety of 3.52 occurs on element ID 66041 and load case 2015 along with the following moments and forces:  
\( (Fx) 4701.1, (Fy) -12932.9, (Fz) -15833.4, (Mx) 68095.3, (My) 17773.2, \) and \( (Mz) -38860.6. \)
2.2.5 RICH Mounting Bracket
Margins of Safety

Table 2.2.5-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135763</td>
<td>RICH Brackets</td>
<td>AL ALY 7050-T7451</td>
<td>Landing</td>
<td>Max Prin. Stress</td>
<td>0.90 (u)</td>
<td>2.2.5-13</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. Boundary condition is at five Trunnion locations.
3. All 192 load cases of Launch and Landing are applied.
4. $u$ = ultimate, $y$ = yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing.

Description of Structure

Figure 2.2.5-1 below shows the location of six RICH Brackets in AMS-02. The Brackets were machined out of 7050-T7451 Aluminum Alloy plate. They were riveted to Centerbody Tubes. Part of a Bracket was bolted to Ring Imaging Cherenkov Counter (RICH).

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built of the RICH Brackets using FEMAP software.

1. Parts were mainly modeled as CQUAD4 and CTRIA3 plate elements.
2. Section of Centerbody Tube, which was coupled with Brackets, was CQUAD4 plate elements.
3. All rivets was modeled as RBE2 rigid elements with DOF’s 1&2, 1&3, or 2&3.
4. Continuation of Centerbody Tube beam elements and plate elements was represented by RBE2 rigid elements with DOF’s 1-6.
5. Bar elements were found at intersection between two plates.

The model of RICH Brackets was then imported into USS2-04 load model. A built PAS model was also integrated into the load model.

Figure 2.2.5-2: FEMAP Model of RICH Brackets
The model was constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.2.5-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5.

All 192 load cases for Launch and Landing were applied.

MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02.

Plate stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in RICH Brackets. Forces at rivet location were also requested.

Table below shows details of model inputs.

### Table 2.2.5-2: Inputs of Finite Element Model of RICH Brackets

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>TYPE</th>
<th>COLOR</th>
<th>PROP</th>
<th>MATL</th>
<th>LC#</th>
<th>SPC#</th>
<th>COORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>rich bracket</td>
<td>200,001 - 212,802</td>
<td>200,001 - 202,424</td>
<td>plate</td>
<td>124</td>
<td>200,001 - 0.25&quot; TK</td>
<td>200,001</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>142,002 - 0.4375&quot; TK</td>
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<td>centerbody tube</td>
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<td></td>
<td>plate</td>
<td>85</td>
<td>200,011 - tube</td>
<td>200,001</td>
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<tr>
<td>@ rich</td>
<td>215,001 - 219,840</td>
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<td></td>
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<td>1001001</td>
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<tr>
<td>rivets</td>
<td>220,001 - 220,464</td>
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<td>bar</td>
<td>24</td>
<td>200,003 - dummy</td>
<td>200,001</td>
<td></td>
<td></td>
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<tr>
<td>misc</td>
<td>215,001 - 215,504</td>
<td>rib2</td>
<td></td>
<td>13</td>
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<td></td>
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</tr>
<tr>
<td>PAS</td>
<td>300,001 - 303,474</td>
<td>300,001 - 304,594</td>
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<td>300,001 - 300,023</td>
<td>300,001 - 300,006</td>
<td>300,001</td>
<td>300,001</td>
<td>300,001 - 300,002</td>
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</tbody>
</table>
**Model Checks**

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

**Results of Rigid Body Checks of Matrix KGG (G-set)**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Strain Energy</th>
<th>Pass/Fail</th>
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<tbody>
<tr>
<td>1</td>
<td>1.273202E-07</td>
<td>PASS</td>
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<tr>
<td>2</td>
<td>4.420144E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.633816E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.057998E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.047791E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.609049E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Results of Rigid Body Checks of Matrix KNN (N-set)**

<table>
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<th>Pass/Fail</th>
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<tbody>
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<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.129834E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.326043E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.075881E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.044385E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.661979E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Results of Rigid Body Checks of Matrix KFF (F-set)**

<table>
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<th>Pass/Fail</th>
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<tr>
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<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.129834E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.326043E-08</td>
<td>PASS</td>
</tr>
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<td>4</td>
<td>5.075881E-05</td>
<td>PASS</td>
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<td>5</td>
<td>1.044385E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.661979E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>
RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1.263888E-07</td>
<td>PASS</td>
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<tr>
<td>2</td>
<td>4.129834E-08</td>
<td>PASS</td>
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<tr>
<td>3</td>
<td>1.326043E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.075881E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.044385E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.661979E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 2.2.5-3: Eigenvalue Summary of RICH Brackets Model

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-5.53E-06</td>
<td>2.35E-03</td>
<td>3.74E-04</td>
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<td>-5.53E-06</td>
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<tr>
<td>2</td>
<td>2</td>
<td>3.02E-06</td>
<td>1.74E-03</td>
<td>2.76E-04</td>
<td>1.00E+00</td>
<td>3.02E-06</td>
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<tr>
<td>3</td>
<td>3</td>
<td>5.91E-06</td>
<td>2.43E-03</td>
<td>3.87E-04</td>
<td>1.00E+00</td>
<td>5.91E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1.21E-05</td>
<td>3.47E-03</td>
<td>5.53E-04</td>
<td>1.00E+00</td>
<td>1.21E-05</td>
</tr>
<tr>
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<td>5</td>
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<td>1.00E+00</td>
<td>2.89E-05</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>3.10E-05</td>
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<td>8.86E-04</td>
<td>1.00E+00</td>
<td>3.10E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3.56E+07</td>
<td>5.97E+03</td>
<td>9.50E+02</td>
<td>1.00E+00</td>
<td>3.56E+07</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>5.44E+07</td>
<td>7.37E+03</td>
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<td>1.00E+00</td>
<td>5.44E+07</td>
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<td>9</td>
<td>9</td>
<td>7.79E+07</td>
<td>8.83E+03</td>
<td>1.41E+03</td>
<td>1.00E+00</td>
<td>7.79E+07</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.61E+08</td>
<td>1.27E+04</td>
<td>2.02E+03</td>
<td>1.00E+00</td>
<td>1.61E+08</td>
</tr>
</tbody>
</table>

Additional check is comparison of the Strap loads between the load model and the detail model. The loads are picked randomly. Loads in both models are closely matched.
### Table 2.2.5-4: Strap Loads (lbf) in Load Model 2-04

<table>
<thead>
<tr>
<th>Case</th>
<th>90001</th>
<th>90002</th>
<th>90003</th>
<th>90004</th>
<th>90005</th>
<th>90006</th>
<th>90007</th>
<th>90008</th>
<th>90009</th>
<th>90010</th>
<th>90011</th>
<th>90012</th>
<th>90013</th>
<th>90014</th>
<th>90015</th>
<th>90016</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>1186.6</td>
<td>1615.3</td>
<td>1495.4</td>
<td>2128.4</td>
<td>1241.3</td>
<td>3808.0</td>
<td>1382.5</td>
<td>5331.2</td>
<td>5259.6</td>
<td>1683.6</td>
<td>10097.9</td>
<td>2054.3</td>
<td>7952.9</td>
<td>3314.8</td>
<td>9044.1</td>
<td>3929.6</td>
</tr>
<tr>
<td>1023</td>
<td>1171.3</td>
<td>2245.6</td>
<td>1605.7</td>
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<td>1670.6</td>
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<td>6207.3</td>
<td>3965.4</td>
<td>6681.8</td>
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<td>10078.1</td>
<td>1914.3</td>
</tr>
<tr>
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<td>3923.0</td>
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<td>1652.1</td>
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<td>5265.2</td>
<td>1564.0</td>
<td>1500.3</td>
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<tr>
<td>2040</td>
<td>2119.5</td>
<td>1696.3</td>
<td>5485.8</td>
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<td>1495.0</td>
<td>1586.5</td>
<td>1980.6</td>
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<tr>
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</table>

### Table 2.2.5-5: Strap Loads (lbf) in RICH Brackets Model

<table>
<thead>
<tr>
<th>Case</th>
<th>90001</th>
<th>90002</th>
<th>90003</th>
<th>90004</th>
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<th>90016</th>
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<tbody>
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<td>1179.8</td>
<td>6366.9</td>
<td>1281.3</td>
<td>884.2</td>
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<td>947.1</td>
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### Table 2.2.5-6: Load Differences (lbf) between Two Models

<table>
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<tr>
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<th>90005</th>
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<td>18.2</td>
<td>-196.7</td>
<td>-12.0</td>
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<td>0.0</td>
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<td>-1.5</td>
<td>-1.9</td>
<td>13.0</td>
<td>28.9</td>
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<td>-0.8</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.6</td>
<td>-0.1</td>
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<td>2.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: 1. Negative sign in Table 2.2.5-6 means load in Detail model greater than in Load model.
Material and Temperature

The RICH Brackets are 7050-T7451 Aluminum Alloy. Material property of 7050-T7451 are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5H. Temperature limits are based upon ICD-2-19001 (Shuttle Orbiter / Cargo Standard Interfaces), Revision-L. For Launch condition, the temperature of 150°F is applied. For Landing condition, the temperature of 220°F is applied.

Analysis

The critical stresses for the RICH Brackets are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. All margins of safety are positive.
Check of RICH Brackets

Material Properties: 7050-T7451 AL ALY, BMS 7-323C or AMS 4050

- $F_{tu} := 68000 \text{psi}$
- $F_{ty} := 57000 \text{psi}$
- $F_{su} := 43000 \text{psi}$

Factors of Safety:
- $FS_{tu} := 1.4$
- $FS_{ty} := 1.1$

(For Launch and Landing conditions)

Table below was drawn from ICD-2-19001, 04-MAR-99. Maximum temperatures of 150°F and 220°F for Launch and Landing respectively are selected in the analysis.

*** In this analysis of RICH Bracket, On-Orbit loads are considered smaller than Launch and Landing. Therefore, On-Orbit loads are neglected.

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>1. Prelaunch (1)</td>
<td>+40°F</td>
</tr>
<tr>
<td>2. Launch (1)</td>
<td>+40°F</td>
</tr>
<tr>
<td>3. On-Orbit (doors open) (2) (4)</td>
<td>-250°F</td>
</tr>
<tr>
<td>4. Entry and Post-landing (3) (4)</td>
<td>-50°F</td>
</tr>
</tbody>
</table>
Temperature Reduction Factors, \textit{(Ref. MIL-HDBK-5H, Figure 3.7.3.2.1)}

+ At 150°F for Launch condition:  
  - Ultimate: $\gamma_{u1} := 0.94$  
  - Yield: $\gamma_{y1} := 0.98$

+ At 220°F for Landing condition:  
  $\gamma_{u2} := 0.84$  
  $\gamma_{y2} := 0.92$

Allowable stresses due to Temperature Reduction Factors:

+ For Launch condition:  
  - $F_{tu1,a} := \gamma_{u1} F_{tu}$  
    $F_{tu1,a} = 63920 \text{ psi}$
  
  - $F_{ty1,a} := \gamma_{y1} F_{ty}$  
    $F_{ty1,a} = 55860 \text{ psi}$

+ For Landing condition:  
  - $F_{tu2,a} := \gamma_{u2} F_{tu}$  
    $F_{tu2,a} = 57120 \text{ psi}$
  
  - $F_{ty2,a} := \gamma_{y2} F_{ty}$  
    $F_{ty2,a} = 52440 \text{ psi}$
  
  - $F_{su1,a} := \gamma_{u1} F_{su}$  
    $F_{su1,a} = 40420 \text{ psi}$
  
  - $F_{su2,a} := \gamma_{u2} F_{su}$  
    $F_{su2,a} = 36120 \text{ psi}$
Maximum Von-Mises, principal, and shear stresses of both plate and solid elements are selected from 192 load cases for Launch and Landing. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

+ For Launch condition:  
(Stress contour plot shown in Figure 2.2.5-3)

\[
\sigma_{uu1,max} := 13223 \text{ psi} \quad LC\# 1015, ELEM\# 202230; p.A8-3
\]

\[
\sigma_{uy1,max} := 11951 \text{ psi} \quad LC\# 1015, ELEM\# 202230; p.A8-3
\]

\[
\sigma_{us1,max} := 6611 \text{ psi} \quad LC\# 1015, ELEM\# 202230; p.A8-3
\]

+ For Landing condition:  
(Stress contour plot shown in Figure 2.2.5-4)

\[
\sigma_{uu2,max} := 21430 \text{ psi} \quad LC\# 4062, ELEM\# 200168; p.A8-7
\]

\[
\sigma_{uy2,max} := 19004 \text{ psi} \quad LC\# 4062, ELEM\# 200168; p.A8-7
\]

\[
\sigma_{us2,max} := 10715 \text{ psi} \quad LC\# 4062, ELEM\# 200168; p.A8-7
\]

The values shown above are maximum stresses.

The following pages show stresses sorted by NASPOST V.2.1.
Margins of Safety,

+ For Launch condition:

\[
MS_{u1} := \frac{F_{u1,a}}{FS_u \sigma_{u1,max}} - 1 \quad MS_{u1} = 2.45
\]

\[
MS_{y1} := \frac{F_{y1,a}}{FS_y \sigma_{y1,max}} - 1 \quad MS_{y1} = 3.25
\]

\[
MS_{s1} := \frac{F_{su1,a}}{FS_u \sigma_{s1,max}} - 1 \quad MS_{s1} = 3.37
\]

+ For Landing condition:

\[
MS_{u2} := \frac{F_{u2,a}}{FS_u \sigma_{u2,max}} - 1 \quad MS_{u2} = 0.9
\]

\[
MS_{y2} := \frac{F_{y2,a}}{FS_y \sigma_{y2,max}} - 1 \quad MS_{y2} = 1.51
\]

\[
MS_{s2} := \frac{F_{su2,a}}{FS_u \sigma_{s2,max}} - 1 \quad MS_{s2} = 1.41
\]
Figure 2.2.5-3 - Stress Contour Plot of RICH Brackets in Launch Condition
Figure 2.2.5-4 - Stress Contour Plot of RICH Brackets in Landing Condition
2.2.6 Lower Angle Beam Assembly
LOWER ANGLE BEAM

Since part is a slender beam with compressive loads, buckling is critical.

In Finite Element Model of USS-02 version 2-04 shown in Figure 2.2.6-1, Lower Angle Beam includes Element Ids of 1602-1603, 1607-1608, 1612-1613, and 1617-1618. These elements has Property Id of 1006.

Figure 2.2.6-1: Lower Angle Beam shown in Lower uss2-04 Model
Factor of Safety,  
\[ \text{FS} := 1.4 \]

Material: AL 7075-T73511  
(Ref. MIL-HDBK-5H, Table 3.7.4.0(g2), p.3-361; Thickness: 0.250-0.499)

- Compressive modulus,  
  \[ E_c := 10700000 \text{ psi} \]

- Ultimate tensile strength,  
  \[ f_{tu} := 68000 \text{ psi} \]

- Tensile yield strength,  
  \[ f_{ty} := 57000 \text{ psi} \]

- Compression yield strength,  
  \[ f_{cy} := 60000 \text{ psi} \]

- Ultimate shear strength,  
  \[ f_{su} := 38000 \text{ psi} \]

Section: 5.0" x 5.0" x 0.25" Tube  
(Ref. Dwg# SDG39135764, Section-A-A & B-B)
Shape Factor, \( f := 1.22 \)  

Supported length, \( L := 9.33 \text{·in} \)

Width, \( D_y := 6.5 \text{·in} \)

For torsional calculation, use: \( D_{yt} := 4.562 \text{·in} \)

Depth, \( D_z := 4.562 \text{·in} \)

For torsional calculation, use: \( D_{zt} := 4.562 \text{·in} \)

Thickness, \( t := 0.3125 \text{·in} \)

Define: \( b := 2 \cdot t \)

Properties of cross-section: \( \text{(Ref. Table 2.2.6-1)} \)

Area, \( A := 6.172 \text{·in}^2 \)

Moment of Inertia, \( I_y := 19.963 \text{·in}^4 \)

\( I_z := 22.526 \text{·in}^4 \)
First moments,

\[ Q_y = 5.154 \text{ in}^3 \]
\[ Q_z = 5.410 \text{ in}^3 \]

Table 2.2.6-1a: Property about Y-Y axis

<table>
<thead>
<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Az</th>
<th>Az²</th>
<th>Icy</th>
<th>Iy²</th>
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<td>0.3229</td>
<td>1.4224</td>
<td>0.0006</td>
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<td>4.4058</td>
<td>0.3229</td>
<td>1.4224</td>
<td>0.0006</td>
<td>1.4230</td>
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<td>1.2303</td>
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<td>2.8061</td>
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<td>Sum</td>
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<td></td>
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\[ z_{\text{bar}} = 2.281 \]
\[ I_{yy} = 19.963 \]

Table 2.2.6-1b: Property about Z-Z axis

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<th>Portion</th>
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<th>Ay²</th>
<th>Icz</th>
<th>Iyz</th>
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<td>1.7091</td>
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<td>1.3844</td>
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<td>1.5781</td>
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<td>0.0733</td>
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<td>0.0086</td>
<td>0.0010</td>
<td>0.0003</td>
<td>0.0013</td>
</tr>
<tr>
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<td>1.7091</td>
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<td>5.5545</td>
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<td>A</td>
<td></td>
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\[ y_{\text{bar}} = 3.250 \]
\[ I_{zz} = 22.526 \]

Table 2.2.6-1c: First Moment about Y-Y axis

<table>
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<tr>
<th>Portion</th>
<th>b</th>
<th>d</th>
<th>Area, A</th>
<th>z</th>
<th>Qyy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.0733</td>
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<tr>
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<td>0.1557</td>
</tr>
<tr>
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<tr>
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<td>A</td>
<td></td>
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Table 2.2.6-1d: First Moment about Z-Z axis

<table>
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<th>Area, A</th>
<th>y</th>
<th>Qzz</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.2345</td>
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<td>0.2296</td>
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<tr>
<td>7</td>
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<td>2.7345</td>
<td>0.8535</td>
<td>1.5673</td>
<td>1.1684</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td>Qzz = 5.410</td>
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</tbody>
</table>

2.2.6-5

ESCG-4005-05-AMS-0039
**Title**  
USS-02 LOWER ANGLE BEAM

<table>
<thead>
<tr>
<th>Mathematical Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section modulus, ( S_y := \frac{1}{2} \cdot \frac{I_y}{D_z} )</td>
<td>( S_y = 8.752 \text{ in}^3 )</td>
</tr>
<tr>
<td>Torsional constant / distance, ( J_o R := \frac{2 \cdot t \cdot (D_{z_{tor}} - t) \cdot (D_{y_{tor}} - t)}{D_z} )</td>
<td>( J_o R = 11.286 \text{ in}^3 )</td>
</tr>
<tr>
<td>Radii of gyration, ( r_y := \sqrt{\frac{I_y}{A}} )</td>
<td>( r_y = 1.798 \text{ in} )</td>
</tr>
<tr>
<td>Fixity coefficient, ( K := 1.2 ) ( (\text{Ref. Structural Engineering Handbook, 4th Edition, Figure 5, p.8-10}) )</td>
<td></td>
</tr>
<tr>
<td>Slenderness ratios, ( S_{Ry} := \frac{K \cdot L}{r_y} )</td>
<td>( S_{Ry} = 6.225 )</td>
</tr>
<tr>
<td>( S_{Rz} := \frac{K \cdot L}{r_z} )</td>
<td>( S_{Rz} = 5.86 )</td>
</tr>
</tbody>
</table>

Constants depending upon the mechanical properties of the material from Ref. Structural Engineering Handbook, 4th Edition, Formulas 5a-c, p.11-6:

\[
B_c := f_{cy} \left[ 1 + \left( \frac{f_{cy}}{2250000 \text{ psi}} \right)^2 \right]^{1/2}
\]

\( B_c = 69798 \text{ psi} \)

\[
D_c := \frac{B_c}{10} \left( \frac{B_c}{E_c} \right)^2
\]

\( D_c = 564 \text{ psi} \)

\[
C_c := 0.41 \left( \frac{2 \cdot B_c}{3 \cdot D_c} \right)
\]

\( C_c = 33.843 \)
Compression allowables:

\[ F_{\text{cy}} := \begin{cases} \frac{B_c - D_c}{E_c} \cdot \sqrt{\frac{\pi}{S_R}} & \text{if } S_R \leq C_c \\ F_{\text{cy}} = 66289 \text{ psi} \\ \text{otherwise} \end{cases} \]

\[ F_{\text{cz}} := \begin{cases} \frac{B_c - D_c}{E_c} \cdot \sqrt{\frac{\pi}{S_R}} & \text{if } S_R \leq C_c \\ F_{\text{cz}} = 66494 \text{ psi} \\ \text{otherwise} \end{cases} \]


\[ F_{\text{ey}} := \frac{102000000 \text{ psi}}{F_S \cdot S_R^2} \quad F_{\text{ey}} = 1879950 \text{ psi} \]

\[ F_{\text{ez}} := \frac{102000000 \text{ psi}}{F_S \cdot S_R^2} \quad F_{\text{ez}} = 2121312 \text{ psi} \]

Ultimate shear allowables:

\[ V_{\text{ulty}} := fsu \cdot \frac{I_z \cdot b}{Q_z} \quad V_{\text{ulty}} = 98890 \text{ lbf} \]

\[ V_{\text{ultz}} := fsu \cdot \frac{I_y \cdot b}{Q_y} \quad V_{\text{ultz}} = 91991 \text{ lbf} \]

Ultimate torsion allowable:

\[ T_{\text{ult}} := fsu \cdot \text{JoR} \quad T_{\text{ult}} = 428883 \text{ in-lbf} \]

Axial tensile allowable:

\[ P_{\text{t}} := ftu \cdot A \quad P_{\text{t}} = 419696 \text{ lbf} \]

Axial compression allowable:

\[ P_{\text{cr}} := \begin{cases} F_{\text{cz}} \cdot A & \text{if } F_{\text{cy}} \geq F_{\text{cz}} \\ F_{\text{cy}} \cdot A & \text{otherwise} \end{cases} \quad P_{\text{cr}} = 409133 \text{ lbf} \]

Ultimate bending allowables:

\[ M_{\text{ulty}} := Sy \cdot [ftu \cdot (f - 1) \cdot fty] \quad M_{\text{ulty}} = 704875 \text{ in-lbf} \]

\[ M_{\text{ultz}} := Sz \cdot [ftu \cdot (f - 1) \cdot fty] \quad M_{\text{ultz}} = 558229 \text{ in-lbf} \]

Combined bending and axial allowables:

\[ P_{\text{ey}} := F_{\text{ey}} \cdot A \quad P_{\text{ey}} = 11603050 \text{ lbf} \]

\[ P_{\text{ez}} := F_{\text{ez}} \cdot A \quad P_{\text{ez}} = 13092737 \text{ lbf} \]
NASPOST was used to list all element loads of Lower Angle Beams in the file named "lab.lis". The file is located at /hsm/phoang/ams2/uss/bklg. Input for NASPOST was taken from 192 punch files in three different folders:

/hsm/bsommer/ams/nonlin/1000/2-04
/hsm/bsommer/ams/nonlin/2000/2-04
/hsm/bsommer/ams/nonlin/4000/2-04

File "lab.txt" was generated from "lab.lis" by removing all texts and comments. MathCAD will read in all datum from "lab.txt" for the calculation below.

\[
\text{load} := \text{READPRN}("lab.txt") \quad i := 1..\text{rows(load)}
\]

Element ID: \( \text{ID} := \text{load}^{(1)} \)  
Load case number: \( \text{LC} := \text{load}^{(2)} \)

+ At end A of beam element:

- Moment: \( M_{1a} := \text{load}^{(3)} \text{in-lbf} \) \( M_{2a} := \text{load}^{(4)} \text{in-lbf} \)
- Shear force: \( V_{1a} := \text{load}^{(5)} \text{lbf} \) \( V_{2a} := \text{load}^{(6)} \text{lbf} \)
- Axial force: \( P_a := \text{load}^{(7)} \text{lbf} \)
- Total torque: \( T_{oa} := \text{load}^{(8)} \text{in-lbf} \)
- Warp torque: \( W_{arpa} := \text{load}^{(9)} \text{in-lbf} \)

+ At end B of beam element:

- Moment: \( M_{1b} := \text{load}^{(10)} \text{in-lbf} \) \( M_{2b} := \text{load}^{(11)} \text{in-lbf} \)
- Shear force: \( V_{1b} := \text{load}^{(12)} \text{lbf} \) \( V_{2b} := \text{load}^{(13)} \text{lbf} \)
- Axial force: \( P_b := \text{load}^{(14)} \text{lbf} \)
- Total torque: \( T_{ob} := \text{load}^{(15)} \text{in-lbf} \)
- Warp torque: \( W_{arbp} := \text{load}^{(16)} \text{in-lbf} \)
Modify end torque by subtracting warping torque:

\[ Ta_i := |Toa_i| - |Warpa_i| \]
\[ Tb_i := |Tob_i| - |Warpb_i| \]

Shear ratios:

\[ RSa_i := \frac{|V1a_i|}{Vulty} + \frac{|V2a_i|}{Vultz} + \frac{Ta_i}{Tult} \]
\[ RSB_i := \frac{|V1b_i|}{Vulty} + \frac{|V2b_i|}{Vultz} + \frac{Tb_i}{Tult} \]

Tensile ratio at end A:

\[ RTa_i := \left| \frac{Pa_i}{Pt} \right| + \left| \frac{M2a_i}{Multy} \right| + \left| \frac{M1a_i}{Multz} \right| \]
if \( Pa_i \geq 0 \cdot \text{lbf} \)
\[ \left| \frac{Pa_i}{Pt} \right| + \frac{M2a_i}{Multy} \cdot \frac{1}{1 - \frac{Pa_i}{Pey}} + \frac{M1a_i}{Multz} \cdot \frac{1}{1 - \frac{Pa_i}{Pez}} \]
otherwise

Tensile ratio at end B:

\[ RTb_i := \left| \frac{Pb_i}{Pt} \right| + \left| \frac{M2b_i}{Multy} \right| + \left| \frac{M1b_i}{Multz} \right| \]
if \( Pb_i \geq 0 \cdot \text{lbf} \)
\[ \left| \frac{Pb_i}{Pt} \right| + \frac{M2b_i}{Multy} \cdot \frac{1}{1 - \frac{Pb_i}{Pey}} + \frac{M1b_i}{Multz} \cdot \frac{1}{1 - \frac{Pb_i}{Pez}} \]
otherwise

Combined Ratios:

\[ \text{RATIO}_a := \sqrt{(RTa_i)^2 + (RSa_i)^2} \]
\[ \text{RATIO}_b := \sqrt{(RTb_i)^2 + (RSb_i)^2} \]
\[ \text{RATIO}_i := \text{if} (\text{RATIO}_a \geq \text{RATIO}_b, \text{RATIO}_a, \text{RATIO}_b) \]

Margin of Safety:

\[ MS_i := \frac{1}{\text{RATIO}_i \cdot FS} - 1 \]

\[ \min(\text{MS}) = 2.5 \]
The worst load case that yielded minimum margin of safety is shown below:

\[
\text{output} := \text{augment}(\text{ID, LC, MS}) \quad \text{sorted} := \text{csort(output, 3)}
\]

\[
\begin{pmatrix}
\text{sorted}^T \\
\end{pmatrix}
\begin{pmatrix}
1 \\
1602 \\
4015 \\
2.5
\end{pmatrix}
= (1602 \ 4015 \ 2.5)
\]

Based upon the output of SORT function above, it reads:

Element ID = 1602

Load ID = 4015

MS = 2.5
2.2.7 PAS RICH Bracket
Margins of Safety

Table 2.2.7-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135766</td>
<td>PAS-RICH Brackets</td>
<td>AL ALY 7050-T7451</td>
<td>On-Orbit</td>
<td>Max Prin. Stress</td>
<td>0.12 (u)</td>
<td>2.2.7-13</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 1.4 and 1.1 for Ultimate and Yield, respectively in Launch and Landing conditions. Factors of Safety are 2.0 and 1.25 for Ultimate and Yield, respectively in On-Orbit condition.
2. Boundary condition is at five Trunnion locations in Launch and Landing condition. Boundary condition is at C.G. of PAS Capture Bar and three Guide Bars in On-Orbit condition.
3. All 192 load cases of Launch and Landing and 8 load cases of On-Orbit are applied.
4. \( u = \) ultimate, \( y = \) yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing. It is also designed with a yield factor of 1.25 and an ultimate factor 2.0 against limit loads for On-Orbit.

Description of Structure

Figure 2.2.7-1 below shows the location of two PAS-RICH Brackets in AMS-02. The Brackets were machined out of 7050-T7451 Aluminum Alloy plate. They were riveted to Centerbody Tubes. Part of a Bracket was bolted to Payload Attach System (PAS). Another part was bolted to Ring Imaging Cherenkov Counter (RICH).

Figure 2.2.7-1: Location of PAS-RICH Brackets in AMS-02

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built of the PAS-RICH Brackets using FEMAP software.

1. Parts were mainly modeled as CQUAD4 and CTRIA3 plate elements.
2. Interface of PAS-RICH brackets and PAS was CHEXA solid elements.
3. Section of Centerbody Tube, which was coupled with Brackets, was CQUAD4 plate elements.
4. All rivets was modeled as RBE2 rigid elements with DOF’s 1&2 or 1&3.
5. Continuation of Centerbody Tube beam and plate elements was represented by RBE2 rigid elements with DOF’s 1-6.
6. Bar elements were found at intersection between two plates.
7. RSSCON element was connector of plate to solid elements.

The model of PAS-RICH Brackets was then imported into USS2-04 load model. A built PAS model was also intergrated into the load model.

Figure 2.2.7-2: FEMAP Model of PAS-RICH Brackets
The model was constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.2.7-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5 for Launch and Landing conditions. The model was also constrained with DOF’s 3 at C.G. of PAS Capture Bar, with DOF’s 236 at two rear Guide Bars, and with DOF’s 136 at front Guide Bar for On-Orbit condition.

All 192 load cases for Launch and Landing, and 8 load cases for On-Orbit were applied.

MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02.

Plate and solid stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in PAS-RICH Brackets. Forces at rivet location were also requested.

Table below shows details of model inputs.

**Table 2.2.7-2: Inputs of Finite Element Model of PAS-RICH Brackets**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>TYPE</th>
<th>PROP#</th>
<th>MATL#</th>
<th>LC#</th>
<th>SPC#</th>
<th>COORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>pas rich bracket</td>
<td>200,001 - 212,802</td>
<td>205,001 - 204,624</td>
<td>plane</td>
<td>200,001 - 0.25” TK</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>205,001 - 206,836</td>
<td>solid</td>
<td>200,021 - solid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>center body tube</td>
<td></td>
<td>210,001 - 211,920</td>
<td>place</td>
<td>200,011 - tube</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@pas rich</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirc</td>
<td></td>
<td>215,001 - 215,504</td>
<td>bar</td>
<td>200,003 - dummy</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rivets</td>
<td></td>
<td>221,001 - 221,096</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAS</td>
<td>300,001 - 303,474</td>
<td>300,001 - 304,504</td>
<td></td>
<td>300,001 - 300,023</td>
<td>300,001 - 300,066</td>
<td>300,001</td>
<td>300,001</td>
<td>300,001 - 300,002</td>
</tr>
</tbody>
</table>
Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.314041E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>7.262543E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.534839E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>9.702608E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.916835E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.171079E-05</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.694130E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>7.125755E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.189959E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>8.980069E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>5.375610E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.025928E-05</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN+AUTO (N+AUTOSPC-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.694130E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>7.125755E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.189959E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>8.980069E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>5.375610E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.025928E-05</td>
<td>PASS</td>
</tr>
</tbody>
</table>
A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

**Table 2.2.7-3: Eigenvalue Summary of PAS-RICH Brackets Model**

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.06E-05</td>
<td>3.25E-03</td>
<td>5.18E-04</td>
<td>1.00E+00</td>
<td>-1.06E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.56E-06</td>
<td>1.25E-03</td>
<td>1.99E-04</td>
<td>1.00E+00</td>
<td>-1.56E-06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>5.29E-06</td>
<td>2.30E-03</td>
<td>3.66E-04</td>
<td>1.00E+00</td>
<td>5.29E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>6.34E-06</td>
<td>2.52E-03</td>
<td>4.01E-04</td>
<td>1.00E+00</td>
<td>6.34E-06</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>8.82E-06</td>
<td>2.97E-03</td>
<td>4.73E-04</td>
<td>1.00E+00</td>
<td>8.82E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1.12E-05</td>
<td>3.34E-03</td>
<td>5.32E-04</td>
<td>1.00E+00</td>
<td>1.12E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3.58E+07</td>
<td>5.98E+03</td>
<td>9.52E+02</td>
<td>1.00E+00</td>
<td>3.58E+07</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>5.07E+07</td>
<td>7.12E+03</td>
<td>1.13E+03</td>
<td>1.00E+00</td>
<td>5.07E+07</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1.24E+08</td>
<td>1.12E+04</td>
<td>1.78E+03</td>
<td>1.00E+00</td>
<td>1.24E+08</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.69E+08</td>
<td>1.30E+04</td>
<td>2.07E+03</td>
<td>1.00E+00</td>
<td>1.69E+08</td>
</tr>
</tbody>
</table>
Additional check is comparison of the interface loads between the load model and the detail model. The loads are picked randomly. Loads in both models are closely matched.

Table 2.2.7-4: Interface Loads (lbf) in Load Model 2-04

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-10265.5</td>
<td>-4218.5</td>
<td>9910.0</td>
<td>7635.5</td>
<td>-785.8</td>
<td>987.6</td>
<td>-3250.9</td>
<td>1119.0</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>19044.8</td>
<td>-16676.0</td>
<td>3404.8</td>
<td>2433.2</td>
<td>-12722.8</td>
<td>7581.0</td>
<td>-11633.1</td>
<td>-519.6</td>
</tr>
<tr>
<td>2033(Fy)</td>
<td>-1601.8</td>
<td>-1942.0</td>
<td>645.2</td>
<td>437.5</td>
<td>-6117.5</td>
<td>-9489.8</td>
<td>-3363.9</td>
<td>5239.9</td>
</tr>
<tr>
<td>2047(Fz)</td>
<td>-1910.6</td>
<td>1228.8</td>
<td>-2868.4</td>
<td>-4166.4</td>
<td>7219.1</td>
<td>5784.0</td>
<td>3041.0</td>
<td>6638.5</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-543.2</td>
<td>11872.4</td>
<td>8070.0</td>
<td>-3118.7</td>
<td>-1324.4</td>
<td>-7806.0</td>
<td>-6032.6</td>
<td>3874.0</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>-3360.5</td>
<td>-834.1</td>
<td>-187.7</td>
<td>1137.0</td>
<td>13878.8</td>
<td>21524.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2.7-5: Interface Loads (lbf) in PAS-RICH Brackets Model

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-10454.2</td>
<td>-4312.0</td>
<td>10003.4</td>
<td>7718.2</td>
<td>-876.5</td>
<td>984.5</td>
<td>-3296.8</td>
<td>1074.5</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>18937.1</td>
<td>-16619.2</td>
<td>3365.7</td>
<td>2397.4</td>
<td>-12670.1</td>
<td>7579.1</td>
<td>-11506.6</td>
<td>-520.1</td>
</tr>
<tr>
<td>2033(Fy)</td>
<td>-1601.8</td>
<td>-1942.6</td>
<td>645.1</td>
<td>434.9</td>
<td>-6112.6</td>
<td>-9495.3</td>
<td>-3371.0</td>
<td>5249.1</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-1905.3</td>
<td>1222.7</td>
<td>-2869.7</td>
<td>-4156.4</td>
<td>7248.5</td>
<td>5782.5</td>
<td>3051.6</td>
<td>6651.5</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-535.4</td>
<td>11877.4</td>
<td>8075.0</td>
<td>-3112.0</td>
<td>-1326.9</td>
<td>-7798.7</td>
<td>-6046.1</td>
<td>3858.6</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>-3361.7</td>
<td>-832.2</td>
<td>-186.9</td>
<td>1132.7</td>
<td>13894.9</td>
<td>21544.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2.7-6: Load Differences (lbf) between Two Models

<table>
<thead>
<tr>
<th>Load</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>188.7</td>
<td>93.5</td>
<td>-93.4</td>
<td>-82.7</td>
<td>90.7</td>
<td>3.1</td>
<td>45.8</td>
<td>44.5</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>107.7</td>
<td>-56.8</td>
<td>39.1</td>
<td>35.8</td>
<td>-52.7</td>
<td>2.0</td>
<td>-126.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2033(Fx)</td>
<td>0.0</td>
<td>0.6</td>
<td>0.1</td>
<td>2.6</td>
<td>-4.9</td>
<td>5.5</td>
<td>7.1</td>
<td>-9.2</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-5.2</td>
<td>6.1</td>
<td>1.3</td>
<td>-10.0</td>
<td>-29.4</td>
<td>1.5</td>
<td>-10.5</td>
<td>-13.0</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-7.8</td>
<td>-5.0</td>
<td>-5.1</td>
<td>-6.7</td>
<td>2.5</td>
<td>-7.4</td>
<td>13.5</td>
<td>15.4</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>1.2</td>
<td>-1.8</td>
<td>-0.8</td>
<td>4.3</td>
<td>-16.1</td>
<td>9.3</td>
<td>23.9</td>
<td>-19.8</td>
</tr>
</tbody>
</table>

Note: 1. Negative sign in Table 2.2.7-6 means load in Detail model greater than in Load model.
Material and Temperature

The PAS-RICH Brackets are 7050-T7451 Aluminum Alloy. Material properties of 7050-T7451 are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5H. Temperature limits are based upon ICD-2-19001 (Shuttle Orbiter / Cargo Standard Interfaces), Revision-L. For Launch condition, the temperature of 150°F is applied. For Landing condition, the temperature of 220°F is applied. For On-Orbit condition, the temperature of 200°F is applied.

Analysis

The critical stresses for the PAS-RICH Brackets are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. All margins of safety are positive.
Check of PAS-RICH Brackets

Material Properties: 7050-T7451 AL ALY, BMS 7-323C or AMS 4050

- $F_{tu} := 67000$ psi
- $F_{ty} := 57000$ psi
- $F_{su} := 43000$ psi

Factors of Safety,
- $FS_u := 1.4$  \hspace{1cm}  $FS_y := 1.1$  \hspace{1cm}  (For Launch and Landing conditions)
- $FS_{u,o} := 2.0$  \hspace{1cm}  $FS_{y,o} := 1.25$  \hspace{1cm}  (For On-Orbit condition)

Table below was drawn from ICD-2-19001, 04-MAR-99. Maximum temperatures of 150°F and 220°F for Launch and Landing respectively are selected in the analysis. Temperature of 200°F is used for On-Orbit condition.

**TABLE 6.1.4.1-1 CARGO BAY WALL TEMPERATURE**

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>1. Prelaunch (1)</td>
<td>+40°F</td>
</tr>
<tr>
<td>2. Launch (1)</td>
<td>+40°F</td>
</tr>
<tr>
<td>3. On-Orbit (doors open) (2) (4)</td>
<td>-250°F</td>
</tr>
<tr>
<td>4. Entry and Post-landing (3) (4)</td>
<td>-50°F</td>
</tr>
</tbody>
</table>
Temperature reduction factors, \((\text{Ref. MIL-HDBK-5H, Figure 3.7.3.2.1})\)

+ At 150°C for Launch condition:  
- Ultimate: \(\gamma_{u1} := 0.94\)  
- Yield: \(\gamma_{y1} := 0.98\)

+ At 220°C for Landing condition:  
- Ultimate: \(\gamma_{u2} := 0.84\)  
- Yield: \(\gamma_{y2} := 0.92\)

+ At 200°C for On-Orbit condition:  
- Ultimate: \(\gamma_{u3} := 0.85\)  
- Yield: \(\gamma_{y3} := 0.93\)

Allowable stresses due to Temperature Reduction Factors:

+ For Launch condition:  
\[F_{tu1.a} := \gamma_{u1} F_{tu}\]
\[F_{tu1.a} = 62980 \text{ psi}\]

+ For Landing condition:  
\[F_{tu2.a} := \gamma_{u2} F_{tu}\]
\[F_{tu2.a} = 56280 \text{ psi}\]

+ For On-Orbit condition:  
\[F_{tu3.a} := \gamma_{u3} F_{tu}\]
\[F_{tu3.a} = 56950 \text{ psi}\]

\[F_{ty1.a} := \gamma_{y1} F_{ty}\]
\[F_{ty1.a} = 55860 \text{ psi}\]

\[F_{ty2.a} := \gamma_{y2} F_{ty}\]
\[F_{ty2.a} = 52440 \text{ psi}\]

\[F_{ty3.a} := \gamma_{y3} F_{ty}\]
\[F_{ty3.a} = 53010 \text{ psi}\]

\[F_{su1.a} := \gamma_{u1} F_{su}\]
\[F_{su1.a} = 40420 \text{ psi}\]

\[F_{su2.a} := \gamma_{u2} F_{su}\]
\[F_{su2.a} = 36120 \text{ psi}\]

\[F_{su3.a} := \gamma_{u3} F_{su}\]
\[F_{su3.a} = 36550 \text{ psi}\]
Maximum Von-Mises, principal, and shear stresses of both plate and solid elements are selected from 192 load cases for Launch and Landing, and 8 cases for On-Orbit. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

+ For Launch condition:  
  (Stress contour plot shown in Figure 2.2.7-3)

\[
\begin{align*}
\sigma_{uu1,\text{max}} & := 27544 \text{ psi} & (LC\# \ 1019, \ ELEM\# \ 203830; \ p.A9-3) \\
\sigma_{uy1,\text{max}} & := 24568 \text{ psi} & (LC\# \ 1019, \ ELEM\# \ 203830; \ p.A9-3) \\
\sigma_{us1,\text{max}} & := 13772 \text{ psi} & (LC\# \ 1019, \ ELEM\# \ 203830; \ p.A9-3)
\end{align*}
\]

+ For Landing condition:  
  (Stress contour plot shown in Figure 2.2.7-4)

\[
\begin{align*}
\sigma_{uu2,\text{max}} & := 23572 \text{ psi} & (LC\# \ 4019, \ ELEM\# \ 203830; \ p.A9-7) \\
\sigma_{uy2,\text{max}} & := 21068 \text{ psi} & (LC\# \ 4019, \ ELEM\# \ 203830; \ p.A9-7) \\
\sigma_{us2,\text{max}} & := 11786 \text{ psi} & (LC\# \ 4019, \ ELEM\# \ 203830; \ p.A9-7)
\end{align*}
\]

+ For On-Orbit condition:  
  (Stress contour plot shown in Figure 2.2.7-5)

\[
\begin{align*}
\sigma_{uu3,\text{max}} & := 25377 \text{ psi} & (LC\# \ 200008, \ ELEM\# \ 203779; \ p.A9-13) \\
\sigma_{uy3,\text{max}} & := 22971 \text{ psi} & (LC\# \ 200008, \ ELEM\# \ 203779; \ p.A9-13) \\
\sigma_{us3,\text{max}} & := 12688 \text{ psi} & (LC\# \ 200008, \ ELEM\# \ 203779; \ p.A9-13)
\end{align*}
\]

The values shown above are maximum stresses.

Note that higher stresses in solid elements can be found in Appendix A9 (p.A9-11 & 12, pp.A9-15 - A9.19). These values are bold. The stresses are artificially high due to RBE2 connection. Therefore, they are not used to perform the stress analysis of PAS-RICH Bracket.
Margins of Safety,

+ For Launch condition:

\[ MS_{u1} := \frac{F_{u1,a}}{F_{Su1} \cdot \sigma_{u1,\text{max}}} - 1 \]

\[ MS_{u1} = 0.63 \]

\[ MS_{y1} := \frac{F_{y1,a}}{F_{Sy1} \cdot \sigma_{uy1,\text{max}}} - 1 \]

\[ MS_{y1} = 1.07 \]

\[ MS_{s1} := \frac{F_{su1,a}}{F_{Su1} \cdot \sigma_{us1,\text{max}}} - 1 \]

\[ MS_{s1} = 1.1 \]

+ For Landing condition:

\[ MS_{u2} := \frac{F_{u2,a}}{F_{Su2} \cdot \sigma_{u2,\text{max}}} - 1 \]

\[ MS_{u2} = 0.71 \]

\[ MS_{y2} := \frac{F_{y2,a}}{F_{Sy2} \cdot \sigma_{uy2,\text{max}}} - 1 \]

\[ MS_{y2} = 1.26 \]

\[ MS_{s2} := \frac{F_{su2,a}}{F_{Su2} \cdot \sigma_{us2,\text{max}}} - 1 \]

\[ MS_{s2} = 1.19 \]

+ For On-Orbit condition:

\[ MS_{u3} := \frac{F_{u3,a}}{F_{Su3,\text{o}} \cdot \sigma_{u3,\text{max}}} - 1 \]

\[ MS_{u3} = 0.12 \]

\[ MS_{y3} := \frac{F_{y3,a}}{F_{Sy3,\text{o}} \cdot \sigma_{uy3,\text{max}}} - 1 \]

\[ MS_{y3} = 0.85 \]

\[ MS_{s3} := \frac{F_{su3,a}}{F_{Su3,\text{o}} \cdot \sigma_{us3,\text{max}}} - 1 \]

\[ MS_{s3} = 0.44 \]
Figure 2.2.7-3: Stress Contour Plot of PAS-RICH Brackets in Launch Condition
Figure 2.2.7-4: Stress Contour Plot of PAS-RICH Brackets in Landing Condition
Figure 2.2.7-5: Stress Contour Plot of PAS-RICH Brackets in On-Orbit Condition

High Stress Area
Element ID# 203779
LC# 200008
2.2.8 Lower Angle Beam Flange
The Lower Angle Beam Flange is part of the Lower Center Body Assembly. Section 2.2.1 of this report covers the Lower Center Body Assembly, where both the Lower Centerbody Joint and the Lower Angle Beam flange is analyzed.

The Lower Centerbody Assembly is shown in the USS-02 Assembly in figure 2.2.8-1. The Lower Angle Beam Flange is shown in Figure 2.2.8-2.

![Lower Centerbody Assembly Diagram](image-url)
The Lower Angle Beam Flange is made of 7050-T7451, per BMS-7-323C

Looking at the contour plots on pages 2.2.1-15 thru 2.2.1-17, high stresses in the Lower Center Body Assembly occur in the Lower Angle Beam Flange.

From page 2.2.1-14, the minimum margins are:
- MSu = 0.185 max principal, Load Case 2058
- MSy = 0.397 max yield (von mises), Load Case 2015
- MSs = 0.44 max shear, Load Case 2015

Factors of safety are:
- FSu = 1.4 ultimate
- FSy = 1.1 yield
2.3 Keel Assembly
2.3.1 Keel Angle Joint
PART: 4.5"x4.5" Tube, 1/4 in. Thick,
From 6" Plate

Beam Cross Section

\[
t := 0.25 \text{ in} \quad \text{Tube thickness}
\]
\[
a := 4.5 \text{ in} \quad \text{Cross sectional height}
\]
\[
b := a - 2 \cdot t \quad \text{Internal height}
\]
\[
A := 4.09 \text{ in}^2 \quad \text{Cross-sectional area, Ref.Steel Manual, p3-43}
\]
\[
A_m := (a - t)^2 \quad A_m = 18.063 \text{in}^2 \quad \text{Enclosure area}
\]
\[
I_y := 12.1 \text{in}^4 \quad c_z := 2.25 \text{in} \quad \text{(Reference Structural Steel Manual, p. 3-43)}
\]
\[
I_z := 12.1 \text{in}^4 \quad c_y := 2.25 \text{in}
\]

ANALYSIS:
Shear and Bending, (Based on local beam coordinate system)

Loads: The highest axial forces and moments were determined through the "naspost" subroutine. The top two load cases, one with the highest bending moment and other with the highest axial load, were used to calculated the minimum Margin of Safety (Reference Subcases 2037 and 2045, ID 1306 and 1305, Appendix A7-4 and A7-6).

\[
F_z := -1385 \cdot \text{lbf}
\]
\[
F_y := -1083 \cdot \text{lbf}
\]
\[
P := 2.4118 \cdot 10^4 \cdot \text{lbf}
\]
\[
M_y := -3.4133 \cdot 10^4 \cdot \text{in-lbf}
\]
\[
M_z := -2.9256 \cdot 10^4 \cdot \text{in-lbf}
\]
\[
T := -728 \cdot \text{in-lbf}
\]
**Stresses on cross section:**

Normal is direct axial plus bending:

\[ \sigma := \frac{|P|}{A} + \frac{|M_y| \cdot c_x}{I_y} + \frac{|M_z| \cdot c_y}{I_z} \]

\[ \sigma = 1.768 \times 10^4 \text{ psi} \]

Shear due to tranverse loading:

\[ \tau_{\text{transv}} := \frac{\sqrt{F_x^2 + F_y^2}}{A} \]

\[ \tau_{\text{transv}} = 429.867 \text{ psi} \]

Shear due to torsion:

(Reference: Blodgett, Omer W., *Design of Welded Structures*, 1966; James F. Lincoln Arc Welding Foundation, pg. 2.10-2.)

\[ \tau_{\text{torsion}} := \frac{|T|}{\text{PMOD}} \]

\[ \tau_{\text{torsion}} = 80.609 \text{ psi} \]

Combined shear:

\[ \tau := \tau_{\text{transv}} + \tau_{\text{torsion}} \]

\[ \tau = 510.476 \text{ psi} \]

Maximum Shear Stress:

\[ \tau_{\text{max}} := \sqrt{\frac{1}{4} \sigma^2 + \tau^2} \]

\[ \tau_{\text{max}} = 8.857 \times 10^3 \text{ psi} \]

Principal Stresses:

\[ \sigma_{p1} := \frac{\sigma}{2} + \left[ \frac{\sigma}{2} + \tau \right] \]

\[ \sigma_{p1} = 1.77 \times 10^4 \text{ psi} \]

\[ \sigma_{p2} := \frac{\sigma}{2} - \left[ \frac{\sigma}{2} + \tau \right] \]

\[ \sigma_{p2} = -14.723 \text{ psi} \]

Maximum principal stress is:

\[ \sigma_{\text{max}} := \max(\sigma_{p1}, \sigma_{p2}) \]

\[ \sigma_{\text{max}} = 1.77 \times 10^4 \text{ psi} \]

Von-Mises Stress:

\[ \sigma_{\text{vm}} := \sqrt{(\sigma_{p1})^2 + (\sigma_{p2})^2 - \sigma_{p1} \sigma_{p2}} \]

\[ \sigma_{\text{vm}} = 1.771 \times 10^4 \text{ psi} \]
Material Properties: Al Alloy 7050-T7451, 6 in. Thk Plate. Thermal knockdown included
(Reference: MIL--HDBK-5H, Table 3.7.3.0(b1), Page 3-308)

\[ F_{tu} := 70000 - 0.92 \text{ psi} \quad F_{ty} := 60000 - 0.98 \text{ psi} \quad F_{su} := 43000 - 0.92 \text{ psi} \]

Factors of safety:

\[ F_{Su} := 1.4 \quad F_{Sy} := 1.1 \]

Margins of safety:

Ultimate (using principal)

\[ MS_u := \left( \frac{F_{tu}}{F_{Su} \cdot \sigma_{max}} \right) - 1 \]

\[ MS_u = 1.599 \]

Yield (using Von-Mises)

\[ MS_y := \left( \frac{F_{ty}}{F_{Sy} \cdot \sigma_{vm}} \right) - 1 \]

\[ MS_y = 2.019 \]

Shear

\[ MS_{\tau} := \left( \frac{F_{su}}{F_{Su} \cdot \tau_{max}} \right) - 1 \]

\[ MS_{\tau} = 2.19 \]
2.3.2 Keel Block
Margins of Safety

Table 2.3.2-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135770</td>
<td>Keel Block Assembly, Keel Assembly</td>
<td>AL ALY 7050-T7451</td>
<td>Launch</td>
<td>Max Prin. Stress</td>
<td>0.63 (u)</td>
<td>2.3.2-13</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. Boundary condition is at five Trunnion locations.
3. All 192 load cases of Launch and Landing are applied.
4. u = ultimate, y = yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing.

Description of Structure

Figure 2.3.2-1 below shows the location of Keel Block in AMS-02. The Block was machined out of 7050-T7451 Aluminum Alloy plate. Part of the Block was riveted to Keel Tubes. The Keel Trunnion was also mounted to Keel Block.

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built of the Keel Block hardware using FEMAP software.

1. Parts were mainly modeled as CHEXA and CPENTA solid elements.
2. The contact surfaces of Keel Tube and Keel Trunnion to Keel Block are represented by RBE2 rigid elements with DOF’s 1-6.

The model of Keel Block was then imported into USS7-03 load model.

Figure 2.3.2-2: FEMAP Model of Keel Block
The model was then constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.3.2-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5.

All 192 load cases for Launch and Landing were applied.

MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02.

Solid stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in Keel Block.

Table below shows detail of model inputs.

Table 2.3.2-2: Inputs of Finite Element Model of Keel Block

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>TYPE</th>
<th>PROP</th>
<th>MATL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keel Block</td>
<td>200,001 - 220,981</td>
<td>200,001 - 223,667</td>
<td>solid</td>
<td>200,001</td>
<td>200,001</td>
</tr>
<tr>
<td>RBE2 connection</td>
<td>223,668 - 223,737</td>
<td></td>
<td>rigid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG  (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.005562E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.503818E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.400719E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.999544E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>8.180187E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>3.117114E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN  (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.793212E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.522567E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>8.568881E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>3.527135E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.834738E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>4.322931E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN+AUTO (N+AUTOSPC-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.793212E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.522567E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>8.568881E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>3.527135E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.834738E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>4.322931E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
---------- -------------  ---------
 1  7.793212E-06    PASS
 2  2.522567E-06    PASS
 3  8.568881E-07    PASS
 4  3.527135E-04    PASS
 5  1.834738E-05    PASS
 6  4.322931E-04    PASS

RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
---------- -------------  ---------
 1  7.793212E-06    PASS
 2  2.522567E-06    PASS
 3  8.568881E-07    PASS
 4  3.527135E-04    PASS
 5  1.834738E-05    PASS
 6  4.322931E-04    PASS

A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 2.3.2-3: Eigenvalues of Finite Element Model of Keel Block

<table>
<thead>
<tr>
<th>NO.</th>
<th>ORDER</th>
<th>EXTRATION</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.08E-04</td>
<td>1.04E-02</td>
<td>1.65E-03</td>
<td>1.00E+00</td>
<td>-1.08E-04</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-4.72E-05</td>
<td>6.87E-03</td>
<td>1.09E-03</td>
<td>1.00E+00</td>
<td>-4.72E-05</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-2.07E-05</td>
<td>4.55E-03</td>
<td>7.25E-04</td>
<td>1.00E+00</td>
<td>-2.07E-05</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1.49E-06</td>
<td>1.22E-03</td>
<td>1.95E-04</td>
<td>1.00E+00</td>
<td>1.49E-06</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>3.69E-05</td>
<td>6.08E-03</td>
<td>9.67E-04</td>
<td>1.00E+00</td>
<td>3.69E-05</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1.99E-04</td>
<td>1.41E-02</td>
<td>2.25E-03</td>
<td>1.00E+00</td>
<td>1.99E-04</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3.28E+07</td>
<td>5.72E+03</td>
<td>9.11E+02</td>
<td>1.00E+00</td>
<td>3.28E+07</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>6.82E+07</td>
<td>8.26E+03</td>
<td>1.31E+03</td>
<td>1.00E+00</td>
<td>6.82E+07</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>7.58E+07</td>
<td>8.71E+03</td>
<td>1.39E+03</td>
<td>1.00E+00</td>
<td>7.58E+07</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.27E+08</td>
<td>1.13E+04</td>
<td>1.79E+03</td>
<td>1.00E+00</td>
<td>1.27E+08</td>
<td></td>
</tr>
</tbody>
</table>
Additional check is comparison of the interface loads between the load model and the detail model. The loads are picked randomly. Loads in both models are closely matched.

**Table 2.3.2-4: Interface loads (lbf) in Load Model 2-04**

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-10265.5</td>
<td>-4218.5</td>
<td>9910.0</td>
<td>7635.5</td>
<td>-785.8</td>
<td>987.6</td>
<td>-3250.9</td>
<td>1119.0</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>19044.8</td>
<td>-16766.0</td>
<td>3404.8</td>
<td>2433.2</td>
<td>-12722.8</td>
<td>7581.0</td>
<td>-11633.1</td>
<td>-519.6</td>
</tr>
<tr>
<td>2033(Fz)</td>
<td>-1601.8</td>
<td>-1942.0</td>
<td>645.2</td>
<td>-437.5</td>
<td>-6117.5</td>
<td>-9489.8</td>
<td>-3363.9</td>
<td>5239.9</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-1910.6</td>
<td>1228.8</td>
<td>-2868.4</td>
<td>-4166.4</td>
<td>7219.1</td>
<td>5784.0</td>
<td>3041.0</td>
<td>6638.5</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-543.2</td>
<td>11872.4</td>
<td>8070.0</td>
<td>-3118.7</td>
<td>-1324.4</td>
<td>-7806.0</td>
<td>-6032.6</td>
<td>3874.0</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>-3360.5</td>
<td>-834.1</td>
<td>-187.7</td>
<td>1137.0</td>
<td>13878.8</td>
<td>15033.1</td>
<td>21524.6</td>
<td>21524.6</td>
</tr>
</tbody>
</table>

**Table 2.3.2-5: Interface loads (lbf) in Keel-Block Model**

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-10205.2</td>
<td>-4178.2</td>
<td>9881.9</td>
<td>7602.6</td>
<td>-771.5</td>
<td>982.3</td>
<td>-3232.2</td>
<td>1118.7</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>19032.8</td>
<td>-16667.3</td>
<td>3398.6</td>
<td>2435.0</td>
<td>-12715.2</td>
<td>7581.8</td>
<td>-11624.2</td>
<td>-524.6</td>
</tr>
<tr>
<td>2033(Fz)</td>
<td>-1601.3</td>
<td>-1944.3</td>
<td>643.9</td>
<td>-437.6</td>
<td>-6115.7</td>
<td>-9485.5</td>
<td>-3366.4</td>
<td>5240.1</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-1907.9</td>
<td>1231.8</td>
<td>-2869.8</td>
<td>-4167.2</td>
<td>7212.2</td>
<td>5781.8</td>
<td>3043.6</td>
<td>6637.6</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-541.9</td>
<td>11875.5</td>
<td>8071.5</td>
<td>-3117.9</td>
<td>-1316.2</td>
<td>-7819.1</td>
<td>-6032.0</td>
<td>3872.7</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>-3361.7</td>
<td>-834.2</td>
<td>-189.1</td>
<td>1137.0</td>
<td>13883.4</td>
<td>15034.2</td>
<td>21519.2</td>
<td>21519.2</td>
</tr>
</tbody>
</table>

**Table 2.3.2-6: Load Differences (lbf) Between Two Models**

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-60.3</td>
<td>-40.3</td>
<td>28.1</td>
<td>32.9</td>
<td>-14.3</td>
<td>5.3</td>
<td>-18.7</td>
<td>0.4</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>12.0</td>
<td>-8.7</td>
<td>6.2</td>
<td>-1.8</td>
<td>-7.7</td>
<td>-0.8</td>
<td>-8.8</td>
<td>4.9</td>
</tr>
<tr>
<td>2033(Fz)</td>
<td>-0.5</td>
<td>2.3</td>
<td>1.3</td>
<td>-0.1</td>
<td>-1.8</td>
<td>-4.2</td>
<td>2.6</td>
<td>-0.3</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-2.6</td>
<td>-3.0</td>
<td>1.4</td>
<td>0.8</td>
<td>6.9</td>
<td>2.1</td>
<td>-2.5</td>
<td>0.9</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-1.3</td>
<td>-3.1</td>
<td>-1.5</td>
<td>-0.8</td>
<td>-8.2</td>
<td>13.0</td>
<td>-0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>1.2</td>
<td>0.1</td>
<td>1.3</td>
<td>0.1</td>
<td>-4.6</td>
<td>-2.8</td>
<td>-1.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

**Note:**

1. Negative sign in Table 2.3.2-6 means load in Keel-Block model greater than in Load model.
Material and Temperature

The Keel Block is 7050-T7451 Aluminum Alloy. Material property of 7050-T7451 are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5H. Temperature limits are based upon ICD-2-19001 (Shuttle Orbiter / Cargo Standard Interfaces), Revision-L. For Launch condition, the temperature of 150°F is applied. For Landing condition, the temperature of 220°F is applied.

Analysis

The critical stresses for the Keel Block are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. All margins of safety are positive.
Check of Keel Block

Material Properties: 7050-T7451 AL ALY, BMS 7-323C or AMS 4050

\[
\begin{align*}
F_{tu} & := 67000 \text{psi} \\
F_{ty} & := 57000 \text{psi} \\
F_{su} & := 43000 \text{psi}
\end{align*}
\]

Factors of Safety:

\[
\begin{align*}
FS_u & := 1.4 \\
FS_y & := 1.1
\end{align*}
\]

(For Launch and Landing conditions)

Table below was drawn from ICD-2-19001, 04-MAR-99. Maximum temperatures of 150°F and 220°F for Launch and Landing respectively are selected in the analysis.

**TABLE 6.1.4.1-1 CARGO BAY WALL TEMPERATURE**

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>1. Prelaunch (1)</td>
<td>+40°F</td>
</tr>
<tr>
<td>2. Launch (1)</td>
<td>+40°F</td>
</tr>
<tr>
<td>3. On-Orbit (doors open) (2) (4)</td>
<td>-250°F</td>
</tr>
<tr>
<td>4. Entry and Post-landing (3) (4)</td>
<td>-50°F</td>
</tr>
</tbody>
</table>
Temperature reduction factors, (Ref. MIL-HDBK-5H, Figure 3.7.3.2.1)

- At 150°F for Launch condition:
  - Ultimate: \( \gamma_{u1} = 0.91 \)
  - Yield: \( \gamma_{y1} = 0.97 \)

- At 220°F for Landing condition:
  - Ultimate: \( \gamma_{u2} = 0.82 \)
  - Yield: \( \gamma_{y2} = 0.90 \)

Allowable stresses due to Temperature Reduction Factors:

+ For Launch condition:

\[
F_{tu1,a} := \gamma_{u1} \cdot F_{tu}
\]
\[
F_{tu1,a} = 60970 \text{ psi}
\]
\[
F_{ty1,a} := \gamma_{y1} \cdot F_{ty}
\]
\[
F_{ty1,a} = 55290 \text{ psi}
\]
\[
F_{su1,a} := \gamma_{u1} \cdot F_{su}
\]
\[
F_{su1,a} = 39130 \text{ psi}
\]

+ For Landing condition:

\[
F_{tu2,a} := \gamma_{u2} \cdot F_{tu}
\]
\[
F_{tu2,a} = 54940 \text{ psi}
\]
\[
F_{ty2,a} := \gamma_{y2} \cdot F_{ty}
\]
\[
F_{ty2,a} = 51300 \text{ psi}
\]
\[
F_{su2,a} := \gamma_{u2} \cdot F_{su}
\]
\[
F_{su2,a} = 35260 \text{ psi}
\]
Maximum Von-Mises, Principal, and Shear stresses of solid elements are selected from 192 load cases for Launch and Landing. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

+ For Launch condition:  
  (Stress contour plot shown in Figure 2.3.2-3)

\[
\sigma_{uu1\text{max}} := 26748 \text{ psi} \quad (LC\# \ 1056, \ ELEM\# \ 219048; \ p.A10-4)
\]

\[
\sigma_{uy1\text{max}} := 22777 \text{ psi} \quad (LC\# \ 1056, \ ELEM\# \ 222463; \ p.A10-5)
\]

\[
\sigma_{us1\text{max}} := 12895 \text{ psi} \quad (LC\# \ 1056, \ ELEM\# \ 222463; \ p.A10-7)
\]

+ For Landing condition:  
  (Stress contour plot shown in Figure 2.3.2-4)

\[
\sigma_{uu2\text{max}} := 17424 \text{ psi} \quad (LC\# \ 4050, \ ELEM\# \ 219048; \ p.A10-12)
\]

\[
\sigma_{uy2\text{max}} := 15028 \text{ psi} \quad (LC\# \ 4053, \ ELEM\# \ 218863; \ p.A10-16)
\]

\[
\sigma_{us2\text{max}} := 8378 \text{ psi} \quad (LC\# \ 4050, \ ELEM\# \ 222463; \ p.A10-15)
\]

The values shown above are maximum stresses.

Note that higher stresses can be found in Appendix A10. These values are bold. The stresses are artificially high due to RBE2 connection. Therefore, they are not used to perform the stress analysis of Keel Block.
Margins of Safety,

+ For Launch condition:

\[
MS_{u1} := \frac{F_{u1,a}}{FS_u\sigma_{uu1.max}} - 1 \quad MS_{u1} = 0.63
\]

\[
MS_{y1} := \frac{F_{y1,a}}{FS_y\sigma_{uy1.max}} - 1 \quad MS_{y1} = 1.21
\]

\[
MS_{s1} := \frac{F_{su1,a}}{FS_u\sigma_{us1.max}} - 1 \quad MS_{s1} = 1.17
\]

+ For Landing condition:

\[
MS_{u2} := \frac{F_{u2,a}}{FS_u\sigma_{uu2.max}} - 1 \quad MS_{u2} = 1.25
\]

\[
MS_{y2} := \frac{F_{y2,a}}{FS_y\sigma_{uy2.max}} - 1 \quad MS_{y2} = 2.1
\]

\[
MS_{s2} := \frac{F_{su2,a}}{FS_u\sigma_{us2.max}} - 1 \quad MS_{s2} = 2.01
\]
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peter Hoang</td>
<td>05/11/05</td>
<td>keelbk.mcd</td>
</tr>
<tr>
<td>Checked By</td>
<td>John Krejci</td>
<td>05/27/05</td>
<td></td>
</tr>
</tbody>
</table>

**Title**

AMS-02 KEEL BLOCK

**High Stress Area**

Maximum "true" stress = 26748 psi
Element ID# 219048
LC# 1056

---

**Figure 2.3.2-3: Stress Contour Plot of Keel Block in Launch Condition**

2.3.2-14 ESCG-4005-05-AMS-0039
Figure 2.3.2-4: Stress Contour Plot of Keel Block in Landing Condition

High Stress Area
Maximum "true" stress = 17424 psi
Element ID# 219048
LC# 4050
2.3.3 Keel Tube
Keel Tube

Drawings no.: SDG39135771
Units used: in, lbf

The objective of this analysis is to demonstrate the structural strength of the Keel Tube. The Keel Tube (SDG39135771) is mounted between the Keel Angle Joint (SDG39135769) and Keel Block (SDG39135770).

Figure 2.3.3-1 Keel Tube
Factor of Safety,  
FS := 1.4

Material:  AL 7075-T73511  (Ref. MIL-HDBK-5J, Table 3.7.6.0(g2). Thickness: 0.250-0.499)

The Expected temperature range is -56 to +181F (Ref. Appendix C2). Temperature de-rating is applied.

Compressive modulus,  
Ec := 10700000-0.97·psi  
Ec = 1.038 × 10^7 psi

Ultimate tensile strength,  
ftu := 68000-0.92·psi  
ftu = 6.256 × 10^4 psi

Tensile yield strength,  
fty := 57000-0.93·psi  
fty = 5.301 × 10^4 psi

Compression yield strength,  
fcy := 60000-0.95·psi  
fcy = 5.7 × 10^4 psi

Ultimate shear strength,  
fsu := 38000-0.98·psi  
fsu = 3.724 × 10^4 psi

Section: 4.0'' x 4.0'' x 0.25'' Tube  (Ref. SDG39135771)

Shape Factor,  

Unsupported length,  
L := 19.035 in

Width,  
Dy := 4 in

Depth,  
Dz := 4 in

Thickness,  
t := 0.25 in

Define:  
b := 2·t

Properties of cross-section:

Outer base:  
bo = 4 in

Inner base:  
bi = 3.5 in

Outer height:  
do = 4 in

Inner height:  
di = 3.5 in

Area,  
A := bo·do − bi·di  
A = 3.75 in^2

Moment of Inertia,  
\[ I_y := \frac{bo·do^3 - bi·di^3}{12} \]  
\[ I_y = 8.828 \text{ in}^4 \]

\[ I_z := \frac{do·bo^3 - di·bi^3}{12} \]  
\[ I_z = 8.828 \text{ in}^4 \]

First moments for shear stress calculation  
\[ Q_z := do·t \left( \frac{bo}{2} - \frac{t}{2} \right) + \left( \frac{bo}{2} - t \right)^2 \cdot t \]  
\[ Q_z = 2.641 \text{ in}^3 \]
Keel Tube

\[ Q_y := \text{bo} \cdot t \left( \frac{\text{do}}{2} - \frac{t}{2} \right) + \left( \frac{\text{do}}{2} - \frac{t}{2} \right)^2 \cdot t \]

\[ Q_y = 2.641 \text{ in}^3 \]

**Section modulus,**

\[ S_y := \frac{1}{4} \cdot \frac{I_y}{D_z} \]

\[ S_z := \frac{1}{4} \cdot \frac{I_z}{D_y} \]

\[ S_y = 4.414 \text{ in}^3 \]

\[ S_z = 4.414 \text{ in}^3 \]

**Torsional constant / distance,**

\[ J_o R := 2 \cdot t \cdot (D_z - t) \cdot (D_y - t) \]

\[ J_o R = 7.031 \text{ in}^3 \]

**Radii of gypration,**

\[ r_y := \sqrt{\frac{I_y}{A}} \]

\[ r_z := \sqrt{\frac{I_z}{A}} \]

\[ r_y = 1.534 \text{ in} \]

\[ r_z = 1.534 \text{ in} \]

**Fixity coefficient, (pin-ended)**

\[ K := 1.0 \]

\( K = 1.0 \)  

*(Ref. Structural Engineering Handbook, 4th Edition, Figure 5, p.8-10)*

**Slenderness ratios,**

\[ S_R y := \frac{K \cdot L}{r_y} \]

\[ S_R y = 12.406 \]

\[ S_R z := \frac{K \cdot L}{r_z} \]

\[ S_R z = 12.406 \]

**Constants depending upon the mechanical properties of the material from Ref. Structural Engineering Handbook, 4th Edition, Formulas 5a-c, p.11-6:**

\[ B_c := f_{c_y} \left[ 1 + \left( \frac{f_{c_y}}{225000 \cdot \text{psi}} \right)^2 \right] \]

\[ B_c = 66072 \text{ psi} \]

\[ D_c := \frac{B_c}{10} \left( \frac{B_c}{E_c} \right)^{\frac{1}{2}} \]

\[ D_c = 527 \text{ psi} \]

\[ C_c := \frac{0.41 \cdot 2B_c}{3D_c} \]

\[ C_c = 34.258 \]
Compression allowables:

\[
F_{cy} := \begin{cases} 
  Bc - Dc \cdot S\!R_y & \text{if } S\!R_y \leq Cc \\
  Ec \left( \frac{\pi}{S\!R_y} \right)^2 & \text{otherwise}
\end{cases}
F_{cy} = 59532 \text{ psi}
\]

\[
F_{cz} := \begin{cases} 
  Bc - Dc \cdot S\!R_z & \text{if } S\!R_z \leq Cc \\
  Ec \left( \frac{\pi}{S\!R_z} \right)^2 & \text{otherwise}
\end{cases}
F_{cz} = 59532 \text{ psi}
\]


\[
F_{ey} := \frac{102000000 \cdot \text{psi}}{FS \cdot S\!R_y^2}
F_{ey} = 473373 \text{ psi}
\]

\[
F_{ez} := \frac{102000000 \cdot \text{psi}}{FS \cdot S\!R_z^2}
F_{ez} = 473373 \text{ psi}
\]

Ultimate shear allowables:

(Ref. Roark's formulas for stress and strain, pp.95)

\[
V_{ulty} := \frac{f_{su} \cdot I_z \cdot b}{Q_z}
V_{ulty} = 62250 \text{ lbf}
\]

\[
V_{ultz} := \frac{f_{su} \cdot I_y \cdot b}{Q_y}
V_{ultz} = 62250 \text{ lbf}
\]

Ultimate torsion allowable:

(Ref. Roark's formulas for stress and strain, 6th Edition, table20, case 16)

\[
T_{ult} := \frac{f_{su} \cdot \text{JoR}}{f_{ty}}
T_{ult} = 261844 \text{ in-lbf}
\]

Axial tensile allowable:

\[
Pt := \frac{f_{tu} \cdot A}{f_{ty}}
Pt = 234600 \text{ lbf}
\]

Axial compression allowable:

\[
P_{cr} := \begin{cases} 
  F_{cz} \cdot A & \text{if } F_{cy} \geq F_{cz} \\
  F_{cy} \cdot A & \text{otherwise}
\end{cases}
P_{cr} = 223246 \text{ lbf}
\]

Ultimate bending allowables:

\[
M_{ulty} := Sy \cdot \left[ f_{tu} + \left( f_0 - 1 \right) \cdot f_{ty} \right]
M_{ulty} = 327621 \text{ in-lbf}
\]

\[
M_{ultz} := Sz \cdot \left[ f_{tu} + \left( f_0 - 1 \right) \cdot f_{ty} \right]
M_{ultz} = 327621 \text{ in-lbf}
\]

Combined bending and axial allowables:

\[
P_{ey} := \frac{F_{ey} \cdot A}{f_{ty}}
P_{ey} = 1775149 \text{ lbf}
\]

\[
P_{ez} := \frac{F_{ez} \cdot A}{f_{ty}}
P_{ez} = 1775149 \text{ lbf}
\]
NASPOST was used to list all element loads of Keel Tube in the file named "bucklgnl.lis". The file is located at /hsm/bsommer/ams/naspost/uss/2-03/ (Ref. Appendix A2 for NASPOST sort).

File "keel.txt" used in Mathcad was generated from "lbucklgnl.lis" by removing all texts and comments.

\[
\text{load} := \text{READPRN}("keel.txt") \quad \text{i} := 1 \ldots \text{rows(load)}
\]

Element ID: \( \text{ID} := \text{load}^{1} \) \quad Load case number: \( \text{LC} := \text{load}^{2} \)

+ At end A of beam element:

- **Moment:** \( \text{M1a} := \text{load}^{3} \cdot \text{in-lbf} \) \quad \( \text{M2a} := \text{load}^{4} \cdot \text{in-lbf} \)
- **Shear force:** \( \text{V1a} := \text{load}^{5} \cdot \text{lbf} \) \quad \( \text{V2a} := \text{load}^{6} \cdot \text{lbf} \)
- **Axial force:** \( \text{Pa} := \text{load}^{7} \cdot \text{lbf} \)
- **Total torque:** \( \text{Toa} := \text{load}^{8} \cdot \text{in-lbf} \)
- **Warp torque:** \( \text{Warpa} := \text{load}^{9} \cdot \text{in-lbf} \)

+ At end B of beam element:

- **Moment:** \( \text{M1b} := \text{load}^{10} \cdot \text{in-lbf} \) \quad \( \text{M2b} := \text{load}^{11} \cdot \text{in-lbf} \)
- **Shear force:** \( \text{V1b} := \text{load}^{12} \cdot \text{lbf} \) \quad \( \text{V2b} := \text{load}^{13} \cdot \text{lbf} \)
- **Axial force:** \( \text{Pb} := \text{load}^{14} \cdot \text{lbf} \)
- **Total torque:** \( \text{Tob} := \text{load}^{15} \cdot \text{in-lbf} \)
- **Warp torque:** \( \text{Warpb} := \text{load}^{16} \cdot \text{in-lbf} \)
Modify end torque by subtracting warping torque:

\[ T_{ai} := \left| T_{oa_i} \right| - \left| \text{Warpa}_i \right| \]

\[ T_{bi} := \left| T_{ob_i} \right| - \left| \text{Warpb}_i \right| \]

Shear ratios:

\[ R_{Sa_i} := \frac{\left| V_{1a_i} \right|}{V_{ulty}} + \frac{\left| V_{2a_i} \right|}{V_{ultz}} + \frac{T_{ai}}{T_{ult}} \]

\[ R_{Sb_i} := \frac{\left| V_{1b_i} \right|}{V_{ulty}} + \frac{\left| V_{2b_i} \right|}{V_{ultz}} + \frac{T_{bi}}{T_{ult}} \]

Tensile ratio at end A:

\[ R_{Ta_i} := \left( \frac{\left| P_{a_i} \right|}{1 - \frac{\left| P_{a_i} \right|}{P_{cr}} \cdot \frac{1}{1 - \frac{\left| P_{a_i} \right|}{P_{e}}}} + \frac{\left| M_{2a_i} \right|}{\text{Multy}} + \frac{\left| M_{1a_i} \right|}{\text{Multz}} \right) \right) \quad \text{if } \left| P_{a_i} \right| \geq 0\text{-lbf} \]

\[ R_{Ta_i} := \left( \frac{\left| P_{a_i} \right|}{1 - \frac{\left| P_{a_i} \right|}{P_{cr}} \cdot \frac{1}{1 - \frac{\left| P_{a_i} \right|}{P_{e}}}} + \frac{\left| M_{2a_i} \right|}{\text{Multy}} + \frac{\left| M_{1a_i} \right|}{\text{Multz}} \right) \quad \text{otherwise} \]

Tensile ratio at end B:

\[ R_{Tb_i} := \left( \frac{\left| P_{b_i} \right|}{1 - \frac{\left| P_{b_i} \right|}{P_{cr}} \cdot \frac{1}{1 - \frac{\left| P_{b_i} \right|}{P_{e}}}} + \frac{\left| M_{2b_i} \right|}{\text{Multy}} + \frac{\left| M_{1b_i} \right|}{\text{Multz}} \right) \quad \text{if } \left| P_{b_i} \right| \geq 0\text{-lbf} \]

\[ R_{Tb_i} := \left( \frac{\left| P_{b_i} \right|}{1 - \frac{\left| P_{b_i} \right|}{P_{cr}} \cdot \frac{1}{1 - \frac{\left| P_{b_i} \right|}{P_{e}}}} + \frac{\left| M_{2b_i} \right|}{\text{Multy}} + \frac{\left| M_{1b_i} \right|}{\text{Multz}} \right) \quad \text{otherwise} \]

Combined Ratios:

\[ \text{RATIO}_{a_i} := \sqrt{\left( R_{Ta_i} \right)^2 + \left( R_{Sa_i} \right)^2} \]

\[ \text{RATIO}_{b_i} := \sqrt{\left( R_{Tb_i} \right)^2 + \left( R_{Sb_i} \right)^2} \]

\[ \text{RATIO}_{i} := \min \left( \text{RATIO}_{a_i}, \text{RATIO}_{b_i}, \text{RATIO}_{a_i}, \text{RATIO}_{b_i} \right) \]

Margin of Safety:

\[ M_{Si} := \frac{1}{\text{RATIO}_{i} \cdot \text{FS}} - 1 \quad \text{min}(MS) = 1.93 \]
The worst load case that yielded minimum margin of safety is shown below:

```
output := augment(ID, LC, MS)  sorted := csort(output, 3)

\left(\text{sorted}^T\right)^{\dagger} = (1303 \ 2037 \ 1.93)
```

Based upon the output of SORT function above, it reads:

```
Element ID = 1303
Load ID = 2037
MS = 1.93
```
2.3.4 Keel Trunnion
USS 02 Keel Trunnion Analysis

The objective of this analysis is to demonstrate the structural strength of the Keel Trunnion (SDG 39135772). The difference in minimum temperature (for launch, abort landing, and nominal landing) can change the friction coefficient and therefore affects the axial load in the trunnion. The Keel Trunnion analysis is performed three times, once for each of the following cases; launch, nominal landing, and abort landing.

Material Properties:

Material Custom 455, H1000 bar AMS5617 (Ref. MIL-HDBK-5J, table 2.6.4.0 (b))

- Ftu := 200·10^3·psi
- Fty := 185·10^3·psi
- Fsu := 124·10^3·psi
- Fbru := 409·10^3·psi
- Fbry := 343·10^3·psi
- Et := 28.9·10^6·psi
- ω := 0.28·lbf·in⁻³

Temp. correction factor, ult & yield:
(Ref. MIL-HDBK-5J, fig.2.6.4.2.1 and Appendix C2)

- Launch Temperatures (40 to 120 F): c1tu := 0.98, c1ty := .98
- Abort Landing Temp. (40 to 150 F): c2tu := 0.97, c2ty := .97
- Nominal Landing Temp. (-78 to 101 F): c3tu := 0.99, c3ty := .99

Geometry:

Section at edge of keel joint (Z= 314.20)

- Max. outer dia. of trunnion: dmax := 2.993-in (Ref. drawing SDG39135772)
- Min. outer diameter of trunnion: dto := 2.9905-in
- Inner diameter of trunnion: dt89 := 2.400-in + 0.005-in

\[ As := \frac{\pi \left( dto^2 - dt89^2 \right)}{4} \]

Area of cross-section

\[ As = 2.481 \text{ in}^2 \]
Moment of inertia
\[ I_s := \frac{\pi (d_{\text{to}}^4 - d_{\text{89}}^4)}{64} \quad I_s = 2.284 \text{ in}^4 \]

Factor of safety, ultimate \( F_{Su} := 1.40 \quad \text{Factor of safety, yield} \quad F_{Sy} := 1.10 \)

**Loads:**
The following NASPOST results were sorted for maximum forces in the y-direction for all trunnions. The keel trunnion has element ID 5 in the loads model (Ref. Appendix A2 for NASPOST sort):

++ + MAX Y LAUNCH TRUNNION FORCES ++ +

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>FX</th>
<th>FY</th>
<th>FZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1060</td>
<td>0.0000000E+00</td>
<td>2.411519E+04</td>
<td>0.0000000E+00</td>
</tr>
</tbody>
</table>

++ + MAX Y ABORT LANDING TRUNNION FORCES ++ +

<table>
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<th>SUBCASE</th>
<th>FX</th>
<th>FY</th>
<th>FZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2017</td>
<td>0.0000000E+00</td>
<td>9.118636E+03</td>
<td>0.0000000E+00</td>
</tr>
</tbody>
</table>

++ + MAX Y NOMLANDING TRUNNION FORCES ++ +

<table>
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<th>SUBCASE</th>
<th>FX</th>
<th>FY</th>
<th>FZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4051</td>
<td>0.0000000E+00</td>
<td>1.559590E+04</td>
<td>0.0000000E+00</td>
</tr>
</tbody>
</table>

**Launch Case:**
Max. load in y direction \( Pr := 24115.19 \text{ lbf} \) (Ref. AMS-02, loads model 2-04, Load case 1060, element ID 5, data file: maxtrunnionforces1000.lis)

The tolerances between the Tube and the Block are tight. Due to this tight tolerance, any side load transferred through the Tube to the Retainer would result in small deflections of the Retainer. This would result in the side load being reacted between the Tube and the Block due to these tight tolerances.

Moment arm from load to edge of keel joint \( d_2 := 5.8 \text{ in} + 0.5 \text{ in} \)
(Ref. CAD model for 5.8" dimension) \( d_2 = 6.3 \text{ in} \)
(Ref. Appendix C6 for the 0.5" dynamic excursion)
Max. bending moment at edge of keel joint \( Mb := Pr \cdot d_2 \quad Mb = 151925.7 \text{ in} \cdot \text{lbf} \)

Friction coefficient is assessed based on Figure 4.1.1.1-1 of NSTS-21000-IDD-ISS, Ref. Appendix C7.

\[ P := Pr = 24115 \text{ lbf} \]
\[ T := 40 \text{ deg} \) (It is conservative to use the minimum temperature (Ref. Appendix C2))
Friction coefficient \( \mu = 0.100 \)

Friction load 10\% of load \( Pf := Pr \cdot \mu \) \( Pf = 2411.5 \text{lbf} \)

Friction moment \( Mf := Pf \cdot \frac{dt_{max}}{2} \) \( Mf = 3608.8 \text{ in\cdotlbf} \)

Total moment \( M := Mb + Mf \) \( M = 155534.5 \text{ in\cdotlbf} \)

Applied limit stress in shaft \( \sigma l := \left( \frac{Mb \cdot dt_{max}}{2 \cdot Is} \right) \) \( \sigma l = 99554.7 \text{ psi} \)
Plastic bending allowable  (Ref.NASA TM X-73305,sect B.4.5)

**Section factor**

Outer radius \( r_o := \frac{d_{to}}{2} \) \( r_o = 1.495 \text{ in} \).

Inner radius \( r_i := \frac{d_{89}}{2} \) \( r_i = 1.202 \text{ in} \).

Area of semicircular segment \( A_{se} := \frac{\pi}{2} \left( r_o^2 - r_i^2 \right) \) \( A_{se} = 1.241 \text{ in}^2 \).

Distance of neutral axis from center line \( y_{bar} := \frac{4}{3 \cdot \pi} \left( \frac{r_o^3 - r_i^3}{r_o^2 - r_i^2} \right) \) \( y_{bar} = 0.862 \text{ in} \).

First moment of area \( Q := A_{se} \cdot y_{bar} \) \( Q = 1.069 \text{ in}^3 \).

Distance of extreme fiber from centerline of shaft \( c := \frac{d_{max}}{2} \) \( c = 1.496 \text{ in} \).

Section factor \( K := \frac{2 \cdot Q \cdot c}{I_s} \) \( K = 1.4016 \).

Allowable bending modulus of rupture ult. \( \sigma_p := 272000 \cdot \text{psi} \) (Ref.NASA TM X-73305, sect B.4.5, fig. B4.5.5.2-7).

Allowable bending modulus of rupture yld. \( \sigma_y := 200000 \cdot \text{psi} \).

**Check**

Section factor \( K := 1.698 \cdot \frac{\left( \frac{r_o^3 - r_i^3}{r_o^4 - r_i^4} \right)}{K = 1.4007} \) (Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6).

\( f_{mu} := 200000 \cdot \text{psi} \) \( f_{ou} := 192000 \cdot \text{psi} \) (Ref. Bruhn, table C3.2 page C3.11).

\( f_{my} := 176000 \cdot \text{psi} \) \( f_{oy} := 65000 \cdot \text{psi} \).

\( F_{bu} := f_{mu} + f_{ou} \cdot (K - 1) \) \( F_{bu} = 276942.5 \text{ psi} \) (Ref. Bruhn page C3.3, equation 3).

\( F_{by} := f_{my} + f_{oy} \cdot (K - 1) \) \( F_{by} = 202048.2 \text{ psi} \) (These numbers match the \( \sigma_p \) and \( \sigma_y \) closely).

Axial tension stress \( \sigma_a := \frac{P_f}{A_s} \) \( \sigma_a = 971.946 \text{ psi} \).

Shear stress \( \tau := \frac{P_r}{A_s} \) \( \tau = 9719.462 \text{ psi} \).
**Stress ratios, Ultimate**

Stress ratio in tension, ultimate  
\[ R_{au} := \frac{\sigma_a - FSu}{Ftu - c1tu} \]  
\[ R_{au} = 0.007 \]

Stress ratio in bending, ultimate  
\[ R_{bu} := \frac{\sigma_l - FSu}{Fbu - c1tu} \]  
\[ R_{bu} = 0.514 \]

Stress ratio in shear, ultimate  
\[ R_{su} := \frac{\tau - FSu}{Fsu - c1tu} \]  
\[ R_{su} = 0.112 \]

Margin of safety ultimate  
\[ MSu := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \]  
\[ MSu = 0.88 \]

**Stress ratios, Yield**

Stress ratio in tension, yield  
\[ R_{ay} := \frac{\sigma_a - FSy}{Fty - c1ty} \]  
\[ R_{ay} = 0.006 \]

Stress ratio in bending, yield  
\[ R_{by} := \frac{\sigma_l - FSy}{Fby - c1ty} \]  
\[ R_{by} = 0.553 \]

Stress ratio in shear, yield  
\[ R_{sy} := \frac{\tau - FSy}{0.5Fty - c1ty} \]  
\[ R_{sy} = 0.118 \]

Margin of safety, yield  
\[ MSy := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \]  
\[ MSy = 0.75 \]
Beam and Socket analysis - Launch Case

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

Resultant shear Load

\[ S := Pr \]

\[ S = 24115 \text{ lbf} \]

Moment at edge of sill joint

\[ M := Mb + Mf \]

\[ M = 155535 \text{ in}\cdot\text{lbf} \]

Length of overlap

\[ L := 3.874 \text{ in} \]

\[ \text{slm}_\text{ratio} := \text{if} \left( M = 0, 1000, \frac{L}{M} \right) \]

\[ \text{slm}_\text{ratio} = 0.601 \]

\[ \text{mls}_\text{ratio} := \text{if} \left( S = 0, 1000, \frac{M}{S\cdot L} \right) \]

\[ \text{mls}_\text{ratio} = 1.665 \]
Beam and Socket Coefficients
Note if abs(SL/M) <= 1, Ratio = SL/M, otherwise Ratio = M/SL.

Coefficients are:

- $K_a = 0.452$
- $K_s = 1.654$
- $K_m = 1.007$
- $K_1 = 8.403$
- $K_2 = 7.201$
Calculated values are then:

\[ w_1 := \begin{cases} \frac{K_1 \cdot M}{L^2} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ K_1 \cdot S & \text{otherwise} \end{cases} \]

\[ w_1 = 87080.7 \text{ lbf in} \]

\[ w_2 := \begin{cases} \frac{K_2 \cdot M}{L^2} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ K_2 \cdot S & \text{otherwise} \end{cases} \]

\[ w_2 = 74630.9 \text{ lbf in} \]

\[ a := K_a \cdot L \quad a = 1.749 \text{ in} \]

\[ \text{Max. shear} \quad S_{\text{max}} := \begin{cases} -\frac{K_s \cdot M}{L} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ -K_s \cdot S & \text{otherwise} \end{cases} \]

\[ S_{\text{max}} = -66392 \text{ lbf} \]

\[ \text{Max. Bending moment} \quad M_{\text{max}} := \begin{cases} 
\frac{K_m \cdot M}{L} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\
K_m \cdot S \cdot L & \text{otherwise} \end{cases} \]

\[ M_{\text{max}} = 156658.1 \text{ in-lbf} \]

Now check:

\[ S_c := \frac{w_1 - w_2}{2} \cdot L \quad S_c = 2.4 \times 10^4 \text{ lbf} \]

\[ M_c := \frac{-w_1 + 2 \cdot w_2}{6} \cdot L^2 \quad M_c = 155534.5 \text{ in-lbf} \]

\[ \text{Percent error: } S_{\text{percentdiff}} := \frac{S - S_c}{S} \quad S_{\text{percentdiff}} = -0\% \]

\[ M_{\text{percentdiff}} := \frac{M - M_c}{M} \quad M_{\text{percentdiff}} = 0\% \]
Actual Shear and Moment Distribution Inside Socket
In the following calculation, conservatively, the maximum values of the bending moment and shear are used.

Max. Shear  \[ S_{\text{max}} = -66392 \text{ lbf} \]
Max. Bending moment  \[ M_{\text{max}} = 156658.1 \text{ in-lbf} \] (see page 2.3.4-9)

Section properties (see page 2.3.4-2 and 3)

Area of cross-section  \[ A_s = 2.481 \text{ in}^2 \]
Moment of inertia  \[ I_s = 2.284 \text{ in}^4 \]
Section modulus  \[ S_1 = \frac{I_s}{d_{\text{max}}} \quad S_1 = 1.526 \text{ in}^3 \]

Stresses

Total moment  \[ M_{\text{socket}} := M_{\text{max}} \quad M_{\text{socket}} = 156658.1 \text{ in-lbf} \]
Bending Tensile stress  \[ \sigma := \frac{M_{\text{socket}}}{S_1} \quad \sigma = 102655.8 \text{ psi} \]
Shear stress  \[ \tau_{\text{soc}} := \frac{|S_{\text{max}}|}{A_s} \quad \tau_{\text{soc}} = 26758.9 \text{ psi} \]
Axial tension stress  \[ \sigma_a := \frac{P_f}{A_s} \quad \sigma_a = 971.946 \text{ psi} \]

Stress Ratios

Axial (ult)  \[ R_a := \frac{\sigma_a \cdot F_{\text{Su}}}{F_{\text{tu}} \cdot c_{\text{ltu}}} \quad R_a = 0.007 \]
Bending (ult)  \[ R_b := \frac{F_{\text{Su}} \cdot \sigma}{F_{\text{bu}} \cdot c_{\text{ltu}}} \quad R_b = 0.53 \]
Shear (ult)  \[ R_s := \frac{F_{\text{Su}} \cdot \tau_{\text{soc}}}{F_{\text{su}} \cdot c_{\text{ltu}}} \quad R_s = 0.308 \]
Axial (yld)  \[ R_{\text{ay}} := \frac{\sigma_a \cdot F_{\text{Sy}}}{F_{\text{ty}} \cdot c_{\text{lty}}} \quad R_{\text{ay}} = 0.006 \]
Bending (yld)  \[ R_{by} := \frac{F_{\text{Sy}} \cdot \sigma}{F_{\text{by}} \cdot c_{\text{lty}}} \quad R_{by} = 0.57 \]
Shear (yld)  \[ R_{sy} := \frac{F_{\text{Sy}} \cdot \tau_{\text{soc}}}{0.50F_{\text{ty}} \cdot c_{\text{lty}}} \quad R_{sy} = 0.325 \]
Margins of safety

Margin of safety ultimate

\[ MSu := \frac{1}{\sqrt{(Ra + Rb)^2 + Rs^2}} - 1 \]

\[ MSu = 0.62 \]

Margin of safety yield

\[ MSy := \frac{1}{\sqrt{(Ray + Rby)^2 + Rsy^2}} - 1 \]

\[ MSy = 0.51 \]

Nominal Landing Case:

Max. load in y direction

\[ Pr := 15595.9 \text{ lbf} \]

(Ref. AMS-02, loads model 2-04, Load case 4051, element ID 5, data file: maxtrunnionforces4000.lis)

The tolerances between the Tube and the Block are tight. Due to this tight tolerance, any side load transferred through the Tube to the Retainer would result in small deflections of the Retainer. This would result in the side load being reacted between the Tube and the Block due to these tight tolerances.

Moment arm from load to edge of keel joint

\[ d2 := 5.8 \text{ in} + 0.5 \text{ in} \]

(Ref. CAD model for 5.8" dimension)

\[ d2 = 6.3 \text{ in} \]

(Ref. Appendix C6 for the 0.5" dynamic excursion)

Max. bending moment at edge of keel joint

\[ Mb := Pr \cdot d2 \]

\[ Mb = 98254.2 \text{ in lbf} \]

Friction coefficient is assessed based on Figure 4.1.1.1-1 of NSTS-21000-IDD-ISS, Ref. Appendix C7.

\[ P := Pr \quad P = 15596 \text{ lbf} \]

\[ T := -56 \text{ deg} \quad \text{(It is conservative to use the minimum temperature (Ref. Appendix C2))} \]
Friction coefficient

\[ \mu = 0.168 \]

Friction load 17% of load

\[ Pf := Pr \cdot \mu \quad Pf = 2613.9 \text{ lbf} \]

Friction moment

\[ Mf := Pf \cdot \frac{dt_{\text{max}}}{2} \quad Mf = 3911.7 \text{ in-lbf} \]

Total moment

\[ M := Mb + Mf \quad M = 102165.8 \text{ in-lbf} \]

Applied limit stress in shaft

\[ \sigma_l := \left( \frac{Mb \cdot dt_{\text{max}}}{2 \cdot I_s} \right) \quad \sigma_l = 64384.5 \text{ psi} \]
Plastic bending allowable (Ref. NASA TM X-73305, sect B.4.5)

**Section factor**

Outer radius \( r_o := \frac{d_{to}}{2} \) \( r_o = 1.495 \text{ in} \)

Inner radius \( r_i := \frac{d_{89}}{2} \) \( r_i = 1.202 \text{ in} \)

Area of semicircular segment \( A_{se} := \frac{\pi}{2} \left( r_o^2 - r_i^2 \right) \) \( A_{se} = 1.241 \text{ in}^2 \)

Distance of neutral axis from center line \( y_{bar} := \frac{4}{3\pi} \left( \frac{r_o^3 - r_i^3}{r_o^2 - r_i^2} \right) \) \( y_{bar} = 0.862 \text{ in} \)

First moment of area \( Q := A_{se} y_{bar} \) \( Q = 1.069 \text{ in}^3 \)

Distance of extreme fiber from centerline of shaft \( c := \frac{d_{\text{max}}}{2} \) \( c = 1.496 \text{ in} \)

Section factor \( K := \frac{2Qc}{Is} \) \( K = 1.4016 \)

Allowable bending modulus of rupture ult. \( \sigma_p := 272000 \text{ psi} \) (Ref. NASA TM X-73305, sect B.4.5 fig. B4.5.5.2-7)

Allowable bending modulus of rupture yld. \( \sigma_y := 200000 \text{ psi} \)

**Check**

Section factor \( K := 1.698 \left( \frac{r_o^3}{r_o^4 - r_i^4} \right) \) \( K = 1.4007 \) (Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)

\( f_{mu} := 200000 \text{ psi} \) \( f_{ou} := 192000 \text{ psi} \) (Ref. Bruhn, table C3.2 page C3.11)

\( f_{my} := 176000 \text{ psi} \) \( f_{oy} := 65000 \text{ psi} \)

\( F_{bu} := f_{mu} + f_{ou}(K - 1) \) \( F_{bu} = 276942.5 \text{ psi} \) (Ref. Bruhn page C3.3, equation 3)

\( F_{by} := f_{my} + f_{oy}(K - 1) \) \( F_{by} = 202048.2 \text{ psi} \) (These numbers match the \( \sigma_p \) and \( \sigma_y \) closely)

Axial tension stress \( \sigma_a := \frac{P_f}{A_s} \) \( \sigma_a = 1053.503 \text{ psi} \)

Shear stress \( \tau := \frac{P_r}{A_s} \) \( \tau = 6285.82 \text{ psi} \)
Stress ratios, Ultimate

Stress ratio in tension, ultimate \[ R_{au} := \frac{\sigma_a - F_{Su}}{F_{tu} - c_{3tu}} \quad R_{au} = 0.007 \]

Stress ratio in bending, ultimate \[ R_{bu} := \frac{\sigma_l - F_{Su}}{F_{bu} - c_{3tu}} \quad R_{bu} = 0.329 \]

Stress ratio in shear, ultimate \[ R_{su} := \frac{\tau - F_{Su}}{F_{su} - c_{3tu}} \quad R_{su} = 0.072 \]

Margin of safety ultimate \[ MS_{u} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \quad MS_{u} = 1.91 \]

Stress ratios, Yield

Stress ratio in tension, yield \[ R_{ay} := \frac{\sigma_a - F_{Sy}}{F_{ty} - c_{3ty}} \quad R_{ay} = 0.006 \]

Stress ratio in bending, yield \[ R_{by} := \frac{\sigma_l - F_{Sy}}{F_{by} - c_{3ty}} \quad R_{by} = 0.354 \]

Stress ratio in shear, yield \[ R_{sy} := \frac{\tau - F_{Sy}}{0.5F_{ty} - c_{3ty}} \quad R_{sy} = 0.076 \]

Margin of safety, yield \[ MS_{y} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad MS_{y} = 1.72 \]
Beam and Socket analysis - Nominal Landing Case

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

Resultant shear Load

\[ S := Pr \]
\[ S = 15596 \text{ lbf} \]

Moment at edge of sill joint

\[ M := Mb + Mf \]
\[ M = 102166 \text{ in-lbf} \]

Length of overlap

\[ L := 3.874 \text{ in} \]

\[ \text{slm}_\text{ratio} := \begin{cases} \frac{L}{M} & \text{if } M = 0, 1000, S \frac{L}{M} \\ \text{slm}_\text{ratio} = 0.591 \end{cases} \]

\[ \text{mls}_\text{ratio} := \begin{cases} \frac{M}{S-L} & \text{if } S = 0, 1000, \frac{M}{S-L} \\ \text{mls}_\text{ratio} = 1.691 \end{cases} \]
Beam and Socket Coefficients

Note if abs(SL/M) <= 1, Ratio = SL/M, otherwise Ratio = M/SL.

Coefficients are:

Ka = 0.451  Ks = 1.652  Km = 1.006
K1 = 8.366  K2 = 7.183
Calculated values are then:

\[ w_1 := \begin{cases} \frac{K_1 \cdot M}{L^2} & \text{if } |\text{slm_ratio}| \leq 1 \\ \frac{K_1 \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ w_1 = 56948 \, \text{lbf/in} \]

\[ w_2 := \begin{cases} \frac{K_2 \cdot M}{L^2} & \text{if } |\text{slm_ratio}| \leq 1 \\ \frac{K_2 \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ w_2 = 48896.5 \, \text{lbf/in} \]

\[ a := K_a \cdot L \quad a = 1.749 \, \text{in} \]

Max. shear
\[ S_{\text{max}} := \begin{cases} -\frac{K_s \cdot M}{L} & \text{if } |\text{slm_ratio}| \leq 1 \\ -\frac{K_s \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ S_{\text{max}} = -43555 \, \text{lbf} \]

Max. Bending moment
\[ M_{\text{max}} := \begin{cases} K_m \cdot M & \text{if } |\text{slm_ratio}| \leq 1 \\ K_m \cdot S \cdot L & \text{otherwise} \end{cases} \]

\[ M_{\text{max}} = 102764.2 \, \text{in-lbf} \]

Now check:
\[ S_c := \frac{w_1 - w_2}{2} \cdot L \quad S_c = 1.6 \times 10^4 \, \text{lbf} \]

\[ M_c := -\frac{w_1 + 2 \cdot w_2}{6} \cdot L^2 \quad M_c = 102165.8 \, \text{in-lbf} \]

Percent error:
\[ S_{\text{percentdiff}} := \frac{S - S_c}{S} \quad S_{\text{percentdiff}} = 0 \% \]

\[ M_{\text{percentdiff}} := \frac{M - M_c}{M} \quad M_{\text{percentdiff}} = 0 \% \]
### USS-02 Keel Trunnion

**Actual Shear and Moment Distribution Inside Socket**

![Graph showing shear and moment distribution](image-url)
In the following calculation, conservatively, the maximum values of the bending moment and shear are used.

Max. Shear \( S_{\text{max}} = -43555 \text{ lbf} \)

Max. Bending moment \( M_{\text{max}} = 102764.2 \text{ in-lbf} \) \( \text{(see page 2.3.4-9)} \)

Section properties (see page 2.3.4-2 and 3)

Area of cross-section \( A_s = 2.481 \text{ in}^2 \)

Moment of inertia \( I_s = 2.284 \text{ in}^4 \)

Section modulus \( S_1 := \frac{I_s}{d_{\text{max}}} \)

\( S_1 = 1.526 \text{ in}^3 \)

Stresses

Total moment \( M_{\text{socket}} := M_{\text{max}} \quad M_{\text{socket}} = 102764.2 \text{ in-lbf} \)

Bending Tensile stress \( \sigma := \frac{M_{\text{socket}}}{S_1} \quad \sigma = 67339.9 \text{ psi} \)

Shear stress \( \tau_{\text{soc}} := \frac{|S_{\text{max}}|}{A_s} \quad \tau_{\text{soc}} = 17554.6 \text{ psi} \)

Axial tension stress \( \sigma_{\text{a}} := \frac{P_f}{A_s} \quad \sigma_{\text{a}} = 1053.503 \text{ psi} \)

Stress Ratios

Axial (ult) \( R_a := \frac{\sigma_{\text{a}}}{F_{\text{tu}} \cdot c_{3\text{tu}}} \quad R_a = 0.007 \)

Bending (ult) \( R_b := \frac{F_{\text{Su}} \cdot \sigma}{F_{\text{bu}} \cdot c_{3\text{tu}}} \quad R_b = 0.344 \)

Shear (ult) \( R_s := \frac{F_{\text{Su}} \cdot \tau_{\text{soc}}}{F_{\text{su}} \cdot c_{3\text{tu}}} \quad R_s = 0.2 \)

Axial (yld) \( R_{\text{ay}} := \frac{\sigma_{\text{a}}}{F_{\text{ty}} \cdot c_{3\text{ty}}} \quad R_{\text{ay}} = 0.006 \)

Bending (yld) \( R_{\text{by}} := \frac{F_{\text{Sy}} \cdot \sigma}{F_{\text{by}} \cdot c_{3\text{ty}}} \quad R_{\text{by}} = 0.37 \)

Shear(yld) \( R_{\text{sy}} := \frac{F_{\text{Sy}} \cdot \tau_{\text{soc}}}{0.50F_{\text{ty}} \cdot c_{3\text{ty}}} \quad R_{\text{sy}} = 0.211 \)
Margins of safety

Margin of safety ultimate

\[
MSu := \frac{1}{\sqrt{(Ra + Rb)^2 + Rs^2}} - 1 \quad MSu = 1.47
\]

Margin of safety yield

\[
MSy := \frac{1}{\sqrt{(Ray + Rby)^2 + Rsy^2}} - 1 \quad MSy = 1.32
\]

Abort Landing Case:

Max. load in y direction

\[
Pr := 9118.63 \text{ lbf} \quad \text{(Ref. AMS-02, loads model 2-04, Load case 2017, element ID 5, data file: maxtrunnionforces2000.lis)}
\]

The tolerances between the Tube and the Block are tight. Due to this tight tolerance, any side load transferred through the Tube to the Retainer would result in small deflections of the Retainer. This would result in the side load being reacted between the Tube and the Block due to these tight tolerances.

Moment arm from load to edge of keel joint

\[
d2 := 5.8 \text{ in} + 0.5 \text{ in}
\]

(Ref. CAD model for 5.8" dimension)

\[
d2 = 6.3 \text{ in}
\]

(Ref. Appendix C6 for the 0.5" dynamic excursion)

Max. bending moment at edge of keel joint

\[
Mb := Pr \cdot d2
\]

\[
Mb = 57447.4 \text{ in lbf}
\]

Friction coefficient is assessed based on Figure 4.1.1.1-1 of NSTS-21000-IDD-ISS, Ref. Appendix C7.

\[
P := Pr \quad P = 9119 \text{ lbf}
\]

\[
T := 40 \text{ deg} \quad \text{(It is conservative to use the minimum temperature (Ref. Appendix C2))}
\]
Friction coefficient

\[ \mu = 0.100 \]

Friction load 10% of load

\[ Pf := Pr \cdot \mu \]

\[ Pf = 911.9 \text{ lbf} \]

Friction moment

\[ Mf := Pf \cdot \frac{dt_{\text{max}}}{2} \]

\[ Mf = 1364.6 \text{ in} \cdot \text{lb} \]

Total moment

\[ M := Mb + Mf \]

\[ M = 58812 \text{ in} \cdot \text{lb} \]

Applied limit stress in shaft

\[ \sigma_l := \left( \frac{Mb \cdot dt_{\text{max}}}{2 \cdot I_s} \right) \]

\[ \sigma_l = 37644.4 \text{ psi} \]
Plastic bending allowable  (Ref.NASA TM X-73305,sect B.4.5)

**Section factor**

Outer radius  
\[ r_o := \frac{d_{to}}{2} \]
\[ r_o = 1.495 \text{ in} \]

Inner radius  
\[ r_i := \frac{d_{89}}{2} \]
\[ r_i = 1.202 \text{ in} \]

Area of semicircular segment  
\[ A_{se} := \frac{\pi}{2} \left( r_o^2 - r_i^2 \right) \]
\[ A_{se} = 1.241 \text{ in}^2 \]

Distance of neutral axis from center line  
\[ y_{bar} := \frac{4}{3\pi} \left( \frac{r_o^3 - r_i^3}{r_o^2 - r_i^2} \right) \]
\[ y_{bar} = 0.862 \text{ in} \]

First moment of area  
\[ Q := A_{se} \cdot y_{bar} \]
\[ Q = 1.069 \text{ in}^3 \]

Distance of extreme fiber from centerline of shaft  
\[ c := \frac{d_{\text{max}}}{2} \]
\[ c = 1.496 \text{ in} \]

Section factor  
\[ K := \frac{2 \cdot Q \cdot c}{I_s} \]
\[ K = 1.4016 \]

Allowable bending modulus of rupture ult.  \( \sigma_p := 272000 \text{ psi} \)  
(Ref.NASA TM X-73305,sect B.4.5 fig. B4.5.5.2-7)

Allowable bending modulus of rupture yld.  \( \sigma_y := 200000 \text{ psi} \)

**Check**

Section factor  
\[ K := 1.698 \cdot \frac{r_o}{r_i} \left( \frac{r_o^3 - r_i^3}{r_o^4 - r_i^4} \right) \]
\[ K = 1.4007 \]  
(Ref. Formulas for Stress, Strain, and Structural Matrices, Table 2-2, Case 6)

\( f_{mu} := 200000 \text{ psi} \)  
\( f_{ou} := 192000 \text{ psi} \)  
(Ref. Bruhn, table C3.2 page C3.11)

\( f_{my} := 176000 \text{ psi} \)  
\( f_{oy} := 65000 \text{ psi} \)

\( F_{bu} := f_{mu} + f_{ou} \cdot (K - 1) \)
\( F_{bu} = 276942.5 \text{ psi} \)  
(Ref. Bruhn page C3.3, equation 3)

\( F_{by} := f_{my} + f_{oy} \cdot (K - 1) \)
\( F_{by} = 202048.2 \text{ psi} \)  
(These numbers match the \( \sigma_p \) and \( \sigma_y \) closely)

Axial tension stress  
\[ \sigma_a := \frac{P_f}{A_s} \]
\[ \sigma_a = 367.52 \text{ psi} \]

Shear stress  
\[ \tau := \frac{P_r}{A_s} \]
\[ \tau = 3675.201 \text{ psi} \]
Stress ratios, Ultimate

Stress ratio in tension, ultimate
\[ R_{au} := \frac{\sigma - F_{Su}}{F_{tu} - c2tu} \quad R_{au} = 0.003 \]

Stress ratio in bending, ultimate
\[ R_{bu} := \frac{\sigma - F_{Su}}{F_{bu} - c2tu} \quad R_{bu} = 0.196 \]

Stress ratio in shear, ultimate
\[ R_{su} := \frac{\tau - F_{Su}}{F_{su} - c2tu} \quad R_{su} = 0.043 \]

Margin of safety ultimate
\[ M_{Su} := \frac{1}{\sqrt{(R_{au} + R_{bu})^2 + R_{su}^2}} - 1 \quad M_{Su} = 3.92 \]

Stress ratios, Yield

Stress ratio in tension, yield
\[ R_{ay} := \frac{\sigma - F_{Sy}}{F_{ty} - c2ty} \quad R_{ay} = 0.002 \]

Stress ratio in bending, yield
\[ R_{by} := \frac{\sigma - F_{Sy}}{F_{by} - c2ty} \quad R_{by} = 0.211 \]

Stress ratio in shear, yield
\[ R_{sy} := \frac{\tau - F_{Sy}}{0.5F_{ty} - c2ty} \quad R_{sy} = 0.045 \]

Margin of safety, yield
\[ M_{Sy} := \frac{1}{\sqrt{(R_{ay} + R_{by})^2 + R_{sy}^2}} - 1 \quad M_{Sy} = 3.58 \]
Beam and Socket analysis - Abort Landing Case

Treating the connection as a Beam in a Socket, as per SMM, Memo 41a

Resultant shear Load

\[ S := Pr \]
\[ S = 9119 \text{ lbf} \]

Moment at edge of sill joint

\[ M := Mb + Mf \]
\[ M = 58812 \text{ in-lbf} \]

Length of overlap

\[ L := 3.874 \text{ in} \]

\[ \text{srm}_{\text{ratio}} := \begin{cases} \frac{L}{M} & \text{if } M = 0, 1000 \frac{S}{M} \\ \text{srm}_{\text{ratio}} = 0.601 \end{cases} \]

\[ \text{mls}_{\text{ratio}} := \begin{cases} \frac{M}{S-L} & \text{if } S = 0, 1000 \frac{M}{S-L} \\ \text{mls}_{\text{ratio}} = 1.665 \end{cases} \]
Beam and Socket Coefficients

Note if \( \text{abs}(\text{SL}/M) \leq 1 \), \( \text{Ratio} = \text{SL}/M \), otherwise \( \text{Ratio} = M/\text{SL} \).

Coefficients are:

- \( K_a = 0.452 \)
- \( K_s = 1.654 \)
- \( K_m = 1.007 \)
- \( K_1 = 8.403 \)
- \( K_2 = 7.201 \)
Calculated values are then:

\[ w_1 := \begin{cases} \frac{K_1 \cdot M}{L^2} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ \frac{K_1 \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ w_1 = 32927.7 \text{ lbf in} \]

\[ w_2 := \begin{cases} \frac{K_2 \cdot M}{L^2} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ \frac{K_2 \cdot S}{L} & \text{otherwise} \end{cases} \]

\[ w_2 = 28220 \text{ lbf in} \]

\[ a := K_a \cdot L \quad a = 1.749 \text{ in} \]

Max. shear

\[ S_{\max} := \begin{cases} -\frac{-K_s \cdot M}{L} & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ -K_s \cdot S & \text{otherwise} \end{cases} \]

\[ S_{\max} = -25104.7 \text{ lbf} \]

Max. Bending moment

\[ M_{\max} := \begin{cases} K_m \cdot M & \text{if } |\text{slm}_\text{ratio}| \leq 1 \\ K_m \cdot S \cdot L & \text{otherwise} \end{cases} \]

\[ M_{\max} = 59236.8 \text{ in-lbf} \]

Now check:

\[ S_c := \frac{w_1 - w_2}{2} \cdot L \quad S_c = 9.1 \times 10^3 \text{ lbf} \]

\[ M_c := \frac{-w_1 + 2 \cdot w_2}{6} \cdot L^2 \quad M_c = 58812 \text{ in-lbf} \]

Percent error:

\[ S_{\text{percentdiff}} := \frac{S - S_c}{S} \quad S_{\text{percentdiff}} = 0\% \]

\[ M_{\text{percentdiff}} := \frac{M - M_c}{M} \quad M_{\text{percentdiff}} = -0\% \]
Actual Shear and Moment Distribution Inside Socket
In the following calculation, conservatively, the maximum values of the bending moment and shear are used.

Max. Shear \[ S_{max} = -25104.7 \text{ lbf} \]

Max. Bending moment \[ M_{max} = 59236.8 \text{ in-lbf} \] (see page 2.3.4-9)

Section properties (see page 2.3.4-2 and 3)

Area of cross-section \[ A_s = 2.481 \text{ in}^2 \]

Moment of inertia \[ I_s = 2.284 \text{ in}^4 \]

Section modulus \[ S_1 = \frac{I_s}{d_{max}} = 1.526 \text{ in}^3 \]

Stresses

Total moment \[ M_{socket} = M_{max} = 59236.8 \text{ in-lbf} \]

Bending Tensile stress \[ \sigma = \frac{M_{socket}}{S_1} = 38817 \text{ psi} \]

Shear stress \[ \tau_{soc} = \frac{|S_{max}|}{A_s} = 10118.3 \text{ psi} \]

Axial tension stress \[ \sigma_a = \frac{P_f}{A_s} = 367.52 \text{ psi} \]

Stress Ratios

Axial (ult) \[ R_a = \frac{\sigma_a - F_{Su}}{F_{tu} - 2tu} \] \[ R_a = 0.003 \]

Bending (ult) \[ R_b = \frac{F_{Su} \cdot \sigma}{F_{bu} - 2tu} \] \[ R_b = 0.202 \]

Shear (ult) \[ R_s = \frac{F_{Su} \cdot \tau_{soc}}{F_{su} - 2tu} \] \[ R_s = 0.118 \]

Axial (yld) \[ R_{ay} = \frac{\sigma_a - F_{Sy}}{F_{ty} - 2ty} \] \[ R_{ay} = 0.002 \]

Bending (yld) \[ R_{by} = \frac{F_{Sy} \cdot \sigma}{F_{by} - 2ty} \] \[ R_{by} = 0.218 \]

Shear(yld) \[ R_{sy} = \frac{F_{Sy} \cdot \tau_{soc}}{0.50F_{ty} - 2ty} \] \[ R_{sy} = 0.124 \]
Margins of safety

Margin of safety ultimate

$$MSu := \frac{1}{\sqrt{(Ra + Rb)^2 + Rs^2}} - 1$$

$$MSu = 3.23$$

Margin of safety yield

$$MSy := \frac{1}{\sqrt{(Ray + Rby)^2 + Rsy^2}} - 1$$

$$MSy = 2.96$$
2.3.5 Keel Retainer
Keel Retainer Analysis

The objective of this analysis is to demonstrate the structural strength of the Keel Retainer. Flat plate stress calculations and FEA stresses are compared. The Keel Retainer (SDG39135773) is mounted on both the Keel Trunion (SDG 39135772) and Keel Block (SDG 39135770).

The tolerances between the keel trunnion and the keel block are tight. Due to this tight tolerance, any side load transferred through the keel trunnion to the keel retainer would result in small deflections of the Retainer. This would result in the side load being reacted between the keel trunnion and the keel block due to these tight tolerances.

\[ P_r := 15595.9 \text{ lbf} \]
\[ P_f := P_r \times 0.168 \]
\[ P_f := 2620.1 \text{ lbf} \]

Figure 2.3.5-1 Keel Assembly SEG39135768

Loads:

The maximum axial load in the keel trunnion comes from the Nominal Landing Case 4051 from loads model 2-04 (Ref. Section 2.3.4 "USS-02 Keel Trunnion" and Appendix A2)

Applied normal loads from the Keel Trunnion

Axial Friction load 16.8% of normal load
**Factors of Safety**:

- \( FS_u = 1.4 \) Ultimate factor of safety
- \( FS_y = 1.1 \) Yield factor of safety

**Temperature Data for Nominal Landing**:

(Ref. MIL-HDBK-5J, figure 2.6.7.1.1 and Appendix C2)

- \( Tmin = -56 \text{-deg} \)
- \( Tmax = 181 \text{-deg} \)

- \( F_{tu} \) Temperature Correction Factor \( T_{ftu} = .95 \)
- \( F_{ty} \) Temperature Correction Factor \( T_{fty} = .95 \)

**Material Properties for 15-5PH (H1025)**:

(Ref. MIL-HDBK-5J, table 2.6.7.0 (c))

- Ultimate Tensile Allowable
  - \( F_{tu} = 155000 \text{-psi} \) \( F_{tu} = 147250 \text{-psi} \)
- Yield Tensile Allowable
  - \( F_{ty} = 145000 \text{-psi} \) \( F_{ty} = 137750 \text{-psi} \)
- Shear allowable
  - \( F_{su} = 97000 \text{-psi} \) \( F_{su} = 92150 \text{-psi} \)

- Modulus of elasticity: \( E = 28.5 \times 10^6 \text{lbf/in}^2 \)
- Poisson’s ratio: \( \nu = 0.27 \)

---

**Figure 2.3.5-2** Keel Retainer
Flat Plate Method:

Flat annular plate with a uniform annular line load $w$ at radius $r_o$
(Ref. Roark’s Formulas for Stress and Strain, Table 24)

Outer edge fixed, inner edge free (Ref. Table 24, Case 1e)

Geometry:
(Ref. SDG39135773)

- Plate thickness: $t := 0.125\text{\,in}$
- Inner Diameter of Trunnion Block (Ref. SDG39135770): $IDbl := 3.0011\text{\,in}$
- Inner Diameter of Trunnion Retainer: $IDb := 2.375\text{\,in}$
- Diameter of Retainer to Block Bolt Pattern: $ODbbp := 3.50\text{\,in}$
- Diameter of Retainer to Trunnion Bolt Pattern: $ODtbp := 2.698\text{\,in}$
- Outer Diameter of Trunnion Retainer: $ODtr := 4.00\text{\,in}$

Location of Line Load:

- bolt hole pattern outer radius: $a := \frac{ODbbp}{2}$, $a = 1.75\text{\,in}$
- inner radius: $b := \frac{IDb}{2}$, $b = 1.188\text{\,in}$
- Radial location of applied line load: $r_o := \frac{ODtbp}{2}$, $r_o = 1.349\text{\,in}$
General Plate Functions and Constants:

\[ F_1(r) := \left[ \frac{1 + \nu \cdot \frac{b}{r} \cdot \ln \left( \frac{r}{b} \right)}{2} + \frac{1 - \nu}{4} \cdot \left( \frac{r}{b} - \frac{b}{r} \right) \right] \]

\[ C_1 := \left[ \frac{1 + \nu \cdot \frac{b}{a} \cdot \ln \left( \frac{a}{b} \right)}{2} + \frac{1 - \nu}{4} \cdot \left( \frac{a}{b} - \frac{b}{a} \right) \right] \]

\[ F_2(r) := \frac{1}{4} \left[ 1 - \left( \frac{b}{r} \right)^2 \cdot \left( 1 + 2 \cdot \ln \left( \frac{r}{b} \right) \right) \right] \]

\[ C_4 := \frac{1}{2} \left( 1 + \nu \right) \cdot \frac{b}{a} + \left( 1 - \nu \right) \cdot \frac{a}{b} \]

\[ F_3(r) := \frac{b}{4r} \left[ \left( \frac{b}{r} \right)^2 + 1 \cdot \ln \left( \frac{r}{b} \right) + \left( \frac{b}{r} \right)^2 - 1 \right] \]

\[ C_7 := \frac{1}{2} \left( 1 - \nu^2 \right) \cdot \frac{a}{b} - \frac{b}{a} \]

\[ F_4(r) := \frac{1}{2} \left[ (1 + \nu) \cdot \frac{b}{r} + (1 - \nu) \cdot \frac{r}{b} \right] \]

\[ L_3 := \frac{r_o}{4a} \left[ \left( \frac{r_0}{a} \right)^2 + 1 \cdot \ln \left( \frac{a}{r_0} \right) + \left( \frac{r_0}{a} \right)^2 - 1 \right] \]

\[ F_5(r) := \frac{1}{2} \left[ 1 - \left( \frac{b}{r} \right)^2 \right] \]

\[ L_6 := \frac{r_o}{4a} \left[ \left( \frac{r_0}{a} \right)^2 - 1 + 2 \cdot \ln \left( \frac{a}{r_0} \right) \right] \]

\[ F_6(r) := \frac{b}{4r} \left[ \left( \frac{b}{r} \right)^2 - 1 + 2 \cdot \ln \left( \frac{r}{b} \right) \right] \]

\[ L_9 := \frac{r_o}{a} \left[ \frac{1 + \nu}{2} \cdot \ln \left( \frac{a}{r_0} \right) + \frac{1 - \nu}{4} \left[ 1 - \left( \frac{r_0}{a} \right)^2 \right] \right] \]

\[ F_7(r) := \frac{1}{2} \left( 1 - \nu^2 \right) \cdot \frac{r}{b} - \frac{b}{r} \]

\[ G_3(r) := \frac{r_o}{4r} \left[ \left( \frac{r_0}{r} \right)^2 + 1 \cdot \ln \left( \frac{r}{r_0} \right) + \left( \frac{r_0}{r} \right)^2 - 1 \right] \left( r \geq r_o \right) \]

\[ F_8(r) := \frac{1}{2} \left[ 1 + \nu + (1 - \nu) \cdot \left( \frac{b}{r} \right)^2 \right] \]

\[ G_6(r) := \frac{r_o}{4r} \left[ \left( \frac{r_0}{r} \right)^2 - 1 + 2 \cdot \ln \left( \frac{r}{r_0} \right) \right] \left( r \geq r_o \right) \]

\[ F_9(r) := \frac{b}{r} \left[ \frac{1 + \nu}{2} \cdot \ln \left( \frac{r}{b} \right) + \frac{1 - \nu}{4} \left[ 1 - \left( \frac{r}{b} \right)^2 \right] \right] \]

\[ G_9(r) := \frac{r_o}{r} \left[ \frac{1 + \nu}{2} \cdot \ln \left( \frac{r}{r_0} \right) + \frac{1 - \nu}{4} \left[ 1 - \left( \frac{r_0}{r} \right)^2 \right] \right] \left( r \geq r_o \right) \]
Total Applied Load: \[ W := Pf \] \[ W = 2620.1 \text{ lbf} \]

Applied unit load: \[ w := \frac{W}{2 \cdot \pi \cdot r_o} \] \[ w = 309.121 \frac{\text{lbf}}{\text{in}} \]

Shear modulus: \[ G := \frac{E}{2 \cdot (1 + \nu)} \] \[ G = 1.122 \times 10^7 \text{ psi} \]

Plate Constant: \[ D := \frac{E \cdot t^3}{12 \left(1 - \nu^2\right)} \] \[ D = 5003.4 \text{ lbf \cdot in} \]

Boundary Values for deformation, moments, and shear:

Unit Radial Moment at End b: \[ M_{rb} := 0 \frac{\text{lbf \cdot in}}{\text{in}} \]

Unit Shear Force at End b: \[ Q_b := 0 \frac{\text{lbf}}{\text{in}} \]

Deflection at End a: \[ y_a := 0 \text{ in} \]

Radial Slope at End a: \[ \theta_a := 0 \text{ deg} \]

Deflection at End b: \[ y_b := \frac{-w \cdot a}{D} \left(\frac{C_1 \cdot L_6}{C_4} - L_3\right) \] \[ y_b = -0.002 \text{ in} \]

Radial Slope at End b: \[ \theta_b := \frac{w \cdot a^2}{D \cdot C_4} \cdot L_6 \] \[ \theta_b = 0.247 \text{ deg} \]

Unit Radial Moment at End a: \[ M_{ra} := -w \cdot a \left(L_0 - \frac{C_7 \cdot L_6}{C_4}\right) \] \[ M_{ra} = -95.245 \frac{\text{lbf \cdot in}}{\text{in}} \]

Unit Shear Force at End a: \[ Q_a := -\frac{r_o}{a} \] \[ Q_a = -238.288 \frac{\text{lbf}}{\text{in}} \]
General Expressions for deformation, moments, and shear:

**Deflection:** Define \( r \), the range of the radius: \( r := (b, 1.0001 \cdot b .. a) \)

\[
y(r) := y_b + r \cdot F_1(r) + M_{rb} \cdot \frac{2}{D} \cdot F_2(r) + Q_b \cdot \frac{3}{D} \cdot F_3(r) - w \cdot \frac{3}{D} \cdot G_3(r)
\]

![Graph of deflection](attachment:image.png)

Deflection at points \( b \) and \( a \) (inner and outer radius) due to bending:

\[
y_b = -0.0018 \text{ in} \quad y_a = 0 \text{ in}
\]

**Large deflection condition check:** \(|y_{max}| \) is less than \( t/2 \) \( \left( \frac{t}{2} = 0.0625 \text{ in} \right) \)

(If \(|y_{max}| \) is greater than \( t/2 \), the equations in the table 24 are subject to large errors.)
Slope:
\[ \theta(r) := \theta_b \cdot F_4(r) + M_{\theta b} \cdot \frac{r}{D} \cdot F_5(r) + Q_b \cdot \frac{r^2}{D} \cdot F_6(r) - w \cdot \frac{r^2}{D} \cdot G_6(r) \]

Slope at points b and a (inner and outer radius):
\[ \theta_b = 0.247 \text{ deg} \quad \theta_a = 0 \text{ deg} \]

Radial moment:
\[ M_{r}(r) := \theta_b \cdot \frac{D}{r} \cdot F_7(r) + M_{\theta b} \cdot F_8(r) + Q_b \cdot r \cdot F_9(r) - w \cdot r \cdot G_9(r) \]

Radial moment at points b and a due to bending:
\[ M_{\theta b} = 0 \text{ lbf-in} \quad M_{\theta a} = -95.245 \text{ lbf-in} \]
Transverse moment:

\[ M_r(r) := \frac{\theta(r) \cdot D \left( 1 - \nu^2 \right)}{r} + \nu \cdot M_r(r) \]

Transverse moment at points b and a due to bending:

\[ M_r(b) = 16.867 \text{ lbf\cdotin} \quad M_r(a) = -25.716 \text{ lbf\cdotin} \]

Shear:

\[ Q_r(r) := Q_b \frac{b}{r} - w \cdot \frac{r_0}{r^2} \left( r \geq r_0 \right) \]

Shear force per unit length at points b and a due to bending:

\[ Q_b = 0 \text{ lbf\cdotin} \quad Q_a = -238.288 \text{ lbf\cdotin} \]
Radial bending stress:  \[ \sigma_r(r) := \frac{6 \cdot M_r(r)}{t^2} \]

Radial bending stress at points b and a (inner and outer radius):
\[
\sigma_r(b) = 0 \text{ psi} \quad \sigma_r(a) = -36574.1 \text{ psi}
\]

Transverse bending stress:  \[ \sigma_t(r) := \frac{6 \cdot M_t(r)}{t^2} \]

Transverse bending stress at points b and a (inner and outer radius):
\[
\sigma_t(b) = 6477 \text{ psi} \quad \sigma_t(a) = -9875 \text{ psi}
\]

Stresses:
Where \( \sigma_s \) is shear stress, \( \sigma_b \) is the bending stress, \( S \) is principal Stress, and \( \sigma_{eq} \) is Von Mises equivalent stress.

\[
\sigma_s := \frac{|Q_a|}{t} \quad \sigma_s = 1906.3 \text{ psi}
\]

\[
\sigma_b := |\sigma_r(a)| + |\sigma_t(a)| \quad \sigma_b = 46449 \text{ psi}
\]

\[
\sigma := \begin{pmatrix}
\sigma_b & \sigma_s & 0 \\
\sigma_s & 0 & 0 \\
0 & 0 & 0
\end{pmatrix} \quad S := \text{eigenvals}(\sigma) \quad S = \begin{pmatrix} 46527 \\ -78 \\ 0 \end{pmatrix} \text{ psi} \quad \text{(Principal stress)}
\]

\[
\sigma_{eq} := \sqrt{\frac{(S_0 - S_1)^2 + (S_1 - S_2)^2 + (S_2 - S_0)^2}{2}} \quad \sigma_{eq} = 46566 \text{ psi} \quad \text{(Von Mises stress)}
\]

\[
\tau_{max} := \frac{S_0 - S_1}{2} \quad \tau_{max} = 23303 \text{ psi} \quad \text{(Max shear)}
\]
**Margin of safety against yield failure:**

\[
MS_y := \frac{F_{ty}}{F_{Sy} \cdot \sigma_{eq}} - 1
\]

\[MS_y = 1.689\]

**Margin of safety against ultimate failure:**

\[
MS_u := \frac{F_{tu}}{F_{Su} \cdot S_0} - 1
\]

\[MS_u = 1.261\]

**Margin of safety against ultimate failure (shear):**

\[
MS_u := \frac{F_{su}}{F_{Su} \cdot \tau_{max}} - 1
\]

\[MS_u = 1.825\]
2.4 USS-02 Bolt and Shear Pin and Bushing Strength Assessment
2.4.1 Upper USS-02 Bolted Interfaces
Upper USS-02 Bolted Interfaces

The Upper USS-02 Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.1.1</td>
<td>Upper Interface Plate to USS-02</td>
</tr>
<tr>
<td>2.4.1.1</td>
<td>Upper Interface Plate to USS-02 Fail-Safe</td>
</tr>
<tr>
<td>2.4.1.1</td>
<td>Upper Interface Plate to USS-02 Fail Safe (Shear Pin Failure)</td>
</tr>
<tr>
<td>2.4.1.2</td>
<td>Lower Interface Plate to USS-02</td>
</tr>
<tr>
<td>2.4.1.2</td>
<td>Lower Interface Plate to USS-02 Fail-Safe</td>
</tr>
<tr>
<td>2.4.1.2</td>
<td>Lower Interface Plate to USS-02 Fail-Safe (Shear Pin Failure)</td>
</tr>
<tr>
<td>2.4.1.3</td>
<td>TRD Corner Bracket to Upper Vacuum Case Joint</td>
</tr>
<tr>
<td>2.4.1.3</td>
<td>TRD Corner Bracket to Upper Vacuum Case Joint Fail Safe</td>
</tr>
<tr>
<td>2.4.1.3</td>
<td>TRD Corner Bracket to Upper Vacuum Case Joint Fail Safe (Shear Pin Failure)</td>
</tr>
<tr>
<td>2.4.1.4</td>
<td>Sill Bracket to Sill Joint</td>
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<tr>
<td>2.4.1.4</td>
<td>Sill Bracket to Sill Joint Fail-Safe</td>
</tr>
<tr>
<td>2.4.1.5</td>
<td>Diagonal Sill Bracket to Sill Joint</td>
</tr>
<tr>
<td>2.4.1.5</td>
<td>Diagonal Sill Bracket to Sill Joint Fail-Safe</td>
</tr>
</tbody>
</table>
2.4.1.1 Upper Interface Plate to USS-02
Upper Vacuum Case Interface Plate to USS-02 Bolt Analysis

The USS-02 assembly consists of four Upper Vacuum Case (VC) Joints. There are a total of 8 fasteners attaching the USS-02 to the upper interface plate. The fasteners are NAS1958C (180 ksi), 0.50-20 UNFJ. There is also one shear pin 0.875” in diameter. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

Bolt Geometry

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
</tbody>
</table>

\[
i := 1 \ldots \text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{t, 2} \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{t, 1} \frac{1}{\text{in}} \quad \text{bolt diameter}
\]

\[
A_{t_i} := \pi \left( \frac{D_i - 0.9743 \frac{1}{N_i}}{2} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
A_{s_i} := \pi \left( \frac{D_i - 1.299038 \frac{1}{N_i}}{2} \right)^2 \quad \text{Shear Area of bolt}
\]
Bolts from Upper Vacuum Case Interface Plate to USS

Location of applied forces and moments

\[
\begin{align*}
x_{\text{force}} &:= 0.0 \text{in} & y_{\text{force}} &:= 0.0 \text{in} & z_{\text{force}} &:= 0.0 \text{in} \\
\end{align*}
\]

\[
c_{\text{load}} := \begin{bmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{in}
\]
Center of gravity of bolt group

\[ \begin{align*}
\text{xcg} &:= \sum_{i} \frac{x_i}{\text{rows}(x)} \\
\text{ycg} &:= \sum_{i} \frac{y_i}{\text{rows}(y)} \\
\text{zcg} &:= \sum_{i} \frac{z_i}{\text{rows}(z)}
\end{align*} \]

\[ \begin{align*}
\text{xcg} &= 0 \text{ in} \\
\text{ycg} &= 0 \text{ in} \\
\text{zcg} &= 0.062 \text{ in}
\end{align*} \]

\[ \mathbf{c_{gbolt}} := \begin{pmatrix} \text{xcg} \\ \text{ycg} \\ \text{zcg} \end{pmatrix} \]

\[ \mathbf{c_{gbolt}} = \begin{pmatrix} 0 \\ 0 \\ 0.062 \end{pmatrix} \text{ in} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis with a zero offset from the center of gravity. However, in the z direction the bolt pattern is unsymmetric and has a .062" offset from the center of gravity.

Load Vector

\[ r_{load} := \mathbf{cgload} - \mathbf{c_{gbolt}} \]

\[ r_{load} = \begin{pmatrix} 0 \\ 0 \\ -0.062 \end{pmatrix} \text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_{i} := \sqrt{(x_{i} - \text{zcg})^{2} + (y_{i} - \text{ycg})^{2}} \]

\[ r = \begin{pmatrix} 4.423 \\ 3.250 \\ 4.423 \\ 3.000 \\ 4.423 \\ 3.000 \\ 4.423 \\ 3.250 \\ 4.423 \end{pmatrix} \text{ in} \]

Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 66001, 66002, 66003, and 66004. These loads are read into an array and distributed out to the 8 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis.)

Reading database file for bolted joint, abort landing case

\[ \text{data} := \text{READPRN}("upperussipf_r2_abortland.txt") \]

\[ \text{num_bolts} := \text{rows(bolt)} \]

\[ j := 1 \ldots \text{rows(data)} \]
Loads from 2-04 loads model, abort landing case

Axial Load \( F_x^j := data_{kj,3} \cdot \text{lbf} \)
Shear in Y axis \( F_y^j := data_{kj,4} \cdot \text{lbf} \)
Shear in Z axis \( F_z^j := data_{kj,5} \cdot \text{lbf} \)
Moment about Y axis \( M_y^j := data_{kj,7} \cdot \text{in-lbf} \)
Moment about Z axis \( M_z^j := data_{kj,8} \cdot \text{in-lbf} \)

Element Identification \( ID_j := data_{kj,1} \)

Load Case Number \( LC_j := data_{kj,2} \)

Applied Bending Moment at Bolts \( M_j := 0 \cdot \text{in-lbf} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

For each element identification, 66001, 66002, 66003, and 66004, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66001 will have bolt numbers 1 thru 8 attached to the end for all 64 load cases. This brings the total number of load cases to 2048 (4 joints x 8 bolts x 64 load cases = 2048). See the array example to the right.

\[
\begin{array}{c|c}
\text{ID} & \text{LC} \\
\hline
660011 & 2001 \\
660011 & 2002 \\
... & ...
660011 & 2064 \\
660012 & 2001 \\
660012 & 2002 \\
... & ...
660012 & 2064 \\
660018 & 2001 \\
660018 & 2002 \\
... & ...
660018 & 2064
\end{array}
\]

Array Example

\[
\text{ID} := \text{stack}(\text{ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5, ID + 6, ID + 7})
\]

\[
\text{LC} := \text{stack}((\text{LC, LC, LC, LC, LC, LC, LC, LC}))
\]
Moment Distribution

\[ M_{\text{tot}} \left( j \right) := \begin{bmatrix} M_{x_j} \\ M_{y_j} \\ M_{z_j} \end{bmatrix} + r_{\text{load}} \times \begin{bmatrix} F_{x_j} \\ F_{y_j} \\ F_{z_j} \end{bmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{\text{boltcg}} := M_{\text{tot1},j} \quad \text{My}_{\text{boltcg}} := M_{\text{tot2},j} \quad \text{Mz}_{\text{boltcg}} := M_{\text{tot3},j} \]

Tension on bolts

\[ F_{\text{direct},i,j} := \begin{cases} 0 \cdot \text{lbf} & \text{if } F_{x_j} \leq 0 \text{lbf} \\ \frac{F_{x_j}}{\text{num_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ F_{mz_{i,j}} := \begin{cases} 0 \cdot \text{lbf} & \text{if } \left( y_i - y_{cg} \right) = 0 \text{ in} \\ \frac{\text{Mz}_{\text{boltcg}_j} \left( y_i - y_{cg} \right) \cdot A_{t_i}}{\sum_i \left( y_i - y_{cg} \right)^2 \cdot A_{t_i}} & \text{otherwise} \end{cases} \]

\[ F_{my_{i,j}} := \begin{cases} 0 \cdot \text{lbf} & \text{if } \left( z_i - z_{cg} \right) = 0 \text{ in} \\ \frac{\text{My}_{\text{boltcg}_j} \left( z_i - z_{cg} \right) \cdot A_{t_i}}{\sum_i \left( z_i - z_{cg} \right)^2 \cdot A_{t_i}} & \text{otherwise} \end{cases} \]

\[ F_{t_{i,j}} := F_{\text{direct},i,j} + F_{mz_{i,j}} + F_{my_{i,j}} \quad \text{Total Tensile load} \]

Shear on bolts

\[ F_{s_{i,j}} := \frac{\text{Mx}_{\text{boltcg}_j} \cdot r_{i} \cdot A_{s_{i,j}}}{\sum_i \left( r_{i} \right)^2 \cdot \left( A_{s_{i,j}} \right)} \quad \text{Total shear load} \quad F_{\text{tot},i,j} := F_{s_{i,j}} \]

(Nota: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}
\begin{bmatrix}
(Ft^T)^{(1)}, (Ft^T)^{(2)}, (Ft^T)^{(3)}, (Ft^T)^{(4)}, (Ft^T)^{(5)}, (Ft^T)^{(6)}, (Ft^T)^{(7)}, (Ft^T)^{(8)}
\end{bmatrix}
\]

\[
V := \text{stack}
\begin{bmatrix}
(Fstot^T)^{(1)}, (Fstot^T)^{(2)}, (Fstot^T)^{(3)}, (Fstot^T)^{(4)}, (Fstot^T)^{(5)}, (Fstot^T)^{(6)}, (Fstot^T)^{(7)}, (Fstot^T)^{(8)}
\end{bmatrix}
\]

\[
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

\[
\text{Output} := \text{augment}
\begin{bmatrix}
\text{ID}, \text{LC}, \text{P}, \text{V}, \text{M}
\end{bmatrix}
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th>P</th>
<th>V</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>660011</td>
<td>2001</td>
<td>-1068.05</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>660011</td>
<td>2002</td>
<td>-1110.33</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>660011</td>
<td>2064</td>
<td>-699.99</td>
<td>-439.08</td>
<td>0</td>
</tr>
<tr>
<td>660012</td>
<td>2001</td>
<td>-813.60</td>
<td>-263.63</td>
<td>0</td>
</tr>
<tr>
<td>660012</td>
<td>2002</td>
<td>-977.16</td>
<td>-342.06</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>660018</td>
<td>2001</td>
<td>1470.8</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>660018</td>
<td>2002</td>
<td>1166.08</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>660018</td>
<td>2064</td>
<td>699.99</td>
<td>-439.07</td>
<td>0</td>
</tr>
</tbody>
</table>

Size of the "Output" Array: rows(\text{Output}) = 2048

(8 bolts x 64 load cases) x 4 joints = 2048 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)

Example of Output Array

\[
\text{WRITEPRN}("output_forces_upperussipf_r2_abortland.txt") := \text{Output}
\]

The array from the text file above is read:

\[ \text{data} := \text{READPRN}("\text{output\_forces\_upperussipf\_r2\_abortland.txt}\"") \]
\[ s := 1 .. \text{rows}(\text{data}) \]

**Flange 1: USS-02 Upper Vacuum Case Joint**
- **Part number**: SDG39135727
- **Material**: 7050-T7451

**Flange 2: Upper Vacuum Case Interface Plate**
- **Part number**: SDG39135788
- **Material**: 7050-T7451

**Loads from Abort Landing Load Cases**

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>Applied Load</th>
<th>Element Identification</th>
<th>Load Case Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>( P_s := \text{data}_{s,3} ) lbf</td>
<td>( \text{ID}<em>s := \text{data}</em>{s,1} )</td>
<td></td>
</tr>
<tr>
<td>Shear</td>
<td>( V_s := \text{data}_{s,4} ) lbf</td>
<td>( \text{LC}<em>s := \text{data}</em>{s,2} )</td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td>( M_s := \text{data}_{s,5} ) in·lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Factors of Safety**

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>( \text{SF} )</th>
<th>Assembly</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>( \text{SFu} := 1.4 )</td>
<td>Temp_initial := 70-deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint Separation</td>
<td>( \text{SFsep} := 1.2 )</td>
<td>FF := 1.15</td>
<td>Temp_max := 150-deg</td>
<td></td>
</tr>
</tbody>
</table>

**Bolt and Insert Data**

- **Nominal diameter of bolt**: \( D := 0.500 \) in
- **Number of threads/inch**: \( N_t := 20 \cdot \frac{1}{\text{in}} \)
- **Total length of bolt**: \( L := 1.923 \) in
- **Length of insert**: \( \text{Lins} := 0.688 \) in
- **Threaded length**: \( L_t := 0.735 \) in
- **Min. external diameter of insert**: \( F_{min} := 0.615 \) in
- **Depth of recess for insert**: \( l_r := 0.02 \) in

(If bolt is fully threaded, input \( L_t = L \))

**Temperature Data (Ref Appendix C2), Abort Landing Case**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>70-deg</td>
</tr>
<tr>
<td>Max</td>
<td>150-deg</td>
</tr>
<tr>
<td>Min</td>
<td>40-deg</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \text{\textbackslash escfil02\2111_mathcad\8307_bolts\thread\data.mcd}
**Title**
Bolts from Upper Vacuum Case Interface Plate to USS

### Washer Data
- Thickness of washer: $\text{tw} := 0.063\text{-in}$
- Outer Diameter of washer: $\text{Dw} := 0.875\text{in}$
- Inner Diameter of washer: $\text{Dwi} := 0.515\text{-in}$
- Bolt head dia. across flats: $\text{dw} := 0.710\text{-in}$ (used only if there is no washer)

### Flange data
- Thickness of flange 1: $\text{tf1} := 0.854\text{-in}$
- Thickness of flange 2: $\text{tf2} := 0.688\text{-in}$ (insert length)
- Diameter of hole: $\text{D_hole} := 0.571\text{-in}$

### Material Property Data
#### Bolt
- Temperature correction factor for bolt strength ultimate: $\text{TSu}_\text{bolt} := 0.96$ yield $\text{TSy}_\text{bolt} := 0.96$
- Bolt ultimate tensile allowable stress: $\text{Ftu}_\text{bolt} := 180000\text{-psi}$ (Ref. NAS1958)
- Bolt ultimate shear allowable stress: $\text{Fsu}_\text{bolt} := 0.6\times\text{Ftu}_\text{bolt}$
- Bolt yield tensile allowable: $\text{Fty}_\text{bolt} := 132353\text{-psi}$ (Ref. Appendix C10)
- Temperature correction factor for bolt modulus: $\text{TE}_\text{bolt} := 0.98$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))
- Modulus of elasticity of bolt: $\text{E}_\text{bolt} := \left(29.1\times10^6\text{-psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
- Thermal coefficient for bolt: $\alpha_{\text{bolt\_hot}} := 9.1\times10^{-6}\text{-in/in/deg}$, $\alpha_{\text{bolt\_cold}} := 8.9\times10^{-6}\text{-in/in/deg}$ (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

#### Insert
- Temperature correction factor for insert strength: $\text{TS}_\text{ins} := 0.96$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress: $\text{Ftu}_\text{ins} := 140000\text{-psi}$ (Ref. MS51831)
- Ultimate shear allowable stress: $\text{Fsu}_\text{ins} := 0.6\times\text{Ftu}_\text{ins}$

#### Washer
- Temperature correction factor for washer modulus: $\text{TE}_\text{washer} := 0.96$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Modulus of elasticity of washer: $\text{E}_\text{washer} := \left(29.1\times10^6\text{-psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1E} := .96 \] (modulus) \hspace{1cm} (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2
\[ T_{f2E} := .96 \] (modulus) \hspace{1cm} (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)
\[ T_{f2s} := .96 \] (strength) \hspace{1cm} (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear Strength Allowable for flanges
\[ F_{su_f2} := 44000 \text{ psi} \] \hspace{1cm} (Ref. MIL-HDBK-5J, table 3.7.4.0(b1))

Modulus of elasticity for the parts in the joint
\[ E_{flange1} := \left(10.3 \cdot 10^6 \text{ psi}\right) \] \hspace{1cm} (Ref. MIL-HDBK-5J, table 3.7.4.0(b1))
\[ E_{flange2} := \left(10.3 \cdot 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges
\[ \alpha_{flange1\_hot} := 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \] \hspace{1cm} (Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)
\[ \alpha_{flange2\_hot} := 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \alpha_{flange1\_cold} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \alpha_{flange2\_cold} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data per SDG39135724

Maximum torque (65% of yield)
\[ T_{max} := 1032 \text{ in-lbf} \]

Loading plane factor:
\[ n := .5 \]

Minimum torque (95% of max. torque)
\[ T_{min} := 980 \text{ in-lbf} \]

Preload Uncertainty:
\[ \Gamma := 0.25 \]

Torque coefficient (Lubricated):
\[ k := 0.15 \]

This file uses the calculations shown in \escfil02\12\11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC

[Insert Stiffness File]
Bolt Load data

Bolt/joint stiffness factor \( \phi = 0.409 \)

Preload due to temperature

- Pthr_pos = 1173.5 lbf
- Pthr_neg = -380.6 lbf

Max. preload

\( PLD_{\text{max}} = 18373.5 \text{lbf} \)

Min. preload

\( PLD_{\text{min}} = 8559.4 \text{lbf} \)

Joint separation load

\( \text{max}(P_{\text{sep}}) = 4423.356 \text{lbf} \)

Max. load on the bolt (ultimate)

\( \text{max}(P_{\text{b}}) = 19586.6 \text{lbf} \)

Max. load on the bolt (yield)

\( \text{max}(P_{\text{y}}) = 19326.7 \text{lbf} \)

Bolt ultimate tensile strength

\( P_{\text{At}} = 27143.2 \text{lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS ( _{\text{min},1} )</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1.115</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>3.574</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>3.280</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.386</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.033</td>
<td>Combined shear, tension and bending</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt}} := \min(\text{MS}) \]

\[ MS_{\text{bolt}} = 0.033 \]

Failure Mode = "Total Tension Yield"

Element Identification (66003) and Bolt Number (1) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Upper Vacuum Case Interface Plate to USS-02 (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-005. All 8 NAS1958 fasteners will take the direct shear load.

\[
F_{sd_{i,j}} := \frac{\sqrt{F_{y_j}^2 + F_{z_j}^2}}{\text{num_bolts}}
\]

Total shear load
\[
F_{stot_{i,j}} := F_{s_{i,j}} + F_{sd_{i,j}} \quad \text{(Note: The } F_s \text{ variable is the secondary shear and calculated above.)}
\]

The stack command below is used to stack the applied shear load (V) in ascending order per bolt. The applied axial load (P) and applied moment (M) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

\[
V := \text{stack}\left[(F_{stot}^T)^{(1)},(F_{stot}^T)^{(2)},(F_{stot}^T)^{(3)},(F_{stot}^T)^{(4)},(F_{stot}^T)^{(5)},(F_{stot}^T)^{(6)},(F_{stot}^T)^{(7)},(F_{stot}^T)^{(8)}\right]
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is written to a text file. For the format of the array see the output example array above.

\[
\text{Output} := \text{augment}\left[\text{ID}, \text{LC}, \frac{P}{\text{lbf}}, \frac{V}{\text{lbf}}, \frac{M}{\text{in-lbf}}\right] \quad \text{(Note: Since the ID and LC numbers are dimensionless, the } P, V, \text{ and } M \text{ values are divided by their units in order to make the array dimensionless.)}
\]

Size of the "Output" Array: \( \text{rows(Output)} = 2048 \)

\((8 \text{ bolts } \times 64 \text{ load cases}) \times 4 \text{ joints} = 2048 \text{ load cases} \)

WRITEPRN("output_forces_upperussipf_r2_abortland_pinfs.txt") := Output

Fail-safe Analysis (Shear Pin Failure)

The array from the text file above is read:

\[
data_{fsp} := \text{READPRN}(\"output_forces_upperussipf_r2_abortland_pinfs.txt\")
\]

\( s := 1 .. \text{rows(data}_{fsp}\)
Fail-safe Loads, abort landing

Fail-safe Factors of Safety

Applied tensile load
\[ P_{FS} := data\_fspm, 3\text{ lbf} \]
ID\_FS := data\_fspm, 1

Applied shear load
\[ V_{FS} := data\_fspm, 4\text{ lbf} \]
LC\_FS := data\_fspm, 2

Applied bending moment
\[ M_{FS} := data\_fspm, 5\text{ in lbf} \]

This file uses the calculations shown in `\escfil02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`

Bolt Fail-safe Load data

Joint separation load
\[ \text{max(Psep\_FS)} = 3686.13\text{ lbf} \]

Max. load on the bolt (ultimate)
\[ \text{max(Pb\_FS)} = 19240\text{ lbf} \]
\[ \text{max(V\_FS)} = 2091.24\text{ lbf} \]

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margins</th>
<th>Joint separation</th>
<th>Direct Tension Ultimate</th>
<th>Total Tension Ultimate</th>
<th>Direct Thread shear Ultimate</th>
<th>Combined shear, tension and bending ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS_minFS</td>
<td>1.538</td>
<td>5.403</td>
<td>0.411</td>
<td>5.62</td>
<td>0.4108</td>
</tr>
<tr>
<td>MS_minID</td>
<td>660031</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS_minLC</td>
<td>2035</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS_minP</td>
<td>3686.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS_minV</td>
<td>63.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS_minM</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ \text{MSbolt\_FS} := \text{min(MS\_FS)} \]
\[ \text{MSbolt\_FS} = 0.411 \]

Failure\_Mode\_FS = "Combined Shear Tension Bending Ultimate"

Element Identification (66003) and Bolt Number (1) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Upper Vacuum Case Interface Plate to USS-02

Since bolt number 1 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 7, NAS1958C 0.50-20 UNFJ fasteners, holding the USS to the upper vacuum case interface plate. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
\text{bolt2} & \quad 0.50 \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20
\end{align*}
\]

\[
s := 1 \ldots \text{rows(bolt2)}
\]

\[
\begin{align*}
N_2^s & := \text{bolt2}_s^2, 2 \frac{1}{\text{in}} \\
P & := \text{bolt2}_s^2, 1 \text{ in} \\
D_2^s & := \text{bolt2}_s^2, 1 \text{ in}
\end{align*}
\]

\[
\begin{align*}
A_t^2 & := \pi \left( \frac{D_2^s - 0.9743 \frac{1}{N_2^s}}{2} \right)^2 \\
A_s^2 & := \pi \left( \frac{D_2^s - 1.299038 \frac{1}{N_2^s}}{2} \right)^2
\end{align*}
\]

\[\text{Tensile Area of bolt} \quad \text{Shear Area of bolt}\]

Upper Vacuum Case Interface Plate to USS Bolt Pattern for Fail-Safe Analysis
Location of applied forces and moments

\[ x_{\text{force2}} := 0.0 \text{in} \quad y_{\text{force2}} := 0.0 \text{in} \quad z_{\text{force2}} := 0.0 \text{in} \]

\[ \text{cgload2} = \begin{bmatrix} x_{\text{force2}} \\ y_{\text{force2}} \\ z_{\text{force2}} \end{bmatrix} \quad \text{cgload2} = \begin{bmatrix} 0 \\ 0 \text{in} \end{bmatrix} \]

Center of gravity of bolt group

\[ x_{\text{cg2}} := \frac{\sum s x_2}{\text{rows}(x2)} \quad x_{\text{cg}} = 0 \text{ in} \]

\[ y_{\text{cg2}} := \frac{\sum s y_2}{\text{rows}(y2)} \quad y_{\text{cg}} = 0.429 \text{ in} \]

\[ z_{\text{cg2}} := \frac{\sum s z_2}{\text{rows}(z2)} \quad z_{\text{cg}} = -0.402 \text{ in} \]

\[ c_{\text{gbolt2}} = \begin{bmatrix} x_{\text{cg2}} \\ y_{\text{cg2}} \\ z_{\text{cg2}} \end{bmatrix} \quad c_{\text{gbolt2}} = \begin{bmatrix} 0 \\ 0.429 \text{ in} \\ -0.402 \text{ in} \end{bmatrix} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 1, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[ r_{\text{load2}} := \text{cgload2} - c_{\text{gbolt2}} \quad r_{\text{load2}} = \begin{bmatrix} 0 \\ -0.429 \text{ in} \\ 0.402 \text{ in} \end{bmatrix} \]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_2 \cdot s = \sqrt{(z_2 - z_{cg})^2 + (y_2 - y_{cg})^2} \]

\[ r_2 = \begin{pmatrix} 3.739 \\ 4.518 \\ 3.460 \\ 2.613 \\ 4.418 \\ 2.818 \\ 3.791 \end{pmatrix} \text{ in} \]

Reading database file for bolted joint, abort landing case

data := READPRN("upperussipf_r2_abortland.txt")

q := 1 .. rows(data) num_bolts2 := rows(bolt2)

Loads from 2-04 loads model, abort landing case

Axial Load  \[ F_{x2q} := \text{data}_{q,3} \cdot \text{lbf} \]
Shear in Y axis  \[ F_{y2q} := \text{data}_{q,4} \cdot \text{lbf} \]
Shear in Z axis  \[ F_{z2q} := \text{data}_{q,5} \cdot \text{lbf} \]
Element Identification  \[ \text{ID2}_q := \text{data}_{q,1} \]
Load Case Number  \[ \text{LC2}_q := \text{data}_{q,2} \]
Applied Bending Moment at Bolts  \[ M_{2q} := 0 \cdot \text{in-lbf} \]

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 1 is not included.

\[ \text{ID2} := \text{stack(ID2} + 1, \text{ID2} + 2, \text{ID2} + 3, \text{ID2} + 4, \text{ID2} + 5, \text{ID2} + 6, \text{ID2} + 7) \]

\[ \text{LC2} := \text{stack(LC2, LC2, LC2, LC2, LC2, LC2, LC2)} \]
Moment Distribution

\[ M_{\text{tot}2}^{(q)} := \begin{pmatrix} Mx_2 \q \My_2 \q \Mz_2 \q \end{pmatrix} + r_{\text{load}} \times \begin{pmatrix} Fx_2 \q \Fy_2 \q \Fz_2 \q \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ \begin{align*}
M_{\text{boltcg}2}^{q} & := M_{\text{tot}1, q} \\
M_{\text{boltcg}2}^{q} & := M_{\text{tot}2, q} \\
M_{\text{boltcg}2}^{q} & := M_{\text{tot}3, q}
\end{align*} \]

Tension on bolts

\[ F_{\text{direct}2, q} := \begin{cases} 0 \text{lbf} & \text{if } Fx_2 \q \leq 0 \text{lbf} \\ \frac{Fx_2 \q}{\text{num}_\text{bolts}_2} & \text{otherwise} \end{cases} \]

Direct tensile load calculation

\[ \begin{align*}
F_{mz}^{q} & := 0 \text{lbf} \text{ if } \left( y_2 \q - y_{cg} \right) \leq 0 \text{ in} \\
& = \frac{M_{\text{boltcg}2, q} \cdot \left( y_2 \q - y_{cg} \right)}{\sum_s \left( \left( y_2 \q - y_{cg} \right)^2 \cdot A_{ts}\right)}
\end{align*} \]

\[ \begin{align*}
F_{my}^{q} & := 0 \text{lbf} \text{ if } \left( z_2 \q - z_{cg} \right) = 0 \text{ in} \\
& = \frac{M_{\text{boltcg}2, q} \cdot \left( z_2 \q - z_{cg} \right)}{\sum_s \left( \left( z_2 \q - z_{cg} \right)^2 \cdot A_{ts}\right)}
\end{align*} \]

\[ F_{t}^{q} := F_{\text{direct}2, q} + F_{mz}^{q} + F_{my}^{q} \text{ Total Tensile load} \]

Shear on bolts

\[ F_{s}^{q} := \frac{M_{\text{boltcg}2, q} \cdot r_2 \q \cdot A_{ts} \q}{\sum_s \left( r_2 \q \cdot A_{ts} \q \right)^2} \text{ Total shear load} \]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 7 bolts, since bolt number 1 is not included.

\[
P2 := \text{stack}\left[ (FT^T)^{(1)}, (FT^T)^{(2)}, (FT^T)^{(3)}, (FT^T)^{(4)}, (FT^T)^{(5)}, (FT^T)^{(6)}, (FT^T)^{(7)} \right]
\]

\[
V2 := \text{stack}\left[ (F_{\text{tot}}^T)^{(1)}, (F_{\text{tot}}^T)^{(2)}, (F_{\text{tot}}^T)^{(3)}, (F_{\text{tot}}^T)^{(4)}, (F_{\text{tot}}^T)^{(5)}, (F_{\text{tot}}^T)^{(6)}, (F_{\text{tot}}^T)^{(7)} \right]
\]

M2 := \text{stack}(M2, M2, M2, M2, M2, M2, M2)

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{Output2} := \text{augment}\left( \begin{array}{c}
\text{ID2}, \text{LC2}, \frac{P2}{\text{lbf}}, \frac{V2}{\text{lbf}}, \frac{M2}{\text{in-lbf}}
\end{array} \right)
\]

(Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: \( \text{rows(Output2)} = 1792 \)

\( 7 \text{ bolts} \times 64 \text{ load cases} \times 4 \text{ joints} = 1792 \text{ load cases} \)

\[
\text{WRITEPRN("output_forces_upperussipf_r2_abortland_fs.txt") := Output2}
\]

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
data_{\text{fs}} := \text{READPRN("output_forces_upperussipf_r2_abortland_fs.txt")}
\]

\[
s := 1..\text{rows(data}_{\text{fs}})
\]
Fail-safe Loads, abort landing

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>SFu_FS := data_{s,s}, 1</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>SFsep_FS := data_{s,s}, 2</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>SFu_FS := data_{s,s}, 3</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`

Bolt Fail-safe Load data

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation load</td>
<td>max(Psep_FS) = 4037.07 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
<td>max(Pb_FS) = 19322.5 lbf</td>
</tr>
</tbody>
</table>

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{minFS_{1_1}} = 1.317</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{minFS_{2_1}} = 4.847</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{minFS_{3_1}} = 0.405</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{minFS_{4_1}} = 5.05</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MS_{bolt_FS} := \min(\text{MS}_{FS})

MS_{bolt_FS} = 0.404  
Failure_Mode_FS = "Combined Shear Tension Bending Ultimate"

MS_{min_ID} = 660022  
Element Identification (66002) and Bolt Number (2) for Minimum Margin

MS_{min_LC} = 2038  
Load Case Number for Minimum Margin

MS_{min_P} = 4037.1  
Applied Tensile Load for Minimum Margin

MS_{min_V} = -810.9  
Applied Shear Load for Minimum Margin

MS_{min_M} = 0  
Applied Bending Moment for Minimum Margin
Shear Pin Analysis for Upper Vacuum Case Interface Plate to USS-02

The USS-02 assembly consists of four Upper Vacuum Case Joints (SDG39135727). Each Upper Vacuum Case Joint has a shear pin (SDG39135755-005) installed with two bushings. The shear pin sets inside of a inner bushing SDG39135757-001 and the inner bushing sets inside of the outer bushing SDG39135757-003.

Shear Pin
SDG39135755-005

Inner Bushing
SDG39135757-001

Outer Bushing
SDG39135757-003

Cross Section of the Bolted Interface

Shear Pin SDG39135755-005

Inner Bushing SDG39135757-001

Outer Bushing SDG39135757-003
### Geometry

- Minimum Diameter of shear pin: $dp := 0.8746$ in (Ref. Drg. SDG39135755-005)
- Outer diameter of outer bushing: $do := 1.3685$ in (Ref. Drg. SDG39135757-003)
- Thickness of interface plate: $tp := 0.75$ in (Ref. Drg. SDG39135788)
- Length of inner bushing: $tpin := 0.78$ in (Ref. Drg. SDG39135757-001)

### Temperature Data

**Shear Pin (Custom 455, H1000 bar, AMS5617):**

- Temperature correction factor for shear: $c_{sp} := 0.96$ (Ref. MIL-HDBK-5J, table 2.6.4.1.2)

**Interface Plate (Al 7050-T7451 Plate):**

- Temperature correction factor for ultimate: $c_{pu} := 0.96$ (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)
- Temperature correction factor for yield: $c_{py} := 0.97$

**Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):**

- Temperature correction factor for ultimate: $c_{bu} := 0.95$ (Ref. Appendix C8)
- Temperature correction factor for yield: $c_{by} := 0.99$

### Material Properties

**Shear Pin (Custom 455, H1000 bar, AMS5617):**

- Allowable shear stress: $F_{su} := 124000$ psi (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

**Interface Plate (Al 7050-T7451 Plate):**

- Allowable bearing stress: $F_{brup} := 141000$ psi
  
  $F_{bryp} := 104000$ psi (Ref. MIL-HDBK-5J, table 3.7.4.0 (b1), 2.5 in. thick, $e/D=2.0$)

**Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):**

- Allowable bearing stress of bushing: $F_{bru} := 125000$ psi
  
  $F_{bry} := 72000$ psi (Ref. Appendix C8, Rockwell Materials data sheet 09.12.01.01,1.0)
Shear Pin Analysis

Loads in shear pin from Bolt Analysis (Direct Shear)

\[ F_{sp,j} := \sqrt{(F_{y,j})^2 + (F_{z,j})^2} \]
rows(Fsp) = 256
(4 joints x 64 load cases = 256 load cases)

Shear Area of pin

\[ Ash := \frac{\pi \cdot dp^2}{4} \]
\[ Ash = 0.601 \text{ in}^2 \]

Allowable shear load

\[ \text{Pall} := F_{su} \cdot Ash \cdot csp \]
\[ \text{Pall} = 71515.8 \text{ lbf} \]

Margin of safety

\[ MS_{pj} := \left( \frac{\text{Pall}}{F_{sp,j} \cdot SFu} - 1 \right) \]
\[ \text{min}(MSp) = 1.55 \]

Bearing of Outer Bushing on Interface Plate

Bearing of the outer bushing on the USS-02 Upper Vacuum Case Joint is not critical since the bearing thickness is .854 in. compared to 0.75 in on the Upper Vacuum Case Interface Plate. So the margin of safety is high for bearing on the USS-02 Upper Vacuum Case. The Upper Vacuum Case Interface Plate thickness is used below.

Bearing area

\[ Ab := do \cdot tp \]
\[ Ab = 1.026 \text{ in}^2 \]

Allowable bearing load

\[ \text{Pbru} := F_{brup} \cdot Ab \cdot cpu \]
\[ \text{Pbru} = 138930.1 \text{ lbf} \]

\[ \text{Pbry} := F_{bryp} \cdot Ab \cdot cpy \]
\[ \text{Pbry} = 103540.7 \text{ lbf} \]

Margin of safety

\[ MS_{u,j} := \frac{\text{Pbru}}{F_{sp,j} \cdot SFu} - 1 \]
\[ MS_{y,j} := \frac{\text{Pbry}}{F_{sp,j} \cdot SFy} - 1 \]
\[ \text{min}(MSu) = 3.95 \]
\[ \text{min}(MSy) = 3.7 \]
**Title**

Bolts from Upper Vacuum Case Interface Plate to USS

---

**Bearing of Shear Pin on Inner Bushing**

**Bearing area**

\[ Abp := dp \times \text{pin} \]

\[ Abp = 0.682 \text{ in}^2 \]

**Allowable bearing load**

\[ Pbrui := Fbru \times Abp \times cbu \]

\[ Pbrui = 81009.8 \text{ lbf} \]

\[ Pbryi := Fbry \times Abp \times cby \]

\[ Pbryi = 48626.4 \text{ lbf} \]

**Margin of safety**

\[ MSbru_j := \frac{Pbrui}{Fsp_j \times SFu} - 1 \]

\[ MSbry_j := \frac{Pbryi}{Fsp_j \times SFy} - 1 \]

**min(MSbru) = 1.89**

**min(MSbry) = 1.21**
2.4.1.2 Lower Interface Plate to USS-02
Lower Vacuum Case Interface Plate to USS-02 Bolt Analysis

The USS-02 assembly consists of four Lower Vacuum Case (VC) Joints. There are a total of 10 fasteners attaching the USS-02 to the lower interface plate. The fasteners are NAS1958C (180 ksi), 0.50-20 UNFJ. There is also one shear pin 0.875" in diameter. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

Bolt Geometry

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
</tbody>
</table>

\[
i := 1..\text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{i,2} \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{i,1} \cdot \text{in} \quad \text{bolt diameter}
\]

\[
A_{ti} := \pi \left( \frac{D_i - 0.9743 \cdot \frac{1}{N_i}}{2} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
A_{si} := \pi \left( \frac{D_i - 1.299038 \cdot \frac{1}{N_i}}{2} \right)^2 \quad \text{Shear Area of bolt}
\]
Bolts from Lower Vacuum Case Interface to USS

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.0</td>
<td>3.3125</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>3.3125</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.0</td>
<td>3.3125</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.0</td>
<td>3.3125</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>3.0</td>
<td>0.0625</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>-4.688</td>
<td>-3.1875</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>-3.0</td>
<td>-3.1875</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>0.0</td>
<td>-3.1875</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>3.0</td>
<td>-3.1875</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>4.688</td>
<td>-3.1875</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
\text{xforce} := 0.0 \text{in} \quad \text{yforce} := 0.0 \text{in} \quad \text{zforce} := 0.0 \text{in}
\]

\[
\text{cgload} := \begin{bmatrix} \text{xforce} \\ \text{yforce} \\ \text{zforce} \end{bmatrix} \quad \text{cgload} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{in}
\]
Center of gravity of bolt group

\[ x_{cg} := \sum_{i}^{\text{rows}(x)} \frac{x_i}{x_i} \quad x_{cg} = 0 \text{ in} \]
\[ y_{cg} := \sum_{i}^{\text{rows}(y)} \frac{y_i}{y_i} \quad y_{cg} = 0 \text{ in} \]
\[ z_{cg} := \sum_{i}^{\text{rows}(z)} \frac{z_i}{z_i} \quad z_{cg} = -0.587 \text{ in} \]

\[ c_{gbolt} := \begin{pmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{pmatrix} \quad c_{gbolt} = \begin{pmatrix} 0 \\ 0 \\ -0.587 \end{pmatrix} \text{ in} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis with a zero offset from the center of gravity. However, in the z direction the bolt pattern is unsymmetric and has a .587" offset from the center of gravity.

Load Vector

\[ r_{load} := c_{gload} - c_{gbolt} \quad r_{load} = \begin{pmatrix} 0 \\ 0 \\ 0.587 \end{pmatrix} \text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_i := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2} \]

\[ r = \begin{pmatrix} 4.920 \\ 3.900 \\ 4.920 \\ 3.070 \\ 3.070 \\ 5.361 \\ 3.970 \\ 2.600 \\ 3.970 \\ 5.361 \end{pmatrix} \text{ in} \]

Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 66011, 66012, 66013, and 66014. These loads are read into an array and distributed out to the 10 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis.)

Reading database file for bolted joint, abort landing case

data := READPRN("lowerussipf_r2_abortland.txt")

j := 1 .. rows(data)

num_bolts := rows(bolt)
Loads from 2-04 loads model, abort landing case

Axial Load \( F_x := \text{data}_{j,3} \text{ lbf} \)

Shear in Y axis \( F_y := \text{data}_{j,4} \text{ lbf} \)

Shear in Z axis \( F_z := \text{data}_{j,5} \text{ lbf} \)

Element Identification \( \text{ID}_j := \text{data}_{j,1} \)

Load Case Number \( \text{LC}_j := \text{data}_{j,2} \)

Applied Bending Moment at Bolts \( M_j := 0 \text{ in-lbf} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 66011, 66012, 66013, and 66014, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66011 will have bolt numbers 1 thru 10 attached to the end for all 64 load cases. This brings the total number of load cases to 2560 (4 joints x 10 bolts x 64 load cases = 2560). See the array example to the right.

\[
\begin{bmatrix}
66011001 & 2001 \\
66011001 & 2002 \\
... & ... \\
66011001 & 2064 \\
66011002 & 2001 \\
66011002 & 2002 \\
... & ... \\
66011002 & 2064 \\
66011010 & 2001 \\
66011010 & 2002 \\
... & ... \\
66018010 & 2064 \\
\end{bmatrix}
\]

Array Example
Moment Distribution

\[ M_{\text{tot}}(j) = \begin{bmatrix} M_{x,j} \\ M_{y,j} \\ M_{z,j} \end{bmatrix} + r_{\text{load}} \times \begin{bmatrix} F_{x,j} \\ F_{y,j} \\ F_{z,j} \end{bmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{\text{boltcg},j} = M_{\text{tot1},j} \]
\[ M_{\text{boltcg},j} = M_{\text{tot2},j} \]
\[ M_{\text{boltcg},j} = M_{\text{tot3},j} \]

Tension on bolts

\[ F_{\text{direct},i,j} := \begin{cases} 0 \text{ lbf} & \text{if } F_{x,j} \leq 0 \text{ lbf} \\ \frac{F_{x,j}}{\text{num_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ F_{mz,i,j} := \begin{cases} 0 \text{ lbf} & \text{if } (y_i - y_{\text{cg}}) = 0 \text{ in} \\ \frac{[M_{\text{boltcg},j}(y_i - y_{\text{cg}})]A_{t,i}}{\sum_i ([y_i - y_{\text{cg}}]^2 \cdot A_{t,i})} & \text{otherwise} \end{cases} \]

\[ F_{my,i,j} := \begin{cases} 0 \text{ lbf} & \text{if } (z_i - z_{\text{cg}}) = 0 \text{ in} \\ \frac{[M_{\text{boltcg},j}(z_i - z_{\text{cg}}) \cdot A_{t,i}}{\sum_i ([z_i - z_{\text{cg}}]^2 \cdot A_{t,i})} & \text{otherwise} \end{cases} \]

\[ F_{t,i,j} := F_{\text{direct},i,j} + F_{mz,i,j} + F_{my,i,j} \]

Total Tensile load

Shear on bolts

Secondary shear on bolts

\[ F_{s,i,j} := \frac{M_{\text{boltcg},j} \cdot r_i \cdot A_{s,i}}{\sum_i [r_{ij}^2 \cdot (A_{s,i})]} \]

Total shear load

\[ F_{\text{stot},i,j} := F_{s,i,j} \]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack} \left[ \left( \frac{Ft}{T} \right)^{(1)}, \left( \frac{Ft}{T} \right)^{(2)}, \left( \frac{Ft}{T} \right)^{(3)}, \left( \frac{Ft}{T} \right)^{(4)}, \left( \frac{Ft}{T} \right)^{(5)}, \left( \frac{Ft}{T} \right)^{(6)}, \left( \frac{Ft}{T} \right)^{(7)}, \left( \frac{Ft}{T} \right)^{(8)}, \left( \frac{Ft}{T} \right)^{(9)}, \left( \frac{Ft}{T} \right)^{(10)} \right]
\]

\[
V := \text{stack} \left[ \left( \frac{Fstot}{T} \right)^{(1)}, \left( \frac{Fstot}{T} \right)^{(2)}, \left( \frac{Fstot}{T} \right)^{(3)}, \left( \frac{Fstot}{T} \right)^{(4)}, \left( \frac{Fstot}{T} \right)^{(5)}, \left( \frac{Fstot}{T} \right)^{(6)}, \left( \frac{Fstot}{T} \right)^{(7)}, \left( \frac{Fstot}{T} \right)^{(8)}, \left( \frac{Fstot}{T} \right)^{(9)}, \left( \frac{Fstot}{T} \right)^{(10)} \right]
\]

\[
M := \text{stack} \left[ \left( \frac{M}{M} \right)^{(1)}, \left( \frac{M}{M} \right)^{(2)}, \left( \frac{M}{M} \right)^{(3)}, \left( \frac{M}{M} \right)^{(4)}, \left( \frac{M}{M} \right)^{(5)}, \left( \frac{M}{M} \right)^{(6)}, \left( \frac{M}{M} \right)^{(7)}, \left( \frac{M}{M} \right)^{(8)}, \left( \frac{M}{M} \right)^{(9)}, \left( \frac{M}{M} \right)^{(10)} \right]
\]

Size of the "Output" Array: rows(Output) = 2560

(10 bolts x 64 load cases) x 4 joints = 2560 load cases

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

\[
\text{Example of Output Array} \quad \text{WRITEPRN} \left( \text{"output_forces_lowerussipf_r2_abortland.txt"} \right) := \text{Output}
\]

\[
\text{Size of the "Output" Array: rows(Output) = 2560}
\]

(10 bolts x 64 load cases) x 4 joints = 2560 load cases
CHECK BOLTS (bolts SDG39135892-811, NAS1958C17 0.500-20UNJF-3A, Material-A-286, Insert MS51831CA206, Washer NAS1149E0863R)

The array from the text file above is read:

\[ \text{data} := \text{READPRN}("output_forces_lowerussipf_r2_abortland.txt") \]
\[ s := 1..\text{rows(data)} \]

Flange 1: USS-02 Lower Vacuum Case Joint
Part number: SDG39135737
Material: 7050-T7451

Flange 2: Lower Vacuum Case Interface Plate
Part number: SDG39135789
Material: 7050-T7451

Loads from Abort Landing Load Cases

- Applied tensile load
  \[ P_s := \text{data}_{s,3}\text{lbf} \]
- Applied shear load
  \[ V_s := \text{data}_{s,4}\text{lbf} \]
- Applied bending moment
  \[ M_s := \text{data}_{s,5}\text{in-lbf} \]

Factors of Safety

- Ultimate
  \[ \text{SFu} := 1.4 \]
- Yield
  \[ \text{SFy} := 1.1 \]
- Joint Separation
  \[ \text{SFsep} := 1.2 \]
- Fitting factor
  \[ \text{FF} := 1.15 \]

Temperature Data (Ref Appendix C2), Abort Landing Case

- Assembly
  \[ \text{Temp}_{\text{initial}} := 70\text{-deg} \]
- Maximum
  \[ \text{Temp}_{\text{max}} := 150\text{-deg} \]
- Minimum
  \[ \text{Temp}_{\text{min}} := 40\text{-deg} \]

Bolt and Insert Data

- Nominal diameter of bolt
  \[ D := 0.500\text{-in} \]
- Number of threads/inch
  \[ N_t := 20\cdot\frac{1}{\text{in}} \]
- Total length of bolt
  \[ L := 1.797\text{-in} \]
- Length of insert
  \[ L_{\text{ins}} := 0.688\text{-in} \]
- Threaded length
  \[ L_t := 0.735\text{-in} \]
- Min. external diameter of insert
  \[ F_{\text{min}} := 0.615\text{-in} \]
- (If bolt is fully threaded, input \( L_t = L \))
- Depth of recess for insert
  \[ l_r := 0.02\text{-in} \]

This file uses the calculations shown in \textlscape{escf102\211_mathcadv8307_bolts\thread_data.mcd}
Washer Data
Thickness of washer \( t_w = 0.063\text{-in} \)
Outer Diameter of washer \( D_w = 0.875\text{in} \)
Inner Diameter of washer \( D_{wi} = 0.515\text{in} \)
Bolt head dia. across flats \( d_w = 0.710\text{-in} \)

Flange data
Thickness of flange 1 \( t_{f1} = 0.854\text{-in} \)
Thickness of flange 2 \( t_{f2} = 0.688\text{-in} \)
Diameter of hole \( D_{\text{hole}} = 0.571\text{-in} \)

Material Property Data
Bolt
Temperature correction factor for bolt strength ultimate \( T_{Su_{\text{bolt}}} = 0.96 \)
Bolt ultimate tensile allowable stress \( F_{tu_{\text{bolt}}} = 180000\text{ psi} \)
Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} = 0.6 \times F_{tu_{\text{bolt}}} \)
Bolt yield tensile allowable \( F_{ty_{\text{bolt}}} = 132353\text{ psi} \)

Insert
Temperature correction factor for insert strength \( T_{S_{\text{ins}}} = 0.96 \)
Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} = 140000\text{ psi} \)
Ultimate shear allowable stress \( F_{su_{\text{ins}}} = 0.6 \times F_{tu_{\text{ins}}} \)

Washer
Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} = 0.96 \)
Modulus of elasticity of washer \( E_{\text{washer}} = 29.1 \times 10^6\text{ psi} \)
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{1E} := .96 \text{ (modulus)} \]
Temperature correction factor for flange 2
\[ T_{2E} := .96 \text{ (modulus)} \]
Shear Strength Allowable for flanges
\[ F_{su_f2} := 44000 \text{ psi} \]

Modulus of elasticity for the parts in the joint
\[ E_{flange1} := \left(10.3 \cdot 10^6 \text{ psi}\right) \quad E_{flange2} := \left(10.3 \cdot 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges
\[ \alpha_{flange1\_hot} := 12.8 \cdot 10^{-6} \text{ in/in/deg} \quad \alpha_{flange2\_hot} := 12.8 \cdot 10^{-6} \text{ in/in/deg} \]
\[ \alpha_{flange1\_cold} := 12.1 \cdot 10^{-6} \text{ in/in/deg} \quad \alpha_{flange2\_cold} := 12.1 \cdot 10^{-6} \text{ in/in/deg} \]

Torque/Preload data

Maximum torque (65% of yield)
\[ T_{max} := 1032 \text{-in-lbf} \]

Minimum torque (95 % of max. torque)
\[ T_{min} := 980 \text{-in-lbf} \]

Torque coefficient:
\[ k := 0.15 \]

Loading plane factor:
\[ n := .5 \]

Preload Uncertainty:
\[ \Gamma := 0.25 \]

This file uses the calculations shown in `\escfile02\2\11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC`
Bolt Load data

Bolt/joint stiffness factor \( \phi = 0.403 \)

Max. preload \( PLD_{\text{max}} = 18357 \text{ lbf} \)

Min. preload \( PLD_{\text{min}} = 8564.8 \text{ lbf} \)

Joint separation load \( \max(P_{\text{sep}}) = 3426.92 \text{ lbf} \)

Max. load on the bolt(ultimate) \( \max(P_b) = 19283.6 \text{ lbf} \)

Max. load on the bolt(yield) \( \max(P_{by}) = 19085 \text{ lbf} \)

Bolt ultimate tensile strength \( PA_t = 27143.2 \text{ lbf} \)

Preload due to temperature \( P_{\text{thr}\_pos} = 1157 \text{ lbf} \)

Uncertainty factor \( \Gamma = 0.25 \)

Torque coefficient \( k = 0.15 \)

Loading plane factor \( n = 0.5 \)

Thread shear pullout load of bolt or insert \( P_{\text{ths}} = 50927.3 \text{ lbf} \)

Thread shear pullout load in parent metal \( P_{\text{pths}} = 28074.2 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

- Joint separation \( MS_{\min,1,1} = 1.722 \) Direct Thread shear Ultimate \( MS_{\min,6,1} = 5.106 \)
- Direct Tension Ultimate \( MS_{\min,2,1} = 4.904 \) Total Thread shear Ultimate \( MS_{\min,7,1} = 0.456 \)
- Direct Tension Yield \( MS_{\min,3,1} = 4.525 \) Shear Ultimate \( MS_{\min,8,1} = 2.55 \)
- Total Tension Ultimate \( MS_{\min,4,1} = 0.408 \) Bending Ultimate \( MS_{\min,9,1} = 10 \)
- Total Tension Yield \( MS_{\min,5,1} = 0.046 \) Combined shear, tension and bending ultimate \( MS_{\min,10,1} = 0.379 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\( MS_{\text{bolt}} := \min(\text{MS}) \)

\( MS_{\text{bolt}} = 0.046 \) Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

\( MS_{\min,\text{ID}} = 66011003 \) Element Identification (66011) and Bolt Number (3) for Minimum Margin

\( MS_{\min,\text{LC}} = 2031 \) Load Case Number for Minimum Margin

\( MS_{\min,P} = 2855.8 \) Applied Tensile Load for Minimum Margin

\( MS_{\min,V} = -2294.4 \) Applied Shear Load for Minimum Margin

\( MS_{\min,M} = 0 \) Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Upper Vacuum Case Interface Plate to USS-02 (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-001. All 10 NAS1958 fasteners will take the direct shear load.

Direct shear Loads

$$\text{Fsd}_{i,j} := \frac{\sqrt{(Fy_j)^2 + (Fz_j)^2}}{\text{num_bolts}}$$

Total shear load

$$\text{Fstot}_{i,j} := \text{Fs}_{i,j} + \text{Fsd}_{i,j}$$

(Note: The Fs variable is the secondary shear and calculated above.)

The stack command below is used to stack the applied shear load (V) in ascending order per bolt. The applied axial load (P) and applied moment (M) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

$$V := \text{stack}(\text{Fstot}_T^{(1)}, \text{Fstot}_T^{(2)}, \text{Fstot}_T^{(3)}, \text{Fstot}_T^{(4)}, \text{Fstot}_T^{(5)}, \text{Fstot}_T^{(6)})$$

$$V := \text{stack}(V, \text{Fstot}_T^{(7)}, \text{Fstot}_T^{(8)}, \text{Fstot}_T^{(9)}, \text{Fstot}_T^{(10)})$$

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is written to a text file. For the format of the array see the output example array above.

$$\text{Output} := \text{augment}(\text{ID}, \text{LC}, \frac{\text{P}}{\text{lb}} \cdot \frac{\text{V}}{\text{lb} \cdot \text{in}} \cdot \frac{\text{M}}{\text{in} \cdot \text{lb}})$$

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: rows(Output) = 2560

(10 bolts x 64 load cases) x 4 joints = 2560 load cases

WRITEPRN("output_forces_lowerussipf_r2_abortland_pinfs.txt") := Output

Fail-safe Analysis (Shear Pin Failure)

The array from the text file above is read:

data_fsp := READPRN("output_forces_lowerussipf_r2_abortland_pinfs.txt")

s := 1 .. rows(data_fsp)
Fail-safe Loads, abort landing

<table>
<thead>
<tr>
<th>Applied</th>
<th>Tensile Load</th>
<th>( P_{FS} := \text{data}_{fssp,3} \cdot \text{lbf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied</td>
<td>Shear Load</td>
<td>( V_{FS} := \text{data}_{fssp,4} \cdot \text{lbf} )</td>
</tr>
<tr>
<td>Applied</td>
<td>Bending Moment</td>
<td>( M_{FS} := \text{data}_{fssp,5} \cdot \text{in\cdot lbf} )</td>
</tr>
</tbody>
</table>

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Applied</th>
<th>Tensile Load</th>
<th>( SF_{FS} := 1.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied</td>
<td>Shear Load</td>
<td>( SF_{sep}_{FS} := 1.0 )</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escfil02\111_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

- Joint separation load: \( \max(P_{sep}_{FS}) = 2855.767 \text{ lbf} \)
- Max. load on the bolt (ultimate): \( \max(P_F{B}) = 19018.8 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

- Joint separation: \( MS_{minFS1,1} = 2.266 \)
- Direct Tension Ultimate: \( MS_{minFS2,1} = 7.265 \)
- Total Tension Ultimate: \( MS_{minFS3,1} = 0.427 \)
- Direct Thread shear Ultimate: \( MS_{minFS4,1} = 7.55 \)
- Total Thread shear Ultimate: \( MS_{minFS5,1} = 0.476 \)
- Shear Ultimate: \( MS_{minFS6,1} = 3.16 \)
- Bending Ultimate: \( MS_{minFS7,1} = 10 \)
- Combined shear, tension and bending ultimate: \( MS_{minFS8,1} = 0.4217 \)

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt}_{FS} := \min(MS_{FS}) \)

\( MS_{bolt}_{FS} = 0.422 \)

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

Element Identification (66012) and Bolt Number (1) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Upper Vacuum Case Interface Plate to USS-02

Since bolt number 3 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 9, NAS1958C 0.50-20 UNFJ fasteners, holding the USS to the lower vacuum case interface plate. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

<table>
<thead>
<tr>
<th>Size</th>
<th>Thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
</tbody>
</table>

\[ \text{s} := 1 \ldots \text{rows(bolt2)} \]

\[ N_2^s := \text{bolt2}_s, \frac{1}{2} \text{ in} \]

\[ \text{pitch of bolt} \]

\[ D_2^s := \text{bolt2}_s, 1 \text{ in} \]

\[ \text{bolt diameter} \]

\[ \text{At}_2^s := \pi \left( \frac{D_2^s - 0.9743 \cdot \frac{1}{N_2^s}}{2} \right)^2 \]

\[ \text{Tensile Area of bolt} \]

\[ \text{As}_2^s := \pi \left( \frac{D_2^s - 1.299038 \cdot \frac{1}{N_2^s}}{2} \right)^2 \]

\[ \text{Shear Area of bolt} \]

Lower Vacuum Case Interface Plate to USS Bolt Pattern for Fail-Safe Analysis
Bolts from Lower Vacuum Case Interface to USS

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.0</td>
<td>3.125</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>3.125</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.0</td>
<td>0.0625</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>3.0</td>
<td>0.0625</td>
</tr>
<tr>
<td>6</td>
<td>x2 := 0.0 in</td>
<td>y2 := -4.688 in</td>
<td>z2 := -3.185 in</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>-3.0</td>
<td>-3.185</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>0.0</td>
<td>-3.185</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>3.0</td>
<td>-3.185</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>4.688</td>
<td>-3.185</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
x_{force2} := 0.0 \text{ in} \quad y_{force2} := 0.0 \text{ in} \quad z_{force2} := 0.0 \text{ in}
\]

\[
c_{gload2} := \begin{pmatrix} x_{force2} \\ y_{force2} \\ z_{force2} \end{pmatrix} \quad \Rightarrow \quad c_{gload2} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

Center of gravity of bolt group

\[
x_{cg2} := -\frac{\sum x_{s}}{\text{rows}(x_{2})} \quad \Rightarrow \quad x_{cg2} = 0 \text{ in} \\
y_{cg2} := -\frac{\sum y_{s}}{\text{rows}(y_{2})} \quad \Rightarrow \quad y_{cg2} = -0.333 \text{ in} \\
z_{cg2} := -\frac{\sum z_{s}}{\text{rows}(z_{2})} \quad \Rightarrow \quad z_{cg2} = -1.021 \text{ in}
\]

\[
c_{gbolt2} := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} \quad \Rightarrow \quad c_{gbolt2} = \begin{pmatrix} 0 \\ -0.333 \\ -1.021 \end{pmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 3, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[
\begin{pmatrix} r_{load2} := c_{gload2} - c_{gbolt2} \end{pmatrix} = \begin{pmatrix} 0 \\ 0.333 \\ 1.021 \end{pmatrix} \text{ in}
\]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_2 := \sqrt{(z_s^2 - z_{cg2})^2 + (y_s^2 - y_{cg2})^2} \]

\[
\begin{array}{c}
5.088 \\
4.346 \\
2.878 \\
3.505 \\
4.864 \\
3.436 \\
2.192 \\
3.976 \\
5.469 \\
\end{array}
\]

Reading database file for bolted joint, abort landing case

data := READPRN("lowerussipf_r2_abortland.txt")

q := 1..rows(data)  num_bolts2 := rows(bolt2)

Loads from 2-04 loads model, abort landing case

Axial Load \( F_{xq} \) \( \text{lbf} \)
Shear in Y axis \( F_{yq} \) \( \text{lbf} \)
Shear in Z axis \( F_{zq} \) \( \text{lbf} \)
Element Identification \( ID_2 \) \( \text{data} \)
Load Case Number \( LC_2 \) \( \text{data} \)
Applied Bending Moment at Bolts \( M_2 \) \( \text{in-lbf} \)

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 3 is not included.

\[
ID2 := \text{stack}(ID2, ID2 + 1, ID2 + 3, ID2 + 4, ID2 + 5, ID2 + 6, ID2 + 7, ID2 + 8, ID2 + 9)
\]

\[
LC2 := \text{stack}(LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2)
\]
Moment Distribution

\[
M_{\text{tot2}}(q) = \left(\begin{array}{c} Mx_2 \\ My_2 \\ Mz_2 \end{array}\right) + r_{\text{load2}} \times \left(\begin{array}{c} Fx_2 \\ Fy_2 \\ Fz_2 \end{array}\right)
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg2}}(q) := M_{\text{tot12}}(q)
\]

Tension on bolts

\[
F_{\text{direct2}}(s,q) := \begin{cases} 
0 \text{-lbf} & \text{if } Fx_2(q) \leq 0 \text{-lbf} \\
\frac{Fx_2(q)}{\text{num_bolts2}} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation

\[
\begin{align*}
F_{\text{mz2}}(s,q) := 0 \text{-lbf} & \text{ if } \left(\frac{y_2(s) - y_{\text{cg2}}}{z_2(s) - z_{\text{cg2}}}\right) \leq 0 \text{-in} \\
& \left[\frac{M_{\text{boltcg2}}(q) \left(\frac{y_2(s) - y_{\text{cg2}}}{z_2(s) - z_{\text{cg2}}}\right)}{\text{At2}}\right] \sum_s \left[\left(\frac{y_2(s) - y_{\text{cg2}}}{z_2(s) - z_{\text{cg2}}}\right)^2 \cdot \text{At2}\right]
\end{align*}
\]

\[
F_{\text{mmy2}}(s,q) := 0 \text{-lbf} & \text{ if } \left(\frac{z_2(s) - z_{\text{cg2}}}{\text{At2}}\right) \leq 0 \text{-in} \\
& \sum_s \left[\left(\frac{z_2(s) - z_{\text{cg2}}}{\text{At2}}\right)^2 \cdot \text{At2}\right]
\]

\[
F_{\text{t2}}(s,q) := F_{\text{direct2}}(s,q) + F_{\text{mz2}}(s,q) + F_{\text{mmy2}}(s,q)
\]

Total Tensile load

Shear on bolts

\[
F_{\text{s2}}(s,q) := \frac{M_{\text{boltcg2}}(q) \cdot r_2 \cdot \text{As2}}{\sum_s \left[\left(\frac{r_2}{\text{As2}}\right)^2 \right]}
\]

Total shear load

\[
F_{\text{stot2}}(s,q) := F_{\text{s2}}(s,q)
\]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load ($P_2$), applied shear load ($V_2$), and applied moment ($M_2$) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 9 bolts, since bolt number 3 is not included.

\[
P_2 := \text{stack}[\left(F_{T2}^{(1)}\right),\left(F_{T2}^{(2)}\right),\left(F_{T2}^{(3)}\right),\left(F_{T2}^{(4)}\right),\left(F_{T2}^{(5)}\right),\left(F_{T2}^{(6)}\right),\left(F_{T2}^{(7)}\right),\left(F_{T2}^{(8)}\right),\left(F_{T2}^{(9)}\right)]
\]

\[
V_2 := \text{stack}[\left(F_{stot2}^{(1)}\right),\left(F_{stot2}^{(2)}\right),\left(F_{stot2}^{(3)}\right),\left(F_{stot2}^{(4)}\right),\left(F_{stot2}^{(5)}\right),\left(F_{stot2}^{(6)}\right),\left(F_{stot2}^{(7)}\right)]
\]

\[
\begin{align*}
V_2 &= \text{stack}\left(V_2,\left(F_{stot2}^{(8)}\right)\right) \\
M_2 &= \text{stack}(M_2,M_2,M_2,M_2,M_2,M_2,M_2,M_2)
\end{align*}
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt ($P_2$), applied shear on the bolt ($V_2$), and applied moment on the bolt ($M_2$). See the output array example above. The array is written to a text file.

\[
\text{Size of the "Output2" Array: } \text{rows}(\text{Output2}) = 2304
\]

\[
(9 \text{ bolts } \times 64 \text{ load cases}) \times 4 \text{ joints} = 2304 \text{ load cases}
\]

\[
\text{WRITEPRN}("\text{output_forces_lowerussipf_r2_abortland_fs.txt}"") := \text{Output2}
\]

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
data_{\text{fs}} := \text{READPRN}("\text{output_forces_lowerussipf_r2_abortland_fs.txt}"")
\]

\[
s := 1 .. \text{rows}(\text{data}_{\text{fs}})
\]
Fail-safe Loads, abort landing

<table>
<thead>
<tr>
<th>Applied tensile load</th>
<th>P_{FS, s} := data_{s, 3}, lbf</th>
<th>ID_{FS, s} := data_{s, 1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear load</td>
<td>V_{FS, s} := data_{s, 4}, lbf</td>
<td>LC_{FS, s} := data_{s, 2}</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_{FS, s} := data_{s, 5}, in-lbf</td>
<td></td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

<table>
<thead>
<tr>
<th>Bolt Fail-safe Load data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation load</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
</tr>
</tbody>
</table>

| MAX, applied tensile load for minimum margin | max(P_{FS}) = 3007.742 lbf |
| applied shear load for minimum margin | max(V_{FS}) = 3223.796 lbf |

Summary of fail-safe Margins for bolt:

| Joint separation | MS_{minFS, 1, 1} = 2.101 | Total Thread shear Ultimate | MS_{minFS, 5, 1} = 0.473 |
| Direct Tension Ultimate | MS_{minFS, 2, 1} = 6.847 | Shear Ultimate | MS_{minFS, 6, 1} = 3.16 |
| Total Tension Ultimate | MS_{minFS, 3, 1} = 0.425 | Bending Ultimate | MS_{minFS, 7, 1} = 10 |
| Direct Thread shear Ultimate | MS_{minFS, 4, 1} = 7.12 | Combined shear, tension and bending ultimate | MS_{minFS, 8, 1} = 0.4180 |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MS_{bolt, FS} := min(MS_{FS})

MS_{bolt, FS} = 0.418

Failure Mode_{FS} = "Combined Shear Tension Bending Ultimate"

MS_{min, ID} = 66011002
Element Identification (66011) and Bolt Number (2) for Minimum Margin

MS_{min, LC} = 2031
Load Case Number for Minimum Margin

MS_{min, P} = 3007.7
Applied Tensile Load for Minimum Margin

MS_{min, V} = -1972.8
Applied Shear Load for Minimum Margin

MS_{min, M} = 0
Applied Bending Moment for Minimum Margin

2.4.1.2 -19  ESCG-4005-05-AMS-0039
Shear Pin Analysis for Lower Vacuum Case Interface Plate to USS-02

The USS-02 assembly consists of four Lower Vacuum Case Joints (SDG39135737). Each Lower Vacuum Case Joint has a shear pin (SDG39135755-001) installed with two bushings. The shear pin sets inside of an inner bushing SDG39135757-001 and the inner bushing sets inside of the outer bushing SDG39135757-003.

Cross Section of the Bolted Interface

Shear Pin SDG39135755-001

Outer Bushing SDG39135757-003

Inner Bushing SDG39135757-001
Geometry

Minimum Diameter of shear pin  \( dp := 0.8746 \text{ in} \) 
(Ref. Drg. SDG39135755-001)

Outer diameter of outer bushing  \( do := 1.3685 \text{ in} \) 
(Ref. Drg. SDG39135757-003)

Thickness of interface plate  \( tp := 0.75 \text{ in} \) 
(Ref. Drg. SDG39135789)

Length of inner bushing  \( tpin := 0.78 \text{ in} \) 
(Ref. Drg. SDG39135757-001)

Temperature Data

Shear Pin (Custom 455, H1000 bar, AMS5617):

Temperature correction factor for shear  \( csp := 0.96 \) 
(Ref. MIL-HDBK-5J, table 2.6.4.1.2)

Interface Plate (Al 7050-T7451 Plate):

Temperature correction factor for ultimate  \( cpu := 0.96 \) 
(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Temperature correction factor for yield  \( cpy := 0.97 \)

Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):

Temperature correction factor for ultimate  \( cbu := 0.95 \) 
(Ref. Appendix C8)

Temperature correction factor for yield  \( cby := 0.99 \)

Material Properties

Shear Pin (Custom 455, H1000 bar, AMS5617):

Allowable shear stress  \( Fsu := 124000 \text{ psi} \) 
(Ref. MIL-HDBK-5J, table 2.6.4.0(b))

Interface Plate (Al 7050-T7451 Plate):

Allowable bearing stress  \( Fbrup := 141000 \text{ psi} \) 
(Ref. MIL-HDBK-5J, table 3.7.4.0 (b1),
2.5 in. thick, e/D=2.0)

\( Fbryp := 104000 \text{ psi} \)

Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):

Allowable bearing stress of bushing  \( Fbru := 125000 \text{ psi} \) 
(Ref. Appendix C8, Rockwell Materials data sheet
09.12.01.01,1.0)

\( Fbry := 72000 \text{ psi} \)
Shear Pin Analysis

Loads in shear pin from Bolt Analysis (Direct Shear)

\[ F_{sp,j} := \sqrt{\left( F_{y,j} \right)^2 + \left( F_{z,j} \right)^2} \]

rows(Fsp) = 256

(4 joints x 64 load cases = 256 load cases)

Shear Area of pin

\[ A_{sh} := \frac{\pi \cdot d_p^2}{4} \]

\[ A_{sh} = 0.601 \text{ in}^2 \]

Allowable shear load

\[ P_{all} := F_{su} \cdot A_{sh} \cdot c_{sp} \]

\[ P_{all} = 71515.8 \text{ lbf} \]

Margin of safety

\[ M_{Sp,j} := \frac{P_{all}}{F_{sp,j} \cdot S_{Fu}} - 1 \]

\[ \min(M_{Sp}) = 0.88 \]

bearing of outer bushing on interface plate

Bearing of the outer bushing on the USS-02 Lower Vacuum Case Joint is not critical since the bearing thickness is .854 in. compared to 0.75 in on the Lower Vacuum Case Interface Plate. So the margin of safety is high for bearing on the USS-02 Lower Vacuum Case. The Lower Vacuum Case Interface Plate thickness is used below.

Bearing area

\[ A_b := d_o \cdot t_p \]

\[ A_b = 1.026 \text{ in}^2 \]

Allowable bearing load

\[ P_{bru} := F_{brup} \cdot A_b \cdot c_{pu} \]

\[ P_{bru} = 138930.1 \text{ lbf} \]

\[ P_{bry} := F_{bryp} \cdot A_b \cdot c_{py} \]

\[ P_{bry} = 103540.7 \text{ lbf} \]

Margin of safety

\[ M_{Su,j} := \frac{P_{bru}}{F_{sp,j} \cdot S_{Fu}} - 1 \]

\[ M_{Sy,j} := \frac{P_{bry}}{F_{sp,j} \cdot S_{Fy}} - 1 \]

\[ \min(M_{Su}) = 2.66 \]

\[ \min(M_{Sy}) = 2.47 \]
Bolts from Lower Vacuum Case Interface to USS

**Bearing of Shear Pin on Inner Bushing**

**Bearing area**

\[ Abp = dp \cdot tpin \]

\[ Abp = 0.682 \text{ in}^2 \]

**Allowable bearing load**

\[ Pbrui = Fbru \cdot Abp \cdot cbu \]

\[ Pbrui = 81009.8 \text{ lbf} \]

\[ Pbryi = Fbry \cdot Abp \cdot cby \]

\[ Pbryi = 48626.4 \text{ lbf} \]

**Margin of safety**

\[ MSbru_j := \frac{Pbrui}{Fsp_j \cdot SFu} - 1 \]

\[ MSbry_j := \frac{Pbryi}{Fsp_j \cdot SFy} - 1 \]

\[ \text{min}(MSbru) = 1.13 \]

\[ \text{min}(MSbry) = 0.63 \]
2.4.1.3 TRD Corner Bracket to Upper Vacuum Case Joint
Upper Vacuum Case Joint to TRD Corner Bracket Bolt Analysis

The AMS-02 assembly consists of four TRD (Transition Radiation Detector) Corner Brackets. There are a total of 6 fasteners attaching the Upper Vacuum Case joint to the TRD bracket. The fasteners are NAS1958C (180 ksi), 0.50-20 UNFJ. There is also one titanium shear pin and titanium bushing between the two interfaces.

There are several analyses for the TRD interface. One of the six bolt holes in the TRD bracket are thinner. (0.354" thick compared to 0.374" thick) A flange 2 thickness of .354" is used in this analysis. A stainless steel shim plate and titanium thermal bushings are assembled between the TRD bracket and upper vacuum case joint.

```
size thread/in
(0.50 20
0.50 20
0.50 20
0.50 20
0.50 20
0.50 20)
bolt :=
i := 1.. rows(bolt)

pitch of bolt
N_i := bolt_i, 2^in

bolt diameter
D_i := bolt_i, 1^in
```

View of TRD Corner Bracket
(Ref. drawing 1811/60_0001_L_VI)

View of the AMS-02 Assembly
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

\[ A_{t_i} := \pi \left( \frac{D_i - 0.9743}{2} \right)^2 \]  
Tensile Area of bolt

\[ A_{s_i} := \pi \left( \frac{D_i - 1.2990}{2} \right)^2 \]  
Shear Area of bolt

Upper Vacuum Case Joint to TRD Corner Bracket Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.188</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.188</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.188</td>
<td>-2.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>3.188</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[ x_{\text{force}} := 0.0 \text{in} \]
\[ y_{\text{force}} := 0.0 \text{in} \]
\[ z_{\text{force}} := 0.0 \text{in} \]

\[ \text{cgload} := \begin{pmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{pmatrix} \]
\[ \text{cgload} = \begin{pmatrix} 0 \\ 0 \text{in} \end{pmatrix} \]
Center of gravity of bolt group

\[
\begin{align*}
\text{xcg} & := \frac{\sum_{i} x_i}{\text{rows}(x)}, & \text{xcg} &= 0 \text{ in} \\
\text{ycg} & := \frac{\sum_{i} y_i}{\text{rows}(y)}, & \text{ycg} &= 0 \text{ in} \\
\text{zcg} & := \frac{\sum_{i} z_i}{\text{rows}(z)}, & \text{zcg} &= 0 \text{ in}
\end{align*}
\]

\[
\text{cg}_{\text{bolt}} := \begin{pmatrix}
\text{xcg} \\
\text{ycg} \\
\text{zcg}
\end{pmatrix}, \quad \text{cg}_{\text{bolt}} = \begin{pmatrix}
0 \\
0 \\
0
\end{pmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis and z-axis with a zero offset from the center of gravity.

Load Vector

\[
\text{r}_{\text{load}} := \text{cg}_{\text{load}} - \text{cg}_{\text{bolt}}
\]

\[
\text{r}_{\text{load}} = \begin{pmatrix}
0 \\
0 \\
0
\end{pmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(z_i - \text{zcg})^2 + (y_i - \text{ycg})^2}
\]

\[
r = \begin{pmatrix}
3.763 \\
2.000 \\
3.763 \\
3.763 \\
2.000 \\
3.763
\end{pmatrix} \text{ in}
\]

Loads model 2-06 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each TRD bracket was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 66061, 66062, 66063, and 66064. These loads are read into an array and distributed out to the 6 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The launch cases combined with launch temperature data resulted in the lowest minimum margins of safety. Therefore, the launch cases are used in this analysis.)

Reading database file for bolted joint, launch case

\[
data := \text{READPRN}("\text{trdussf_r5_launch.dat}")
\]

\[
\text{num\_bolts} := \text{rows(bolt)}
\]

\[
j := 1 \ldots \text{rows(data)}
\]

\[
\text{rows(data)} = 256
\]
Loads from 2-06 loads model, launch case

Axial Load
\[ F_{xj} := \text{data}_{j,3} \cdot \text{lbf} \]

Torsion
\[ M_{xj} := \text{data}_{j,6} \cdot \text{in}\cdot\text{lbf} \]

Shear in Y axis
\[ F_{yj} := \text{data}_{j,4} \cdot \text{lbf} \]

Moment about Y axis
\[ M_{yj} := \text{data}_{j,7} \cdot \text{in}\cdot\text{lbf} \]

Shear in Z axis
\[ F_{zj} := \text{data}_{j,5} \cdot \text{lbf} \]

Moment about Z axis
\[ M_{zj} := \text{data}_{j,8} \cdot \text{in}\cdot\text{lbf} \]

Element Identification
\[ \text{ID}_{j} := \text{data}_{j,1} \]

Counter for number of bolts in pattern
\[ \text{ID}_{j} := \text{ID}_{j,10} + 1 \]

Load Case Number
\[ \text{LC}_{j} := \text{data}_{j,2} \]

Applied Bending Moment at Bolts
\[ M_{j} := 0 \cdot \text{in}\cdot\text{lbf} \]

\[ \text{rows}(Fy) = 256 \]

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in asending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 66061, 66062, 66063, and 66064, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66061 will have bolt numbers 1 thru 6 attached to the end for all 64 load cases. This brings the total number of load cases to 1536 (4 joints x 6 bolts x 64 load cases = 1536). See the array example to the right.

\[
\begin{array}{ll}
\text{ID} & \text{LC} \\
6606101 & 2001 \\
6606101 & 2002 \\
... & ... \\
6606101 & 2064 \\
6606102 & 2001 \\
6606102 & 2002 \\
... & ... \\
6606102 & 2064 \\
6606106 & 2001 \\
6606106 & 2002 \\
... & ... \\
6606106 & 2064 \\
\end{array}
\]

Array Example

ID := stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5)

LC := stack(LC, LC, LC, LC, LC, LC)
Moment Distribution

\[
M_{tot,j}^{(j)} := \begin{pmatrix} M_x_j \\ M_y_j \\ M_z_j \end{pmatrix} + \eta_{load} \times \begin{pmatrix} F_x_j \\ F_y_j \\ F_z_j \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x_{boltcg}}, j := M_{tot1,j} \\
M_{y_{boltcg}}, j := M_{tot2,j} \\
M_{z_{boltcg}}, j := M_{tot3,j}
\]

Tension on bolts

\[
F_{direct_{,i,j}} := \begin{cases} 0-lbf & \text{if } F_{x_{,j}} \leq 0-lbf \\ \frac{F_{x_{,j}}}{\text{num_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz_{,i,j}} := \begin{cases} 0-lbf & \text{if } (y_{i,ycg} - y_{cg}) = 0-\text{in} \\ \frac{M_{z_{boltcg},j}(y_{i,ycg} - y_{cg})}{\sum_i (y_{i,ycg} - y_{cg})^2 \cdot A_t_i} & \text{otherwise} \end{cases}
\]

\[
F_{my_{,i,j}} := \begin{cases} 0-lbf & \text{if } (z_{i,zcg} - z_{cg}) = 0-\text{in} \\ \frac{M_{y_{boltcg},j}(z_{i,zcg} - z_{cg}) \cdot A_t_i}{\sum_i (|z_{i,zcg} - z_{cg}|)^2 \cdot A_t_i} & \text{otherwise} \end{cases}
\]

\[
F_{t_{,i,j}} := F_{direct_{,i,j}} + F_{mz_{,i,j}} + F_{my_{,i,j}}
\]

Total Tensile load

Shear on bolts

\[
F_{s_{,i,j}} := \frac{M_{x_{boltcg} \cdot r_{,i} \cdot A_{t_i}}}{\sum_i (r_{ij})^2 \cdot (A_{t_i})}
\]

Secondary shear on bolts

Total shear load

\[
F_{stot_{,i,j}} := F_{s_{,i,j}}
\]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}
\begin{bmatrix}
(F_t^1) & (F_t^2) & (F_t^3) & (F_t^4) & (F_t^5) & (F_t^6)
\end{bmatrix}
\]

\[
V := \text{stack}
\begin{bmatrix}
(F_{stot}^1) & (F_{stot}^2) & (F_{stot}^3) & (F_{stot}^4) & (F_{stot}^5) & (F_{stot}^6)
\end{bmatrix}
\]

\[
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

Output := augment(ID, LC, P, V, M)

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th>P</th>
<th>V</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>6606101</td>
<td>2001</td>
<td>-1068.05</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>6606101</td>
<td>2002</td>
<td>-1110.33</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6606101</td>
<td>2064</td>
<td>-699.99</td>
<td>-439.08</td>
<td>0</td>
</tr>
<tr>
<td>6606102</td>
<td>2001</td>
<td>-813.60</td>
<td>-263.63</td>
<td>0</td>
</tr>
<tr>
<td>6606102</td>
<td>2002</td>
<td>-977.16</td>
<td>-342.06</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6606102</td>
<td>2064</td>
<td>-658.71</td>
<td>-322.63</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6606106</td>
<td>2001</td>
<td>1470.8</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>6606106</td>
<td>2002</td>
<td>1166.08</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6606106</td>
<td>2064</td>
<td>699.99</td>
<td>-439.07</td>
<td>0</td>
</tr>
</tbody>
</table>

Size of the "Output" array: rows(Output) = 1536

(6 bolts x 64 load cases) x 4 joints = 1536 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)

Example of Output Array

WRITEPRN("output_forces_trdussf_r5_launch.txt") := Output
CHECK BOLTS (NAS1958C24 0.500"-20 Material-A-286), Nut NAS1291-C8M, Washer NAS1587-8C

data := READPRN("output_forces_trdussf_r5_launch.txt")
s := 1..rows(data)

Flange 1: Upper USS VC Joint
Part number: SEG39135727
Material: 7050-T7451

Flange 2: TRD Bracket
Part number: 1811/60_0001_1_VI (I.S.A. tec)
Material: 7050-T7451

Loads from Launch Load Cases

Applied tensile load
$P_s := \text{data}_{s,3}\text{lbf}$

Applied shear load
$V_s := \text{data}_{s,4}\text{lbf}$

Applied bending moment
$M_s := \text{data}_{s,5}\text{in-lbf}$

Factors of Safety

Ultimate $SF_u := 1.4$
Yield $SF_y := 1.1$
Joint Separation $SF_{sep} := 1.2$
Fitting factor $FF := 1.15$
Assembly

Temperature Data (Ref Appendix C2), Launch Case

$Temp_{initial} := 70\text{-deg}$
$Temp_{max} := 120\text{-deg}$
$Temp_{min} := 40\text{-deg}$

Bolt and Nut Data

Nominal diameter of bolt $D := .500\text{-in}$
Number of threads/inch $N_t := 20\frac{1}{\text{in}}$
Total length of bolt $L := 2.235\text{-in}$
Height of nut $H := 0.350\text{-in}$
Threaded length $L_t := 0.735\text{-in}$
(If bolt is fully threaded, input $L_t = L$)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
Washer Data
- Thickness of washers (2X): \( tw = 0.156\) in
- Outer Diameter of washer: \( Dw = 0.875\) in
- Inner Diameter of washer: \( D_{wi} = 0.515\) in
- Bolt head dia. across flats (used only if there is no washer): \( dw = 0.741\) in

Flange Data
- Thickness of flange 1: \( tf_1 = 0.854\) in
- Thickness of flange 2: \( tf_2 = 0.354\) in
- Diameter of hole: \( D_{hole} = 0.563\) in

Shim Data
- Thickness of Shim: \( t_{sh} = 0.0787\) in (2mm)

Bushing Data
- Thickness of bushing: \( tb = 0.630\) in
- Outer Diameter of bushing: \( D_{bo} = 0.9567\) in
- Inner Diameter of bushing: \( D_{bi} = 0.563\) in

Material Property Data

Bolt
- Temperature correction factor for bolt strength ultimate: \( T_{Su_bolt} = 0.96\)
- Ultimate tensile allowable stress: \( F_{tu_bolt} = 180000\) psi
- Ultimate shear allowable stress: \( F_{su_bolt} = 0.6 F_{tu_bolt} \)
- Ultimate axial strength of bolt: \( P_{tu_bolt} = 21110\) lbf
- Temperature correction factor for bolt modulus: \( T_{E_bolt} = 0.98\)
- Modulus of elasticity of bolt: \( E_{bolt} = (29.1 \cdot 10^6)\) psi
- Thermal coefficient for bolt: \( \alpha_{bolt\_hot} = 9.1 \cdot 10^{-6}\) in/in/deg, \( \alpha_{bolt\_cold} = 8.9 \cdot 10^{-6}\) in/in/deg

Nut
- Temperature correction factor for nut strength: \( T_{Su_nut} = 0.96\)
- Ultimate tensile allowable stress: \( F_{tu_nut} = 125000\) psi
- Ultimate shear allowable stress: \( F_{su_nut} = 0.6 F_{tu_nut} \)
- Ultimate axial strength of nut: \( P_{tu_nut} = 21110\) lbf
Washer
Temperature correction factor for washer modulus $T_{E_{\text{washer}}} := .96$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Modulus of elasticity of washer: $E_{\text{washer}} := \left(29.1 \cdot 10^6 \text{psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Shim
Temperature correction factor for shim modulus $T_{E_{\text{shim}}} := .96$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Modulus of elasticity of shim: $E_{\text{shim}} := \left(29.1 \cdot 10^6 \text{psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Thermal coefficient for shim
\[ \alpha_{\text{shim\_hot}} := 9.1 \cdot 10^{-6} \text{in/in/deg} \] (Ref. MIL-HDBK-5J, fig. 6.2.1.0)
\[ \alpha_{\text{shim\_cold}} := 8.9 \cdot 10^{-6} \text{in/in/deg} \]

Bushing
Temperature correction factor for bushing modulus $T_{E_{\text{bushing}}} := .97$ (Ref. MIL-HDBK-5J, fig. 5.4.1.1.1)
Modulus of elasticity of bushing: $E_{\text{bushing}} := \left(16 \cdot 10^6 \text{psi}\right)$ (Ref. MIL-HDBK-5J, table 5.4.1.0(c1))

Thermal coefficient for bushing
\[ \alpha_{\text{bushing\_hot}} := 4.9 \cdot 10^{-6} \text{in/in/deg} \]
\[ \alpha_{\text{bushing\_cold}} := 4.7 \cdot 10^{-6} \text{in/in/deg} \]

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 $T_{1E} := .96$ (modulus) (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)
Temperature correction factor for flange 2 $T_{2E} := .96$ (modulus)

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := \left(10.3 \cdot 10^6 \text{psi}\right) \]
\[ E_{\text{flange2}} := \left(10.3 \cdot 10^6 \text{psi}\right) \]

Coefficient of thermal expansion for flanges
\[ \alpha_{\text{flange1\_hot}} := 12.8 \cdot 10^{-6} \text{in/in/deg} \]
\[ \alpha_{\text{flange2\_hot}} := 12.8 \cdot 10^{-6} \text{in/in/deg} \]
\[ \alpha_{\text{flange1\_cold}} := 12.1 \cdot 10^{-6} \text{in/in/deg} \]
\[ \alpha_{\text{flange2\_cold}} := 12.1 \cdot 10^{-6} \text{in/in/deg} \]

Torque/Preload data
Maximum torque (65% of yield) $T_{\text{max}} := 1032\text{-in\_lbf}$
Loading plane factor $n := 0.5$
Minimum torque (95% of max. torque) $T_{\text{min}} := 980\text{in\_lbf}$
Preload Uncertainty $\Gamma := 0.25$
This collapsed section includes the strength calculations as in the bolt template.

**Joint load factor:**

The joint load factor (f) is specified by Ref. 1 as:

$$\phi = \frac{K_b}{K_b + K_j}$$

where $K_b$ is the stiffness of the bolt and $K_j$ the stiffness of the joint. Ref. 1 does not give a method for calculating these stiffnesses. $K_b$ and $K_j$ will be calculated using a cylindrical stiffness method.

$$k_{bolt} := \frac{A_d \cdot A_t \cdot E_{bolt}}{A_d \cdot l_t + A_t \cdot l_d}$$

(Ref. 2, page 461)

This gives the washer area as:

$$A_{washer} := \pi \cdot \frac{D_w^2 - D_{wi}^2}{4}$$

This gives the flange 1 area as:

$$A_{f1} := \pi \cdot \frac{D_{bo}^2 - D_{bi}^2}{4}$$

This gives the shim area as:

$$A_{shim} := \pi \cdot \frac{D_{bo}^2 - D_{bi}^2}{4}$$

This gives the titanium bushing area as:

$$A_{bushing} := \pi \cdot \frac{D_{bo}^2 - D_{bi}^2}{4}$$

This gives the flange 2 area as:

$$A_{f2} := \pi \cdot \frac{D_{bo}^2 - D_{bi}^2}{4}$$

The stiffness for each of the members is then given by treating each one as a cylinder:

$$k_{washer} := \begin{cases} 0.0 \frac{\text{lbf}}{\text{in}} & \text{if } tw = 0.0 \\ \frac{A_{washer} \cdot E_{washer}}{tw} & \text{otherwise} \end{cases}$$
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

The joint stiffness will be

\[ K_j := \begin{cases} 
\frac{1}{k_{\text{flange 1}}} + \frac{1}{k_{\text{shim}}} + \frac{1}{k_{\text{bushing}}} + \frac{1}{k_{\text{flange 2}}} & \text{if } tw = 0 \\
\frac{1}{k_{\text{flange 1}}} + \frac{1}{k_{\text{shim}}} + \frac{1}{k_{\text{bushing}}} + \frac{1}{k_{\text{flange 2}}} + \frac{1}{k_{\text{washer}}} & \text{otherwise}
\end{cases} \]

The joint load factor will then be:

\[ \phi := \frac{k_{\text{bolt}}}{K_j + k_{\text{bolt}}} \]

Stiffness of joint

\[ K_{\text{therm}} := \frac{k_{\text{bolt}} \cdot K_j}{k_{\text{bolt}} + K_j} \]

Calculation of Preload on the Bolt:

Increase in preload due to increase in temperature:

\[ P_{\text{thr 1}} := \left[ (t_{\text{fl}}) \cdot (T_{\text{max}} - T_{\text{initial}}) \cdot (\alpha_{\text{flange 1, hot}} - \alpha_{\text{bolt, hot}}) \right] \cdot K_{\text{therm}} + \left[ (t_{\text{fl}}) \cdot (T_{\text{max}} - T_{\text{initial}}) \cdot (\alpha_{\text{flange 2, hot}} - \alpha_{\text{bolt, hot}}) \right] + \left[ (t_{\text{shim}}) \cdot (T_{\text{max}} - T_{\text{initial}}) \cdot (\alpha_{\text{shim, hot}} - \alpha_{\text{bolt, hot}}) \right] + \left[ (t_{\text{bushing}}) \cdot (T_{\text{max}} - T_{\text{initial}}) \cdot (\alpha_{\text{bushing, hot}} - \alpha_{\text{bolt, hot}}) \right] \]

Decrease in preload due to reduction in temperature:

\[ P_{\text{thr 2}} := \left[ (t_{\text{fl}}) \cdot (T_{\text{min}} - T_{\text{initial}}) \cdot (\alpha_{\text{flange 1, cold}} - \alpha_{\text{bolt, cold}}) \right] \cdot K_{\text{therm}} + \left[ (t_{\text{fl}}) \cdot (T_{\text{min}} - T_{\text{initial}}) \cdot (\alpha_{\text{flange 2, cold}} - \alpha_{\text{bolt, cold}}) \right] + \left[ (t_{\text{shim}}) \cdot (T_{\text{min}} - T_{\text{initial}}) \cdot (\alpha_{\text{shim, cold}} - \alpha_{\text{bolt, cold}}) \right] + \left[ (t_{\text{bushing}}) \cdot (T_{\text{min}} - T_{\text{initial}}) \cdot (\alpha_{\text{bushing, cold}} - \alpha_{\text{bolt, cold}}) \right] \]

This collapsed section includes the rest of the calculations for the bolt template.
<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
<th>Checked By</th>
<th>Drawing No.</th>
<th>Prepared By</th>
<th>Engineering and Science Contract Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brent Dyer</td>
<td>12/29/06</td>
<td>UPVC_TRD_r5.mcd</td>
<td>C. Bala</td>
<td>SDG39135720</td>
<td></td>
<td>Structural Analysis Section</td>
</tr>
</tbody>
</table>

**Title**
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

**Bolt Load Data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>$\phi = 0.607$</td>
</tr>
<tr>
<td>Max. preload</td>
<td>$PLD_{\text{max}} = 17350.9 \text{ lbf}$</td>
</tr>
<tr>
<td>Min. preload</td>
<td>$PLD_{\text{min}} = 8879.4 \text{ lbf}$</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>$\max(P_{\text{sep}}) = 2754.298 \text{ lbf}$</td>
</tr>
<tr>
<td>Max. load on the bolt (ultimate)</td>
<td>$\max(P_b) = 18472.1 \text{ lbf}$</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>$\max(P_{by}) = 18231.9 \text{ lbf}$</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$P_{At} = 20265.6 \text{ lbf}$</td>
</tr>
</tbody>
</table>

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$MS_{\text{min}6,1} = 7.814$</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>$MS_{\text{min}7,1} = 0.763$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$MS_{\text{min}8,1} = 9.76$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_{\text{min}9,1} = 10$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_{\text{min}10,1} = 0.097$</td>
</tr>
</tbody>
</table>

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

$MS_{\text{bolt}} := \min(\text{MS})$  
$MS_{\text{bolt}} = 0.095$  
Failure Mode = "Total Tension Yield"

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element ID</td>
<td>660633</td>
</tr>
<tr>
<td>Load Case</td>
<td>1019</td>
</tr>
<tr>
<td>Tensile Load</td>
<td>2295.2</td>
</tr>
<tr>
<td>Shear Load</td>
<td>$-1130$</td>
</tr>
<tr>
<td>Bending Moment</td>
<td>0</td>
</tr>
</tbody>
</table>

2.4.1.3 - 13 ESCG-4005-05-AMS-0039
Fail-Safe Analysis for Upper Vacuum Case Interface Plate to TRD Corner Bracket (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-005. All 6 NAS1958 fasteners will take the direct shear load.

Direct shear Loads

\[ F_{sd_{i,j}} := \sqrt{\left(F_{y_{j}}\right)^2 + \left(F_{z_{j}}\right)^2} \]  

Total shear load

\[ F_{stot_{i,j}} := F_{s_{i,j}} + F_{sd_{i,j}} \]  
(Note: The \( F_s \) variable is the secondary shear and calculated above.)

The stack command below is used to stack the applied shear load (\( V \)) in ascending order per bolt. The applied axial load (\( P \)) and applied moment (\( M \)) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

\[ V := \text{stack} \left( \left[ F_{stot}^{(1)} \right], \left[ F_{stot}^{(2)} \right], \left[ F_{stot}^{(3)} \right], \left[ F_{stot}^{(4)} \right], \left[ F_{stot}^{(5)} \right], \left[ F_{stot}^{(6)} \right] \right) \]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (\( P \)), applied shear on the bolt (\( V \)), and applied moment on the bolt (\( M \)). The array is written to a text file. For the format of the array see the output example array above.

\[ \text{Output} := \text{augment} \left( \text{ID, LC, } \frac{P}{\text{lb}}, \frac{V}{\text{lb}}, \frac{M}{\text{in-lbf}} \right) \]  
(Note: Since the ID and LC numbers are dimensionless, the \( P, V, \) and \( M \) values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array:  \( \text{rows} \left( \text{Output} \right) = 1536 \)

\( \left(6 \text{ bolts} \times 64 \text{ load cases}\right) \times 4 \text{ joints} = 1536 \text{ load cases} \)

\text{WRITEPRN("output_forces_upperussipf_r5_launch_pinsfs.txt") := Output}

Fail-safe Analysis (Shear Pin Failure)

The array from the text file above is read:

\[ \text{data}_{\text{fsp}} := \text{READPRN("output_forces_upperussipf_r5_launch_pinsfs.txt")} \]

\[ s := 1 \ldots \text{rows} \left( \text{data}_{\text{fsp}} \right) \]
Fail-safe Loads, launch cases

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Applied Load</th>
<th>Ultimate SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load</td>
<td>( P_{FS} = \text{data}_{fsp3} ) lbf</td>
<td>( \text{ID}<em>{FS} = \text{data}</em>{fsp1} )</td>
</tr>
<tr>
<td>Shear load</td>
<td>( V_{FS} = \text{data}_{fsp4} ) lbf</td>
<td>( \text{LC}<em>{FS} = \text{data}</em>{fsp2} )</td>
</tr>
<tr>
<td>Bending moment</td>
<td>( M_{FS} = \text{data}_{fsp5} ) in lbf</td>
<td></td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`.

Bolt Fail-safe Load data

- Joint separation load: \( \text{max}(P_{sep_{FS}}) = 2295.248 \text{ lbf} \)
- Max. load on the bolt (ultimate): \( \text{max}(P_{b_{FS}}) = 18151.8 \text{ lbf} \)
- Max. shear load: \( \text{max}(V_{FS}) = 2273.481 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Margin</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{minFS11} = 3.829 )</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{minFS21} = 6.678 )</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{minFS31} = 0.116 )</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{minFS41} = 10.000 )</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt_{FS}} = \min(\text{MS}_{FS}) \]

\[ MS_{bolt_{FS}} = 0.116 \]  
Failure mode: "Combined Shear Tension Bending Ultimate"

Element Identification (66063) and Bolt Number (3) for Minimum Margin

- \( MS_{min_{ID}} = 660633 \)
- \( MS_{min_{LC}} = 1019 \)
- \( MS_{min_{P}} = 2295.2 \)
- \( MS_{min_{V}} = 28.5 \)
- \( MS_{min_{M}} = 0 \)
Bolt Fail-Safe Analysis for Upper Vacuum Case Interface Plate to TRD Corner Bracket

Since bolt number 3 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 5, NAS1958C 0.50-20 UNFJ fasteners, holding the upper vacuum case joint to the TRD corner bracket. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
\text{bolt2} & := \begin{pmatrix} 0.50 & 20 \\ 0.50 & 20 \\ 0.50 & 20 \\ 0.50 & 20 \\ 0.50 & 20 \end{pmatrix} \\
\end{align*}
\]

\[
s := 1 \cdot \text{rows(bolt2)}
\]

\[
N2_s := \text{bolt2}_s,2 \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt} \quad D2_s := \text{bolt2}_s,1 \cdot \text{in} \quad \text{bolt diameter}
\]

\[
\begin{align*}
\text{At2}_s & := \pi \cdot \left( \frac{D2_s - 0.9743 \cdot \frac{1}{N2_s}}{2} \right) \quad \text{Tensile Area of bolt} \\
\text{As2}_s & := \pi \cdot \left( \frac{D2_s - 1.299038 \cdot \frac{1}{N2_s}}{2} \right) \quad \text{Shear Area of bolt}
\end{align*}
\]
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.188</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.188</td>
<td>-2.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>3.188</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

**Location of applied forces and moments**

\[ \begin{align*}
\text{xforce2} & := 0.0 \text{in} \\
\text{yforce2} & := 0.0 \text{in} \\
\text{zforce2} & := 0.0 \text{in}
\end{align*} \]

\[ \begin{align*}
\text{cgload2} & := \begin{pmatrix}
\text{xforce2} \\
\text{yforce2} \\
\text{zforce2}
\end{pmatrix} \\
\text{cgbolt2} & := \begin{pmatrix}
0 \\
-0.638 \\
-0.4
\end{pmatrix} \text{in}
\end{align*} \]

**Center of gravity of bolt group**

\[ \begin{align*}
\text{xcg2} & := \frac{\sum x^2_s}{\text{rows(x2)}} \\
\text{ycg2} & := \frac{\sum y^2_s}{\text{rows(y2)}} \\
\text{zcg2} & := \frac{\sum z^2_s}{\text{rows(z2)}}
\end{align*} \]

\[ \begin{align*}
\text{xcg2} & = 0 \text{ in} \\
\text{ycg2} & = -0.638 \text{ in} \\
\text{zcg2} & = -0.4 \text{ in}
\end{align*} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 3, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[ \begin{align*}
\text{rload2} & := \text{cgload2} - \text{cgbolt2} \\
\text{rload2} & = \begin{pmatrix}
0 \\
0.638 \\
0.4
\end{pmatrix} \text{in}
\end{align*} \]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_2 := \left( z^2_s - z_{cg}^2 \right)^2 + \left( y^2_s - y_{cg}^2 \right)^2
\]

\[r_2 = \left[ \begin{array}{c}
3.502 \\
2.483 \\
3.011 \\
1.722 \\
4.147
\end{array} \right]\text{ in}
\]

Reading database file for bolted joint, launch case

data := READPRN("trdussf_r5_launch.dat")
q := 1..rows(data)  \text{ num_bolts2 := rows(bolt2) }

Loads from 2-04 loads model, launch case

Axial Load  \quad F_{x2q} := \text{data}_{q,3}\text{lbf}  \quad Torsion  \quad M_{x2q} := \text{data}_{q,6}\text{in-lbf}
Shear in Y axis  \quad F_{y2q} := \text{data}_{q,4}\text{lbf}  \quad \text{Moment about Y axis}  \quad M_{y2q} := \text{data}_{q,7}\text{in-lbf}
Shear in Z axis  \quad F_{z2q} := \text{data}_{q,5}\text{lbf}  \quad \text{Moment about Z axis}  \quad M_{z2q} := \text{data}_{q,8}\text{in-lbf}
Element Identification  \quad \text{ID2}_q := \text{data}_{q,1}
Load Case Number  \quad \text{LC2}_q := \text{data}_{q,2}

Counter for number of bolts in pattern  \quad \text{ID2}_q := \text{ID2}_q \cdot 10 + 1

Applied Bending Moment at Bolts  \quad M_{2q} := 0\text{in-lbf}

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 3 is not included.

\[\text{ID2} := \text{stack(ID2, ID2 + 1, ID2 + 3, ID2 + 4, ID2 + 5)}\]
\[\text{LC2} := \text{stack(LC2, LC2, LC2, LC2, LC2)}\]
Moment Distribution

\[ M_{tot2}^\text{\{q\}} := \begin{pmatrix} Mx_2^\text{\{q\}} \\ My_2^\text{\{q\}} \\ Mz_2^\text{\{q\}} \end{pmatrix} + r_{load2} \times \begin{pmatrix} Fx_2^\text{\{q\}} \\ Fy_2^\text{\{q\}} \\ Fz_2^\text{\{q\}} \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ \text{M}_{x,\text{boltcg}}^\text{\{q\}} := M_{tot2,1,\text{q}} \quad \text{M}_{y,\text{boltcg}}^\text{\{q\}} := M_{tot2,2,\text{q}} \quad \text{M}_{z,\text{boltcg}}^\text{\{q\}} := M_{tot2,3,\text{q}} \]

Tension on bolts

\[ F_{\text{direct}}^\text{\{s, q\}} := \begin{cases} 0\text{-lbf} & \text{if } Fx_2^\text{\{q\}} \leq 0\text{lbf} \\ \frac{Fx_2^\text{\{q\}}}{\text{num_bolts}_2} & \text{otherwise} \end{cases} \]

Direct tensile load calculation

\[ F_{mz}^\text{\{s, q\}} := \begin{cases} 0\text{-lbf} & \text{if } \left(y_s^2 - y_{cg2}\right) = 0\text{-in} \\ \left[M_{z,\text{boltcg}}^\text{\{q\}} \left(y_s^2 - y_{cg2}\right)\right] \frac{At_s}{\sum_s \left[y_s^2 - y_{cg2}\right]^2 \cdot At_s} & \text{otherwise} \end{cases} \]

\[ F_{my}^\text{\{s, q\}} := \begin{cases} 0\text{-lbf} & \text{if } \left(z_s^2 - z_{cg2}\right) = 0\text{-in} \\ \left[M_{y,\text{boltcg}}^\text{\{q\}} \left(z_s^2 - z_{cg2}\right)\cdot At_s \right] \frac{\sum_s \left[z_s^2 - z_{cg2}\right]^2 \cdot At_s}{\sum_s \left[z_s^2 - z_{cg2}\right]^2 \cdot At_s} & \text{otherwise} \end{cases} \]

\[ F_{t}^\text{\{s, q\}} := F_{\text{direct}}^\text{\{s, q\}} + F_{mz}^\text{\{s, q\}} + F_{my}^\text{\{s, q\}} \] Total Tensile load

Shear on bolts

Secondary shear on bolts

\[ F_{s}^\text{\{s, q\}} := \frac{M_{x,\text{boltcg}}^\text{\{q\}} \cdot r_s \cdot As_s}{\sum_s \left[r_s^2 \cdot (As_s)\right]} \] Total shear load

\[ F_{stot}^\text{\{s, q\}} := F_{s}^\text{\{s, q\}} \]
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 7 bolts, since bolt number 3 is not included.

\[
P2 := \text{stack}\left(\left[\left(Ft_2^T\right)^{(1)}, \left(Ft_2^T\right)^{(2)}, \left(Ft_2^T\right)^{(3)}, \left(Ft_2^T\right)^{(4)}, \left(Ft_2^T\right)^{(5)}\right]\right)
\]

\[
V2 := \text{stack}\left(\left[\left(F_{\text{stot}2}^T\right)^{(1)}, \left(F_{\text{stot}2}^T\right)^{(2)}, \left(F_{\text{stot}2}^T\right)^{(3)}, \left(F_{\text{stot}2}^T\right)^{(4)}, \left(F_{\text{stot}2}^T\right)^{(5)}\right]\right)
\]

\[
M2 := \text{stack}(M2, M2, M2, M2, M2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{Output2} := \text{augment}\left(\begin{pmatrix} \text{ID2} & \text{LC2} & \frac{\text{P2}}{\text{lbf}} & \frac{\text{V2}}{\text{lbf}} & \frac{\text{M2}}{\text{in-lbf}} \end{pmatrix}\right) \quad \text{(Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)}
\]

Size of the "Output2" Array: rows(Output2) = 1280

(5 bolts x 64 load cases) x 4 joints = 1280 load cases

WRITEPRN("output_forces_upperussipf_r5_launch_fs.txt") := Output2

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
data_{fs} := \text{READPRN("output_forces_upperussipf_r5_launch_fs.txt")}
\]

\[
s := 1 \ldots \text{rows}(data_{fs})
\]
**Fail-safe Loads, launch cases**

- **Applied tensile load**
  \[ P_{FS} := \text{data}_{fs,s,3}, \text{lbf} \]
  \[ ID_{FS} := \text{data}_{fs,s,1} \]

- **Applied shear load**
  \[ V_{FS} := \text{data}_{fs,s,4}, \text{lbf} \]
  \[ LC_{FS} := \text{data}_{fs,s,2} \]

- **Applied bending moment**
  \[ M_{FS} := \text{data}_{fs,s,5}, \text{in} \cdot \text{lbf} \]

**Fail-safe Factors of Safety**

- **Ultimate**
  \[ SF_{u,FS} := 1.0 \]

- **Joint Separation**
  \[ SF_{sep,FS} := 1.0 \]

**This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC**

**Bolt Fail-safe Load data**

- **Joint separation load**
  \[ \max(P_{sep,FS}) = 3749.381 \text{lbf} \]

- **Max. load on the bolt(ultimate)**
  \[ \max(P_b,FS) = 18659.2 \text{lbf} \]

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>MS_minFS</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1.956</td>
<td>0.746</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>3.700</td>
<td>6.79</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.086</td>
<td>10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>6.55</td>
<td></td>
</tr>
<tr>
<td>Combined shear, tension and</td>
<td></td>
<td>0.086</td>
</tr>
<tr>
<td>bending ultimate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ MS_{bolt,FS} := \min(\text{MS}_{FS}) \]

\[ MS_{bolt,FS} = 0.086 \]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

- **Element Identification** (66061) and Bolt Number (6) for Minimum Margin
- **Load Case Number for Minimum Margin**
- **Applied Tensile Load for Minimum Margin**
- **Applied Shear Load for Minimum Margin**
- **Applied Bending Moment for Minimum Margin**
Shear Pin Analysis for Upper Vacuum Case Joint to TRD Corner Bracket

The USS-02 assembly consists of four Upper Vacuum Case Joints (SDG39135727). Each Upper Vacuum Case Joint to TRD corner bracket has a titanium shear pin (ams02-06-3045b). The shear pin sets inside of a bushing (ams02-06-3044b).

Cross Section of the Shear Pin Interface

Reading database file for bolted joint, launch case

```plaintext
data3 := READPRN(“trdussf_r5_launch.dat”)
num_bolts := rows(bolt)
j := 1..rows(data3)
rows(data3) = 256
```

Loads from 2-06 loads model, launch case

Shear in Y axis

\[ F_y := data3[j,4]\text{, lbf} \]

Shear in Z axis

\[ F_z := data3[j,5]\text{, lbf} \]

Element Identification

\[ ID3 := data3[j,1] \]

Load Case Number

\[ LC3 := data3[j,2] \]
Geometry
(Note: Shear Pin is stepped. Small diameter geometry is used)

Minimum Diameter of shear pin \( dp := 0.7087 \text{ in} \) (Ref. Drg. ams02-06-3045b)
Outer diameter of eccentric bushing \( do := 1.315 \text{ in} \) (Ref. Drg. ams02-06-3044b)
Thickness of TRD Bracket \( tp := 0.630 \text{ in} \) (Ref. Drg. 1811/60_0001_1_VI)
Length of eccentric bushing \( tpin := 0.630 \text{ in} \) (Ref. Drg. ams02-06-3044b)

(Ref. new drawing for bushing for \( tpin \), was 18.75mm now 16.00mm)

Temperature Data
Shear Pin (Titanium TI6AL4V, AMS4928):
Temperature correction factor for shear \( csp := 0.94 \) (Ref. MIL-HDBK-5J, fig. 5.4.1.1.1)

TRD Bracket (Al 7050-T7451 Plate):
Temperature correction factor for ultimate \( cpu := 0.91 \) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)
Temperature correction factor for yield \( cpy := 0.97 \)

Bushings (Titanium TI6AL4V AMS4928):
Temperature correction factor for ultimate \( cbu := 0.94 \) (Ref. MIL-HDBK-5J, fig. 5.4.1.1.1)
Temperature correction factor for yield \( cby := 0.93 \) (Ref. MIL-HDBK-5J, fig. 5.4.1.1.1)

Material Properties
Shear Pin (Titanium TI6AL4V, AMS4928):
Allowable shear stress \( F_{su} := 82000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 5.4.1.0(c1))
Allowable ultimate stress \( F_{tu} := 134000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 5.4.1.0(c1))

TRD Bracket (Al 7050-T7451 Plate):
Allowable bearing stress \( F_{bru} := 141000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 3.7.4.0 (b1), 2.5 in. thick, e/D=2.0)
\( F_{bry} := 104000 \text{ psi} \)

Bushings (Titanium TI6AL4V AMS4928):
Allowable bearing stress of bushing \( F_{bru} := 200000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 5.4.1.0(c1))
\( F_{bry} := 177000 \text{ psi} \)
Shear Pin Analysis

Shear Loads in shear pin 
from Bolt Analysis 
(Direct Shear)

\[ F_{sp,j} := \sqrt{\left( F_{yj} \right)^2 + \left( F_{zj} \right)^2} \]

(rows(Fsp) = 256 
(4 joints x 64 load cases = 256 load cases)

Gap between Interface Face 

\[ \text{gap} := 0.197\text{-in} \] 
(Maximum gap of 5mm) 
(Ref. ams02-1697e)

Moment due to Gap 
(Pin is guided)

\[ M_{g,j} := \frac{F_{sp,j} \cdot \text{gap}}{2} \]

Shear Area of pin

\[ A_{sh} := \frac{\pi \cdot dp^2}{4} \]

\[ A_{sh} = 0.394 \text{ in}^2 \]

Moment of Inertia of pin

\[ I_{nt} := \frac{\pi \cdot dp^4}{64} \]

\[ I_{nt} = 0.012 \text{ in}^4 \]

Outer Most Fiber

\[ c_1 := \frac{dp}{2} \]

\[ c = 0.226 \text{ in} \]

Stresses on cross section:

Normal Stress is bending:

\[ \sigma_{g,j} := \frac{M_{g,j} \cdot c_1}{I_{nt}} \]

\[ \max(\sigma_g) = 20507 \text{ psi} \]

Shear due to transverse loading

\[ \tau_{v,j} := \sqrt{\left( \frac{F_{yj}}{A_{sh}} \right)^2 + \left( \frac{F_{zj}}{A_{sh}} \right)^2} \]

\[ \max(\tau_v) = 18443 \text{ psi} \]

Principal Stresses:

\[ \sigma_{1pg,j} := \frac{\sigma_{g,j}}{2} + \left[ \left( \frac{\sigma_{g,j}}{2} \right)^2 + \left( \tau_{v,j} \right)^2 \right]^{\frac{1}{2}} \]

\[ \max(\sigma_{1pg}) = 31355 \text{ psi} \]

\[ \min(\sigma_{1pg}) = 2654 \text{ psi} \]

\[ \sigma_{2pg,j} := \frac{\sigma_{g,j}}{2} - \left[ \left( \frac{\sigma_{g,j}}{2} \right)^2 + \left( \tau_{v,j} \right)^2 \right]^{\frac{1}{2}} \]

\[ \min(\sigma_{2pg}) = -10848 \text{ psi} \]

max(\sigma_{2pg}) = -918.176 psi
Maximum principal stress is:

\[
\sigma_{\text{max}_j} := \begin{cases} 
\sigma_{1pg_j} & \text{if } \sigma_{1pg_j} \geq \sigma_{2pg_j} \\
\sigma_{2pg_j} & \text{otherwise}
\end{cases}
\]

\[
\max(\sigma_{\text{max}_j}) = 31354.788 \text{ psi}
\]

Maximum shear:

\[
\tau_{\text{max}_j} := \sqrt{(\sigma_{g_j}^2 + \tau_{v_j}^2)}
\]

\[
\max(\tau_{\text{max}_j}) = 27580 \text{ psi}
\]

Margins of safety:

Ultimate

\[
MS_{u_j} := \begin{cases} 
\frac{F_{tu}}{SFu \cdot \sigma_{\text{max}_j}} - 1 & \text{if } \sigma_{\text{max}_j} \neq 0 \text{ psi} \\
10000 & \text{otherwise}
\end{cases}
\]

\[
\min(\text{MSu}) = 2.05
\]

Ultimate, shear

\[
MS_{su_j} := \begin{cases} 
\frac{F_{su}}{SFu \cdot \tau_{\text{max}_j}} - 1 & \text{if } \tau_{\text{max}_j} \neq 0 \text{ psi} \\
10000 & \text{otherwise}
\end{cases}
\]

\[
\min(\text{MSsu}) = 1.12
\]

Determine Elem ID and Load Case

Identifying Element ID Number, Load Case Number, and Loads for Minimum Margin

\[
\begin{align*}
\text{MS\_min\_ID4} &= 66063 & \text{Element Identification for Minimum Margin} \\
\text{MS\_min\_LC4} &= 1020 & \text{Load Case Number for Minimum Margin} \\
\text{MS\_min\_Fy4} &= 7035 & \text{Shear in Y axis} \\
\text{MS\_min\_Fz4} &= -1854 & \text{Shear in Z axis}
\end{align*}
\]

\[
\text{output} := \text{augment(ID3, LC3, MSsu)} \quad \text{sorted} := \text{csort(output, 3)}
\]

\[
\begin{pmatrix}
\text{sorted}^T \end{pmatrix}^T = \begin{pmatrix}
66063 & 1020 & 1.12
\end{pmatrix}
\]

2.4.1.3 - 25

ESCG-4005-05-AMS-0039
Bearing of Titanium Shear Pin Bushing on TRD Bracket

Bearing of the shear pin on the USS-02 Upper Vacuum Case Joint is not critical since the bearing thickness is .854" compared to 0.630" on the TRD Bracket. So the margin of safety is high for bearing on the USS-02 Upper Vacuum Case. The TRD Bracket thickness is used below.

Bearing area

\[ Ab := \text{do-tp} \]
\[ Ab = 0.828 \text{ in}^2 \]

Allowable bearing load

\[ Pbru := Fbru \cdot Ab \cdot \text{cpu} \]
\[ Pbru = 150777.9 \text{ lbf} \]

\[ Pbry := Fbry \cdot Ab \cdot \text{cpy} \]
\[ Pbry = 142236.6 \text{ lbf} \]

Margin of safety

\[ MSu := \frac{Pbru}{Fsp \cdot SFu} - 1 \]
\[ MS_y := \frac{Pbry}{Fsp \cdot SFy} - 1 \]

\[ \min(\text{MSu}) = 13.804 \]
\[ \min(\text{MSy}) = 16.774 \]

Bearing of Shear Pin on Bushing

Gap between shear pin and retainer

\[ \text{gap2} := .0787 \text{ in} \] (2mm from drawing ams02-1697e)

Bearing area

\[ Abp := \text{dp} \cdot (\text{tpin} - \text{gap2}) \]
\[ Abp = 0.391 \text{ in}^2 \]

Allowable bearing load

\[ Pbrui := Fbru \cdot Abp \cdot \text{cpu} \]
\[ Pbrui = 73452.8 \text{ lbf} \]

\[ Pbryi := Fbry \cdot Abp \cdot \text{cpy} \]
\[ Pbryi = 64314.2 \text{ lbf} \]

Margin of safety

\[ MSbru := \frac{Pbrui}{Fsp \cdot SFu} - 1 \]
\[ MSbry := \frac{Pbryi}{Fsp \cdot SFy} - 1 \]

\[ \min(\text{MSbru}) = 6.212 \]
\[ \min(\text{MSbry}) = 7.037 \]
Stress Concentration Factor on Stepped Shear Pin:

Diameter of large portion of shear pin \( D_{lo} := 1.00\text{-in} \)

Radius on stepped shear pin \( \frac{D_{lo}}{d_p} = 1.411 \) \( \text{(radius of 2.0mm)} \)

(Ref. new drawing for shear pin for rad, was .5mm now 2.0mm)

Stress Concentration Factor \( SCF := 1.61 \)

Peak Stress

\( \sigma_{peak_j} := SCF \cdot \sigma_{g_j} \) \( \max(\sigma_{peak}) = 33015.7 \text{ psi} \)

\( \tau_{peak_j} := SCF \cdot \tau_{j} \) \( \max(\tau_{peak}) = 29693.1 \text{ psi} \)

\[
MS_{Sup_j} := \frac{F_{tu}}{SF_u \cdot \sigma_{peak_j}} - 1 \quad \text{min}(MS_{Sup}) = 1.899
\]

\[
MS_{Sup_j} := \frac{F_{tu}}{SF_u \cdot \tau_{peak_j}} - 1 \quad \text{min}(MS_{Sup}) = 0.973
\]
Fracture Assessment for Stepped Titanium Shear Pin:

Radius on stepped shear pin \( \text{rad} = 0.0787 \text{ in} \) (radius of 2.0mm) \(^{(\text{Ref. new drawing for shear pin for rad, was .5mm now 2.0mm})}\)

FATIGUE CRACK GROWTH ANALYSIS
---------------------------------
DATE: 19-Jan-07   TIME: 09:48:34
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PROBLEM TITLE
-------------
TI Shear Pin rad 2.0mm
U.S. customary units [inches, ksi, ksi sqrt(in)]

Crack Growth Model: Non Interaction
Ratio of growth increment to current crk size=  0.0050

Mode of Computations: Regular
Beta factors computed regularly
(Cycle-by-cycle, if the block is such)

Equation/Table  : NASGRO Equation
Material Data Entry : Manual

GEOMETRY
--------
MODEL: SC13-Surface crack at fillet (cut) - shear bolt.

Major Diameter, \( D = 0.7500 \)
Fillet Radius = 0.0787
a/c is constant = 0.6450

FLAW SIZE: (User specified)
a (init.) = 0.5000E-01
c (init.) = 0.7752E-01
a/c (init.) = 0.6450
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

MATERIAL
--------

MATL 1: TITANIUM ALLOYS [**Manual data input**]
Ternary alloys

Material Header Info.:

Material 1 Data ID: P3EM23AB1
Alloy Description: Ti-6Al-4V (ELI); RA(1700F/4h)

Alloy Cond/HT: Forged; L-T & T-L; LA; Room temp

Product Form:

Environment:

Specimen Type:
Specimen Orientation:
Specimen Thickness:
Specimen Width:
Specimen Test Frequency:
Data Reference:

Material Properties:

<table>
<thead>
<tr>
<th>Matl:</th>
<th>UTS</th>
<th>YS</th>
<th>Kle</th>
<th>K1c</th>
<th>Ak</th>
<th>Bk</th>
<th>Thk</th>
<th>Kc</th>
<th>Keac</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>134.0</td>
<td>82.0</td>
<td>95.0</td>
<td>75.0</td>
<td></td>
<td></td>
<td>75.0</td>
<td>75.0</td>
<td></td>
</tr>
</tbody>
</table>

Crack Growth Eqn Constants

<table>
<thead>
<tr>
<th>No.:</th>
<th>C</th>
<th>n</th>
<th>p</th>
<th>q</th>
<th>DK1</th>
<th>Cth+</th>
<th>Cth-</th>
<th>Alpha</th>
<th>SMax</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.150D-08</td>
<td>3.000</td>
<td>0.50</td>
<td>0.75</td>
<td>5.27</td>
<td>0.06</td>
<td>0.10</td>
<td>2.50</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Small crack threshold parameters:

a0 = 0.00150

Limit of ratio DKth(S)/DKth(L) = 0.20

Environmental FCG factor for matl no. 1 is = 1.0000

Cth+ = 0, Cth- = 0 are used throughout
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

TI Shear Pin rad 2.0mm
MODEL: SC13

FATIGUE SPECTRUM
----------------

[Note: Stress = Input Value * Scale Factor]

Stress Scaling Factors for Block Case: 1
Scale Factor for Stress S0: 0.20507
Scale Factor for Stress S1: 0.0000

Equiv. flights or hours for Block Case: 1

No. Flights per block: 1.0000

Schedule info. was input manually

Total No. of Blocks in Schedule = 4

<table>
<thead>
<tr>
<th>Block Number</th>
<th>Block Case No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>From - To</td>
<td>1 - 4</td>
</tr>
</tbody>
</table>

Stresses: Tension, bending or pin

---------------------------------------------------------------

SINGLE DISTINCT BLOCK

S : M: NUMBER : S0 : S1 :
T : A: OF :
E : T: FATIGUE :
P : L: CYCLES : (t1) : (t2) : (t1) : (t2) :

| 1: 1: 2.00 | -100.00: 100.00: -100.00: 100.00: |
| 2: 1: 4.00 | -90.00: 90.00: -90.00: 90.00: |
| 3: 1: 8.00 | -80.00: 80.00: -80.00: 80.00: |
| 4: 1: 15.00 | -70.00: 70.00: -70.00: 70.00: |
| 5: 1: 49.00 | -60.00: 60.00: -60.00: 60.00: |
| 6: 1: 81.00 | -50.00: 50.00: -50.00: 50.00: |
| 7: 1: 178.00 | -40.00: 40.00: -40.00: 40.00: |
| 8: 1: 641.00 | -30.00: 30.00: -30.00: 30.00: |
| 9: 1: 3120.00 | -20.00: 20.00: -20.00: 20.00: |
| 10: 1: 3405.00 | -10.00: 10.00: -10.00: 10.00: |
| 11: 1: 5019.00 | -7.00: 7.00: -7.00: 7.00: |
| 12: 1: 28853.00 | -5.00: 5.00: -5.00: 5.00: |
| 13: 1: 91655.00 | -3.00: 3.00: -3.00: 3.00: |

Environmental Crack Growth Check for Sustained Stresses
(Kmax less than Keac): NOT SET

---
Bolts from Upper Vacuum Case Joint to TRD Corner Bracket

TI Shear Pin rad 2.0mm
MODEL: SC13

FATIGUE SCHEDULE BLOCK STRESS TABLE
-----------------------------------
S  : M:  NUMBER :      SO :      SL :
T  : A:   OF :      :       :
E  : T: FATIGUE :      (ksi) :      (ksi) :
P  : L: Cycles : (t1) : (t2) : (t1) : (t2) :
-----------------------------------
1: 1: 2.00 : -20.51: 20.51: 0.00: 0.00:
2: 1: 4.00 : -18.46: 18.46: 0.00: 0.00:
3: 1: 8.00 : -16.41: 16.41: 0.00: 0.00:
4: 1: 15.00: -14.35: 14.35: 0.00: 0.00:
5: 1: 49.00: -12.30: 12.30: 0.00: 0.00:
6: 1: 81.00: -10.25: 10.25: 0.00: 0.00:
7: 1: 178.00: -8.20: 8.20: 0.00: 0.00:
8: 1: 641.00: -6.15: 6.15: 0.00: 0.00:
9: 1: 3120.00: -4.10: 4.10: 0.00: 0.00:
10: 1: 3405.00: -2.05: 2.05: 0.00: 0.00:
11: 1: 5019.00: -1.44: 1.44: 0.00: 0.00:
12: 1: 28853.00: -1.03: 1.03: 0.00: 0.00:
13: 1: 91655.00: -0.62: 0.62: 0.00: 0.00:

Environmental Crack Growth Check for Sustained Stresses
(Kmax less than Keac): NOT SET

TI Shear Pin rad 2.0mm
MODEL: SC13

ANALYSIS RESULTS:
------------------
Schedule Block Step Cycles Crack a Crack c
0 0 0 0.00 0.50000E-01 0.77519E-01
1 1 - 133030.00 0.50022E-01 0.77522E-01
1 2 - 266060.00 0.50004E-01 0.77525E-01
1 3 - 399090.00 0.50005E-01 0.77528E-01
1 4 - 532120.00 0.50007E-01 0.77530E-01
2 1 - 665150.00 0.50009E-01 0.77533E-01
2 2 - 798180.00 0.50011E-01 0.77536E-01
2 3 - 931210.00 0.50013E-01 0.77539E-01
2 4 - 1064240.00 0.50014E-01 0.77542E-01

FINAL RESULTS:
Critical Crack Size has NOT been reached.
at Cycle No. 91655.00
of Load Step No. 13
of Block No. 4
of Schedule No. 2
Crack Size a = 0.500143E-01
Total Cycles = 1064240.0
Total Flights = 8.0000000
Corresponding semi crack length, c = 0.775416E-01

Execution time (hh:mm:ss): 00:00:00.0
Note: this is elapsed wall-clock time, not CPU time!
2.4.1.4 Sill Bracket to Sill Joint
Sill Bracket to Sill Joint Bolt Analysis

The USS-02 assembly consists of two Sill Brackets. There are a total of 6 fasteners attaching the Sill Bracket to the Sill Joint. The fasteners are NAS1958C (180 ksi), 0.50-20 UNFJ. The drawing number for the Upper USS-02 Assembly is SDG39135726.

\[ \text{size} \quad \text{thread/in} \]
\[
\begin{array}{c}
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
\end{array}
\]

\[ \text{bolt} := \]
\[
\begin{array}{c}
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
0.50 \quad 20 \\
\end{array}
\]

\[ i := 1 \ldots \text{rows(bolt)} \]

\[ N_i := \text{bolt}_i, 2 \frac{1}{\text{in}} \]

\[ D_i := \text{bolt}_i, 1 \cdot \text{in} \]

\[ \text{Tensile Area of bolt} \quad A_{t_i} := \pi \left( \frac{D_i - 0.9743 \cdot \frac{1}{N_i}}{2} \right)^2 \]

\[ \text{Shear Area of bolt} \quad A_{s_i} := \pi \left( \frac{D_i - 1.299038 \cdot \frac{1}{N_i}}{2} \right)^2 \]
Bolts from Sill Bracket to Sill Joint

Bolt no. | x co-ord | y co-ord | z co-ord
--- | --- | --- | ---
1 | 0.0 | 3.25 | -1.875
2 | 0.0 | 3.25 | 0.0
3 | 0.0 | -3.25 | -1.875
4 | 0.0 | -3.25 | 1.875
5 | 0.0 | -3.25 | 0.0
6 | 0.0 | -3.25 | 1.875

Location of applied forces and moments

xforce := 0.0in  yforce := 0.0in  zforce := 0.0in

cgload := \begin{pmatrix} xforce \\ yforce \\ zforce \end{pmatrix}  \quad \text{cgload} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}
Center of gravity of bolt group

\[
\begin{align*}
\text{xcg} &:= \frac{\sum x_i}{\text{rows}(x)} & \text{xcg} = 0 \text{ in} \\
\text{ycg} &:= \frac{\sum y_i}{\text{rows}(y)} & \text{ycg} = 0 \text{ in} \\
\text{zcg} &:= \frac{\sum z_i}{\text{rows}(z)} & \text{zcg} = 0 \text{ in}
\end{align*}
\]

\[
\begin{bmatrix}
\text{xcg} \\
\text{ycg} \\
\text{zcg}
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis and z-axis with a zero offset from the center of gravity.

Load Vector

\[
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(z_i - \text{zcg})^2 + (y_i - \text{ycg})^2}
\]

\[
\begin{bmatrix}
3.752 \\
3.250 \\
3.752 \\
3.752 \\
3.250 \\
3.752
\end{bmatrix} \text{ in}
\]

Loads model 2-04 was used to retrieve loads at the two bolted interfaces. A Cbeam element located at the center of each sill bracket was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbeam element identifications for the two bolted interfaces are 1705 and 1706. These loads are read into an array and distributed out to the 6 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The launch cases combined with launch temperature data resulted in the lowest minimum margins of safety. Therefore, the launch cases are used in this analysis.)

**Reading database file for bolted joint, launch case**

data := READPRN("sillbracket_r2_launch.txt")

j := 1 .. rows(data)

num_bolts := rows(bolt)
Loads from 2-04 loads model, launch case

- Axial Load: \( F_x := \text{data}_{j,7}\)-lbf
- Shear in Y axis: \( F_y := \text{data}_{j,5}\)-lbf
- Shear in Z axis: \( F_z := \text{data}_{j,6}\)-lbf
- Element Identification: \( ID_j := \text{data}_{j,1}\)
- Load Case Number: \( LC_j := \text{data}_{j,2}\)
- Torsion: \( M_x := \text{data}_{j,8}\)-in-lbf
- Moment about Y axis: \( M_y := \text{data}_{j,4}\)-in-lbf
- Moment about Z axis: \( M_z := \text{data}_{j,3}\)-in-lbf

Element Identification Counter: \( ID_j := ID_j \cdot 100 + 1\) for number of bolts in pattern

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in asending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

For each element identification, 1705 and 1706, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 1705 will have bolt numbers 1 thru 6 attached to the end for all 64 load cases. This brings the total number of load cases to 768 (2 joints x 6 bolts x 64 load cases = 768). See the array example to the right.

\[
\begin{array}{ll}
\text{ID} & \text{LC} \\
170501 & 2001 \\
170501 & 2002 \\
\ldots & \ldots \\
170501 & 2064 \\
170502 & 2001 \\
170502 & 2002 \\
\ldots & \ldots \\
170502 & 2064 \\
170506 & 2001 \\
170506 & 2002 \\
\ldots & \ldots \\
170506 & 2064 \\
\end{array}
\]

Array Example
Moment Distribution

\[
M_{\text{tot}}^{(j)} := \begin{pmatrix} M_x^{(j)} \\ M_y^{(j)} \\ M_z^{(j)} \end{pmatrix} + r_{\text{load}} \times \begin{pmatrix} F_x^{(j)} \\ F_y^{(j)} \\ F_z^{(j)} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x_{\text{boltcg}}}^{(j)} := M_{\text{tot}1,j} \quad M_{y_{\text{boltcg}}}^{(j)} := M_{\text{tot}2,j} \quad M_{z_{\text{boltcg}}}^{(j)} := M_{\text{tot}3,j}
\]

Tension on bolts

\[
F_{\text{direct}}_{i,j} := \begin{cases} 0\text{-lbf} & \text{if } F_{x_{i,j}} \leq 0\text{lbf} \\ \frac{F_{x_{i,j}}}{\text{num\_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz_{i,j}} := \begin{cases} 0\text{-lbf} & \text{if } (y_{i,j} - \text{ycg}) = 0\text{-in} \\ \frac{[M_{z_{\text{boltcg}}}^{(j)}(y_{i,j} - \text{ycg})]A_{t_i}}{\sum_i [(y_{i,j} - \text{ycg})^2 \cdot A_{t_i}]} & \text{otherwise} \end{cases}
\]

\[
F_{my_{i,j}} := \begin{cases} 0\text{-lbf} & \text{if } (z_{i,j} - \text{zcg}) = 0\text{-in} \\ \frac{[M_{y_{\text{boltcg}}}^{(j)}(z_{i,j} - \text{zcg})]A_{t_i}}{\sum_i [(z_{i,j} - \text{zcg})^2 \cdot A_{t_i}]} & \text{otherwise} \end{cases}
\]

\[
F_{t_{i,j}} := F_{\text{direct}}_{i,j} + F_{mz_{i,j}} + F_{my_{i,j}}
\]

Total Tensile load

Shear on bolts

Secondary shear on bolts

\[
F_{s_{i,j}} := \frac{M_{x_{\text{boltcg}}}^{(j)} \cdot r_{ij} \cdot A_{s_{i,j}}}{\sum_i [r_{ij}^2 \cdot (A_{s_{i,j}})]}
\]

Direct shear on bolts

\[
F_{sd_{i,j}} := \frac{(F_{z_{i,j}})^2 + (F_{y_{i,j}})^2}{\text{num\_bolts}}
\]

Total shear load

\[
F_{stot_{i,j}} := F_{sd_{i,j}} + F_{s_{i,j}}
\]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack} \begin{bmatrix}
(Ft)^{(1)}, (Ft)^{(2)}, (Ft)^{(3)}, (Ft)^{(4)}, (Ft)^{(5)}, (Ft)^{(6)}
\end{bmatrix}
\]

\[
V := \text{stack} \begin{bmatrix}
(F\text{stot})^{(1)}, (F\text{stot})^{(2)}, (F\text{stot})^{(3)}, (F\text{stot})^{(4)}, (F\text{stot})^{(5)}, (F\text{stot})^{(6)}
\end{bmatrix}
\]

\[
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

Output := augment \(ID, LC, \frac{P}{\text{lbf}}, \frac{V}{\text{lbf}}, \frac{M}{\text{in-lbf}}\)

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th>P</th>
<th>V</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>170501</td>
<td>2001</td>
<td>-1068.05</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>170501</td>
<td>2002</td>
<td>-1110.33</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>170501</td>
<td>2064</td>
<td>-699.99</td>
<td>-439.08</td>
<td>0</td>
</tr>
<tr>
<td>170502</td>
<td>2001</td>
<td>-813.60</td>
<td>-263.63</td>
<td>0</td>
</tr>
<tr>
<td>170502</td>
<td>2002</td>
<td>-977.16</td>
<td>-342.06</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>170502</td>
<td>2064</td>
<td>-658.71</td>
<td>-322.63</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>170506</td>
<td>2001</td>
<td>1470.80</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>170506</td>
<td>2002</td>
<td>1166.08</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>170506</td>
<td>2064</td>
<td>699.99</td>
<td>-439.07</td>
<td>0</td>
</tr>
</tbody>
</table>

Size of the "Output" Array: rows(Output) = 768

(6 bolts x 64 load cases) x 2 joints = 768 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)

Example of Output Array

WRITEPRN("output_forces_sillbracket_r3_launch.txt") := Output
CHECK BOLTS (bolts SDG39135892-815, NAS1958C13 0.500-20UNJF-3A, Material-A-286, Insert MS51831CA206, Washer NAS1149E0863R)

The array from the text file above is read:

```plaintext
data READPRN("output_forces_sillbracket_r2_launch.txt")
s := 1 .. rows(data)
```

**Flange 1: Sill Bracket**
- Part number: SDG39135738
- Material: 7050-T7451

**Flange 2: Sill Joint**
- Part number: SEG39135730
- Material: 7050-T7451

**Loads**
- Applied tensile load: \( P_s := \text{data}_{s,3} \cdot \text{lbf} \)
- Applied shear load: \( V_s := \text{data}_{s,4} \cdot \text{lbf} \)
- Applied bending moment: \( M_s := \text{data}_{s,5} \cdot \text{in} \cdot \text{lbf} \)

**Factors of Safety**
- Ultimate: \( SFu := 1.4 \)
- Yield: \( SFy := 1.1 \)
- Joint Separation: \( SFsep := 1.2 \)
- Fitting factor: \( FF := 1.15 \)

**Temperature Data (Ref Appendix C2), Launch Case**
- Assembly: \( \text{Temp}_{\text{initial}} := 70\text{-deg} \)
- Maximum: \( \text{Temp}_{\text{max}} := 120\text{-deg} \)
- Minimum: \( \text{Temp}_{\text{min}} := 40\text{-deg} \)

**Bolt and Insert Data**
- Nominal diameter of bolt: \( D := 0.500\text{-in} \)
- Total length of bolt: \( L := 1.547\text{-in} \)
- Threaded length: \( Lt := 0.735\text{-in} \)
- Number of threads/\text{inch}: \( Nt := 20 \cdot \frac{1}{\text{in}} \)
- Length of insert: \( Lins := 0.688\text{-in} \)
- Min. external diameter of insert: \( F_{\text{min}} := 0.615\text{-in} \)
- Depth of recess for insert: \( lr := 0.02\text{-in} \)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
**Washer Data**

Thickness of washer \( t_w := 0.063 \text{ in} \)  
Outer Diameter of washer \( D_w := 0.875 \text{ in} \)  
Inner Diameter of washer \( D_{wi} := 0.515 \text{ in} \)

Bolt head dia. across flats \( d_w := 0.710 \text{ in} \)  
(used only if there is no washer)

Note: If there is no washer, \( t_w, D_w, \) and \( D_{wi} \) should be zero.

**Flange data**

Thickness of flange 1 \( t_{f1} := 0.750 \text{ in} \)  
Thickness of flange 2 \( t_{f2} := 0.688 \text{ in} \)  
Diameter of hole \( D_{\text{hole}} := 0.539 \text{ in} \)

**Material Property Data**

**Bolt**

Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1) \( T_{Su_{\text{bolt}}} := 0.98 \)  
Bolt ultimate tensile allowable stress \( F_{tu_{\text{bolt}}} := 180000 \text{ psi} \)  
(Ref. NAS1958)

Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 \cdot F_{tu_{\text{bolt}}} \)

Bolt yield tensile allowable \( F_{ty_{\text{bolt}}} := 132353 \text{ psi} \)  
(Ref. Appendix C10)

Temperature correction factor for bolt modulus \( T_{E_{\text{bolt}}} := 0.98 \)  
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \cdot 10^6 \text{ psi}\right) \)  
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Thermal coefficient for bolt: \( \alpha_{\text{bolt}_{\text{hot}}} := 9.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \) \( \alpha_{\text{bolt}_{\text{cold}}} := 8.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)  
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

**Insert**

Temperature correction factor for insert strength \( T_{S_{\text{ins}}} := 0.98 \)  
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} := 140000 \text{ psi} \)  
(Ref. MS51831)

Ultimate shear allowable stress \( F_{su_{\text{ins}}} := 0.6 \cdot F_{tu_{\text{ins}}} \)

**Washer**

Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} := 0.98 \)  
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer \( E_{\text{washer}} := \left(29.1 \cdot 10^6 \text{ psi}\right) \)  
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_f1E := 0.98 \] (modulus) (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2
\[ T_f2E := 0.98 \] (modulus) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

\[ T_f2s := 0.98 \] (strength) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear Strength Allowable for flanges
\[ F_{su\_f2} := 44000 \text{ psi} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(b1))

Modulus of elasticity for the parts in the joint
\[ E_{flange1} := (10.3 \times 10^6 \text{ psi}) \quad E_{flange2} := (10.3 \times 10^6 \text{ psi}) \] (Ref. MIL-HDBK-5J, table 3.7.4.0(b1))

Coefficient of thermal expansion for flanges
\[ \alpha_{flange1\_hot} := 12.8 \times 10^{-6} \text{ in/deg} \quad \alpha_{flange2\_hot} := 12.8 \times 10^{-6} \text{ in/deg} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)
\[ \alpha_{flange1\_cold} := 12.1 \times 10^{-6} \text{ in/deg} \quad \alpha_{flange2\_cold} := 12.1 \times 10^{-6} \text{ in/deg} \]

Torque/Preload data

Maximum torque (65% of yield)
\[ T_{max} := 1032 \text{ in-lbf} \]

Minimum torque (95% of max. torque)
\[ T_{min} := 980 \text{ in-lbf} \]

Loading plane factor:
\[ n := 0.5 \]

Preload Uncertainty:
\[ \Gamma := 0.25 \]

Torque coefficient:
\[ k := 0.15 \]

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

- Bolt/joint stiffness factor: $\phi = 0.391$
- Preload due to temperature: $P_{\text{thr\_pos}} = 725.8 \text{ lbf}$
- Max. preload: $PLD_{\text{max}} = 17925.8 \text{ lbf}$
- Uncertainty factor: $\Gamma = 0.25$
- Min. preload: $PLD_{\text{min}} = 8563.4 \text{ lbf}$
- Torque coefficient: $k = 0.15$
- Joint separation load: $\max(P_{\text{sep}}) = 5888.489 \text{ lbf}$
- Loading plane factor: $n = 0.5$
- Max. load on the bolt(ultimate): $\max(P_b) = 19468.5 \text{ lbf}$
- Thread shear pullout load of bolt or insert: $P_{\text{ths}} = 43162.3 \text{ lbf}$
- Max. load on the bolt(yield): $\max(P_{by}) = 19137.9 \text{ lbf}$
- Thread shear pullout load in parent metal: $P_{\text{pths}} = 28659.1 \text{ lbf}$
- Bolt ultimate tensile strength: $PA_t = 27708.6 \text{ lbf}$
- Joint separation load: $\max(P_{\text{sep}}) = 5888.489 \text{ lbf}$
- Loading plane factor: $n = 0.5$
- Max. load on the bolt(ultimate): $\max(P_b) = 19468.5 \text{ lbf}$
- Thread shear pullout load of bolt or insert: $P_{\text{ths}} = 43162.3 \text{ lbf}$
- Max. load on the bolt(yield): $\max(P_{by}) = 19137.9 \text{ lbf}$
- Thread shear pullout load in parent metal: $P_{\text{pths}} = 28659.1 \text{ lbf}$
- Bolt ultimate tensile strength: $PA_t = 27708.6 \text{ lbf}$

Summary of Margins for bolt:

- Joint separation: $MS_{\min,1} = 0.571$
- Direct Thread shear Ultimate: $MS_{\min,6} = 2.628$
- Direct Tension Ultimate: $MS_{\min,2} = 2.507$
- Total Thread shear Ultimate: $MS_{\min,7} = 0.472$
- Direct Tension Yield: $MS_{\min,3} = 2.282$
- Shear Ultimate: $MS_{\min,8} = 74.13$
- Total Tension Ultimate: $MS_{\min,4} = 0.423$
- Bending Ultimate: $MS_{\min,9} = 10$
- Total Tension Yield: $MS_{\min,5} = 0.065$
- Combined shear, tension and bending ultimate: $MS_{\min,10} = 0.423$

Determination of the smallest margin of safety for the bolt, and the failure mode:

$MS_{\text{bolt}} := \min(\text{MS})$

$MS_{\text{bolt}} = 0.065$

Failure Mode = "Total Tension Yield"

- $MS_{\min\_ID} = 170601$: Element Identification (1706) and Bolt Number (1) for Minimum Margin
- $MS_{\min\_LC} = 1016$: Load Case Number for Minimum Margin
- $MS_{\min\_P} = 4907.1$: Applied Tensile Load for Minimum Margin
- $MS_{\min\_V} = 65$: Applied Shear Load for Minimum Margin
- $MS_{\min\_M} = 0$: Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Sill Bracket to Sill Joint

Since bolt number 1 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 5, NAS1958C 0.50-20 UNFJ fasteners, holding the sill bracket to the sill joint. The drawing number for the Upper USS-02 Assembly is SDG39135726.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
\end{align*}
\]

\[
bolt2 := \begin{pmatrix}
0.50 \\
0.50 \\
0.50 \\
\end{pmatrix}
\]

\[
s := 1.0 \text{ rows(bolt2)}
\]

\[
N_2 := bolt2, \frac{1}{2} \text{ in} \quad \text{pitch of bolt}
\]

\[
D_2 := bolt2, 1 \text{ in} \quad \text{bolt diameter}
\]

\[
\begin{aligned}
A_{t2} & := \pi \left( \frac{D_2 - 0.9743 - \frac{1}{N_2}}{2} \right)^2 \quad \text{Tensile Area of bolt} \\
A_{s2} & := \pi \left( \frac{D_2 - 1.299038 - \frac{1}{N_2}}{2} \right)^2 \quad \text{Shear Area of bolt}
\end{aligned}
\]
Bolt from Sill Bracket to Sill Joint

Bolt no. | x co-ord | y co-ord | z co-ord
--- | --- | --- | ---
2 | 0.0 | 3.25 | 0.0
3 | 0.0 | 3.25 | 1.875
4 | x2 := 0.0 in | y2 := −3.25 in | z2 := −1.875 in
5 | 0.0 | −3.25 | 0.0
6 | 0.0 | −3.25 | 1.875

Location of applied forces and moments

\[
x_{\text{force}2} := 0.0 \text{in} \quad y_{\text{force}2} := 0.0 \text{in} \quad z_{\text{force}2} := 0.0 \text{in}
\]

\[
\text{cgload2} := \begin{pmatrix} x_{\text{force}2} \\ y_{\text{force}2} \\ z_{\text{force}2} \end{pmatrix} \quad \text{cgload2} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}
\]

Center of gravity of bolt group

\[
\begin{align*}
x_{\text{cg}2} &:= \frac{\sum x_{2s}}{\text{rows}(x2)} \quad x_{\text{cg}2} = 0 \text{ in} \\
y_{\text{cg}2} &:= \frac{\sum y_{2s}}{\text{rows}(y2)} \quad y_{\text{cg}2} = −0.65 \text{ in} \\
z_{\text{cg}2} &:= \frac{\sum z_{2s}}{\text{rows}(z2)} \quad z_{\text{cg}2} = 0.375 \text{ in}
\end{align*}
\]

\[
\text{cg}_{\text{bolt}2} := \begin{pmatrix} x_{\text{cg}2} \\ y_{\text{cg}2} \\ z_{\text{cg}2} \end{pmatrix} \quad \text{cg}_{\text{bolt}2} = \begin{pmatrix} 0 \\ −0.65 \\ 0.375 \end{pmatrix} \text{in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 1, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[
r_{\text{load}2} := \text{cgload2} − \text{cg}_{\text{bolt}2} \quad r_{\text{load}2} = \begin{pmatrix} 0 \\ 0.65 \\ −0.375 \end{pmatrix} \text{in}
\]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_s^2 := \sqrt{(z_s - z_{cg})^2 + (y_s - y_{cg})^2} \]

\[ r_s^2 = \begin{pmatrix} 3.918 \\ 4.179 \\ 3.438 \\ 2.627 \\ 3.002 \end{pmatrix} \text{ in} \]

**Reading database file for bolted joint, abort landing case**

data := READPRN("sillbracket_r2_launch.txt")

\[ q := 1 .. \text{rows(data)} \quad \text{num_bolts2} := \text{rows(bolt2)} \]

**Loads from 2-04 loads model, abort landing case**

- Axial Load
  \[ F_{xq} := \text{data}_{q, 7} \text{lbf} \]
  \[ M_{xq} := \text{data}_{q, 8} \text{in-lbf} \]

- Shear in Y axis
  \[ F_{yq} := \text{data}_{q, 5} \text{lbf} \]
  \[ M_{yq} := \text{data}_{q, 4} \text{in-lbf} \]

- Shear in Z axis
  \[ F_{zq} := \text{data}_{q, 6} \text{lbf} \]
  \[ M_{zq} := \text{data}_{q, 3} \text{in-lbf} \]

- Element Identification
  \[ ID_{2q} := \text{data}_{q, 1} \]
  \[ ID_{2q} := ID_{2q} \cdot 100 + 1 \text{ Counter for number of bolts in pattern} \]

- Load Case Number
  \[ LC_{2q} := \text{data}_{q, 2} \]

- Applied Bending Moment at Bolts
  \[ M_{2q} := 0 \text{in-lbf} \]

**Format of Output File**

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 1 is not included.

\[ \text{ID2} := \text{stack(ID2 + 1, ID2 + 2, ID2 + 3, ID2 + 4, ID2 + 5)} \]

\[ \text{LC2} := \text{stack(LC2, LC2, LC2, LC2, LC2)} \]
Moment Distribution

\[
M_{\text{tot}}^q := \begin{pmatrix}
M_x^q \\
M_y^q \\
M_z^q
\end{pmatrix} + r_{\text{load}} \times \begin{pmatrix}
F_x^q \\
F_y^q \\
F_z^q
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg}}^q := M_{\text{tot}}^{1,q} \\
M_{\text{boltcg}}^q := M_{\text{tot}}^{2,q} \\
M_{\text{boltcg}}^q := M_{\text{tot}}^{3,q}
\]

Tension on bolts

\[
F_{\text{direct}}^q := \begin{cases}
0 \text{-lbf} & \text{if } F_{x}^q \leq 0 \text{lbf} \\
F_{x}^q / \text{num\_bolts} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation

\[
F_{\text{mz}}^q := 0 \text{-lbf} \text{ if } \left( y_{s}^2 - y_{cg}^2 \right) = 0 \text{-in} \\
\left[ M_{\text{boltcg}}^q \left( y_{s}^2 - y_{cg}^2 \right) \right] A_{t}^2 \\
\sum_s \left[ \left( y_{s}^2 - y_{cg}^2 \right)^2 \cdot A_{t}^2_s \right]
\]

\[
F_{\text{my}}^q := 0 \text{-lbf} \text{ if } \left( z_{s}^2 - z_{cg}^2 \right) = 0 \text{-in} \\
\left[ M_{\text{boltcg}}^q \left( z_{s}^2 - z_{cg}^2 \right) \cdot A_{t}^2_s \right] \\
\sum_s \left[ \left( z_{s}^2 - z_{cg}^2 \right)^2 \cdot A_{t}^2_s \right]
\]

\[
F_{t}^q := F_{\text{direct}}^q + F_{\text{mz}}^q + F_{\text{my}}^q
\]

Total Tensile load

Shear on bolts

Secondary shear on bolts \[
F_{s}^q := \frac{M_{\text{boltcg}}^q \cdot r_{s} \cdot A_{s}^2}{\sum_s \left[ r_{s}^2 \cdot A_{s}^2 \right]}
\]

Direct shear on bolts \[
F_{sd}^q := \sqrt{\left( F_{x}^q \right)^2 + \left( F_{y}^q \right)^2} / \text{num\_bolts}
\]

Total shear load \[
F_{stot}^q := F_{sd}^q + F_{s}^q
\]
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 5 bolts, since bolt number 1 is not included.

\[
P_2 := \text{stack} \left( \begin{array}{c} (Ft_2^T)^{(1)} \, (Ft_2^T)^{(2)} \, (Ft_2^T)^{(3)} \, (Ft_2^T)^{(4)} \, (Ft_2^T)^{(5)} \end{array} \right)
\]

\[
V_2 := \text{stack} \left( \begin{array}{c} (F_{\text{stot}2}^T)^{(1)} \, (F_{\text{stot}2}^T)^{(2)} \, (F_{\text{stot}2}^T)^{(3)} \, (F_{\text{stot}2}^T)^{(4)} \, (F_{\text{stot}2}^T)^{(5)} \end{array} \right)
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{Output2} := \text{augment}(\text{ID2}, \text{LC2}, \frac{P_2}{\text{lbf}}, \frac{V_2}{\text{lbf}}, \frac{M_2}{\text{in lbf}})
\]

(Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: \( \text{rows(Output2)} = 640 \)

\( \text{(5 bolts x 64 load cases) x 2 joints = 640 load cases} \)

\[
\text{WRITEPRN("output_forces_sillbracket_r2_launch_fs.txt") := Output2}
\]

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
\text{data_fs := READPRN("output_forces_sillbracket_r2_launch_fs.txt")}
\]

\[
s := 1..\text{rows(data_fs)}
\]
Fail-safe Analysis, launch

Applied tensile load \( P_{FS} := \text{data}_{FS,3}, \text{lbf} \)
ID \( ID_{FS} := \text{data}_{FS,1} \)

Applied shear load \( V_{FS} := \text{data}_{FS,4}, \text{lbf} \)
LC \( LC_{FS} := \text{data}_{FS,2} \)

Applied bending moment \( M_{FS} := \text{data}_{FS,5}, \text{in-lbf} \)

This file uses the calculations shown in `\escfil02\11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`

Bolt Fail-safe Load data

Joint separation load \( \max(P_{sep_{FS}}) = 5626.781 \text{lbf} \)

Max. load on the bolt(ultimate) \( \max(P_{b_{FS}}) = 19189.4 \text{lbf} \)

Summary of fail-safe Margins for bolt:

Joint separation \( MS_{minFS,1,1} = 0.645 \)
Total Thread shear Ultimate \( MS_{minFS,5,1} = 0.493 \)

Direct Tension Ultimate \( MS_{minFS,2,1} = 3.282 \)
Shear Ultimate \( MS_{minFS,6,1} = 101.25 \)

Total Tension Ultimate \( MS_{minFS,3,1} = 0.444 \)
Bending Ultimate \( MS_{minFS,7,1} = 10 \)

Direct Thread shear Ultimate \( MS_{minFS,4,1} = 3.43 \)
Combined shear, tension and bending ultimate \( MS_{minFS,8,1} = 0.4440 \)

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt_{FS}} := \min(MS_{FS}) \)

\( MS_{bolt_{FS}} = 0.444 \)

Failure Mode \( FS = \text{"Combined Shear Tension Bending Ultimate"} \)

\( MS_{\text{min ID}} = 170604 \) Element Identification (1706) and Bolt Number (4) for Minimum Margin

\( MS_{\text{min LC}} = 1004 \) Load Case Number for Minimum Margin

\( MS_{\text{min P}} = 5626.8 \) Applied Tensile Load for Minimum Margin

\( MS_{\text{min V}} = 67.9 \) Applied Shear Load for Minimum Margin

\( MS_{\text{min M}} = 0 \) Applied Bending Moment for Minimum Margin
2.4.1.5 Diagonal Sill Bracket to Sill Joint
Diagonal Sill Bracket to Sill Joint Bolt Analysis

The USS-02 assembly consists of two Diagonal Sill Brackets. There are a total of 10 fasteners attaching the Diagonal Sill Bracket to the Sill Joint. The fasteners are EWB0420 (200 ksi), 0.50-20 UNFJ. The drawing number for the Upper USS-02 Assembly is SDG39135726.

<table>
<thead>
<tr>
<th>Size</th>
<th>Thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
</tbody>
</table>

\[ \text{Tensile Area of bolt} \]
\[
\text{At}_i := \pi \left( \frac{D_i - 0.9743 \times \frac{1}{N_i}}{2} \right)^2
\]

\[ \text{Shear Area of bolt} \]
\[
\text{As}_i := \pi \left( \frac{D_i - 1.299038 \times \frac{1}{N_i}}{2} \right)^2
\]
Bolts from Diagonal Sill Bracket to Sill Joint

Diagonal Sill Bracket to Sill Joint Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>4.00</td>
<td>-0.9375</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>4.00</td>
<td>0.9375</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.25</td>
<td>-1.875</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>3.25</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>3.25</td>
<td>1.875</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>-3.25</td>
<td>-1.875</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>-3.25</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>-3.25</td>
<td>1.875</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-4.0</td>
<td>-0.9375</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>-4.0</td>
<td>0.9375</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
\text{xforce} := 0.0 \text{in} \quad \text{yforce} := 0.0 \text{in} \quad \text{zforce} := 0.0 \text{in}
\]

\[
\text{cgload} := \begin{pmatrix} \text{xforce} \\ \text{yforce} \\ \text{zforce} \end{pmatrix} \quad \text{cgload} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in}
\]
Center of gravity of bolt group

\[
x_{cg} := \sum_{i} \frac{x_i}{rows(x)} \quad x_{cg} = 0 \text{ in} \\
y_{cg} := \sum_{i} \frac{y_i}{rows(y)} \quad y_{cg} = 0 \text{ in} \\
z_{cg} := \sum_{i} \frac{z_i}{rows(z)} \quad z_{cg} = 0 \text{ in}
\]

\[
c_{gbolt} := \begin{bmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{bmatrix} \quad c_{gbolt} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis and z-axis with a zero offset from the center of gravity.

Load Vector

\[
r_{load} := c_{gload} - c_{gbolt} \quad r_{load} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2}
\]

\[
r = \begin{bmatrix} 4.108 \\ 4.108 \\ 3.752 \\ 3.250 \\ 3.752 \\ 3.752 \\ 3.752 \\ 4.108 \\ 4.108 \end{bmatrix} \text{ in}
\]

Loads model 2-04 was used to retrieve loads at the two bolted interfaces. A Cbeam element located at the center of each diagonal sill bracket was post processed in NASPOST for end A forces and moments in the x, y, and z directions. The Cbeam element identifications for the two bolted interfaces are 1722 and 1721. These loads are read into an array and distributed out to the 10 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The launch cases combined with launch temperature data resulted in the lowest minimum margins of safety. Therefore, the launch cases are used in this analysis.)

Reading database file for bolted joint, launch case

\[
data := \text{READPRN("diagsillforces_r2_launch.txt")}
\]

\[
j := 1 \ldots \text{rows(data)}
\]

\[
\text{num_bolts} := \text{rows(bolt)}
\]
Bolts from Diagonal Sill Bracket to Sill Joint

**Loads from 2-04 loads model, launch case**  (Note: These loads are taken from end A of the Cbeam element)

- **Axial Load**  \( F_x \) := \( \text{data}_{j,7} \) lbf
- **Shear in Y axis**  \( F_y \) := \( \text{data}_{j,5} \) lbf
- **Shear in Z axis**  \( F_z \) := \( \text{data}_{j,6} \) lbf
- **Element Identification**  \( \text{ID}_j \) := \( \text{data}_{j,1} \)
- **Load Case Number**  \( \text{LC}_j \) := \( \text{data}_{j,2} \)
- **Applied Bending Moment at Bolts**  \( M_j \) := 0-in-lbf

**Format of Output File**

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 1722 and 1721, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 1722 will have bolt numbers 1 thru 10 attached to the end for all 64 load cases. This brings the total number of load cases to 1280 (2 joints x 10 bolts x 64 load cases = 1280). See the array example to the right.

\[
\begin{array}{c|c}
\text{ID} & \text{LC} \\
1722001 & 1001 \\
1722001 & 1002 \\
\vdots & \vdots \\
1722001 & 1064 \\
1722002 & 1001 \\
1722002 & 1002 \\
\vdots & \vdots \\
1722002 & 1064 \\
1722010 & 1001 \\
1722010 & 1002 \\
\vdots & \vdots \\
1722010 & 1064 \\
\end{array}
\]

Array Example
Moment Distribution

\[
M_{\text{tot}}^{(j)} := \begin{pmatrix}
M_{x_j} \\
M_{y_j} \\
M_{z_j}
\end{pmatrix} + r_{\text{load}} \times \begin{pmatrix}
F_{x_j} \\
F_{y_j} \\
F_{z_j}
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg}}_{x_j} := M_{\text{tot}1,j} \\
M_{\text{boltcg}}_{y_j} := M_{\text{tot}2,j} \\
M_{\text{boltcg}}_{z_j} := M_{\text{tot}3,j}
\]

Tension on bolts

\[
F_{\text{direct}}_{i,j} := \begin{cases}
0 \text{-lbf} & \text{if } F_{x_j} \leq 0 \text{lbf} \\
\frac{F_{x_j}}{\text{num_bolts}} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz_{i,j}} := \begin{cases}
0 \text{-lbf} & \text{if } (y_i - y_{cg}) = 0 \text{-in} \\
\frac{M_{z_{\text{boltcg}}_{j}} (y_i - y_{cg}) A_t_{i}}{\sum_i \left( (y_i - y_{cg})^2 A_t_{i} \right)} & \text{otherwise}
\end{cases}
\]

\[
F_{my_{i,j}} := \begin{cases}
0 \text{-lbf} & \text{if } (z_i - z_{cg}) = 0 \text{-in} \\
\frac{M_{y_{\text{boltcg}}_{j}} (z_i - z_{cg}) A_t_{i}}{\sum_i \left( (z_i - z_{cg})^2 A_t_{i} \right)} & \text{otherwise}
\end{cases}
\]

\[
F_{t_{i,j}} := F_{\text{direct}}_{i,j} + F_{mz_{i,j}} + F_{my_{i,j}}
\]

Total Tensile load

Shear on bolts

Secondary shear on bolts

\[
F_{s_{i,j}} := \frac{M_{x_{\text{boltcg}}_{j}} r_{i} A_{s_{i}}}{\sum_i \left( r_{ij}^2 (A_{s_{i}}) \right)}
\]

Direct shear on bolts

\[
F_{sd_{i,j}} := \frac{\sqrt{\left( F_{z_{j}} \right)^2 + \left( F_{y_{j}} \right)^2}}{\text{num_bolts}}
\]

Total shear load

\[
F_{stot_{i,j}} := F_{sd_{i,j}} + F_{s_{i,j}}
\]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}\left[\left(\text{Ft}T\right)^{(1)}, \left(\text{Ft}T\right)^{(2)}, \left(\text{Ft}T\right)^{(3)}, \left(\text{Ft}T\right)^{(4)}, \left(\text{Ft}T\right)^{(5)}, \left(\text{Ft}T\right)^{(6)}, \left(\text{Ft}T\right)^{(7)}, \left(\text{Ft}T\right)^{(8)}, \left(\text{Ft}T\right)^{(9)}, \left(\text{Ft}T\right)^{(10)}\right]\]

\[
V := \text{stack}\left[\left(\text{Fstot}T\right)^{(1)}, \left(\text{Fstot}T\right)^{(2)}, \left(\text{Fstot}T\right)^{(3)}, \left(\text{Fstot}T\right)^{(4)}, \left(\text{Fstot}T\right)^{(5)}, \left(\text{Fstot}T\right)^{(6)}, \left(\text{Fstot}T\right)^{(7)}, \left(\text{Fstot}T\right)^{(8)}, \left(\text{Fstot}T\right)^{(9)}, \left(\text{Fstot}T\right)^{(10)}\right]\]

\[
V := \text{stack}\left[\left(\text{Fstot}T\right)^{(9)}, \left(\text{Fstot}T\right)^{(8)}, \left(\text{Fstot}T\right)^{(7)}, \left(\text{Fstot}T\right)^{(6)}, \left(\text{Fstot}T\right)^{(5)}\right] \quad \text{M} := \text{stack}(\text{M}, \text{M}, \text{M}, \text{M}, \text{M}, \text{M}, \text{M}, \text{M})
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

\[
\text{Output} := \text{augment}(\text{ID}, \text{LC}, \frac{P}{\text{lb}f}, \frac{V}{\text{lb}f}, \frac{M}{\text{in-lb}f})
\]

\[
\begin{array}{cccccc}
1722001 & 1001 & -1068.05 & -358.78 & 0 \\
1722001 & 1002 & -1110.33 & -465.51 & 0 \\
... & ... & ... & ... & ... \\
1722001 & 1064 & -699.99 & -439.08 & 0 \\
1722002 & 1001 & -813.60 & -263.63 & 0 \\
1722002 & 1002 & -977.16 & -342.06 & 0 \\
... & ... & ... & ... & ... \\
1722002 & 1064 & -658.71 & -322.63 & 0 \\
... & ... & ... & ... & ... \\
1722010 & 1001 & 1470.8 & -358.78 & 0 \\
1722010 & 1002 & 1166.08 & -465.51 & 0 \\
... & ... & ... & ... & ... \\
1722010 & 1064 & 699.99 & -439.07 & 0 \\
\end{array}
\]

Size of the "Output" Array: \(\text{rows}(\text{Output}) = 1280\)

\(10\ \text{bolts} \times 64\ \text{load cases} = 1280\ \text{load cases}\)

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)
CHECK BOLTS (bolts SDG39135892-813, EWB 0420-8-16  0.50-20UNJF-3A, Material-A-286),
Insert MS51832CA206, Washer NAS1587-8C

data := READPRN("output_forces_diagsillbrack_r2_launch.txt")

s := 1 .. rows(data)

Flange 1: Diagonal Sill Bracket
Part number: SDG39135740
Material: 7050-T7451

Flange 2: Sill Joint
Part number: SDG39135730
Material: 7050-T7451

Loads
Applied tensile load
\( P_s := \text{data}_{s,3} \cdot \text{lbf} \)

Applied shear load
\( V_s := \text{data}_{s,4} \cdot \text{lbf} \)

Applied bending moment
\( M_s := \text{data}_{s,5} \cdot \text{in-lbf} \)

Factors of Safety
Ultimate \( SFu := 1.4 \)
Yield \( SFy := 1.1 \)
Joint Separation \( SFsep := 1.2 \)
Fitting factor \( FF := 1.15 \)

Temperature Data (Ref Appendix C2), Launch Case
Assembly
Temp_initial := 70-deg

Maximum
Temp_max := 120-deg

Minimum
Temp_min := 40-deg

Bolt and Insert Data
Nominal diameter of bolt \( D := 0.500 \cdot \text{in} \)
Number of threads/inch \( Nt := 20 \cdot \frac{1}{\text{in}} \)

Total length of bolt \( L := 1.838 \cdot \text{in} \)
Length of insert \( Lins := 0.688 \cdot \text{in} \)

Threaded length \( L_t := 0.838 \cdot \text{in} \)
Min. external diameter of insert \( Fmin := 0.744 \cdot \text{in} \)

(If bolt is fully threaded, input \( L_t = L \))
Depth of recess for insert \( lr := 0.02 \cdot \text{in} \)

This file uses the calculations shown in \escfil02\2i11\mathcad\8307_bolts\thread_data.mcd
**Washer Data**

- Thickness of washer: $tw := 0.078$ in  
- Outer Diameter of washer: $Dw := 0.875$ in  
- Inner Diameter of washer: $Dwi := 0.515$ in  
- Bolt head dia. across flats: $dw := 0.818$ in

**Flange data**

- Thickness of flange 1: $tf1 := 1.0$ in  
- Thickness of flange 2: $tf2 := 0.688$ in (Insert Length)  
- Diameter of hole: $D_{hole} := 0.539$ in

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate: $TSu_{bolt} := .97$  
- Ultimate tensile allowable stress: $Ftu_{bolt} := 200000$ psi  
- Ultimate shear allowable stress: $Fsu_{bolt} := 0.6 \times Ftu_{bolt}$  
- Bolt yield tensile allowable: $Fty_{bolt} := 180000$ psi  
- Temperature correction factor for bolt modulus: $TE_{bolt} := .98$  
- Modulus of elasticity of bolt: $E_{bolt} := \left(29.1 \times 10^6 \text{ psi}\right)$  
- Thermal coefficient for bolt: $\alpha_{bolt\_hot} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{deg}}$  
  $\alpha_{bolt\_cold} := 8.9 \times 10^{-6} \frac{\text{in}}{\text{deg}}$

**Insert**

- Temperature correction factor for insert strength: $TS_{ins} := .97$  
- Ultimate tensile allowable stress: $Ftu_{ins} := 140000$ psi  
- Ultimate shear allowable stress: $Fsu_{ins} := 0.6 \times Ftu_{ins}$

**Washer**

- Temperature correction factor for washer modulus: $TE_{washer} := .97$  
- Modulus of elasticity of washer: $E_{washer} := \left(29.1 \times 10^6 \text{ psi}\right)$
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{1E} := .97 \text{ (modulus)} \] (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2
\[ T_{2E} := .97 \text{ (modulus)} \] (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4)

\[ T_{2s} := .97 \text{ (strength)} \] (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear Strength Allowable for flanges
\[ F_{s}\text{su}_2 := 44000 \text{ psi} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(b1))

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := (10.3 \cdot 10^6 \text{ psi}) \] \[ E_{\text{flange2}} := (10.3 \cdot 10^6 \text{ psi}) \] (Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)

Coefficient of thermal expansion for flanges
\[ \alpha_{\text{flange1 hot}} := 12.8 \cdot 10^{-6} \text{ in} \cdot \text{in}^{-1} \cdot \text{deg}^{-1} \] \[ \alpha_{\text{flange2 hot}} := 12.8 \cdot 10^{-6} \text{ in} \cdot \text{in}^{-1} \cdot \text{deg}^{-1} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)

\[ \alpha_{\text{flange1 cold}} := 12.1 \cdot 10^{-6} \text{ in} \cdot \text{in}^{-1} \cdot \text{deg}^{-1} \] \[ \alpha_{\text{flange2 cold}} := 12.1 \cdot 10^{-6} \text{ in} \cdot \text{in}^{-1} \cdot \text{deg}^{-1} \]

Torque/Preload data

Maximum torque (65% of yield)
\[ T_{\text{max}} := 1403.1 \text{ in-lbf} \]

Minimum torque (95% of max. torque)
\[ T_{\text{min}} := 1333 \text{ in-lbf} \]

Loading plane factor:
\[ n := .5 \]

Preload Uncertainty:
\[ \Gamma := 0.25 \]

Torque coefficient:
\[ k := 0.15 \]

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Bolt/joint stiffness factor \(\phi = 0.370\)

Preload due to temperature \(P_{\text{thr pos}} = 718.5\) lbf

\(P_{\text{thr neg}} = -372.9\) lbf

Uncertainty factor \(\Gamma = 0.25\)

Torque coefficient \(k = 0.15\)

Loading plane factor \(n = 0.5\)

Max. load on the bolt (ultimate) \(\max(P_b) = 27800.6\) lbf

Thread shear pullout load of bolt or insert \(P_{\text{ths}} = 44277.6\) lbf

Min. load on the bolt (yield) \(\max(P_{by}) = 27008.4\) lbf

Thread shear pullout load in parent metal \(P_{\text{pths}} = 34316.7\) lbf

Bolt ultimate tensile strength \(P_{At} = 30473.2\) lbf

Length check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>-0.157</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>0.523</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.096</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.015</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>0.715</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>0.234</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>4.27</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>10</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>0.091</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[MS_{\text{bolt}} = \min(\text{MS})\]

\[MS_{\text{bolt}} = -0.157\]

Minimum Margin of Safety (Note: See Minimum Margin of Safety Summary below.)

Failure Mode = "Joint Separation"

Element Identification (1721) and Bolt Number (9) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Minimum Margin of Safety Summary:

Although the minimum margin of safety is negative for joint separation, all other margins of safety are positive. Even though two out of 10 bolts result in negative margins of safety on joint separation across 13 load cases, the joint flanges do not separate.

Bolts 6 and 9, in joint 1721, have negative margins of safety on joint separation for 12 load cases. Negative margins of safety on joint separation occurs at the same time for bolts 6 and 9. Negative margins of safety on joint separation occurs 4 times for bolt 9 only. See table below. For liftoff and landing, the fatigue spectrum (ref NASGRO manual for Goddard spectrum) for these fasteners shows that bolts 6 and 9 incur only 14 cycles above which the fastener experiences 80% of applied axial load. At 84% of applied axial load, analysis shows these fasteners have positive margins of safety against joint separation.

Bolts 1 and 3, in joint 1722, have negative margins of safety on joint separation for 2 load cases. Negative margins of safety on joint separation occurs at the same time for bolts 1 and 3. Negative margins of safety on joint separation occurs 6 times for bolt 1 only. See table below. For liftoff and landing, the fatigue spectrum (ref NASGRO manual for Goddard spectrum) for these fasteners shows that bolts 1 and 3 incur only 6 cycles above which the fastener experiences 90% of applied axial load. At 92% of applied axial load, analysis shows these fasteners have positive margins of safety against joint separation.

Joint 1721, bolt numbers 6 and 9 result in joint separation in 12 load cases

<table>
<thead>
<tr>
<th>Bolt ID</th>
<th>Load Case</th>
<th>M.S. for Joint Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1721009</td>
<td>1032</td>
<td>-0.157</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.145</td>
</tr>
<tr>
<td>1721009</td>
<td>1031</td>
<td>-0.058</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.048</td>
</tr>
<tr>
<td>1721009</td>
<td>1030</td>
<td>-0.12</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.088</td>
</tr>
<tr>
<td>1721009</td>
<td>1029</td>
<td>-0.026</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.026</td>
</tr>
<tr>
<td>1721009</td>
<td>1028</td>
<td>-0.141</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.126</td>
</tr>
<tr>
<td>1721009</td>
<td>1027</td>
<td>-0.056</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.042</td>
</tr>
<tr>
<td>1721009</td>
<td>1026</td>
<td>-0.117</td>
</tr>
<tr>
<td>1721006</td>
<td></td>
<td>-0.08</td>
</tr>
<tr>
<td>1721009</td>
<td>1025</td>
<td>-0.02</td>
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<tr>
<td>1721009</td>
<td>1024</td>
<td>-0.142</td>
</tr>
<tr>
<td>1721009</td>
<td>1023</td>
<td>-0.142</td>
</tr>
<tr>
<td>1721009</td>
<td>1022</td>
<td>-0.106</td>
</tr>
<tr>
<td>1721009</td>
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<td>1721009</td>
<td>1020</td>
<td>-0.134</td>
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<tr>
<td>1721009</td>
<td>1019</td>
<td>-0.034</td>
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<td>1721009</td>
<td>1018</td>
<td>-0.113</td>
</tr>
<tr>
<td>1721009</td>
<td>1017</td>
<td>-0.067</td>
</tr>
</tbody>
</table>

Joint 1722, bolt numbers 1 and 3 result in joint separation in 1 load case

<table>
<thead>
<tr>
<th>Bolt ID</th>
<th>Load Case</th>
<th>M.S. for Joint Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1722003</td>
<td>1015</td>
<td>-0.012</td>
</tr>
<tr>
<td>1722001</td>
<td></td>
<td>-0.075</td>
</tr>
<tr>
<td>1722001</td>
<td>1013</td>
<td>-0.027</td>
</tr>
<tr>
<td>1722003</td>
<td>1011</td>
<td>-0.019</td>
</tr>
<tr>
<td>1722001</td>
<td>1009</td>
<td>-0.031</td>
</tr>
<tr>
<td>1722001</td>
<td>1007</td>
<td>-0.059</td>
</tr>
<tr>
<td>1722001</td>
<td>1005</td>
<td>-0.021</td>
</tr>
<tr>
<td>1722001</td>
<td>1003</td>
<td>-0.065</td>
</tr>
<tr>
<td>1722001</td>
<td>1001</td>
<td>-0.031</td>
</tr>
</tbody>
</table>

Goddard Spectrum

<table>
<thead>
<tr>
<th>Cycles</th>
<th>S0</th>
<th>S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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<td>100</td>
</tr>
<tr>
<td>4</td>
<td>-90</td>
<td>90</td>
</tr>
<tr>
<td>8</td>
<td>-80</td>
<td>80</td>
</tr>
<tr>
<td>15</td>
<td>-70</td>
<td>70</td>
</tr>
<tr>
<td>49</td>
<td>-60</td>
<td>60</td>
</tr>
<tr>
<td>81</td>
<td>-50</td>
<td>50</td>
</tr>
<tr>
<td>178</td>
<td>-40</td>
<td>40</td>
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<tr>
<td>641</td>
<td>-30</td>
<td>30</td>
</tr>
<tr>
<td>3120</td>
<td>-20</td>
<td>20</td>
</tr>
<tr>
<td>3405</td>
<td>-10</td>
<td>10</td>
</tr>
<tr>
<td>5019</td>
<td>-7</td>
<td>7</td>
</tr>
<tr>
<td>28853</td>
<td>-5</td>
<td>5</td>
</tr>
<tr>
<td>91655</td>
<td>-3</td>
<td>3</td>
</tr>
</tbody>
</table>
Bolt Fail-Safe Analysis for Diagonal Sill Bracket to Sill Joint

Since bolt number 9 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 9, EWB0420 0.50-20 UNFJ fasteners, holding the Diagonal Sill Bracket to Sill Joint. The drawing number for the USS-02 Assembly is SDG39135726.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20
\end{align*}
\]

\[
bolt2 := \\
0.50 \\
0.50 \\
0.50 \\
0.50 \\
0.50 \\
0.50 \\
0.50 \\
0.50
\]

\[
s := 1..\text{rows}(bolt2)
\]

\[
N2_s := bolt2_{s,2}\frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D2_s := bolt2_{s,1}\text{in} \quad \text{bolt diameter}
\]

\[
A_{t2_s} := \pi \left( \frac{D2_s - 0.9743}{2} \right) \frac{1}{N2_s} \quad \text{Tensile Area of bolt}
\]

\[
A_{s2_s} := \pi \left( \frac{D2_s - 1.299038}{2} \right) \frac{1}{N2_s} \quad \text{Shear Area of bolt}
\]
### Location of applied forces and moments

\[
\begin{align*}
&x^{\text{force2}} := 0.0 \text{in} & &y^{\text{force2}} := 0.0 \text{in} & &z^{\text{force2}} := 0.0 \text{in} \\
\text{cgload2} := \begin{pmatrix} x^{\text{force2}} \\ y^{\text{force2}} \\ z^{\text{force2}} \end{pmatrix} & &\text{cgload2} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in}
\end{align*}
\]

### Center of gravity of bolt group

\[
\begin{align*}
&x^{\text{cg2}} := \frac{\sum x^2_s}{\text{rows}(x2)} & &y^{\text{cg2}} := \frac{\sum y^2_s}{\text{rows}(y2)} & &z^{\text{cg2}} := \frac{\sum z^2_s}{\text{rows}(z2)} \\
&x^{\text{cg2}} = 0 \text{ in} & &y^{\text{cg2}} = 0.444 \text{ in} & &z^{\text{cg2}} = 0.104 \text{ in} \\
\text{cbolt2} := \begin{pmatrix} x^{\text{cg2}} \\ y^{\text{cg2}} \\ z^{\text{cg2}} \end{pmatrix} & &\text{cbolt2} = \begin{pmatrix} 0 \\ 0.444 \\ 0.104 \end{pmatrix} \text{in}
\end{align*}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 9, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

### Load Vector

\[
\begin{align*}
&\text{rl2} := \text{cgload2} - \text{cbolt2} & &\text{rl2} = \begin{pmatrix} 0 \\ -0.444 \\ -0.104 \end{pmatrix} \text{in}
\end{align*}
\]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_2s := \sqrt{(z_2s - zcg2)^2 + (y_2s - ycg2)^2}
\]

\[
\begin{align*}
r_2 s & = \begin{pmatrix} 3.705 \\ 3.652 \\ 3.433 \\ 2.807 \\ 3.318 \\ 4.191 \\ 3.696 \\ 4.097 \\ 4.522 \end{pmatrix} \text{ in}
\end{align*}
\]

**Reading database file for bolted joint, launch case**

\[
data := \text{READPRN}("diagsillforces_r2_launch.txt")
\]

\[
q := 1..\text{rows(data)} \quad \text{num_bolts2} := \text{rows(bolt2)}
\]

**Loads from 2-04 loads model, launch case**

- Axial Load: \( Fxq \) := data\_q,7\_lbf
- Torsion: \( Mxq \) := data\_q,8\_in\_lbf
- Shear in Y axis: \( Fy_2q \) := data\_q,5\_lbf
- Moment about Y axis: \( My_2q \) := data\_q,4\_in\_lbf
- Shear in Z axis: \( Fz_2q \) := data\_q,6\_lbf
- Moment about Z axis: \( Mz_2q \) := data\_q,3\_in\_lbf
- Element Identification: \( ID_2q \) := data\_q,1
- \( ID_q := ID_2q \cdot 1000 + 1 \) Counter for number of bolts in pattern
- Load Case Number: \( LC_2q \) := data\_q,2
- Applied Bending Moment at Bolts: \( M_2q \) := 0\_in\_lbf

**Format of Output File**

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 9 is not included.

\[
\text{ID2} := \text{stack(ID2, ID2 + 1, ID2 + 2, ID2 + 3, ID2 + 4, ID2 + 5, ID2 + 6, ID2 + 7, ID2 + 9)}
\]

\[
\text{LC2} := \text{stack(LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2)}
\]
Moment Distribution

\[ M_{tot}^q := \begin{pmatrix} Mx_q \\ My_q \\ Mz_q \end{pmatrix} + r_{load}^q \times \begin{pmatrix} Fx_q \\ Fy_q \\ Fz_q \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ Mx_{boltcg} := M_{tot1}^q, \quad My_{boltcg} := M_{tot2}^q, \quad Mz_{boltcg} := M_{tot3}^q \]

Tension on bolts

\[ F_{direct}^q := \begin{cases} 0 \text{-lbf} & \text{if } Fx_q \leq 0 \text{-lbf} \\ \frac{Fx_q}{\text{num_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation

\[ F_{z}^q := 0 \text{-lbf} \quad \text{if } \left( \frac{y_s - y_{cg}}{z_s - z_{cg}} \right) = 0 \text{-in} \]

\[ \sum_s \left[ \frac{Mz_{boltcg} \cdot (y^2 - y_{cg}^2)}{At_s^2} \right] \]

\[ F_{my}^q := 0 \text{-lbf} \quad \text{if } \left( \frac{z_s - z_{cg}}{y_s - y_{cg}} \right) = 0 \text{-in} \]

\[ \sum_s \left[ \frac{My_{boltcg} \cdot (z^2 - z_{cg}^2)}{At_s^2} \right] \]

\[ F_{t}^q := F_{direct}^q + F_{z}^q + F_{my}^q \]

Total Tensile load

Shear on bolts

Secondary shear on bolts \[ F_{s}^q := \frac{Mx_{boltcg} \cdot r_{2s} \cdot As_{s}}{\sum_s \left[ \left( r_{2s}^2 \right) \cdot (As_s^2) \right]} \]

Direct shear on bolts \[ F_{sd}^q := \sqrt{\left( Fz_q \right)^2 + \left( Fy_q \right)^2} \]

\[ \text{num_bolts} \]

Total shear load \[ F_{stot}^q := F_{sd}^q + F_{s}^q \]

2.4.1.5 -16 ESCG-4005-05-AMS-0039
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below. Notice how there is only 9 bolts, since bolt number 9 is not included.

\[
P_2 := \text{stack} \left[ \left( \text{Ft}_2 T \right)^{(1)}, \left( \text{Ft}_2 T \right)^{(2)}, \left( \text{Ft}_2 T \right)^{(3)}, \left( \text{Ft}_2 T \right)^{(4)}, \left( \text{Ft}_2 T \right)^{(5)}, \left( \text{Ft}_2 T \right)^{(6)}, \left( \text{Ft}_2 T \right)^{(7)}, \left( \text{Ft}_2 T \right)^{(8)}, \left( \text{Ft}_2 T \right)^{(9)} \right]
\]

\[
V_2 := \text{stack} \left[ \left( \text{Fstot}_2 T \right)^{(1)}, \left( \text{Fstot}_2 T \right)^{(2)}, \left( \text{Fstot}_2 T \right)^{(3)}, \left( \text{Fstot}_2 T \right)^{(4)}, \left( \text{Fstot}_2 T \right)^{(5)}, \left( \text{Fstot}_2 T \right)^{(6)}, \left( \text{Fstot}_2 T \right)^{(7)}, \left( \text{Fstot}_2 T \right)^{(8)}, \left( \text{Fstot}_2 T \right)^{(9)} \right]
\]

\[
V_2 := \text{stack} \left[ \left( \text{V}_2 \right)^{(7)}, \left( \text{Fstot}_2 T \right)^{(8)}, \left( \text{Fstot}_2 T \right)^{(9)} \right]
\]

\[
M_2 := \text{stack} (M_2, M_2, M_2, M_2, M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file. (Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

\[
\text{Output2} := \text{augment} \left( \text{ID2}, \text{LC2}, \frac{\text{P}_2}{\text{lbf}}, \frac{\text{V}_2}{\text{lbf}}, \frac{\text{M}_2}{\text{in\cdot lbf}} \right)
\]

Size of the "Output2" Array: \(\text{rows(Output2)} = 1152\)

\((9 \text{ bolts} \times 64 \text{ load cases}) \times 2 \text{ joints} = 1152 \text{ load cases}\)

\[
\text{WRITEPRN}("output_forces_diagsillbrack_r2_launch_fs.txt") := \text{Output2}
\]

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
data_{\text{fs}} := \text{READPRN}("output_forces_diagsillbrack_r2_launch_fs.txt")
\]

\[
s := 1 \ldots \text{rows(data_{\text{fs}})}
\]
Fail-safe Loads, launch

Applied tensile load

\[ P_{FS} = \text{data}_{fs,3}, \text{lbf} \]

ID \_FS \_s := \text{data}_{fs,1}

Applied shear load

\[ V_{FS} = \text{data}_{fs,4}, \text{lbf} \]

LC \_FS \_s := \text{data}_{fs,2}

Applied bending moment

\[ M_{FS} = \text{data}_{fs,5}, \text{in-lbf} \]

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Factor</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu_FS := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep_FS := 1.0</td>
</tr>
</tbody>
</table>

Bolt Fail-safe Load data

Joint separation load

\[ \text{max}(P_{sep\_FS}) = 14893.56 \text{ lbf} \]

\[ \text{max}(P_{FS}) = 14893.56 \text{ lbf} \]

Max. load on the bolt(ultimate)

\[ \text{max}(P_{b\_FS}) = 27268 \text{ lbf} \]

\[ \text{max}(V_{FS}) = 2330.345 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_minFS_1,1 = -0.156</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_minFS_2,1 = 0.779</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_minFS_3,1 = 0.118</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_minFS_4,1 = 1</td>
</tr>
<tr>
<td>Combined shear, tension and</td>
<td>MS_minFS_8,1 = 0.1151</td>
</tr>
<tr>
<td>bending ultimate</td>
<td>MS_minFS_7,1 = 10</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt\_FS} := \min(\text{MS}_{FS}) \]

\[ MS_{bolt\_FS} = -0.156 \]

Failure Mode FS = "Joint Separation"  
(Note: For fail-safe analysis, negative margins of safety are allowed for joint separation)

<table>
<thead>
<tr>
<th>Minimum Identification Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS_min_ID = 1721006</td>
</tr>
<tr>
<td>MS_min_LC = 1032</td>
</tr>
<tr>
<td>MS_min_P = 14893.6</td>
</tr>
<tr>
<td>MS_min_V = 2192.2</td>
</tr>
<tr>
<td>MS_min_M = 0</td>
</tr>
</tbody>
</table>

Element Identification (1721) and Bolt Number (6) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin

2.4.1.5 -18 ESCG-4005-05-AMS-0039
2.4.1.6 WIF to Sill Tube Bolted Interfaces
WIF to Sill Tube Bolted Interfaces

The WIF to Sill Tube Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.16.1</td>
<td>WIF Adaptor Plate to Sill Tube</td>
</tr>
<tr>
<td>2.4.16.1</td>
<td>WIF Adaptor Plate to Sill Tube Fail-Safe</td>
</tr>
<tr>
<td>2.4.16.2</td>
<td>WIF Socket to WIF Adaptor Plate</td>
</tr>
<tr>
<td>2.4.16.2</td>
<td>WIF Socket to WIF Adaptor Plate Fail-Safe</td>
</tr>
</tbody>
</table>
2.4.1.6.1 WIF Adaptor Plate to Sill Tube
WIF Adapter Plate to Sill Tube

Drawing: SDG31135747

Part number: NAS1953C6

The objective of this analysis is to demonstrate the structural strength of the fasteners connecting the WIF Adapter Plate (SDG31135747) to Sill Tube (SDG39135739). The WIF adapter plate is mounted on the sill tube to support the WIF socket. Finite element analysis of the WIF Adapter Plate was performed (see section 2.1.15).

Load

Per CARD JSC-33499, WIF Socket is subjected to 4200 in-lbf (bending moment), 4200 in-lbf (torsional moment), 274 (shear force), and 274 lbf (axial force).

Load case 1

ID := 1011 for normal analysis
ID := 10011 for fail-safe analysis
Fx := 274 lbf Axial force
Fy := 274 lbf Shear force
Mx := 4200 in-lbf Torsion moment
Mz := 4200 in-lbf Bending moment

Load case 2

ID := 1022 for normal analysis
ID := 10022 for fail-safe analysis
Fx := 274 lbf Axial force
Fz := 274 lbf Shear force
Mx := 4200 in-lbf Torsion moment
My := 4200 in-lbf Bending moment
Bolt forces were retrieved from the post-processing of FE model data:

1. Normal analysis (file name: bolt12.txt)

<table>
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<th>Bolt ID</th>
<th>Element ID</th>
<th>Load Case ID</th>
<th>Tension</th>
<th>Shear</th>
<th>Moment</th>
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<tbody>
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</table>
2. Fail-safe analysis (file name: bolt12f.txt)

<table>
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<th>Bolt ID</th>
<th>Element ID</th>
<th>Load Case ID</th>
<th>Tension</th>
<th>Shear</th>
<th>Moment</th>
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</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

(In the fail safe analysis, one critical fastener is removed.)
CHECK BOLTS (NAS1953C6 Socket Head Screw Material A286 CRES, Washer NAS1587A3C, Insert MS21209F1-10L, dry film lubricated)

data := READPRN("BOLT12.txt")
s := 1..rows(data)

Flange 1: Adapter plate
Part number: SDG39135747
Material: 6061-T651

Flange 2: Still Tube
Part number: SDG39135739
Material: 7075-T7351

Loads
Applied tensile load
\[ P_s := \text{data}_{s,3}, \text{lbf} \]
\[ ID_s := \text{data}_{s,1} \]

Applied shear load
\[ V_s := \text{data}_{s,4}, \text{lbf} \]
\[ LC_s := \text{data}_{s,2} \]

Applied bending moment
\[ M_s := \text{data}_{s,5}, \text{in}-\text{lbf} \]

Factors of Safety
Ultimate \[ SF_u := 2.0 \]
Yield \[ SF_y := 1.25 \]
Assembly \[ FF := 1.15 \]

Temperature data
(Ref. Appendix C2)

Joint Separation \[ SF_{sep} := 1.2 \]

Fitting factor
Min. \[ FF := 1.15 \]
Min. \[ Temp_{min} := -50\text{deg} \]

Maximum \[ Temp_{max} := 140\text{deg} \]

Bolt and Insert Data
Nominal diameter of bolt \[ D := 0.19\text{in} \]
Number of threads/inch \[ Nt := 32, \frac{1}{\text{in}} \]

Total length of bolt \[ L := 0.713\text{in} \]
Length of insert \[ L_{\text{ins}} := 0.19\text{in} \]

Threaded length \[ L_t := 0.338\text{in} \]
Min. external diameter of insert \[ F_{\text{min}} := 0.236\text{in} \]

Depth of recess for insert \[ L_r := 0.02\text{in} \]

(IF bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\thread_data.mcd`

Washer Data
Thickness of washer \[ tw := 0.062\text{in} \]

Outer Diameter of washer \[ D_w := 0.469\text{in} \]

Inner Diameter of washer \[ D_{\text{wi}} := 0.192\text{in} \]

Bolt head dia. across flats \[ d_w := 0.335\text{in} \]

(Flange data)
Thickness of flange 1 \[ tf_1 := 0.435\text{in} \]

Thickness of flange 2 \[ tf_2 := 0.25\text{in} \]

Diameter of hole \[ D_{\text{hole}} := 0.218\text{in} \]

Note: If there is no washer, \( tw, D_w, \) and \( D_{\text{wi}} \) should be zero.
**Material Property Data**

**Bolt**

Temperature correction factor for bolt strength ultimate \( T_{Su\_bolt} := 0.98 \)  
Bolt ultimate tensile allowable stress \( F_{tu\_bolt} := 180000 \text{ psi} \)  
Bolt ultimate shear allowable stress \( F_{su\_bolt} := 0.6 \cdot F_{tu\_bolt} \)  
Bolt yield tensile allowable \( F_{ty\_bolt} := 132000 \text{ psi} \)  
Temperature correction factor for bolt modulus \( T_{E\_bolt} := 0.98 \)  

\[ \beta_{\_bolt\_hot} := 9.1 \cdot 10^{-6} \cdot \text{in} \cdot \text{in}^{-1} \cdot \text{deg} \]  

Modulus of elasticity of bolt \( E_{\_bolt} := (29.1 \cdot 10^6 \cdot \text{psi}) \)  

**Insert**

Temperature correction factor for insert strength \( T_{S\_ins} := 0.98 \)  
Ultimate tensile allowable stress \( F_{tu\_ins} := 150000 \text{ psi} \)  
Ultimate shear allowable stress \( F_{su\_ins} := 0.6 \cdot F_{tu\_ins} \)  

**Washer**

Temperature correction factor for washer modulus \( T_{E\_washer} := 0.98 \)  
Modulus of elasticity of washer \( E_{\_washer} := (29.1 \cdot 10^6 \cdot \text{psi}) \)  

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, 
Modulus of elasticity of these members, and diameters of the bolt and the washer.  

Temperature correction factor for flange 1 \( T_{1\_E} := 0.99 \) (modulus) \( T_{1\_2} := 0.96 \) (strength)  
Temperature correction factor for flange 2 \( T_{2\_E} := 0.98 \) (modulus) \( F_{su\_2} := 37000 \text{ psi} \)  
Modulus of elasticity for the parts in the joint \( E_{\_flange1} := (10.1 \cdot 10^6 \cdot \text{psi}) \) \( E_{\_flange2} := (10.6 \cdot 10^6 \cdot \text{psi}) \)  

Coefficient of thermal expansion for flanges \( \beta_{\_flange1\_hot} := 12.8 \cdot 10^{-6} \cdot \text{in} \cdot \text{in}^{-1} \cdot \text{deg} \) \( \beta_{\_flange2\_hot} := 12.6 \cdot 10^{-6} \cdot \text{in} \cdot \text{in}^{-1} \cdot \text{deg} \)  
\[ \beta_{\_flange1\_cold} := 12.2 \cdot 10^{-6} \cdot \text{in} \cdot \text{in}^{-1} \cdot \text{deg} \] \[ \beta_{\_flange2\_cold} := 12.2 \cdot 10^{-6} \cdot \text{in} \cdot \text{in}^{-1} \cdot \text{deg} \]  

**Torque/Preload data**

Maximum torque \( T_{\text{max}} := 48.257 \cdot \text{in} \cdot \text{lbf} \)  
Loading plane factor: \( n := 0.5 \)  
Minimum torque \( T_{\text{min}} := 45.844 \cdot \text{in} \cdot \text{lbf} \)  
Preload Uncertainty: \( u := 0.25 \)  
Torque coefficient: \( k := 0.15 \)
This file uses the calculations shown in  \\escfil02\2i11_mathcad8307_bolts\multi_bolt_stiffness_insert_RevA

**Bolt Load data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.204</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td></td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLDmax = 2262.4-lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLDmin = 846.1-lbf</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>max(Psep) = 1120.899-lbf</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
<td>max(Pb) = 2481.8-lbf</td>
</tr>
<tr>
<td>Max. load on the bolt(yield)</td>
<td>max(Pby) = 2399.5-lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PAt = 3395.5-lbf</td>
</tr>
</tbody>
</table>
| Preload due to temperature:  
  Pthr_pos = 145.8-lbf                           |
| Uncertainty factor:                           |
| u = 0.25                                       |
| Torque coefficient:                           |
| k = 0.15                                       |
| Loading plane factor:                         |
| n = 0.5                                        |
| Thread shear pullout load of bolt or insert:   |
| Pths = 4608.1-lbf                             |
| Thread shear pullout load in parent metal:     |
| Ppths = 2501.8-lbf                            |

Length_check = "Bolt length is sufficient"

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Margin Value</th>
<th>Description</th>
<th>MS_min Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>-0.269</td>
<td>Direct Thread shear Ultimate</td>
<td>0.165</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>0.580</td>
<td>Total Thread shear Ultimate</td>
<td>0.008</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>0.854</td>
<td>Shear Ultimate</td>
<td>4.15</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.368</td>
<td>Bending Ultimate</td>
<td>10</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.038</td>
<td>Combined shear, tension and bending ultimate</td>
<td>0.356</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

```
MSbolt := min(MS)
```

```
MSbolt = -0.269
Failure_Mode = "Joint Separation"
```

```
MS_min_ID = 30002
MS_min_LC = 1011
```

*Note: As shown in the next page, three out of twelve bolts of the bolt group have negative Margin of Safety against Joint Separation.*
## Summary of Margins for bolts:

### Load Case 1:

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>Direct Tension</th>
<th>Direct Tension</th>
<th>Total Tension</th>
<th>Total Tension</th>
<th>Direct Thread shear</th>
<th>Total Thread shear</th>
<th>Shear Ultimate</th>
<th>Ultimate</th>
<th>Ultimate</th>
<th>Ultimate</th>
<th>Ultimate</th>
<th>Ultimate</th>
<th>Ultimate</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.18</td>
<td>1.55</td>
<td>1.992</td>
<td>0.416</td>
<td>0.061</td>
<td>0.879</td>
<td>0.043</td>
<td>10.063</td>
<td>10</td>
<td>0.414</td>
<td></td>
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<tr>
<td>2</td>
<td>3.833</td>
<td>9.449</td>
<td>11.26</td>
<td>0.479</td>
<td>0.091</td>
<td>6.699</td>
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<td>37.38</td>
<td>10</td>
<td>0.479</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.269</td>
<td>0.58</td>
<td>0.854</td>
<td>0.368</td>
<td>0.038</td>
<td>0.165</td>
<td>8.08×10⁻³</td>
<td>4.151</td>
<td>10</td>
<td>0.356</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>82.611</td>
<td>179.775</td>
<td>211.086</td>
<td>0.5</td>
<td>0.1</td>
<td>132.183</td>
<td>0.105</td>
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<td>10</td>
<td>0.499</td>
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<td>5</td>
<td>1.203</td>
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<td>4.588</td>
<td>0.454</td>
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<td>15.307</td>
<td>10</td>
<td>0.454</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.137</td>
<td>0.866</td>
<td>1.189</td>
<td>0.387</td>
<td>0.047</td>
<td>0.375</td>
<td>0.022</td>
<td>41.82</td>
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<td>0.603</td>
<td>2.465</td>
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<tr>
<td>10</td>
<td>6.894</td>
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<td>0.094</td>
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</tr>
</tbody>
</table>

### Load Case 2:

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>Direct Tension</th>
<th>Direct Tension</th>
<th>Total Tension</th>
<th>Total Tension</th>
<th>Direct Thread shear</th>
<th>Total Thread shear</th>
<th>Shear Ultimate</th>
<th>Ultimate</th>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fail-safe Analysis

data_fs := READPRN("BOLT12f.txt")

s := 1..rows(data_fs)

Applied tensile load
\begin{align*}
P_{FS,s} & := \text{data}_{fs,s,3}\text{lbf} \\
\text{ID}_{FS,s} & := \text{data}_{fs,s,1}
\end{align*}

Applied shear load
\begin{align*}
V_{FS,s} & := \text{data}_{fs,s,4}\text{lbf} \\
\text{LC}_{FS,s} & := \text{data}_{fs,s,2}
\end{align*}

Applied bending moment
\begin{align*}
M_{FS,s} & := \text{data}_{fs,s,5}\text{in-lbf}
\end{align*}

Fail-safe Factors of Safety

\text{Ultimate} \quad \text{SF}_{u,FS} := 1.0

\text{Joint Separation} \quad \text{SF}_{sep,FS} := 1.0

This file uses the calculations shown in \c:\escg\02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevA

**Bolt Fail-safe Load data**

Joint separation load \( \max(P_{sep,FS}) = 1035.94 \text{lbf} \)

Max. load on the bolt (ultimate) \( \max(P_{b,FS}) = 2384 \text{lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Main Failure Mode</th>
<th>Minimum Margin of Safety</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{minFS,1,1} = -0.209 )</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{minFS,2,1} = 1.850 )</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{minFS,3,1} = 0.424 )</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{minFS,4,1} = 1.1 )</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt,FS} := \min(MS_{FS}) \)

\( MS_{bolt,FS} = -0.209 \quad \text{Failure Mode } _{FS} = \text{"Joint Separation"} \)

\( MS_{min,ID} = 30005 \)

\( MS_{min,LC} = 10011 \)

**Note:** The fail-safe does not require the Margin of Safety against Joint Separation. Therefore, the minimum Margin of Safety should be 0.049 with the failure mode of Total Thread shear Ultimate.
Bearing on Hole Wall

SDG39135747

Ref. Drg. SDG39135747

Edge distance
e := 0.5-in

Hole diameter
dh := 0.218-in

Plate thickness
.tp := 0.435-in

Bearing area
Ab := dh·tp

Nominal diameter of bolt
D = 0.19-in

e
D

= 2.632

Plate material 6061-T651, e/D=2

Allowable bearing strength
Fbru := 88·10^3·psi

Ref. MIL-HDBK-5J, Table 3.6.2.0(b2)

Load per bolt
V = ·lbf

bearing stress
=b := V

MS := − 1

Max. load per bolt
Vmax := max(V)

Max. bearing stress
=bmax := max(=b)

Margin of safety
MSmin := min(MS)

Vmax = 156.641 lbf

=bmax = 1.652 × 10^3 psi

MSmin = 24.572
Shear tear out

Shear out area: 
\[ As := 2 \left( e - \frac{dh}{2} \right) \cdot tp \quad As = 0.34 \text{ in}^2 \]

Plate material: 6061-T651

Allowable shear strength: 
\[ F_{su} := 27 \cdot 10^3 \text{ psi} \quad \text{Ref. MIL-HDBK-5J, Table 3.6.2.0(b2)} \]

Load per bolt: 
Shear tear out stress: 
\[ y_s := \frac{V}{As} \]
Margin of safety: 
\[ MS := \frac{F_{su} \cdot 0.96}{y_s S_{Fu}} - 1 \]

<table>
<thead>
<tr>
<th>1</th>
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<tbody>
<tr>
<td>1</td>
<td>72.921</td>
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<tr>
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<td>2</td>
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<tr>
<td>3</td>
<td>156.612</td>
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<td>4</td>
<td>55.82</td>
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<td>10</td>
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<td>14</td>
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<td>14</td>
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<td>15</td>
<td>112.048</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>82.899</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>23.056</td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td>72.757</td>
<td>18</td>
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<tr>
<td>19</td>
<td>73.553</td>
<td>19</td>
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<tr>
<td>20</td>
<td>107.309</td>
<td>20</td>
</tr>
<tr>
<td>21</td>
<td>95.101</td>
<td>21</td>
</tr>
<tr>
<td>22</td>
<td>116.278</td>
<td>22</td>
</tr>
<tr>
<td>23</td>
<td>109.904</td>
<td>23</td>
</tr>
<tr>
<td>24</td>
<td>156.641</td>
<td>24</td>
</tr>
</tbody>
</table>

Max. load per bolt: 
Max. shear tear out stress: 
Margin of safety: 
\[ V_{max} := \max(V) \quad y_{smax} := \max(y_s) \quad M_{smin} := \min(MS) \]
\[ V_{max} = 156.641 \text{ lbf} \quad y_{smax} = 460.477 \text{ psi} \quad M_{smin} = 27.145 \]
2.4.1.6.2  WIF Socket to WIF Adaptor Plate
WIF Socket to WIF Adapter Plate

Drawing: SDG39135747
Part number: NAS1954C6 HEX HEAD

The objective of this analysis is to demonstrate the structural strength of the fasteners connecting the WIF Socket (SEG33106860) to WIF Adapter Plate (SDG39135747). The WIF adapter plate is mounted on the sill tube to support the WIF socket. Finite element analysis of the WIF Adapter Plate was performed (see section 2.1.15).

Load

Per CARD JSC-33499, WIF Socket is subjected to 4200 in-lbf (bending moment), 4200 in-lbf (torsional moment), 274 (shear force), and 274 lbf (axial force).

Load case 1

- ID = 1001 for normal analysis
- ID = 1011 for fail-safe analysis
- Fx := 274 lbf Axial force
- Fy := 274 lbf Shear force
- Mx := 4200 in-lbf Torsion moment
- Mz := 4200 in-lbf Bending moment

Load case 2

- ID = 1002 for normal analysis
- ID = 1022 for fail-safe analysis
- Fx := 274 lbf Axial force
- Fz := 274 lbf Shear force
- Mx := 4200 in-lbf Torsion moment
- My := 4200 in-lbf Bending moment
Bolt forces were retrieved from the post-processing of FE model data:

1. Normal analysis (file name: bolt1-4.txt)

<table>
<thead>
<tr>
<th>Bolt ID</th>
<th>Element ID</th>
<th>Load Case ID</th>
<th>Tension</th>
<th>Shear</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>75</td>
<td>1001</td>
<td>328</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>87</td>
<td>1001</td>
<td>577</td>
<td>47</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>1001</td>
<td>220</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>120</td>
<td>1001</td>
<td>736</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>244</td>
<td>1001</td>
<td>646</td>
<td>103</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>286</td>
<td>1001</td>
<td>1122</td>
<td>109</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>373</td>
<td>1001</td>
<td>529</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>415</td>
<td>1001</td>
<td>1246</td>
<td>65</td>
<td>0</td>
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<tr>
<td>A</td>
<td>75</td>
<td>1002</td>
<td>553</td>
<td>175</td>
<td>0</td>
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<tr>
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<td>87</td>
<td>1002</td>
<td>390</td>
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</tr>
<tr>
<td>C</td>
<td>108</td>
<td>1002</td>
<td>407</td>
<td>246</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>120</td>
<td>1002</td>
<td>512</td>
<td>152</td>
<td>0</td>
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<tr>
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</tr>
<tr>
<td>F</td>
<td>286</td>
<td>1002</td>
<td>257</td>
<td>545</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>373</td>
<td>1002</td>
<td>336</td>
<td>586</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>415</td>
<td>1002</td>
<td>206</td>
<td>368</td>
<td>0</td>
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</table>
2. Fail-safe analysis (file name: bolt1-4f.txt)

<table>
<thead>
<tr>
<th>Bolt ID</th>
<th>Element ID</th>
<th>Load Case ID</th>
<th>Tension</th>
<th>Shear</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>1241</td>
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<tr>
<td>A</td>
<td>75</td>
<td>1022</td>
<td>545</td>
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<tr>
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<td>405</td>
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<td>1022</td>
<td>276</td>
<td>549</td>
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<td>373</td>
<td>1022</td>
<td>298</td>
<td>675</td>
<td>0</td>
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</table>

In the fail safe analysis, one critical fastener is removed.
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KC San</td>
<td>06/22/05</td>
<td>WIF socket to plate</td>
</tr>
</tbody>
</table>

**Title**

WIF Socket to WIF Adapter Plate

**CHECK BOLTS (NAS1954C6 HEX Head Screw, Material A286 CRES, Washer NAS1587-4C, Insert MS21209F4-15, dry film lubricated)**

```plaintext
data := READPRN("bolt1-4.txt")
s := 1..rows(data)
```

**Flange 1**
- Part name: WIF Adapter Plate
- Part number: SDG39135747
- Material: AL 6061-T651

**Flange 2**
- Part name: Side Mounted Passive WIF
- Part number: SEG33106860
- Material: AL 7075-T7351

**Loads**
- **Applied tensile load**
  - $P_s := data_{s, 3} \text{ lbf}$
  - $ID_s := data_{s, 1}$
- **Applied shear load**
  - $V_s := data_{s, 4} \text{ lbf}$
  - $LC_s := data_{s, 2}$
- **Applied bending moment**
  - $M_s := data_{s, 5} \text{ in}-\text{lbf}$

**Factors of Safety**
- **Ultimate** $SF_u := 2.0$
- **Yield** $SF_y := 1.25$
- **Assembly**
  - Temp_initial := 70-deg
- **Joint Separation** $SF_{sep} := 1.2$
- **Fitting factor** $FF := 1.15$
- **Maximum**
  - Temp_max := 140-deg
- **Minimum**
  - Temp_min := -50-deg

**Bolt and Insert Data**
- Nominal diameter of bolt $D := 0.250\text{ in}$
- Number of threads/inch $Nt := 28\frac{1}{4}\text{ in}$
- Total length of bolt $L := 0.8\text{ in}$
- Length of insert $Lins := 0.375\text{ in}$
- Threaded length $Lt := 0.425\text{ in}$
- Min. external diameter of insert $Fmin := 0.306\text{ in}$
- (If bolt is fully threaded, input $Lt = L$)

**Washer Data**
- Thickness of washer $tw := 0.078\text{ in}$
- Outer Diameter of washer $Dw := 0.531\text{ in}$
- Inner Diameter of washer $Dwi := 0.252\text{ in}$
- Bolt head dia. across flats $dw := 0.398\text{ in}$

**Flange data**
- Thickness of flange 1 $tf1 := 0.375\text{ in}$
- Thickness of flange 2 $tf2 := 0.375\text{ in}$
- Diameter of hole $D_{\text{hole}} := 0.281\text{ in}$

Note: If there is no washer, $tw$, $Dw$, and $Dwi$ should be zero.

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\thread_data.mcd`
Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate
TSu_bolt := 0.98 \quad \text{yield} \quad TSy_bolt := 0.98

Bolt ultimate tensile allowable stress
Ftu_bolt := 180000-psi

Bolt ultimate shear allowable stress
Fsu_bolt := 0.6-Ftu_bolt

Bolt yield tensile allowable
Fty_bolt := 132000-psi

Temperature correction factor for bolt modulus
TE_bolt := 0.98 \quad \beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \text{in} \cdot \text{in}^{-1} \text{deg}^{-1}

Modulus of elasticity of bolt
E_bolt := \left(29.1 \times 10^6 \text{psi}\right)

Thermal coefficient for bolt:

Insert
Temperature correction factor for insert strength
TS_ins := 0.98

Ultimate tensile allowable stress
Ftu_ins := 150000-psi

Ultimate shear allowable stress
Fsu_ins := 0.6-Ftu_ins

Washer
Temperature correction factor for washer modulus
TE_washer := 0.98

Modulus of elasticity of washer
E_washer := \left(29.1 \times 10^6 \text{psi}\right)

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
Tf1E := 0.99 (modulus) \quad Tf2s := 0.96 \quad \text{(strength)}

Temperature correction factor for flange 2
Tf2E := 0.98 (modulus) \quad Fsu_f2 := 39000-psi

Modulus of elasticity for the parts in the joint
E_flange1 := \left(10.1 \times 10^6 \text{psi}\right) \quad E_flange2 := \left(10.6 \times 10^6 \text{psi}\right)

Coefficient of thermal expansion for flanges
\beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \text{in} \cdot \text{in}^{-1} \text{deg}^{-1} \quad \beta_{\text{flange2\_hot}} := 12.6 \times 10^{-6} \text{in} \cdot \text{in}^{-1} \text{deg}^{-1}

\beta_{\text{flange1\_cold}} := 12.2 \times 10^{-6} \text{in} \cdot \text{in}^{-1} \text{deg}^{-1} \quad \beta_{\text{flange2\_cold}} := 12.2 \times 10^{-6} \text{in} \cdot \text{in}^{-1} \text{deg}^{-1}

Torque/Preload data
Maximum torque
Tmax := 121.521-\text{in-lbf} \quad \text{Loading plane factor:} \quad n := 0.5

Minimum torque
Tmin := 115.445-\text{in-lbf} \quad \text{Preload Uncertainty:} \quad u := 0.25

Torque coefficient:
k := 0.15
This file uses the calculations shown in `\escfil02\211_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevA`.

### Bolt Load data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.278</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td>Pthr_pos = 249.2 lbf</td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLDmax = 4299.9 lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLDmin = 1667.8 lbf</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>max(Psep) = 1494.83 lbf</td>
</tr>
<tr>
<td>Uncertainty factor</td>
<td>u = 0.25</td>
</tr>
<tr>
<td>Max. load on the bolt (ultimate)</td>
<td>max(Pb) = 4698.1 lbf</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>n = 0.5</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>max(Pby) = 4548.8 lbf</td>
</tr>
<tr>
<td>Thread shear pullout load in parent metal</td>
<td>Pths = 10274.9 lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PAt = 6223.9 lbf</td>
</tr>
<tr>
<td>Thread shear pullout load of bolt or insert</td>
<td>Ppths = 6748.5 lbf</td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"

### Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_min 1, 1 = 0.127</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_min 6, 1 = 1.355</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_min 2, 1 = 1.172</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS_min 7, 1 = 0.436</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS_min 3, 1 = 1.549</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS_min 8, 1 = 1.56</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_min 4, 1 = 0.325</td>
</tr>
<tr>
<td>MS_min 9, 1 = 10</td>
<td></td>
</tr>
<tr>
<td>MS_min 5, 1 = 0.003</td>
<td></td>
</tr>
<tr>
<td>MS_min 10, 1 = 0.313</td>
<td></td>
</tr>
</tbody>
</table>

### Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MSbolt} := \min(\text{MS}) \]

\[ \text{MSbolt} = 0.003 \]

Failure Mode = "Total Tension Yield"

\[ \text{MS_min_ID} = 415 \]

\[ \text{MS_min_LC} = 1001 \]
Fail-safe Analysis

data_fs := READPRN("bolt1-4f.txt")

s := 1..rows(data_fs)

<table>
<thead>
<tr>
<th>Applied load</th>
<th>ID FS</th>
<th>( s ), lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>ID FS</td>
<td>( s ), lbf</td>
</tr>
<tr>
<td>Shear</td>
<td>LC FS</td>
<td>( s ), lbf</td>
</tr>
<tr>
<td>Bending</td>
<td>M FS</td>
<td>( s ), in-lbf</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

- **Ultimate**
  - \( P_{FS} \) = \( s \), lbf
  - \( V_{FS} \) = \( s \), lbf
  - \( M_{FS} \) = \( s \), in-lbf

**Joint Separation**

- \( SF_{sep-FS} := 1.0 \)

This file uses the calculations shown in `\escfl02\211\_mathcad\8307\_bolts\multi\_bolt\_stiffness\_insert\_FS\_RevA`

**Bolt Fail-safe Load data**

- **Joint separation load**  \( \max(P_{sep-FS}) = 2305.979 \text{ lbf} \)
- **Max. load on the bolt (ultimate)**  \( \max(P_{b-FS}) = 4668.5 \text{ lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>MS_minFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( 1, 1 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( 2, 1 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( 3, 1 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( 4, 1 )</td>
</tr>
<tr>
<td>Combined shear, tension and</td>
<td>( 8, 1 )</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( 6, 1 )</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( 5, 1 )</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[
MS_{bolt-FS} = \min(\{MS_{FS}\})
\]

\[
MS_{bolt-FS} = -0.270 \quad \text{Failure Mode}_{FS} = "\text{Joint Separation}" \\
MS_{\text{min ID}} = 120 \\
MS_{\text{min LC}} = 1011
\]

**Note:** The fail-safe does not require the Margin of Safety against Joint Separation. Therefore, the minimum Margin of Safety should be 0.333 with the failure mode of Total Tension Ultimate.
**Bearing on Hole Wall**  
SDG39135747

**Edge distance**  
\( e := 0.562 \text{-in} \)  
Ref. Drg. SDG39135747

**Hole diameter**  
\( d_h := 0.281 \text{-in} \)

**Plate thickness**  
\( t_p := 0.375 \text{-in} \)

**Bearing area**  
\( A_b := d_h t_p \)  
\( A_b = 0.105 \text{-in}^2 \)

**Nominal diameter of bolt**  
\( D := 0.250 \text{-in} \)  
\( \frac{e}{D} = 2.248 \)

**Plate material 6061-T651, e/D=2**

**Allowable bearing strength**  
\( F_{bru} := 8.8 \times 10^3 \text{-psi} \)  
Ref. MIL-HDBK-5J, Table 3.6.2.0(b2)

**bearing stress**  
\[ b := \frac{V}{A_b} \]

**load per bolt**  
**b**  
**V**  
\( V = \text{lb}f \)

**Max. load per bolt**  
\( V_{\text{max}} := \max(V) \)

**Max. bearing stress**  
\( b_{\text{max}} := \max(b) \)

**Margin of safety**  
\( MS : = \frac{F_{bru} \cdot 0.96}{b \cdot S_Fu} - 1 \)

<table>
<thead>
<tr>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>459.5</td>
<td>90.93</td>
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<td>94.623</td>
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<tr>
<td>3</td>
<td>265.7</td>
<td>157.988</td>
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<tr>
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<tr>
<td>6</td>
<td>1031.3</td>
<td>39.96</td>
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<td>7</td>
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<td>64.726</td>
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<td>17.107</td>
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<td>28.201</td>
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<td>9.942</td>
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<tr>
<td>14</td>
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<td>7.173</td>
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<tr>
<td>15</td>
<td>5558.1</td>
<td>6.6</td>
</tr>
<tr>
<td>16</td>
<td>3492.8</td>
<td>11.093</td>
</tr>
</tbody>
</table>

**Vmax = 585.686 lbf**  
\( V_{\text{max}} = 585.686 \text{ lb}f \)

**bmax = \( 5.558 \times 10^3 \text{ psi} \)**  
\( b_{\text{max}} = 5.558 \times 10^3 \text{ psi} \)

**MSmin = 6.6**
### Shear tear out

**Shear out area**
\[ A_s := 2 \left( e - \frac{dh}{2} \right) \cdot tp \quad A_s = 0.316 \text{ in}^2 \]

**Plate material** 6061-T651

**Allowable shear strength**
\[ F_{su} := 27 \times 10^3 \text{ psi} \quad \text{Ref. MIL-HDBK-5H, Table 3.6.2.0(b2)} \]

<table>
<thead>
<tr>
<th>V (lbf)</th>
<th>[ \frac{V}{As} ]</th>
<th>ys (psi)</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>84.418</td>
<td>153.2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>46.548</td>
<td>147.2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>27.996</td>
<td>88.6</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>31.783</td>
<td>100.5</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>102.723</td>
<td>324.9</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>108.668</td>
<td>343.8</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>67.721</td>
<td>214.2</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>64.55</td>
<td>204.2</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>175.131</td>
<td>554</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>224.938</td>
<td>711.5</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>245.814</td>
<td>777.6</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>152.43</td>
<td>482.2</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>406.787</td>
<td>1286.8</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>544.634</td>
<td>1722.8</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>585.686</td>
<td>1852.7</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>368.052</td>
<td>1164.3</td>
<td>16</td>
</tr>
</tbody>
</table>

**Max. load per bolt**
\[ V_{max} := \max(V) \]

**Max. shear tear out stress**
\[ y_{s max} := \max(ys) \]

**Margin of safety**
\[ MS_{min} := \min(MS) \]

Max. load per bolt: \[ V_{max} = 585.686 \text{ lbf} \]
Max. shear tear out stress: \[ y_{s max} = 1.853 \times 10^3 \text{ psi} \]
Margin of safety: \[ MS_{min} = 5.995 \]
2.4.1.7 Bushing Plate to Upper and Lower USS-02 Vacuum Case Joint
Bolts from Bushing Plate to Vacuum Case Joint

The USS Vacuum Case Joints are connected to the Interface Plates with a combination of fasteners and shear pins. Each Joint has one shear pin. The shear pin is prevented from backing out of the joint by the Bushing plate. The Bushing plate is held in place with two .086-56 screws. This is shown in the figure below.

Loading on the screws will come from inertial loading of the plate. We'll use simplified design options which means we'll use 40g as the inertial load.

\[ LF := 40 \text{ g} \]

Since there is also a shim (SDG39135751), we'll use the mass of both the plate and the shim to calculate the resultant load.

Shim is shown here:

dia := .875-in
ts := .125-in
Bushing Plate is shown in the figure to the right

Plate dimensions are:

\[ \text{Lp} := 2.407\text{-in} \]
\[ \text{Wp} := 0.376\text{-in} \]
\[ \text{Tp} := 0.125\text{-in} \]

Volume of plate and shim is therefore:

\[ V := \text{Lp} \times \text{Wp} \times \text{Tp} + \pi \left( \frac{\text{dia}}{2} \right)^2 \times \text{ts} \]

\[ V = 0.188\text{in}^3 \]

Plate is made of 6061-T651 aluminium. Use density as:

\[ \omega := 0.098 \frac{\text{lb}}{\text{in}^3} \]

this gives the mass of the plate as:

\[ W := V \times \omega \]

\[ W = 0.018\text{lb} \]

\[ P := W \times \text{LF} \]

\[ P = 0.738\text{lbf} \]

Assume that the plate sees this load in two directions simultaneously

\[ V := P \]
CHECK BOLTS (NAS1352N02-6 bolts 0.086-56UNJC-3A, Material-A-286), Insert MS21209C0220L, Washer NAS1149EN232R

Flange 1: Bushing Plate
Part number: SDG39135749-001
Material: 6061-T651

Flange 2: Vacuum Case Joint
Part number: SEG39135737
Material: 7050-T7451

Loads - loads model 0602
Applied tensile load \( P = 0.738 \text{ lbf} \)
Applied shear load \( V = 0.738 \text{ lbf} \)
Applied bending moment \( M := 0 \text{ in-lbf} \)

Factors of Safety

<table>
<thead>
<tr>
<th></th>
<th>Ultimate</th>
<th>SFu := 1.4</th>
<th>Yield</th>
<th>SFy := 1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>SFsep := 1.2</td>
<td>Fitting factor</td>
<td>FF := 1.15</td>
<td></td>
</tr>
</tbody>
</table>

Temperature data

<table>
<thead>
<tr>
<th></th>
<th>Assembly</th>
<th>Temp_initial := 70-deg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Temp_max := 70-deg</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>Temp_min := 70-deg</td>
</tr>
</tbody>
</table>

Bolt and Insert Data

<table>
<thead>
<tr>
<th></th>
<th>D := 0.086-in</th>
<th>Number of threads/inch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L := .375-in</td>
<td>Lins := 0.172-in</td>
</tr>
<tr>
<td>Threaded length</td>
<td>Lt := 0.375-in</td>
<td>Fmin := 0.110-in</td>
</tr>
<tr>
<td>(If bolt is fully threaded, input Lt = L)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \lesc\fil02\2ii11\mathcad\8307_bolts\thread_data.mcd

Washer Data

<table>
<thead>
<tr>
<th></th>
<th>tw := 0.032-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := .250-in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.099-in</td>
</tr>
</tbody>
</table>

Bolt head dia. across flats \( dw := 0.134 \text{ in} \) (used only if there is no washer)

Note: If there is no washer, \( tw, Dw, \) and \( Dwi \) should be zero.
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate \( \text{T_SU_{bolt}} := 1.0 \quad \text{yield} \quad \text{T_SY_{bolt}} := 1.0 \)

Bolt ultimate tensile allowable stress \( \text{Ftu_{bolt}} := 160000\text{-psi} \)

Bolt ultimate shear allowable stress \( \text{Fsu_{bolt}} := 0.6 \cdot \text{Ftu_{bolt}} \)

Bolt yield tensile allowable \( \text{Fty_{bolt}} := 120000\text{-psi} \)

Temperature correction factor for bolt modulus \( \text{TE_{bolt}} := 1.0 \)

Modulus of elasticity of bolt \( \text{E_{bolt}} := \left(29.1 \cdot 10^6\text{-psi}\right) \)

Thermal coefficient for bolt:

\[ \alpha_{\text{bolt\_hot}} := 8.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

\[ \alpha_{\text{bolt\_cold}} := 8.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Insert

Temperature correction factor for insert strength \( \text{TS_{ins}} := 1.0 \)

Ultimate tensile allowable stress \( \text{Ftu_{ins}} := 140000\text{-psi} \)

Ultimate shear allowable stress \( \text{Fsu_{ins}} := 0.6 \cdot \text{Ftu_{ins}} \)

Washer

Temperature correction factor for washer modulus \( \text{TE_{washer}} := 1.0 \)

Modulus of elasticity of washer \( \text{E_{washer}} := \left(29.1 \cdot 10^6\text{-psi}\right) \)

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( \text{Tf1E} := 1.0 \) (modulus) \( \text{Tf2s} := 1.0 \) (strength)

Temperature correction factor for flange 2 \( \text{Tf2E} := 1.0 \) (modulus) \( \text{Fsu_{f2}} := 46000\text{-psi} \)

Modulus of elasticity for the parts in the joint \( \text{E_{flange1}} := \left(9.9 \cdot 10^6\text{-psi}\right) \)
\( \text{E_{flange2}} := \left(10.3 \cdot 10^6\text{-psi}\right) \)

Coefficient of thermal expansion for flanges \( \alpha_{\text{flange1\_hot}} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)
\( \alpha_{\text{flange2\_hot}} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

\( \alpha_{\text{flange1\_cold}} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)
\( \alpha_{\text{flange2\_cold}} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

Torque/Preload data

Maximum torque (63% of yield) \( \text{T_{max}} := 3.6\text{-in\.-lb} \)
Loading plane factor: \( \text{n} := 0.5 \)

Minimum torque (85% of max. torque) \( \text{T_{min}} := 3.1\text{-in\.-lb} \)
Preload Uncertainty: \( \Gamma := 0.25 \)

Torque coefficient: \( k := 0.15 \)

2.4.1.7-5
Bolts from Bushing Plate to Vacuum Case Joint

This file uses the calculations shown in \escfll0\escfl1\mathcad\8307\bolts\bolt_stiffness_insert_RevC

Mon Feb 14 12:49:24 2005

**Bolt Load data**

- Bolt/joint stiffness factor: \(\phi = 0.123\)
- Preload due to temperature
- Max. preload: \(PLD_{\text{max}} = 348.8\text{ lbf}\)
- Min. preload: \(PLD_{\text{min}} = 162.8\text{ lbf}\)
- Joint separation load: \(P_{\text{sep}} = 0.886\text{ lbf}\)
- Max. load on the bolt (ultimate): \(P_{\text{b}} = 348.9\text{ lbf}\)
- Max. load on the bolt (yield): \(P_{\text{by}} = 348.9\text{ lbf}\)
- Bolt ultimate tensile strength: \(P_{\text{At}} = 556.6\text{ lbf}\)

- Torque coefficient: \(k = 0.15\)
- Loading plane factor: \(n = 0.5\)
- Thread shear pullout load of bolt or insert: \(P_{\text{ths}} = 1943.7\text{ lbf}\)
- Thread shear pullout load in parent metal: \(P_{\text{pths}} = 1367.1\text{ lbf}\)

Length check = "Bolt length is sufficient"

**Summary of Margins for bolt:**

- Joint separation: \(MS_1 = 169.308\)
- Direct Thread shear Ultimate: \(MS_6 = 1.15 \times 10^{3}\)
- Direct Tension Ultimate: \(MS_2 = 467.35\)
- Total Thread shear Ultimate: \(MS_7 = 2.9182\)
- Direct Tension Yield: \(MS_3 = 446.06\)
- Shear Ultimate: \(MS_8 = 249.25\)
- Total Tension Ultimate: \(MS_4 = 0.6\)
- Bending Ultimate: \(MS_9 = 10\)
- Total Tension Yield: \(MS_5 = 0.196\)
- Combined shear, tension and bending ultimate: \(MS_{10} = 0.595\)

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

\[ MS_{\text{bolt}} := \min(\{MS\}) \]

\[ MS_{\text{bolt}} = 0.196 \quad \text{Failure Mode = "Total Tension Yield"} \]
Fail-safe Analysis
Assume one of the two fasteners have failed.

The remaining fastener must take the increased load (i.e., \(2P\) and \(2V\)), but must also help couple out the moment caused by the c.g. offset from the remaining fastener.

Assume this moment is coupled out in contact with the Sill Joint. This is shown in the adjacent figure.

\[ l_2 = 1.2035\text{-in} \quad l_3 = .188\text{-in} \]

Fail-safe Loads
- **Applied tensile load**
  \[ P_{FS} := P + \frac{P \cdot l_2}{l_3} \]
  \[ P_{FS} = 5.463\text{lbf} \]
- **Applied shear load**
  \[ V_{FS} := 2\cdot V \]
- **Applied bending moment**
  \[ M_{FS} := 0\cdot \text{in-lbf} \]

Fail-safe Factors of Safety
- **Ultimate**
  \[ SF_{u,FS} := 1.0 \]
- **Joint Separation**
  \[ SF_{sep,FS} := 1.0 \]

Bolt Fail-safe Load data
- **Joint separation load**
  \[ P_{sep,FS} = 5.463\text{lbf} \]
- **Max. load on the bolt (ultimate)**
  \[ P_{b,FS} = 349.2\text{lbf} \]

Summary of fail-safe Margins for bolt:
- **Joint separation**
  \[ MS_{FS_1} = 26.61 \]
- **Total Thread shear Ultimate**
  \[ MS_{FS_5} = 2.91 \]
- **Direct Tension Ultimate**
  \[ MS_{FS_2} = 87.59 \]
- **Shear Ultimate**
  \[ MS_{FS_6} = 174.17 \]
- **Total Tension Ultimate**
  \[ MS_{FS_3} = 0.59 \]
- **Bending Ultimate**
  \[ MS_{FS_7} = 10 \]
- **Direct Thread shear Ultimate**
  \[ MS_{FS_4} = 216.6 \]
- **Combined shear, tension and bending ultimate**
  \[ MS_{FS_8} = 0.59 \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt,FS} := \min(MS_{FS}) \]

\[ MS_{bolt,FS} = 0.59 \]

**Failure Mode** FS = "Combined Shear Tension Bending Ultimate"
2.4.1.8  Sill Plate to USS-02 Sill Joint
The Sill Plate is used as a cover to prevent backout of the Sill Pins; thus, there are 4 total plates. Each plate is held in place with 2 .112-40 flat head screws which go into inserts in the Sill Joint.

The Plate with its position in the USS assembly is shown below.

Loading on the screws will come from inertial loading of the plate. We'll use simplified design options which means we'll use 40g as the inertial load.

LF := 40-g
Plate is shown in the figure below.

Plate dimensions are:

\[ L_p := 1.98 \text{-in} \]
\[ W_p := 0.855 \text{-in} \]
\[ T_p := 0.125 \text{-in} \]

Volume of plate is therefore:

\[ V := L_p \cdot W_p \cdot T_p \quad V = 0.212 \text{in}^3 \]

Plate is made of 6061-T651 aluminium. Use density as:

\[ \rho := 0.098 \frac{\text{lb}}{\text{in}^3} \]

this gives the mass of the plate as:

\[ W := V \cdot \rho \quad W = 0.021 \text{lb} \]

\[ P := W \cdot LF \quad P = 0.83 \text{lbf} \]

Assume that the plate sees this load in two directions simultaneously

\[ V := P \]
CHECK BOLTS (NAS1102E04-6 bolts 0.112-40UNJC-3A, Material-A-286), Insert MS51830CA102L

Flange 1: Sill Plate  
Part number: SDG39135733  
Material: 6061-T651

Flange 2: Sill Joint  
Part number: SEG39135730  
Material: 7075-T7451

Loads - loads model 0602
Applied tensile load \( P = 0.83 \text{ lbf} \)
Applied shear load \( V = 0.83 \text{ lbf} \)
Applied bending moment \( M = 0 \text{-in-lbf} \)

Factors of Safety
Ultimate \( SF_u = 1.4 \)
Yield \( SF_y = 1.1 \)
Joint Separation \( SF_{sep} = 1.2 \)
Fitting factor \( FF = 1.15 \)

Temperature data
Assembly \( Temp_{initial} = 70 \text{-deg} \)
Maximum \( Temp_{max} = 70 \text{-deg} \)
Minimum \( Temp_{min} = 70 \text{-deg} \)

Bolt and Insert Data
Nominal diameter of bolt \( D = 0.112 \text{-in} \)
Number of threads/inch \( N_t = 40 \frac{-1}{\text{in}} \)
Total length of bolt \( L = 0.375 \text{-in} \)
Length of insert \( L_{ins} = 0.170 \text{-in} \)
Threaded length \( L_t = 0.317 \text{-in} \)
Min. external diameter of insert \( F_{min} = 0.134 \text{-in} \)
Depth of recess for insert \( l_r = 0.02 \text{-in} \)

This file uses the calculations shown in \escfil02\l11_mathcad8307_bolts\thread_data.mcd

Tue Feb 15 10:38:17 AM 2005

Washer Data
Thickness of washer \( t_w = 0.0 \text{-in} \)
Outer Diameter of washer \( D_w = 0.0 \text{in} \)
Inner Diameter of washer \( D_{wi} = 0.0 \text{-in} \)
Bolt head dia. across flats \( d_w = 0.177 \text{-in} \)

Flange data
Thickness of flange 1 \( t_{fl} = 0.125 \text{-in} \)
Thickness of flange 2 \( t_{f2} = 0.170 \text{-in} \)
Diameter of hole \( D_{hole} = 0.140 \text{-in} \)
(used only if there is no washer)

Note: If there is no washer, \( t_w, D_w, \) and \( D_{wi} \) should be zero.
Bolts from Sill Plate to Sill Joint

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate

\[ T_{Su\_bolt} := 1.0 \quad \text{yield} \quad T_{Sy\_bolt} := 1.0 \]

Bolt ultimate tensile allowable stress

\[ F_{tu\_bolt} := 160000\text{-psi} \]

Bolt ultimate shear allowable stress

\[ F_{su\_bolt} := 0.6 \cdot F_{tu\_bolt} \]

Bolt yield tensile allowable

\[ F_{ty\_bolt} := 120000\text{-psi} \]

Temperature correction factor for bolt modulus

\[ T_{E\_bolt} := 1.0 \]

\[ \alpha_{\text{bolt\_hot}} := 8.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

\[ \alpha_{\text{bolt\_cold}} := 8.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Modulus of elasticity of bolt

\[ E_{\text{bolt}} := \left(29.1 \cdot 10^6\text{-psi}\right) \]

Thermal coefficient for bolt:

Insert

Temperature correction factor for insert strength

\[ T_{S\_ins} := 1.0 \]

Ultimate tensile allowable stress

\[ F_{tu\_ins} := 140000\text{-psi} \]

Ultimate shear allowable stress

\[ F_{su\_ins} := 0.6 \cdot F_{tu\_ins} \]

Washer

Temperature correction factor for washer modulus

\[ T_{E\_washer} := 1.0 \]

Modulus of elasticity of washer

\[ E_{\text{washer}} := \left(29.1 \cdot 10^6\text{-psi}\right) \]

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1\_E} := 1.0 \quad \text{(modulus)} \quad T_{f1\_s} := 1.0 \quad \text{(strength)} \]

Temperature correction factor for flange 2

\[ T_{f2\_E} := 1.0 \quad \text{(modulus)} \quad F_{s1\_f2} := 44000\text{-psi} \]

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange}1} := \left(10.3 \cdot 10^6\text{-psi}\right) \quad E_{\text{flange}2} := \left(10.3 \cdot 10^6\text{-psi}\right) \]

Coefficient of thermal expansion for flanges

\[ \alpha_{\text{flange}1\_hot} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \quad \alpha_{\text{flange}2\_hot} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

\[ \alpha_{\text{flange}1\_cold} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \quad \alpha_{\text{flange}2\_cold} := 12.6 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data

Maximum torque (69% of yield)

\[ T_{\text{max}} := 7.9\text{-in-lbf} \]

Loading plane factor:

\[ n := .5 \]

Minimum torque (85% of max. torque)

\[ T_{\text{min}} := 6.7\text{-in-lbf} \]

Preload Uncertainty:

\[ \Gamma := 0.25 \]

Torque coefficient:

\[ k := 0.15 \]
Bolt Load data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>$\phi = 0.41$</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td>$P_{thr_pos} = 0$ lbf</td>
</tr>
<tr>
<td>Max. preload</td>
<td>$PLD_{max} = 587.8$ lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>$PLD_{min} = 269.7$ lbf</td>
</tr>
<tr>
<td>Uncertainty factor</td>
<td>$\Gamma = 0.25$</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>$P_{sep} = 0.995$ lbf</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>$k = 0.15$</td>
</tr>
<tr>
<td>Max. load on the bolt (ultimate)</td>
<td>$P_b = 588.1$ lbf</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>$n = 0.5$</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>$P_{by} = 588$ lbf</td>
</tr>
<tr>
<td>Thread shear pullout load of bolt or insert</td>
<td>$P_{ths} = 2907.3$ lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$P_{At} = 910.7$ lbf</td>
</tr>
<tr>
<td>Thread shear pullout load in parent metal</td>
<td>$P_{pths} = 1574.4$ lbf</td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_1 = 295.350$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$MS_6 = 1.18 \times 10^3$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_2 = 680.92$</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>$MS_7 = 1.6773$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_3 = 649.92$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$MS_8 = 356.03$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_4 = 0.55$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_9 = 10$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_5 = 0.162$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_{10} = 0.549$</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

$$MS_{bolt} = \min(MS)$$

$$MS_{bolt} = 0.162$$

Failure Mode = "Total Tension Yield"
Fail-safe Analysis

Assume one of the two fasteners have failed.

The remaining fastener must take the increased load (i.e., 2*P and 2*V), but must also help couple out the moment caused by the c.g. offset from the remaining fastener.

Assume this moment is coupled out in contact with the Sill Joint. This is shown in the adjacent figure.

\[
I_2 := 0.99 \text{ in} \quad I_3 := 0.275 \text{ in}
\]

Fail-safe Loads

Applied tensile load \[ P_{FS} := P + P \cdot \frac{I_2}{I_3} \quad P_{FS} = 3.816 \text{lbf} \]

Applied shear load \[ V_{FS} := 2 \cdot V \]

Applied bending moment \[ M_{FS} := 0 \text{-in-lbf} \]

Fail-safe Factors of Safety

Ultimate \[ SFu_{FS} := 1.0 \]
Joint Separation \[ SFsep_{FS} := 1.0 \]

This file uses the calculations shown in \escf021211_mathcad\8307_bolts\bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

Joint separation load \[ P_{sep_{FS}} = 3.816 \text{lbf} \]
Max. load on the bolt(ultimate) \[ P_b_{FS} = 588.7 \text{lbf} \]

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Condition</th>
<th>MS_FS</th>
<th>Total Thread shear Ultimate</th>
<th>MS_FS</th>
<th>Shear Ultimate</th>
<th>MS_FS</th>
<th>Bending Ultimate</th>
<th>MS_FS</th>
<th>Combined shear, tension and bending ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>76.31</td>
<td>MS_FS_1 = 206.54</td>
<td>1.67</td>
<td>MS_FS_2 = 248.92</td>
<td>10</td>
<td>MS_FS_3 = 0.55</td>
<td>0.55</td>
<td>MS_FS_4 = 357.79</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>357.79</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bbolt_{FS}} := \min(\text{MS_FS}) \]

\[ MS_{bolt_{FS}} = 0.55 \quad \text{Failure Mode}_{FS} = "\text{Combined Shear Tension Bending Ultimate"} \]

2.4.1.8-7
2.4.2 Lower USS-02 Bolted Interfaces
Lower USS-02 Bolted Interfaces

The Lower USS-02 Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>2.4.2.1</th>
<th>Lower USS to Upper USS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.2.1</td>
<td>Lower USS to Upper USS Fail-Safe</td>
</tr>
<tr>
<td>2.4.2.1</td>
<td>Lower USS to Upper USS Fail-Safe (Shear Pin Failure)</td>
</tr>
<tr>
<td>2.4.2.2</td>
<td>Lower Angle Beam Flange to Centerbody Box Joint</td>
</tr>
<tr>
<td>2.4.2.2</td>
<td>Lower Angle Beam Flange to Centerbody Box Joint Fail-Safe</td>
</tr>
</tbody>
</table>
2.4.2.1 Lower USS to Upper USS
Lower USS-02 to Upper USS-02 Bolt Analysis

The USS-02 assembly consists of four Lower Vacuum Case (VC) Joints. There are a total of 8 fasteners attaching the Lower USS-02 joint to the Lower Vacuum Case joint. The fasteners are NAS1958C (180 ksi), 0.50-20 UNFJ. There is also one shear pin 0.875" in diameter. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

**Bolt Geometry**

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
</tbody>
</table>

bolt :=

\[
i := 1..\text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{i, 1}^\text{2} \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{i, 1} \text{in} \quad \text{bolt diameter}
\]

**Tensile Area of bolt**

\[
A_{t_i} := \beta \left( \frac{D_i - 0.9743 \frac{1}{N_i}}{2} \right)^2
\]

**Shear Area of bolt**

\[
A_{s_i} := \beta \left( \frac{D_i - 1.299038 \frac{1}{N_i}}{2} \right)^2
\]
Bolts from Lower USS-02 to Upper USS-02

Lower VC Joint to Lower/Upper USS-02 Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-2.75</td>
<td>2.50</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>2.50</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>2.75</td>
<td>2.50</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>2.75</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>2.75</td>
<td>-2.75</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.75</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.75</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>2.75</td>
<td>-2.75</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
\text{xf} := 0.0 \text{in} \quad \text{yf} := 0.0 \text{in} \quad \text{zf} := 0.0 \text{in}
\]

\[
\text{cgload} := \begin{pmatrix} \text{xf} \\ \text{yf} \\ \text{zf} \end{pmatrix} \quad \text{cgload} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}
\]
Center of gravity of bolt group

\[ x_{cg} := \frac{\sum_{i} x_i}{\text{rows}(x)} \quad x_{cg} = 0 \text{ in} \]

\[ y_{cg} := \frac{\sum_{i} y_i}{\text{rows}(y)} \quad y_{cg} = 0 \text{ in} \]

\[ z_{cg} := \frac{\sum_{i} z_i}{\text{rows}(z)} \quad z_{cg} = -0.094 \text{ in} \]

\[ c\_\text{bolt} := \begin{pmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{pmatrix} \quad c\_\text{bolt} = \begin{pmatrix} 0 \\ 0 \\ -0.094 \end{pmatrix} \text{ in} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis with a zero offset from the center of gravity. However, in the z direction the bolt pattern is unsymmetric and has a .094" offset from the center of gravity.

Load Vector

\[ r_{\text{load}} := c\_\text{load} - c\_\text{bolt} \]

\[ r_{\text{load}} = \begin{pmatrix} 0 \\ 0 \\ 0.094 \end{pmatrix} \text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_i := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2} \]

\[ r = \begin{pmatrix} 3.780 \\ 2.594 \\ 3.780 \\ 2.752 \\ 2.752 \\ 3.823 \\ 2.656 \\ 3.823 \end{pmatrix} \text{ in} \]

Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each Lower USS-02 joint was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 66041, 66042, 66043, and 66044. These loads are read into an array and distributed out to the 8 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The nominal landing cases combined with nominal landing temperature data resulted in the lowest minimum margins of safety. Therefore, the nominal landing cases are used in this analysis.)

Reading database file for bolted joint, nominal landing case

\[ \text{data} := \text{READPRN}("\text{lowerussvcf_r2_nomland.txt}" \) \]

\[ j := 1..\text{rows(data)} \]

\[ \text{num_bolts} := \text{rows(bolt)} \]
Loads from 2-04 loads model, nominal landing case

Axial Load \( F_x := \text{data}_{j, 3} \cdot \text{lb} \)  
Shear in Y axis \( F_y := \text{data}_{j, 4} \cdot \text{lb} \)  
Shear in Z axis \( F_z := \text{data}_{j, 5} \cdot \text{lb} \)  
Element Identification \( \text{ID}_j := \text{data}_{j, 1} \)  
Load Case Number \( \text{LC}_j := \text{data}_{j, 2} \)  

Applied Bending Moment at Bolts \( M_{ij} := 0 \cdot \text{in-lb} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 66041, 66042, 66043, and 66044, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66041 will have bolt numbers 1 thru 8 attached to the end for all 64 load cases. This brings the total number of load cases to 2048 (4 joints x 8 bolts x 64 load cases = 2048). See the array example to the right.

\[
\text{ID} := \text{stack(} \text{ID}, \text{ID} + 1, \text{ID} + 2, \text{ID} + 3, \text{ID} + 4, \text{ID} + 5, \text{ID} + 6, \text{ID} + 7) \\
\text{LC} := \text{stack(} \text{LC}, \text{LC}, \text{LC}, \text{LC}, \text{LC}, \text{LC}, \text{LC})
\]

Array Example

\[
\begin{bmatrix}
6604101 & 4001 \\
6604101 & 4002 \\
\vdots & \vdots \\
6604101 & 4064 \\
6604102 & 4001 \\
6604102 & 4002 \\
\vdots & \vdots \\
6604102 & 4064 \\
6604108 & 4001 \\
6604108 & 4002 \\
\vdots & \vdots \\
6604108 & 4064
\end{bmatrix}
\]
Moment Distribution

\[
M_{\text{tot}}(j) = \begin{pmatrix}
M_{x,j} \\
M_{y,j} \\
M_{z,j}
\end{pmatrix} + \eta_{\text{load}} \times \begin{pmatrix}
F_{x,j} \\
F_{y,j} \\
F_{z,j}
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x,\text{boltcg}} := M_{\text{tot1},j} \\
M_{y,\text{boltcg}} := M_{\text{tot2},j} \\
M_{z,\text{boltcg}} := M_{\text{tot3},j}
\]

Tension on bolts

\[
F_{\text{direct},i,j} := \begin{cases}
0 \text{lbf} & \text{if } F_{x,j} \leq 0 \text{lbf} \\
\frac{F_{x,j}}{\text{num_bolts}} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{\text{mz},i,j} := \begin{cases}
0 \text{lbf} & \text{if } \left( y_{i,ycg} \right) \neq 0 \text{ in} \\
\frac{M_{z,\text{boltcg}}(i)\left( y_{i,ycg} \right)}{\sum_{i} \left( y_{i,ycg} \right)^2 \cdot A_{t,i}} & \text{(Note: The direct shear is taken by the shear pin.)}
\end{cases}
\]

Secondary shear on bolts

\[
F_{s,\text{tot},i,j} := \sum_{i} \frac{M_{x,\text{boltcg}}(i,r_{i},A_{s,i})}{\sum_{i} r_{i}^2 \cdot \left( A_{s,i} \right)}
\]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}
\begin{bmatrix}
(F_T)^1, & (F_T)^2, & (F_T)^3, & (F_T)^4, & (F_T)^5, & (F_T)^6, & (F_T)^7, & (F_T)^8
\end{bmatrix}
\]

\[
V := \text{stack}
\begin{bmatrix}
(F_{stot})^1, & (F_{stot})^2, & (F_{stot})^3, & (F_{stot})^4, & (F_{stot})^5, & (F_{stot})^6, & (F_{stot})^7, & (F_{stot})^8
\end{bmatrix}
\]

\[
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

\[
\text{Output} := \text{augment}
\begin{bmatrix}
\text{ID}, & \text{LC}, & \frac{P}{\text{lbf}}, & \frac{V}{\text{lbf}}, & \frac{M}{\text{in-lbf}}
\end{bmatrix}
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th>P</th>
<th>V</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>6604101</td>
<td>4001</td>
<td>1068.05</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>6604101</td>
<td>4002</td>
<td>1110.33</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6604101</td>
<td>4064</td>
<td>699.99</td>
<td>-439.08</td>
<td>0</td>
</tr>
<tr>
<td>6604102</td>
<td>4001</td>
<td>813.60</td>
<td>-263.63</td>
<td>0</td>
</tr>
<tr>
<td>6604102</td>
<td>4002</td>
<td>977.16</td>
<td>-342.06</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6604102</td>
<td>4064</td>
<td>658.71</td>
<td>-322.63</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6604108</td>
<td>4001</td>
<td>1470.8</td>
<td>-358.78</td>
<td>0</td>
</tr>
<tr>
<td>6604108</td>
<td>4002</td>
<td>1166.08</td>
<td>-465.51</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Size of the "Output" Array: rows(Output) = 2048

(8 bolts x 64 load cases) x 4 joints = 2048 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)
### Flange 1: Lower VC Joint
- Part number: SDG39135737
- Material: 7050-T7451

### Flange 2: Lower USS to Upper USS Joint
- Part number: SDG39135762
- Material: 7050-T7451

### Loads
- **Applied tensile load**
  - \( P_s := \text{data}_s,3 \text{ lbf} \)
- **Applied shear load**
  - \( V_s := \text{data}_s,4 \text{ lbf} \)
- **Applied bending moment**
  - \( M_s := \text{data}_s,5 \text{ in-lbf} \)

### Factors of Safety
- **Ultimate**
  - \( SF_u := 1.4 \)
- **Yield**
  - \( SF_y := 1.1 \)
- **Assembly**
  - Temperature data (Ref Appendix C2), Nominal Landing Case
  - \( \text{Temp}_{\text{initial}} := 70 \text{ deg} \)
- **Joint Separation**
  - \( SF_{\text{sep}} := 1.2 \)
- **Fitting factor**
  - \( FF := 1.15 \)
- **Maximum**
  - \( \text{Temp}_{\text{max}} := 161 \text{ deg} \)
- **Minimum**
  - \( \text{Temp}_{\text{min}} := -41 \text{ deg} \)

### Bolt and Insert Data
- **Nominal diameter of bolt**
  - \( D := 0.500 \text{ in} \)
- **Number of threads/inch**
  - \( N_t := 20 \frac{1}{\text{in}} \)
- **Total length of bolt**
  - \( L := 1.673 \text{ in} \)
- **Length of insert**
  - \( L_{\text{ins}} := 0.688 \text{ in} \)
- **Threaded length**
  - \( L_t := 0.735 \text{ in} \)
  - **Min. external diameter of insert**
    - \( F_{\text{min}} := 0.615 \text{ in} \)
  - **Depth of recess for insert**
    - \( l_r := 0.02 \text{ in} \)

This file uses the calculations shown in `\escfil02\i211_mathcad\8307_bolts\thread_data.mcd`

---

**Thread Data File**
Washer Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of washer</td>
<td>tw := 0.078-in</td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := .875-in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.515-in</td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>dw := 0.710-in</td>
</tr>
</tbody>
</table>

Note: If there is no washer, tw, Dw, and Dwi should be zero.

Material Property Data

Bolt

- Temperature correction factor for bolt strength ultimate: 
  \[ TS_{u\_bolt} := .97 \] 
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress: 
  \[ Ft_{u\_bolt} := 180000\-psi \] 
  (Ref. NAS1958)
- Ultimate shear allowable stress: 
  \[ Fs_{u\_bolt} := 0.6\cdot Ft_{u\_bolt} \]
- Bolt yield tensile allowable: 
  \[ Fy_{\_bolt} := 132353\-psi \] 
  (Ref. Appendix C10)
- Temperature correction factor for bolt modulus: 
  \[ TE_{\_bolt} := .97 \] 
  (Ref. MIL-HDBK-5J, fig. 6.2.1.4(a))

\[ E_{\_bolt} := \left(29.1\cdot 10^6\-psi\right) \] 
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt: 
  \[ u_{\_bolt\_hot} := 9.1\cdot 10^{-6}\-\frac{\text{in}}{\text{deg}} \] 
  \[ u_{\_bolt\_cold} := 8.6\cdot 10^{-6}\-\frac{\text{in}}{\text{deg}} \]

Insert

- Temperature correction factor for insert strength: 
  \[ TS_{\_ins} := .97 \] 
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress: 
  \[ Ft_{\_ins} := 140000\-psi \] 
  (Ref. MS51831)
- Ultimate shear allowable stress: 
  \[ Fs_{\_ins} := 0.6\cdot Ft_{\_ins} \]

Washer

- Temperature correction factor for washer modulus: 
  \[ TE_{\_washer} := .97 \] 
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Modulus of elasticity of washer: 
  \[ E_{\_washer} := \left(29.1\cdot 10^6\-psi\right) \] 
  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1E} := 0.95 \] (modulus)  
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2
\[ T_{f2E} := 0.95 \] (modulus)
\[ T_{f2s} := 0.89 \] (strength)  
(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear Strength Allowable for flanges
\[ F_{su_{f2}} := 44000 \text{ psi} \]  
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1))

Modulus of elasticity for the parts in the joint
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1))
\[ E_{flange1} := \left( 10.3 \cdot 10^{-6} \frac{\text{psi}}{\text{in}} \right) \]
\[ E_{flange2} := \left( 10.3 \cdot 10^{-6} \frac{\text{psi}}{\text{in}} \right) \]

Coefficient of thermal expansion for flanges
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)
\[ u_{flange1_{hot}} := 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ u_{flange2_{hot}} := 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ u_{flange1_{cold}} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ u_{flange2_{cold}} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data

Maximum torque (63% of yield)
\[ T_{max} := 1000 \text{ in-lbf} \]

Minimum torque (95% of max. torque)
\[ T_{min} := 950 \text{ in-lbf} \]

Torque coefficient:
\[ k := 0.15 \]

Loading plane factor:
\[ n := .5 \]

Preload Uncertainty:
\[ := 0.25 \]

This file uses the calculations shown in \escfl02\2i11\mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.407</td>
<td>Preload due to temperature</td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLD_{\text{max}} = 17951.8 lbf</td>
<td>Uncertainty factor</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLD_{\text{min}} = 7183.8 lbf</td>
<td>Torque coefficient</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>max(P_{\text{sep}}) = 7362.823 lbf</td>
<td>Loading plane factor</td>
</tr>
<tr>
<td>Max. load on the bolt (ultimate)</td>
<td>max(P_b) = 19961.9 lbf</td>
<td>Thread shear pullout load of bolt or insert</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>max(P_{\text{by}}) = 19531.2 lbf</td>
<td>Thread shear pullout load in parent metal</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PA = 27425.9 lbf</td>
<td></td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Margin</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{\text{min,1}} = 0.065</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{\text{min,2}} = 1.776</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_{\text{min,3}} = 1.598</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{\text{min,4}} = 0.374</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_{\text{min,5}} = 0.033</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

MS_{\text{bolt}} := \min(\text{MS})

MS_{\text{bolt}} = 0.033

Minimum Margin of Safety

Failure Mode = "Total Tension Yield"

Element Identification (66041) and Bolt Number (8) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Lower USS-02 to Upper USS-02 (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-003. All 8 NAS1958 fasteners will take the direct shear load.

Direct shear Loads

\[ F_{sd_{i,j}} = \sqrt{\left(\frac{F_{y_{j}}}{\text{num_bolts}}\right)^2 + \left(\frac{F_{z_{j}}}{\text{num_bolts}}\right)^2} \]

(Note: The Fs variable is the secondary shear and calculated above.)

Total shear load

\[ F_{stot_{i,j}} = F_{s_{i,j}} + F_{sd_{i,j}} \]

The stack command below is used to stack the applied shear load (V) in ascending order per bolt. The applied axial load (P) and applied moment (M) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

\[ V := \text{stack}\left[\left(V_{stot}^{(1)}\right), \left(V_{stot}^{(2)}\right), \left(V_{stot}^{(3)}\right), \left(V_{stot}^{(4)}\right), \left(V_{stot}^{(5)}\right), \left(V_{stot}^{(6)}\right), \left(V_{stot}^{(7)}\right), \left(V_{stot}^{(8)}\right)\right] \]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is written to a text file. For the format of the array see the output example array above.

\[ \text{Output} := \text{augment}\left[\text{ID}, \text{LC}, \frac{P}{\text{lbf}}, \frac{V}{\text{lbf}}, \frac{M}{\text{in-lbf}}\right] \]  
(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array:  rows(Output) = 2048

(8 bolts x 64 load cases) x 4 joints = 2048 load cases

WRITEPRN("output_forces_lowerussvcf_r2_nomland_pinfs.txt") := Output

Fail-safe Analysis (Shear Pin Failure)

The array from the text file above is read:

\[ \text{datafsp} := \text{READPRN("output_forces_lowerussvcf_r2_nomland_pinfs.txt"}) \]

\[ s := 1..\text{rows(datafsp)} \]
Bolt Fail-safe Load data

Joint separation load \( \max(P_{sep,FS}) = 6135.686 \text{lbf} \)

Max. load on the bolt (ultimate) \( \max(P_b,FS) = 19387.6 \text{lbf} \)

Summary of fail-safe Margins for bolt:

- Joint separation \( \text{MS}_{min,FS} = 0.278 \)
- Direct Tension Ultimate \( \text{MS}_{min,FS} = 2.887 \)
- Total Tension Ultimate \( \text{MS}_{min,FS} = 0.415 \)
- Direct Thread shear Ultimate \( \text{MS}_{min,FS} = 2.69 \)

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{bolt,FS} := \min(\text{MS}_{FS}) \]

\( \text{MS}_{bolt,FS} = 0.278 \) \( \text{Failure_mode}_{FS} = "\text{Joint Separation}" \)

\( \text{MS}_{min,ID} = 66041008 \) Element Identification (66041) and Bolt Number (8) for Minimum Margin

\( \text{MS}_{min,LC} = 4015 \) Load Case Number for Minimum Margin

\( \text{MS}_{min,P} = 6135.7 \) Applied Tensile Load for Minimum Margin

\( \text{MS}_{min,V} = -641 \) Applied Shear Load for Minimum Margin

\( \text{MS}_{min,M} = 0.0 \) Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Lower USS-02 to Upper USS-02

Since bolt number 8 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 7, NAS1958C15 0.50-20 UNFJ fasteners, holding the lower USS to the lower vacuum case joint. The drawing number for the USS-02 Assembly to Vacuum Case Assembly is SDG39135724.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
\text{bolt2} & := \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
\end{align*}
\]

\[
s := 1 .. \text{rows(bolt2)}
\]

\[
N_s := \text{bolt2}_{s,2} \frac{1}{\text{in}}
\]

\[
D_s := \text{bolt2}_{s,1} \frac{1}{\text{in}}
\]

\[
\text{Tensile Area of bolt}
\]

\[
A_t := \beta \left( \frac{D_s - 0.9743 \frac{1}{N_s}}{2} \right)^2
\]

\[
\text{Shear Area of bolt}
\]

\[
A_s := \beta \left( \frac{D_s - 1.299038 \frac{1}{N_s}}{2} \right)^2
\]
Title: Bolts from Lower USS-02 to Upper USS-02

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-2.75</td>
<td>2.50</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>2.50</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>2.75</td>
<td>2.50</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-2.75</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>2.75</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>-2.75</td>
<td>-2.75</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.75</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

xforce := 0.0in  yforce := 0.0in  zforce := 0.0in

cgload := \begin{pmatrix} xforce \\ yforce \\ zforce \end{pmatrix}

cgload = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} in

Center of gravity of bolt group

\[
\begin{align*}
\sum_{s} x_s &= \text{xcg} := \frac{\text{xcg}}{\text{rows(x)}} = 0 \text{ in} \\
\sum_{s} y_s &= \text{ycg} := \frac{\text{ycg}}{\text{rows(y)}} = -0.393 \text{ in} \\
\sum_{s} z_s &= \text{zcg} := \frac{\text{zcg}}{\text{rows(z)}} = 0.286 \text{ in}
\end{align*}
\]

cgbolt := \begin{pmatrix} xcg \\ ycg \\ zcg \end{pmatrix}

cgbolt = \begin{pmatrix} 0 \\ -0.393 \\ 0.286 \end{pmatrix} in

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 8, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

rload := cgload - cgbolt

rload = \begin{pmatrix} 0 \\ 0.393 \\ -0.286 \end{pmatrix} in
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_s := \sqrt{(z_s - z_{cg})^2 + (y_s - y_{cg})^2} \]

\[
\begin{align*}
3.234 \\
2.249 \\
3.845 \\
2.374 \\
3.156 \\
3.843 \\
3.061 \\
3.823
\end{align*}
\]

Reading database file for bolted joint, nominal landing case

data := READPRN("lowerussvcf_r2_nomland.txt")

q := 1..rows(data)  num_bolts := rows(bolt2)

Loads from 2-04 loads model, nominal landing case

Axial Load  \( F_x \) := data_{q,3} lbf  Torsion  \( M_x \) := data_{q,6} in-lbf
Shear in Y axis \( F_y \) := data_{q,4} lbf  Moment about Y axis \( M_y \) := data_{q,7} in-lbf
Shear in Z axis \( F_z \) := data_{q,5} lbf  Moment about Z axis \( M_z \) := data_{q,8} in-lbf
Element Identification \( ID_2 \) := data_{q,1} \ ID_2 := ID_2 \times 100 + 1 \text{Counter for number of bolts in pattern}
Load Case Number \( LC_2 \) := data_{q,2}

Applied Bending Moment at Bolts \( M_2 \) := 0 in-lbf

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 8 is not included.

\[
ID_2 := \text{stack}(ID_2, ID_2 + 1, ID_2 + 2, ID_2 + 3, ID_2 + 4, ID_2 + 5, ID_2 + 6)
\]
\[
LC_2 := \text{stack}(LC_2, LC_2, LC_2, LC_2, LC_2, LC_2, LC_2)
\]
Moment Distribution

\[
M\text{\textsubscript{tot}}(q) := \begin{pmatrix} Mx(q) \\ My(q) \\ Mz(q) \end{pmatrix} + r\text{\textsubscript{load}} \times \begin{pmatrix} Fx(q) \\ Fy(q) \\ Fz(q) \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M\text{\textsubscript{x,boltcg}}(q) := M\text{\textsubscript{tot1,q}}, \quad M\text{\textsubscript{y,boltcg}}(q) := M\text{\textsubscript{tot2,q}}, \quad M\text{\textsubscript{z,boltcg}}(q) := M\text{\textsubscript{tot3,q}}
\]

Tension on bolts

\[
F\text{\textsubscript{direct}}(s,q) := \begin{cases} 0 \text{-lb} & \text{if } Fx(q) \leq 0 \text{lb} \\ \frac{Fx(q)}{\text{num_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation

\[
F\text{\textsubscript{mz}}(s,q) := \begin{cases} 0 \text{-lb} & \text{if } (y_s - y\text{\textsubscript{cg}}) = 0 \text{-in} \\ \frac{M\text{\textsubscript{z,boltcg}}(q)(y_s - y\text{\textsubscript{cg}})A\text{\textsubscript{ts}}}{\sum_s [(y_s - y\text{\textsubscript{cg}})^2A\text{\textsubscript{ts}}]} & \text{otherwise} \end{cases}
\]

\[
F\text{\textsubscript{my}}(s,q) := \begin{cases} 0 \text{-lb} & \text{if } (z_s - z\text{\textsubscript{cg}}) = 0 \text{-in} \\ \frac{M\text{\textsubscript{y,boltcg}}(q)(z_s - z\text{\textsubscript{cg}})A\text{\textsubscript{ts}}}{\sum_s [(z_s - z\text{\textsubscript{cg}})^2A\text{\textsubscript{ts}}]} & \text{otherwise} \end{cases}
\]

\[
F\text{\textsubscript{t2}}(s,q) := F\text{\textsubscript{direct}}(s,q) + F\text{\textsubscript{mz}}(s,q) + F\text{\textsubscript{my}}(s,q)
\]

Total Tensile load

Shear on bolts

\[
F\text{\textsubscript{s}}(s,q) := \frac{M\text{\textsubscript{x,boltcg}}(q)r_sA\text{\textsubscript{s}}}{\sum_s [(r_s)^2A\text{\textsubscript{s}}]}
\]

Total shear load

\[
F\text{\textsubscript{stot}}(s,q) := F\text{\textsubscript{s}}(s,q)
\]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the “Output” file below. Notice how there is only 7 bolts, since bolt number 8 is not included.

\[
P_2 := \text{stack} \left[ \left( F_{\text{tilt}} \right)^{(1)}, \left( F_{\text{tilt}} \right)^{(2)}, \left( F_{\text{tilt}} \right)^{(3)}, \left( F_{\text{tilt}} \right)^{(4)}, \left( F_{\text{tilt}} \right)^{(5)}, \left( F_{\text{tilt}} \right)^{(6)}, \left( F_{\text{tilt}} \right)^{(7)} \right]
\]

\[
V_2 := \text{stack} \left[ \left( F_{\text{shear}} \right)^{(1)}, \left( F_{\text{shear}} \right)^{(2)}, \left( F_{\text{shear}} \right)^{(3)}, \left( F_{\text{shear}} \right)^{(4)}, \left( F_{\text{shear}} \right)^{(5)}, \left( F_{\text{shear}} \right)^{(6)}, \left( F_{\text{shear}} \right)^{(7)} \right]
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{Output2 := augment}(\text{ID2}, \text{LC2}, \frac{P_2}{\text{lbf}}, \frac{V_2}{\text{lbf}}, \frac{M_2}{\text{in-lbf}})
\]

(Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: \( \text{rows(Output2)} = 1792 \)

(7 bolts x 64 load cases) x 4 joints = 1792 load cases

\[
\text{WRITEPRN}(\text{"output_forces_lowerussvcf_r2_nomland_fs.txt"}) := \text{Output2}
\]

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
data_{\text{fs}} := \text{READPRN}(\text{"output_forces_lowerussvcf_r2_nomland_fs.txt"})
\]

\[
s := 1..\text{rows}(data_{\text{fs}})
\]
Fail-safe Loads, nominal landing

Applied tensile load
\[ P_{FS} = \text{data}_{fs,3}, \text{lbf} \]

Applied shear load
\[ V_{FS} = \text{data}_{fs,4}, \text{lbf} \]

Applied bending moment
\[ M_{FS} = \text{data}_{fs,5}, \text{in-lbf} \]

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>SFu_FS := 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>SFsep_FS := 1.0</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escf\02\211\mathcad\8307\bolts\multi_bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

Joint separation load
\[ \text{max}(P_{sep,FS}) = 6341.621 \text{lbf} \]
\[ \text{max}(P_{FS}) = 6341.621 \text{lbf} \]

Max. load on the bolt(ultimate)
\[ \text{max}(P_{b,FS}) = 19435.8 \text{lbf} \]
\[ \text{max}(V_{FS}) = 4942.859 \text{lbf} \]

Summary of fail-safe Margins for bolt:

| Joint separation | MS_minFS_{1,1} = 0.237 |
| Direct Tension Ultimate | MS_minFS_{2,1} = 2.761 |
| Total Tension Ultimate | MS_minFS_{3,1} = 0.411 |
| Direct Thread shear Ultimate | MS_minFS_{4,1} = 2.57 |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt,FS} := \min(\text{MS}_{FS}) \]

\[ MS_{bolt,FS} = 0.237 \]

Failure Mode_FS = "Joint Separation"

| MS_min_ID = 6604206 | Element Identification (66041) and Bolt Number (5) for Minimum Margin |
| MS_min_DC = 4028 | Load Case Number for Minimum Margin |
| MS_min_P = 6341.6 | Applied Tensile Load for Minimum Margin |
| MS_min_V = 3953.4 | Applied Shear Load for Minimum Margin |
| MS_min_M = 0 | Applied Bending Moment for Minimum Margin |
Shear Pin Analysis for Lower USS-02 to Upper USS-02

The USS-02 assembly consists of four Lower Vacuum Case Joints (SDG39135737). Each Lower Vacuum Case Joint to Lower USS-02 joint has a shear pin (SDG39135755-003) installed with two bushings. The shear pin sets inside of a inner bushing SDG39135757-009 and the inner bushing sets inside of the outer bushing SDG39135757-011.

Cross Section of the Bolted Interface

Shear Pin SDG39135755-003

Inner Bushing SDG39135757-009

Outer Bushing SDG39135757-011
Bolts from Lower USS-02 to Upper USS-02

**Geometry**

- Minimum Diameter of shear pin: \( dp = 0.8746 \text{ in} \) (Ref. Drg. SDG39135755-003)
- Outer diameter of outer bushing: \( do = 1.4945 \text{ in} \) (Ref. Drg. SDG39135757-011)
- Thickness of lower VC joint: \( tp = 1.5 \text{ in} \) (Ref. Drg. SDG39135737)
- Length of inner bushing: \( tpin = 1.625 \text{ in} \) (Ref. Drg. SDG39135757-009)

**Temperature Data**

**Shear Pin (Custom 455, H1000 bar, AMS5617):**

- Temperature correction factor for shear: \( csp = 0.96 \) (Ref. MIL-HDBK-5J, table 2.6.4.1.2)

**Interface Plate (Al 7050-T7451 Plate):**

- Temperature correction factor for ultimate: \( cpu = 0.89 \) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)
- Temperature correction factor for yield: \( cpy = 0.96 \)

**Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):**

- Temperature correction factor for ultimate: \( cbu = 0.95 \) (Ref. Appendix C8)
- Temperature correction factor for yield: \( cby = 0.99 \)

**Material Properties**

**Shear Pin (Custom 455, H1000 bar, AMS5617):**

- Allowable shear stress: \( Fsu = 124000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

**Interface Plate (Al 7050-T7451 Plate):**

- Allowable bearing stress of bushing: \( Fbry = 72000 \text{ psi} \) (Ref. Appendix C8, Rockwell Materials data sheet 09.12.01.01,1.0)

**Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):**

- Allowable bearing stress of bushing: \( Fbru = 125000 \text{ psi} \)
### Shear Pin Analysis

**Loads in shear pin from Bolt Analysis (Direct Shear)**

\[ F_{sp,j} := \sqrt{(F_{y,j})^2 + (F_{z,j})^2} \]

rows(Fsp) = 256

(4 joints x 64 load cases = 256 load cases)

**Shear Area of pin**

\[ A_{sh} := \frac{\beta - dp^2}{4} \]

\[ A_{sh} = 0.601 \text{ in}^2 \]

**Allowable shear load**

\[ P_{all} := F_{su}.A_{sh}.csp \]

\[ P_{all} = 71515.8 \text{ lbf} \]

**Margin of safety**

\[ M_{Sp,j} := \left( \frac{P_{all}}{F_{sp,j}.S_{Fu}} - 1 \right) \]

\[ \min(M_{Sp}) = 1.76 \]

### Bearing of Outer Bushing on Interface Plate

Bearing of the outer bushing on the Lower USS-02 to Upper USS-02 Joint is not critical since the bearing thickness is 1.750 in. compared to 1.500 in. on the Lower Vacuum Case Joint. So the margin of safety is high for bearing on the Lower USS-02 to Upper USS-02 Joint. The Lower Vacuum Case Joint thickness is used below.

**Bearing area**

\[ A_{b} := do\cdot tp \]

\[ A_{b} = 2.242 \text{ in}^2 \]

**Allowable bearing load**

\[ P_{bru} := F_{brup}\cdot A_{b}\cdot c_{pu} \]

\[ P_{bru} = 281317.2 \text{ lbf} \]

\[ P_{bry} := F_{bryp}\cdot A_{b}\cdot c_{py} \]

\[ P_{bry} = 223816.3 \text{ lbf} \]

**Margin of safety**

\[ M_{Su,j} := \frac{P_{bru}}{F_{sp,j}.S_{Fu}} - 1 \]

\[ M_{Sy,j} := \frac{P_{bry}}{F_{sp,j}.S_{Fy}} - 1 \]

\[ \min(M_{Su}) = 9.87 \]

\[ \min(M_{Sy}) = 10.01 \]
### Bearing of Shear Pin on Inner Bushing

<table>
<thead>
<tr>
<th>Section</th>
<th>Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing area</td>
<td>$A_{bp} := d_p \cdot t_{pin}$</td>
<td>$1.421 \text{ in}^2$</td>
</tr>
<tr>
<td>Allowable bearing load</td>
<td>$P_{bru} := F_{bru} \cdot A_{bpu}$</td>
<td>$168770.5 \text{lbf}$</td>
</tr>
<tr>
<td></td>
<td>$P_{bry} := F_{bry} \cdot A_{bby}$</td>
<td>$101304.9 \text{lbf}$</td>
</tr>
<tr>
<td>Margin of safety</td>
<td>$M_{Sbru} := \frac{P_{bru}}{F_{S_p} \cdot S_{Fu}} - 1$</td>
<td>$M_{Sbry} := \frac{P_{bry}}{F_{S_p} \cdot S_{Fy}} - 1$</td>
</tr>
</tbody>
</table>
2.4.2.2  Lower Angle Beam Flange to Centerbody Box Joint
Lower Angle Beam Flange to Centerbody Box Joint Bolt Analysis

The Lower USS-02 assembly consists of four Lower Angle Beam Flanges and Centerbody Box Joints. There are a total of 8 fasteners attaching the Lower Angle Beam Flange to the Centerbody Box Joint. The fasteners are EWB0420 (200 ksi), 0.50-20 UNFJ. The drawing number for the Lower USS-02 Assembly is SDG39135758.

\[
\begin{align*}
\text{thread/in} & \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
\end{align*}
\]

\[
i := 1.. \text{rows(bolt)}
\]

\[
N_i := \frac{1}{2} \frac{1}{\text{pitch of bolt}}
\]

\[
D_i := \frac{1}{\text{bolt diameter}}
\]

View of Lower USS-02 Assembly SDG39135758

Lower Angle Beam Flange Joint
SDG39135767

Centerbody Box Joint
SDG39135759

Lower Angle Beam Flange to Centerbody Box Joint

\[
A_t_i := \beta \left( \frac{D_i - 0.9743}{N_i} \right)^2
\]

Tensile Area of bolt

\[
A_s_i := \beta \left( \frac{D_i - 1.299038}{N_i} \right)^2
\]

Shear Area of bolt
Bolts from Lower Angle Beam Flange to Centerbody Box Joint

Lower Angle Beam Flange to Centerbody Box Joint Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-2.841</td>
<td>2.841</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>-2.841</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>-2.841</td>
<td>-2.841</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>0.0</td>
<td>2.841</td>
</tr>
<tr>
<td>5</td>
<td>2.841</td>
<td>2.841</td>
<td>-2.841</td>
</tr>
<tr>
<td>6</td>
<td>2.841</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>2.841</td>
<td>0.0</td>
<td>2.841</td>
</tr>
<tr>
<td>8</td>
<td>2.841</td>
<td>-2.841</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
\begin{align*}
xforce & = 0.0 \text{in} & yforce & = 0.0 \text{in} & zforce & = 0.0 \text{in} \\
\text{cgload} & = \begin{pmatrix} xforce \\ yforce \\ zforce \end{pmatrix} & \text{cgload} & = \begin{pmatrix} 0 \\ 0 \text{in} \\ 0 \end{pmatrix}
\end{align*}
\]
Center of gravity of bolt group

\[
x_{cg} := \sum_{i} \frac{x_i}{\text{rows}(x)} \quad x_{cg} = 0 \text{ in}
\]

\[
y_{cg} := \sum_{i} \frac{y_i}{\text{rows}(y)} \quad y_{cg} = 0 \text{ in}
\]

\[
z_{cg} := \sum_{i} \frac{z_i}{\text{rows}(z)} \quad z_{cg} = 0 \text{ in}
\]

\[
c_{gbolt} := \begin{pmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{pmatrix} \quad c_{gbolt} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis and z-axis with a zero offset from the center of gravity.

Load Vector

\[
r_{load} := c_{gload} - c_{gbolt} \quad r_{load} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2}
\]

\[
r = \begin{pmatrix} 4.018 \\ 2.841 \\ 2.841 \\ 4.018 \\ 2.841 \\ 2.841 \\ 4.018 \\ 4.018 \end{pmatrix} \text{ in}
\]

Loads model 2-06 was used to retrieve loads at the four bolted interfaces. A Cbeam element located at the center of each lower angle beam flange was post processed in NASPOST for end A forces and moments in the x, y, and z directions. The Cbeam element identifications for the four bolted interfaces are 1625, 1628, 1630, and 1632. These loads are read into an array and distributed out to the 8 bolts for each lower angle beam flange.

(Note: This joint was checked for minimum margins of safety for launch and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis.)

Reading database file for bolted joint, abort landing case

data := READPRN("lowerusstocenter_r2_abortland.txt")

j := 1..rows(data)

num_bolts := rows(bolt)
Loads from 2-06 loads model, abort landing case

(Note: These loads are taken from end A of the Cbeam element)

Axial Load \( F_x := \text{data}_{j,7} \text{lbf} \)

Shear in Y axis \( F_y := \text{data}_{j,5} \text{lbf} \)

Shear in Z axis \( F_z := \text{data}_{j,6} \text{lbf} \)

Torsion \( M_x := \text{data}_{j,8} \text{in-lbf} \)

Moment about Y axis \( M_y := \text{data}_{j,4} \text{in-lbf} \)

Moment about Z axis \( M_z := \text{data}_{j,3} \text{in-lbf} \)

Element Identification \( \text{ID}_j := \text{data}_{j,1} \)

Load Case Number \( \text{LC}_j := \text{data}_{j,2} \)

Applied Bending Moment at Bolts \( M_j := 0 \text{-in-lbf} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 1625, 1628, 1630, and 1632, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 1625 will have bolt numbers 1 thru 8 attached to the end for all 64 load cases. This brings the total number of load cases to 2048 (4 joints x 8 bolts x 64 load cases = 2048). See the array example to the right.

\[
\text{ID} := \text{stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5, ID + 6, ID + 7)}
\]

\[
\text{LC} := \text{stack(LC, LC, LC, LC, LC, LC, LC, LC)}
\]

Array Example

\[
\begin{bmatrix}
1625001 & 1001 \\
1625001 & 1002 \\
\vdots & \vdots \\
1625001 & 1064 \\
1625002 & 1001 \\
1625002 & 1002 \\
\vdots & \vdots \\
1625002 & 1064 \\
1625008 & 1001 \\
1625008 & 1002 \\
\vdots & \vdots \\
1625008 & 1064 \\
\end{bmatrix}
\]
Moment Distribution

\[
M_{\text{tot}}^{(j)} := \begin{pmatrix} M_{x_{i,j}} \\ M_{y_{i,j}} \\ M_{z_{i,j}} \end{pmatrix} + r_{\text{load}} \begin{pmatrix} F_{x_{j}} \\ F_{y_{j}} \\ F_{z_{j}} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x_{\text{boltcg},j}} := M_{\text{tot}1,j} \\
M_{y_{\text{boltcg},j}} := M_{\text{tot}2,j} \\
M_{z_{\text{boltcg},j}} := M_{\text{tot}3,j}
\]

Tension on bolts

\[
F_{\text{direct},i,j} := \begin{cases} 0 \cdot \text{lbf} & \text{if } F_{x_{j}} \leq 0 \text{lbf} \\ \frac{F_{x_{j}}}{\text{num_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz,i,j} := \begin{cases} 0 \cdot \text{lbf} & \text{if } (y_{i} - y_{\text{cg}}) = 0 \cdot \text{in} \\ \frac{M_{z_{\text{boltcg},j}}(y_{i} - y_{\text{cg}})}{\sum_{i}(y_{i} - y_{\text{cg}})^{2} \cdot \text{At}_{i}} & \text{otherwise} \end{cases}
\]

\[
F_{my,i,j} := \begin{cases} 0 \cdot \text{lbf} & \text{if } (z_{i} - z_{\text{cg}}) = 0 \cdot \text{in} \\ \frac{M_{y_{\text{boltcg},j}}(z_{i} - z_{\text{cg}}) \cdot \text{At}_{i}}{\sum_{i}[(z_{i} - z_{\text{cg}})^{2} \cdot \text{At}_{i}]} & \text{otherwise} \end{cases}
\]

\[
F_{t,i,j} := F_{\text{direct},i,j} + F_{mz,i,j} + F_{my,i,j}
\]

Total Tensile load

Shear on bolts

Secondary shear on bolts \[
F_{s_{i,j}} := \frac{M_{x_{\text{boltcg},j}} \cdot \text{As}_{i}}{\sum_{i}(r_{j_{i}})^{2} \cdot \text{As}_{j}}
\]

Direct shear on bolts \[
F_{sd_{i,j}} := \frac{(F_{z_{j}})^{2} + (F_{y_{j}})^{2}}{\text{num_bolts}}
\]

Total shear load \[
F_{stot,i,j} := F_{sd_{i,j}} + F_{s_{i,j}}
\]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}[Ft(T)^{(1)}, (Ft(T)^{(2)}, Ft(T)^{(3)}, Ft(T)^{(4)}, Ft(T)^{(5)}, Ft(T)^{(6)}, Ft(T)^{(7)}, Ft(T)^{(8)})]
\]

\[
V := \text{stack}[\text{Fstot}(T)^{(1)}, \text{Fstot}(T)^{(2)}, \text{Fstot}(T)^{(3)}, \text{Fstot}(T)^{(4)}, \text{Fstot}(T)^{(5)}, \text{Fstot}(T)^{(6)}, \text{Fstot}(T)^{(7)}, \text{Fstot}(T)^{(8)})]
\]

\[
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

\[
\text{Output} := \text{augment}(\text{ID, LC, } P_{\text{lb}}^{\text{lb}}, V_{\text{lb}}^{\text{lb}}, M_{\text{in-lb}}^{\text{lb}})
\]

\[
\begin{array}{cccccc}
\text{ID} & \text{LC} & P & V & M \\
1625001 & 1001 & -1068.05 & -358.78 & 0 \\
1625001 & 1002 & -1110.33 & -465.51 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
1625002 & 1064 & -699.99 & -439.08 & 0 \\
1625002 & 1001 & -813.60 & -263.63 & 0 \\
1625002 & 1002 & -977.16 & -342.06 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
1625002 & 1064 & -658.71 & -322.63 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
1625008 & 1001 & 1470.8 & -358.78 & 0 \\
1625008 & 1002 & 1166.08 & -465.51 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
1625008 & 1064 & 699.99 & -439.07 & 0 \\
\end{array}
\]

Size of the "Output" Array: \(\text{rows(Output)} = 2048\)

\((8 \text{ bolts} \times 64 \text{ load cases}) \times 4 \text{ joints} = 2048 \text{ load cases}\)

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)

Example of Output Array

WRITEPRN("output_forces_lowerusstocenter_r2_abortland.txt") := Output
CHECK BOLTS (bolts SDG39135892-807, EWB 0420-8-13, 0.50-20UNJF-3A, Material-A-286), Insert MS51831CA206L, Washer NAS1587-8C

data := READPRN(“output_forces_lowerusstocenter_r2_abortland.txt”)

s := 1..rows(data)

Flange 1: Lower Angle Beam Flange
Part number: SDG39135767
Material: 7050-T7451

Flange 2: Centerbody Box Joint
Part number: SEG39135759
Material: 7050-T7451

Loads

Applied tensile load \( P_s := data_{s,3} \text{lbf} \)

Applied shear load \( V_s := data_{s,4} \text{lbf} \)

Applied bending moment \( M_s := data_{s,5} \text{in-lbf} \)

Factors of Safety

Ultimate SFu := 1.4  Yield SFy := 1.1  Assembly Temp_initial := 70-deg

Joint Separation SFsep := 1.2  Fitting factor FF := 1.15  Maximum Temp_max := 150-deg

Minimum Temp_min := 40-deg

Bolt and Insert Data

Nominal diameter of bolt \( D := 0.500\text{-in} \)

Number of threads/inch \( N_t := 20 \frac{1}{\text{in}} \)

Total length of bolt \( L := 1.651\text{-in} \)

Length of insert \( \text{Lins} := 0.688\text{-in} \)

Threaded length \( \text{Lt} := 0.838\text{-in} \)

Min. external diameter of insert \( \text{Fmin} := 0.615\text{-in} \)

(If bolt is fully threaded, input Lt = L)

Depth of recess for insert \( \text{Ir} := 0.02\text{-in} \)

Temperature Data (Ref Appendix C2), Abort Landing Case

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Thread Data File
### Washer Data

<table>
<thead>
<tr>
<th>Thickness of washer</th>
<th>tw := 0.078-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := .875-in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.515-in</td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>dw := 0.823-in</td>
</tr>
</tbody>
</table>

(used only if there is no washer)

Note: If there is no washer, tw, Dw, and Dwi should be zero.

### Flange data

<table>
<thead>
<tr>
<th>Thickness of flange 1</th>
<th>tf1 := .750-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 2</td>
<td>tf2 := .688-in (Insert Length)</td>
</tr>
</tbody>
</table>

### Material Property Data

**Bolt**

Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- TSu_bolt := .96
- yield
- TSy_bolt := .96

Bolt ultimate tensile allowable stress

- Ftu_bolt := 200000-psi

Bolt ultimate shear allowable stress

- Fsu_bolt := 0.6-Ftu_bolt

Bolt yield tensile allowable

- Fty_bolt := 180000-psi

Temperature correction factor for bolt modulus (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

- TE_bolt := .97

Modulus of elasticity of bolt

- \( E_{\text{bolt}} := \left( 29.1 \cdot 10^6 \cdot \text{psi} \right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

**Insert**

Temperature correction factor for insert strength (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- TS_ins := .96

Ultimate tensile allowable stress (Ref. MS51831)

- Ftu_ins := 140000-psi

Ultimate shear allowable stress

- Fsu_ins := 0.6-Ftu_ins

### Washer

Temperature correction factor for washer modulus (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- TE_washer := .96

Modulus of elasticity of washer

- \( E_{\text{washer}} := \left( 29.1 \cdot 10^6 \cdot \text{psi} \right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1  
**Tf1E := .96** (modulus)  
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2  
**Tf2E := .96** (modulus)  
**Tf2s := .95** (strength)  
(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear Strength Allowable for flanges  
**Fsu_f2 := 44000-psi**  
(Ref. MIL-HDBK-5J, table 3.7.4(b1))

Modulus of elasticity for the parts in the joint  
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1))  
**E_flange1 := \left(10.3\cdot10^6\text{-psi}\right)**  
**E_flange2 := \left(10.3\cdot10^6\text{-psi}\right)**

Coefficient of thermal expansion for flanges  
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)  
**u_flange1_hot := 12.8\cdot10^{-6}\text{-in/deg}**  
**u_flange2_hot := 12.8\cdot10^{-6}\text{-in/deg}**  
**u_flange1_cold := 12.1\cdot10^{-6}\text{-in/deg}**  
**u_flange2_cold := 12.1\cdot10^{-6}\text{-in/deg}**

**Torque/Preload data**

Maximum torque (63% of yield)  
**Tmax := 1360\text{-in-lbf}**  
**Loading plane factor:**  
**n := .5**

Minimum torque (95% of max. torque)  
**Tmin := 1292\text{-in-lbf}**  
**Preload Uncertainty:**  
**\text{:= 0.25}**

Torque coefficient:  
**k := 0.15**

This file uses the calculations shown in \escf\file{escg-4005-05-AMS-0039\multi_bolt_stiffness_insert_RevC}
Bolt Load data

Bolt/joint stiffness factor = 0.399
Preload due to temperature $P_{thr\_pos} = 1117 \text{ lbf}$
Max. preload $PLD_{max} = 23783.7 \text{ lbf}$
Uncertainty factor $P_{thr\_neg} = -373.6 \text{ lbf}$
Min. preload $PLD_{min} = 11413.1 \text{ lbf}$
Torque coefficient $= 0.25$
Joint separation load $\max(P_{sep}) = 9212.491 \text{ lbf}$
Loading plane factor $k = 0.15$
Max. load on the bolt (ultimate) $\max(P_b) = 26250 \text{ lbf}$
Max. load on the bolt (yield) $\max(P_{by}) = 25721.5 \text{ lbf}$
Thread shear pullout load of bolt or insert $P_{ths} = 47551.9 \text{ lbf}$
Bolt ultimate tensile strength $P_{At} = 30159.1 \text{ lbf}$
Thread shear pullout load in parent metal $P_{pths} = 27781.8 \text{ lbf}$

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation $MS_{\min,1} = 0.346$
Direct Thread shear Ultimate $MS_{\min,6} = 1.248$
Direct Tension Ultimate $MS_{\min,2} = 1.440$
Total Thread shear Ultimate $MS_{\min,7} = 0.058$
Direct Tension Yield $MS_{\min,3} = 1.795$
Shear Ultimate $MS_{\min,8} = 12.64$
Total Tension Ultimate $MS_{\min,4} = 0.149$
Bending Ultimate $MS_{\min,9} = 10$
Total Tension Yield $MS_{\min,5} = 0.055$
Combined shear, tension and bending ultimate $MS_{\min,10} = 0.149$

Determination of the smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} := \min(MS)$

$MS_{bolt} = 0.055$
Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

$MS_{\min\_ID} = 1625001$
Element Identification (1625) and Bolt Number (1) for Minimum Margin

$MS_{\min\_LC} = 2015$
Load Case Number for Minimum Margin

$MS_{\min\_P} = 7677.1$
Applied Tensile Load for Minimum Margin

$MS_{\min\_V} = 436.1$
Applied Shear Load for Minimum Margin

$MS_{\min\_M} = 0$
Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Lower Angle Beam Flange to Centerbody Box Joint

Since bolt number 1 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 7, EWB0420 0.50-20 UNFJ fasteners, holding the Lower Angle Beam Flange to the Centerbody Box Joint. The drawing number for the Lower USS-02 Assembly is SDG39135758.

\[
\text{thread/in} \begin{array}{c} \hline \
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
\hline \end{array}
\]

\[
bolt2 := \begin{array}{c} \hline \
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
0.500 & 20 \\
\hline \end{array}
\]

\[
s := 1 \ldots \text{rows}(bolt2)
\]

\[
N2_s := \frac{\text{bolt2}_s,1\text{ in}}{2} \quad \text{pitch of bolt}
\]

\[
D2_s := \text{bolt2}_s,1\text{ in} \quad \text{bolt diameter}
\]

Tensile Area of bolt

\[
\text{At2}_s := \beta \cdot \left( \frac{\left(2 - 0.9743 - \frac{\text{bolt2} - 1}{2} \right)}{N2_s} \right)^2
\]

Shear Area of bolt

\[
\text{As2}_s := \beta \cdot \left( \frac{\left(2 - 1.579038 - \frac{\text{bolt2} - 1}{2} \right)}{N2_s} \right)^2
\]
Bolt no.  x co-ord  y co-ord  z co-ord

\[
\begin{align*}
2 & : & (0.0) & (-2.841) & (0.0) \\
3 & : & (0.0) & (-2.841) & (-2.841) \\
4 & : & (0.0) & (0.0) & (2.841) \\
5 & : & (0.0, x2 := 0.0\text{in}) & (0.0, y2 := 0.0\text{in}) & (-2.841, z2 := -2.841\text{in}) \\
6 & : & (0.0) & (2.841) & (2.841) \\
7 & : & (0.0) & (2.841) & (0.0) \\
8 & : & (0.0) & (2.841) & (-2.841)
\end{align*}
\]

**Location of applied forces and moments**

\[
xforce2 := 0.0\text{in} \quad yforce2 := 0.0\text{in} \quad zforce2 := 0.0\text{in}
\]

\[
cgload2 := \begin{pmatrix} xforce2 \\ yforce2 \\ zforce2 \end{pmatrix}
\quad cgload2 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}\text{in}
\]

**Center of gravity of bolt group**

\[
xcg2 := \frac{\sum x2_s}{\text{rows}(x2)} \quad xcg2 = 0\text{in} \\
ycg2 := \frac{\sum y2_s}{\text{rows}(y2)} \quad ycg2 = 0.406\text{in} \\
zcg2 := \frac{\sum z2_s}{\text{rows}(z2)} \quad zcg2 = -0.406\text{in}
\]

\[
cgbolt2 := \begin{pmatrix} xcg2 \\ ycg2 \\ zcg2 \end{pmatrix} \quad cgbolt2 = \begin{pmatrix} 0 \\ 0.406 \end{pmatrix}\text{in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 1, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

**Load Vector**

\[
\begin{pmatrix} \text{r}_{\text{load2}} := \text{cgload2} - \text{cgbolt2} \\
0 & -0.406 \\
-0.406 & 0.406
\end{pmatrix}\text{in}
\]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_s^2 = \sqrt{(z_s - z_{cg})^2 + (y_s - y_{cg})^2} \]

\[ r_s = \begin{bmatrix} 3.272 \\ 4.059 \\ 3.272 \\ 2.469 \\ 4.059 \\ 2.469 \\ 3.444 \end{bmatrix} \text{ in} \]

Reading database file for bolted joint, abort landing case

data := READPRN("lowerusstocenter_r2_abortland.txt")

q := 1 .. rows(data)  num_bolts2 := rows(bolt2)

Loads from 2-06 loads model, abort landing case

Axial Load \( F_x \) := data \(_{q,5}\) lbf

Shear in Y axis \( F_y \) := data \(_{q,5}\) lbf

Shear in Z axis \( F_z \) := data \(_{q,6}\) lbf

Element Identification \( \text{ID2} \) := data \(_{q,1}\)

Load Case Number \( \text{LC2} \) := data \(_{q,2}\)

Applied Bending Moment at Bolts \( \text{M2} \) := 0 in-lbf

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 1 is not included.

\[ \text{ID2} := \text{stack(ID2} + 1, \text{ID2} + 2, \text{ID2} + 3, \text{ID2} + 4, \text{ID2} + 5, \text{ID2} + 6, \text{ID2} + 7) \]

\[ \text{LC2} := \text{stack(LC2, LC2, LC2, LC2, LC2, LC2, LC2)} \]
Moment Distribution

\[ M_{\text{tot}2}^{(q)} := \begin{pmatrix} Mx_{2}^{q} \\ My_{2}^{q} \\ Mz_{2}^{q} \end{pmatrix} + f_{\text{load}2} \times \begin{pmatrix} Fx_{2}^{q} \\ Fy_{2}^{q} \\ Fz_{2}^{q} \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{\text{bolt}2}^{q} := M_{\text{tot}1,2}^{q}, \quad My_{\text{bolt}2}^{q} := M_{\text{tot}2,1}^{q}, \quad Mz_{\text{bolt}2}^{q} := M_{\text{tot}2,2}^{q} \]

Tension on bolts

\[ F_{\text{direct}2, s, q} := \begin{cases} 0 \text{-lbf} & \text{if } Fx_{2}^{q} \leq 0 \text{lbf} \\ \frac{Fx_{2}^{q}}{\text{num\_bolts}2} & \text{otherwise} \end{cases} \]

Direct tensile load calculation

\[ Fm_{2, s, q} := \begin{cases} 0 \text{-lbf} & \text{if } \left( y_{2}^{s} - y_{\text{cg}2} \right) = 0 \text{-in} \\ \frac{Mz_{\text{bolt}2}^{q} \cdot \left( y_{2}^{s} - y_{\text{cg}2} \right) \cdot A_{t2}^{s}}{\sum_{s} \left( y_{2}^{s} - y_{\text{cg}2} \right)^{2} \cdot A_{t2}^{s}} & \text{otherwise} \end{cases} \]

Tension on bolts

\[ F_{t2, s, q} := F_{\text{direct}2, s, q} + Fm_{2, s, q} + Fm_{2, s, q} \]

Total Tensile load

Shear on bolts

\[ F_{s2, s, q} := \frac{Mx_{\text{bolt}2}^{q} \cdot r_{2}^{s} \cdot A_{s2}^{s}}{\sum_{s} \left( r_{2}^{s} \right)^{2} \cdot A_{s2}^{s}} \]

Direct shear on bolts

\[ F_{s2, s, q} := \frac{\sqrt{\left( Fz_{2}^{s} \right)^{2} + \left( Fy_{2}^{s} \right)^{2}}}{\text{num\_bolts}2} \]

Total shear load

\[ F_{\text{tot}2, s, q} := F_{s2, s, q} + F_{s2, s, q} \]
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below. Notice how there is only 7 bolts, since bolt number 1 is not included.

\[
P_2 := \text{stack} \left[ \left( F_{t2}^T \right)^{(1)}, \left( F_{t2}^T \right)^{(2)}, \left( F_{t2}^T \right)^{(3)}, \left( F_{t2}^T \right)^{(4)}, \left( F_{t2}^T \right)^{(5)}, \left( F_{t2}^T \right)^{(6)}, \left( F_{t2}^T \right)^{(7)} \right]
\]

\[
V_2 := \text{stack} \left[ \left( F_{stot2}^T \right)^{(1)}, \left( F_{stot2}^T \right)^{(2)}, \left( F_{stot2}^T \right)^{(3)}, \left( F_{stot2}^T \right)^{(4)}, \left( F_{stot2}^T \right)^{(5)}, \left( F_{stot2}^T \right)^{(6)}, \left( F_{stot2}^T \right)^{(7)} \right]
\]

\[
M_2 := \text{stack} \left( M_2, M_2, M_2, M_2, M_2, M_2, M_2 \right)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{Output2 := augment} \left( \text{ID2, LC2, } \frac{P_2}{\text{lbf}}, \frac{V_2}{\text{lbf}}, \frac{M_2}{\text{in}-\text{lbf}} \right) \quad (\text{Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)}
\]

Size of the "Output2" Array: rows(Output2) = 1792

(7 bolts x 64 load cases) x 4 joints = 1792 load cases

WRITEPRN("output_forces_lowerusstocenter_r2_abortland_fs.txt") := Output2

\section*{Bolt Fail-safe Results}

The array from the text file above is read:

\[
data_{\text{fs}} := \text{READPRN} \left( \text{"output_forces_lowerusstocenter_r2_abortland_fs.txt"} \right)
\]

s := 1 .. rows(data_{\text{fs}})

2.4.2.2 -16 ESCG-4005-05-AMS-0039
Fail-safe Loads, abort landing

Applyd tensile load: $P_{FS_s} := \text{data}_{fs_s,3} \cdot \text{lbf}$

Applied shear load: $V_{FS_s} := \text{data}_{fs_s,4} \cdot \text{lbf}$

Applied bending moment: $M_{FS_s} := \text{data}_{fs_s,5} \cdot \text{in} \cdot \text{lbf}$

Fail-safe Factors of Safety

- **Ultimate**
  - $S_{F_U} := 1.0$

- **Joint Separation**
  - $S_{F_{sep}} := 1.0$

Summary of fail-safe Margins for bolt:

- Joint separation: $M_{S_{min,FS}} = 0.618$
- Total Thread shear: $M_{S_{min,FS}} = 0.088$
- Direct Tension Ultimate: $M_{S_{min,FS}} = 2.422$
- Shear Ultimate: $M_{S_{min,FS}} = 14.92$
- Total Tension Ultimate: $M_{S_{min,FS}} = 0.181$
- Bending Ultimate: $M_{S_{min,FS}} = 10$
- Direct Thread shear Ultimate: $M_{S_{min,FS}} = 2.15$
- Combined shear, tension and bending ultimate: $M_{S_{min,FS}} = 0.1807$

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

$M_{S_{min,FS}} = \min(M_{S_{FS}})$

$M_{S_{min,FS}} = 0.088$  
Failure Mode FS = "Total Thread Shear Ultimate"

Element identification (1632) and Bolt number (3) for Minimum Margin:

- $M_{S_{min,ID}} = 1625003$
- $M_{S_{min,LC}} = 2032$
- $M_{S_{min,P}} = 7663.3$
- $M_{S_{min,V}} = 587.1$
- $M_{S_{min,M}} = 0$

Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
2.4.3 Keel Assembly Bolted Interfaces
Keel Assembly Bolted Interfaces

The Keel Assembly Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.3.1</td>
<td>Keel Angle Joint to Lower USS Assembly</td>
</tr>
<tr>
<td>2.4.3.1</td>
<td>Keel Angle Joint to Lower USS Assembly Fail-Safe</td>
</tr>
<tr>
<td>2.4.3.2</td>
<td>Keel Retainer to Keel Trunnion and Keel Block</td>
</tr>
<tr>
<td>2.4.3.2</td>
<td>Keel Retainer to Keel Trunnion and Keel Block Fail-Safe</td>
</tr>
</tbody>
</table>
2.4.3.1 Keel Angle Joint to Lower USS Assembly
Keel Angle Joint to Lower USS-02 Assembly Bolt Analysis

The Keel Assembly consists of two Keel Angle Joints. There are a total of 7 fasteners attaching the Keel Angle Joint to the Lower USS-02 Centerbody Box Joint. The fasteners are EWB0420 (200 ksi), 0.50-20 UNFJ. The drawing number for the USS-02 Assembly is SEG39135724.

![Diagram of Keel Assembly and Lower USS-02 Assembly]

Front View of Keel Assembly and Lower USS-02 Assembly

Side View of Keel Assembly and Lower USS-02 Assembly

\[ N_i := \text{bolt}_{i, \frac{1}{2}} \text{in} \quad \text{pitch of bolt} \]
\[ D_i := \text{bolt}_{i, \frac{1}{2}} \text{in} \quad \text{bolt diameter} \]
\[ A_t := \beta \left( \frac{D_i - 0.9743}{N_i} \right)^2 \quad \text{Tensile Area of bolt} \]
\[ A_s := \beta \left( \frac{D_i - 1.299038}{N_i} \right)^2 \quad \text{Shear Area of bolt} \]
Bolts from Keel Angle Joint to Lower USS-02 Assembly

Keel Angle Joint to Lower USS-02 Centerbody Box Joint Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord (in)</th>
<th>y co-ord (in)</th>
<th>z co-ord (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.159</td>
<td>4.063</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>4.063</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.159</td>
<td>4.063</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.159</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>3.159</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>-3.159</td>
<td>-4.063</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>3.159</td>
<td>-4.063</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[ x_{\text{force}} := 0.0 \text{in} \quad y_{\text{force}} := 0.0 \text{in} \quad z_{\text{force}} := 0.0 \text{in} \]

\[ \text{cgload} := \begin{pmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{pmatrix} \quad \text{cgload} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in} \]
Center of gravity of bolt group

\[
x_{cg} := \sum_{i} \frac{x_i}{\text{rows}(x)} \\
y_{cg} := \sum_{i} \frac{y_i}{\text{rows}(y)} \\
z_{cg} := \sum_{i} \frac{z_i}{\text{rows}(z)}
\]

\[
x_{cg} = 0 \text{ in} \\
y_{cg} = 0 \text{ in} \\
z_{cg} = 0.58 \text{ in}
\]

\[
c_{gbolt} := \begin{bmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{bmatrix}
\]

\[
c_{gbolt} = \begin{bmatrix} 0 \\ 0 \\ 0.58 \end{bmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is unsymmetric about the z-axis and has an offset of 0.58". The y-axis has a zero offset from the center of gravity.

Load Vector

\[
r_{load} := c_{gload} - c_{gbolt}
\]

\[
r_{load} = \begin{bmatrix} 0 \\ 0 \\ -0.58 \end{bmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_{i} := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2}
\]

\[
r = \begin{bmatrix} 4.702 \\ 3.483 \\ 4.702 \\ 3.212 \\ 5.616 \\ 3.212 \\ 5.616 \end{bmatrix} \text{ in}
\]

Loads model 2-04 was used to retrieve loads at the two bolted interfaces. A Cbeam element located at the center of each keel angle joint was post processed in NASPOST for end A forces and moments in the x, y, and z directions. The Cbeam element identifications for the two bolted interfaces are 66045 and 66046. These loads are read into an array and distributed out to the 7 bolts for each keel angle joint.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The nominal landing cases combined with nominal landing temperature data resulted in the lowest minimum margins of safety. Therefore, the nominal landing cases are used in this analysis.)

Reading database file for bolted joint, nominal landing case

\[
data := \text{READPRN}("keelboltsf_r2_nomland.txt")
\]

\[
j := 1..\text{rows(data)}
\]

\[
\text{num_bolts} := \text{rows(bolt)}
\]
Loads from 2-04 loads model, nominal landing case

(Note: These loads are taken from end A of the Cbeam element)

Axial Load \( F_x \) := data\textsubscript{j,7} lbf

Torsion \( M_x \) := data\textsubscript{j,8} in-lbf

Shear in Y axis \( F_y \) := data\textsubscript{j,5} lbf

Moment about Y axis \( M_y \) := data\textsubscript{j,4} in-lbf

Shear in Z axis \( F_z \) := data\textsubscript{j,6} lbf

Moment about Z axis \( M_z \) := data\textsubscript{j,3} in-lbf

Element Identification ID\textsubscript{j} := data\textsubscript{j,1}

ID := ID\textsubscript{j} \cdot 1000 + 1 Counter for number of bolts in pattern

Load Case Number LC\textsubscript{j} := data\textsubscript{j,2}

Applied Bending Moment at Bolts \( M_j := 0 \cdot \text{in-lbf} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

For each element identification, 66045 and 66046, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66045 will have bolt numbers 1 thru 7 attached to the end for all 64 load cases. This brings the total number of load cases to 896 (2 joints x 7 bolts x 64 load cases = 896). See the array example to the right.

\[
\begin{array}{c}
\text{ID} \\
6604501 \\
6604502 \\
\vdots \\
6604501 \\
6604502 \\
\vdots \\
6604507 \\
6604507 \\
\vdots \\
6604507 \\
\end{array}
\begin{array}{c}
\text{LC} \\
4001 \\
4002 \\
\vdots \\
4064 \\
4001 \\
4002 \\
\vdots \\
4064 \\
\end{array}
\]

ID := stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5, ID + 6)

LC := stack(LC, LC, LC, LC, LC, LC, LC)

Array Example
Bolts from Keel Angle Joint to Lower USS-02 Assembly

### Moment Distribution

\[
M_{\text{tot}}^{(j)} := \begin{pmatrix} M_x^{(j)} \\ M_y^{(j)} \\ M_z^{(j)} \end{pmatrix} + \mathbf{r}_{\text{load}} \times \begin{pmatrix} F_x^{(j)} \\ F_y^{(j)} \\ F_z^{(j)} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{tot}1,j}^{(j)} := M_x^{(j)} \\
M_{\text{tot}2,j}^{(j)} := M_y^{(j)} \\
M_{\text{tot}3,j}^{(j)} := M_z^{(j)}
\]

### Tension on bolts

\[
\text{Ft}_{i,j} := \begin{cases} 0 \text{-lbf if } Fx_j \leq 0 \text{lbf} \\ \frac{Fx_j}{\text{num}_\text{bolts}} \text{ otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
\text{Fm}_{z,j} := \begin{cases} 0 \text{-lbf if } \left(y_i - y_{\text{ycg}}\right) = 0 \text{-in} \\ \frac{\left[Mz_{\text{boltcg}} \cdot \left(y_i - y_{\text{ycg}}\right)\right]}{\text{At}_i} \sum_i \left[\left(y_i - y_{\text{ycg}}\right)^2 \cdot \text{At}_i\right] \text{ otherwise} \end{cases}
\]

\[
\text{Fs}_{i,j} := \begin{cases} 0 \text{-lbf if } \left(z_i - z_{\text{scg}}\right) = 0 \text{-in} \\ \frac{M_{\text{boltcg}} \cdot \left(z_i - z_{\text{scg}}\right) \cdot \text{At}_i}{\sum_i \left[\left(z_i - z_{\text{scg}}\right)^2 \cdot \text{At}_i\right]} \end{cases}
\]

\[
\text{Ft}_{i,j} := \text{Ft}_{i,j} + \text{Fm}_{z,j} + \text{Fs}_{i,j}
\]

Total Tensile load

### Shear on bolts

\[
\text{Fs}_{i,j} := \frac{M_{\text{boltcg}} \cdot r_i \cdot A_{s_i}}{\sum_i \left[r_i^2 \cdot (A_{s_i})\right]}
\]

\[
\text{Fsd}_{i,j} := \frac{\sqrt{(Fz_j)^2 + (Fy_j)^2}}{\text{num}_\text{bolts}}
\]

Total shear load

\[
\text{Fstot}_{i,j} := \text{Fsd}_{i,j} + \text{Fs}_{i,j}
\]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}\left[ (\text{Ft})^1, (\text{Ft})^2, (\text{Ft})^3, (\text{Ft})^4, (\text{Ft})^5, (\text{Ft})^6, (\text{Ft})^7 \right]
\]

\[
V := \text{stack}\left[ (\text{Fstot})^1, (\text{Fstot})^2, (\text{Fstot})^3, (\text{Fstot})^4, (\text{Fstot})^5, (\text{Fstot})^6, (\text{Fstot})^7 \right]
\]

\[
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

Output := augment(\begin{bmatrix} ID & LC & P & V & M \end{bmatrix}, \begin{bmatrix} \text{lbf} & \text{lbf} & \text{in}-\text{lbf} \end{bmatrix})

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

\[
\begin{array}{cccc}
6604501 & 4001 & -1068.05 & -358.78 & 0 \\
6604501 & 4002 & -1110.33 & -465.51 & 0 \\
... & ... & ... & ... & ... \\
6604501 & 4064 & -699.99 & -439.08 & 0 \\
6604502 & 4001 & -813.60 & -263.63 & 0 \\
6604502 & 4002 & -977.16 & -342.06 & 0 \\
... & ... & ... & ... & ... \\
6604502 & 4064 & -658.71 & -322.63 & 0 \\
... & ... & ... & ... & ... \\
... & ... & ... & ... & ... \\
6604507 & 4001 & 1470.8 & -358.78 & 0 \\
6604507 & 4002 & 1166.08 & -465.51 & 0 \\
... & ... & ... & ... & ... \\
6604507 & 4064 & 699.99 & -439.07 & 0 \\
\end{array}
\]

Size of the "Output" Array: rows(Output) = 896

(7 bolts x 64 load cases) x 2 joints = 896 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)
CHECK BOLTS (bolts SDG39135892-807, EWB 0420-8, 0.50-20UNJF-3A, Material-A-286), Insert MS51831CA206L, Washer NAS1587-8C

data := READPRN("output_forces_keelbolts_r2_nomland.txt")

s := 1..rows(data)

Flange 1: Keel Angle Joint
Part number: SDG39135769
Material: 7050-T7451

Flange 2: Lower USS Centerbody
Part number: SEG39135759
Material: 7050-T7451

Loads
Applied tensile load
\[ P_s := data_{s,3}, \text{lbf} \]

Applied shear load
\[ V_s := data_{s,4}, \text{lbf} \]

Applied bending moment
\[ M_s := data_{s,5}, \text{in-lbf} \]

Factors of Safety
Ultimate
\[ SF_u := 1.4 \]

Yield
\[ SF_y := 1.1 \]

Assembly Temp_initial := 70\text{ deg}

Joint Separation
\[ SF_{sep} := 1.2 \]

Fitting factor
\[ FF := 1.15 \]

Maximum Temp_max := 173\text{ deg}

Minimum Temp_min := -53\text{ deg}

Bolt and Insert Data
Nominal diameter of bolt
\[ D := 0.500\text{-in} \]

Number of threads/inch
\[ N_t := 20 \frac{1}{\text{in}} \]

Total length of bolt
\[ L := 1.651\text{-in} \]

Length of insert
\[ L_{ins} := 0.688\text{-in} \]

Threaded length
\[ L_t := 0.838\text{-in} \]

Min. external diameter of insert
\[ F_{min} := 0.615\text{-in} \]

Depth of recess for insert
\[ l_r := 0.02\text{-in} \]

(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Thread Data File

2.4.3.1 -8  ESCG-4005-05-AMS-0039
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brent Dyer</td>
<td>10/27/05</td>
<td>KAJ_LwUSS_r3.mcd</td>
</tr>
<tr>
<td>Checked By</td>
<td>John Krejci</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Title</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Title**: Bolts from Keel Angle Joint to Lower USS-02 Assembly

### Washer Data
- **Thickness of washer**: \( tw := 0.078\text{ in} \)
- **Outer Diameter of washer**: \( Dw := 0.875\text{ in} \)
- **Inner Diameter of washer**: \( Dwi := 0.515\text{ in} \)
- **Bolt head dia. across flats** (used only if there is no washer): \( dw := 0.823\text{ in} \)

**Note**: If there is no washer, \( tw, Dw, \) and \( Dwi \) should be zero.

### Material Property Data

#### Bolt
- Temperature correction factor for bolt strength ultimate: \( TSu\text{\_bolt} := 0.96 \)
- Ultimate tensile allowable stress: \( Fu\text{\_bolt} := 200,000\text{ psi} \)
- Ultimate shear allowable stress: \( Fsu\text{\_bolt} := 0.6\times Fu\text{\_bolt} \)
- Bolt yield tensile allowable: \( Fty\text{\_bolt} := 180,000\text{ psi} \)
- Temperature correction factor for bolt modulus: \( TE\text{\_bolt} := 0.97 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))
- Modulus of elasticity of bolt: \( E\text{\_bolt} := \left(29.1\times10^6\text{ psi}\right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

#### Insert
- Temperature correction factor for insert strength: \( TS\text{\_ins} := 0.96 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress: \( Fu\text{\_ins} := 140,000\text{ psi} \) (Ref. MS51831)
- Ultimate shear allowable stress: \( Fsu\text{\_ins} := 0.6\times Fu\text{\_ins} \)

#### Washer
- Temperature correction factor for washer modulus: \( TE\text{\_washer} := 0.96 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Modulus of elasticity of washer: \( E\text{\_washer} := \left(29.1\times10^6\text{ psi}\right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1E} := 0.96 \quad \text{(modulus)} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)} \]

Temperature correction factor for flange 2
\[ T_{f2E} := 0.96 \quad \text{(modulus)} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)} \]

Temperature correction factor stylight for flange 2
\[ T_{f2s} := 0.89 \quad \text{(strength)} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)} \]

Shear Strength Allowable for flanges
\[ F_{su_f2} := 44000 \text{ psi} \quad \text{(Ref. MIL-HDBK-5J, table 3.7.4.0(b1))} \]

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange}1} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{\text{flange}2} := \left(10.3 \times 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges
\[ u_{\text{flange}1\text{ hot}} := 12.8 \times 10^{-6} \text{ in} / \text{deg} \quad u_{\text{flange}2\text{ hot}} := 12.8 \times 10^{-6} \text{ in} / \text{deg} \]
\[ u_{\text{flange}1\text{ cold}} := 12.1 \times 10^{-6} \text{ in} / \text{deg} \quad u_{\text{flange}2\text{ cold}} := 12.1 \times 10^{-6} \text{ in} / \text{deg} \]

Torque/Preload data

Maximum torque (62% of yield)
\[ T_{\text{max}} := 1339 \text{ in-lbf} \]

Minimum torque (95% of max. torque)
\[ T_{\text{min}} := 1272 \text{ in-lbf} \]

Torque coefficient:
\[ k := 0.15 \]

Loading plane factor:
\[ n := 0.5 \]

Preload Uncertainty:
\[ := 0.25 \]

This file uses the calculations shown in \escfl02\211_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolts from Keel Angle Joint to Lower USS-02 Assembly

Bolt Load data

Bolt/joint stiffness factor \[ \beta = 0.392 \]

Max. preload \[ \text{P}_{\text{LDM}_\text{a}x} = 23772.4 \, \text{lbf} \]

Min. preload \[ \text{P}_{\text{LDM}_\text{in}} = 9959.7 \, \text{lbf} \]

Joint separation load \[ \text{max}(P_{\text{sep}}) = 2259.897 \, \text{lbf} \]

Max. load on the bolt (ultimate) \[ \text{max}(P_b) = 24366.3 \, \text{lbf} \]

Max. load on the bolt (yield) \[ \text{max}(P_{by}) = 24239 \, \text{lbf} \]

Bolt ultimate tensile strength \[ P_{At} = 30159.1 \, \text{lbf} \]

Preload due to temperature \( \text{P}_{\text{thr, pos}} = 1455.7 \, \text{lbf} \)

Uncertainty factor \( k = 0.15 \)

Torque coefficient \( n = 0.5 \)

Loading plane factor \( \text{P}_{\text{ths}} = 47551.9 \, \text{lbf} \)

Thread shear pullout load of bolt or insert \( \text{P}_{\text{pths}} = 26027.1 \, \text{lbf} \)

Thread shear pullout load in parent metal

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

- Joint separation \[ \text{MS}_{\text{min},1,1} = 3.766 \]
- Direct Tension Ultimate \[ \text{MS}_{\text{min},2,1} = 8.947 \]
- Direct Tension Yield \[ \text{MS}_{\text{min},3,1} = 10.000 \]
- Total Tension Ultimate \[ \text{MS}_{\text{min},4,1} = 0.238 \]
- Total Tension Yield \[ \text{MS}_{\text{min},5,1} = 0.120 \]

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{M}_{\text{S, bolt}} = 0.068 \]

Minimum Margin of Safety

Failure Mode = "Total Thread Shear Ultimate"

- Element Identification (66045) and Bolt Number (1) for Minimum Margin
- Load Case Number for Minimum Margin
- Applied Tensile Load for Minimum Margin
- Applied Shear Load for Minimum Margin
- Applied Bending Moment for Minimum Margin

2.4.3.1 -11 ESCG-4005-05-AMS-0039
Bolt Fail-Safe Analysis for Keel Angle Joint to Lower USS-02 Centerbody Box Joint

Since bolt number 1 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 6, EWB0420 0.50-20 UNFJ fasteners, holding the Keel Angle Joint to the Lower USS-02 Centerbody Box Joint. The drawing number for the USS-02 Assembly is SDG39135724.

Front View of Keel Assembly and Lower USS-02 Assembly

Keel Angle Joint  to Lower USS-02 Centerbody Box Joint Bolt Pattern

Tensile Area of bolt

\[ A_{t2} := \beta \left( \frac{D_{2s} - 0.9743 - \frac{1}{N_{2s}}}{2} \right)^2 \]

Shear Area of bolt

\[ A_{s2} := \beta \left( \frac{D_{2s} - 1.299038 - \frac{1}{N_{2s}}}{2} \right)^2 \]
Bolts from Keel Angle Joint to Lower USS-02 Assembly

Bolt no.  x co-ord   y co-ord   z co-ord
2         0.0        0.0       4.063
3         0.0        -3.159    4.063
4         0.0       -3.159     0.0
5         0.0       -3.159      0.0
6         0.0       -3.159    -4.063
7         0.0       -3.159     -4.063

Location of applied forces and moments

\[ \text{xforce2} := 0.0 \text{in} \quad \text{yforce2} := 0.0 \text{in} \quad \text{zforce2} := 0.0 \text{in} \]

\[ \text{cgload2} := \begin{pmatrix} \text{xforce2} \\ \text{yforce2} \\ \text{zforce2} \end{pmatrix} \quad \text{cgload2} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in} \]

Center of gravity of bolt group

\[ \sum_{s=1}^{\text{rows}(x2)} x2_s = \frac{xcg2}{\text{rows}(x2)} = 0 \text{in} \quad \sum_{s=1}^{\text{rows}(y2)} y2_s = \frac{ycg2}{\text{rows}(y2)} = 0.526 \text{in} \quad \sum_{s=1}^{\text{rows}(z2)} z2_s = \frac{zcg2}{\text{rows}(z2)} = 0 \text{in} \]

\[ \text{cgbolt2} := \begin{pmatrix} \text{xcg2} \\ \text{ycg2} \\ \text{zcg2} \end{pmatrix} \quad \text{cgbolt2} = \begin{pmatrix} 0 \\ 0.526 \\ 0 \end{pmatrix} \text{in} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 1, the y direction in the bolt pattern is unsymmetric and has a offset from the center of gravity.

Load Vector

\[ \text{rload2} := \text{cgload2} - \text{cgbolt2} \quad \text{rload2} = \begin{pmatrix} 0 \\ -0.526 \\ 0 \end{pmatrix} \text{in} \]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r^2_\text{s} := \sqrt{(z^2_\text{s} - z_{\text{cg}}^2)^2 + (y^2_\text{s} - y_{\text{cg}}^2)^2} \]

\[ r^2_\text{s} = \begin{bmatrix} 4.097 \\ 4.841 \\ 3.685 \\ 2.632 \\ 5.486 \\ 4.841 \end{bmatrix} \text{ in} \]

Reading database file for bolted joint, nominal landing case

data := READPRN("keelboltsf_r2_nomland.txt")

q := 1 .. rows(data)  num_bolts2 := rows(bolt2)

Loads from 2-04 loads model, nominal landing case

Axial Load \( F_x \) \( q \) := data \( q,7 \) lbf

Shear in Y axis \( F_y \) \( q \) := data \( q,5 \) lbf

Shear in Z axis \( F_z \) \( q \) := data \( q,6 \) lbf

Element Identification \( ID_2 \) \( q \) := data \( q,1 \)

Load Case Number \( LC_2 \) \( q \) := data \( q,2 \)

Applied Bending Moment at Bolts \( M_2 \) \( q \) := 0-in-lbf

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 1 is not included.

\[ ID_2 := \text{stack}(ID_2 + 1, \ldots, ID_2 + 6) \]

\[ LC_2 := \text{stack}(LC_2, LC_2, LC_2, LC_2, LC_2, LC_2) \]
**Moment Distribution**

\[
\begin{align*}
M_{tot2}^{(q)} &= \begin{pmatrix}
Mx_{q}^{2} \\
My_{q}^{2} \\
Mz_{q}^{2}
\end{pmatrix} + r_{load2} \times \begin{pmatrix}
Fx_{q}^{2} \\
Fy_{q}^{2} \\
Fz_{q}^{2}
\end{pmatrix}
\end{align*}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
Mx_{boltcg2}^{(q)} := M_{tot1, q} \\
My_{boltcg2}^{(q)} := M_{tot2, q} \\
Mz_{boltcg2}^{(q)} := M_{tot3, q}
\]

**Tension on bolts**

\[
\begin{align*}
F_{direct2, s, q} := \begin{cases} 
0 \text{ lbf} & \text{if } F_{x_{q}}^{2} \leq 0 \text{lbf} \\
F_{x_{q}}^{2} & \text{otherwise}
\end{cases}
\end{align*}
\]

Direct tensile load calculation

\[
\begin{align*}
Fmz_{s, q}^{2} := \begin{cases} 
0 \text{ lbf} & \text{if } (y_{s}^{2} - y_{crg2}) = 0 \text{ in} \\
\frac{Mz_{boltcg2}^{(q)}(y_{s}^{2} - y_{crg2})}{\sum_{s}(y_{s}^{2} - y_{crg2})^{2} \cdot A_{t2}^{s}} & \text{otherwise}
\end{cases}
\end{align*}
\]

\[
\begin{align*}
Fmy_{s, q}^{2} := \begin{cases} 
0 \text{ lbf} & \text{if } (z_{s}^{2} - z_{crg2}) = 0 \text{ in} \\
\frac{My_{boltcg2}^{(q)}(z_{s}^{2} - z_{crg2}) \cdot A_{t2}^{s}}{\sum_{s}[(z_{s}^{2} - z_{crg2})^{2} \cdot A_{t2}^{s}]} & \text{otherwise}
\end{cases}
\end{align*}
\]

\[
F_{t2, s, q} := F_{direct2, s, q} + Fmz_{s, q}^{2} + Fmy_{s, q}^{2}
\]

Total Tensile load

**Shear on bolts**

Secondary shear on bolts

\[
Fs_{s, q}^{2} := \frac{Mx_{boltcg2}^{(q)} \cdot r_{s}^{2} \cdot A_{s}^{2}}{\sum_{s}(r_{s}^{2} \cdot A_{s}^{2})}
\]

Direct shear on bolts

\[
F_{sd2}^{s, q} := \sqrt{\left(F_{x_{q}}^{2}\right)^{2} + \left(F_{y_{q}}^{2}\right)^{2}}
\]

\[
F_{tot2}^{s, q} := F_{sd2}^{s, q} + Fs_{s, q}^{2}
\]

Total shear load

2.4.3.1 -15

ESCG-4005-05-AMS-0039
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below. Notice how there is only 6 bolts, since bolt number 1 is not included.

\[
P_2 := \text{stack}\left[\left(F_{2T}\right)^{(1)}, \left(F_{2T}\right)^{(2)}, \left(F_{2T}\right)^{(3)}, \left(F_{2T}\right)^{(4)}, \left(F_{2T}\right)^{(5)}, \left(F_{2T}\right)^{(6)}\right]
\]

\[
V_2 := \text{stack}\left[\left(F_{\text{total}}\right)^{(1)}, \left(F_{\text{total}}\right)^{(2)}, \left(F_{\text{total}}\right)^{(3)}, \left(F_{\text{total}}\right)^{(4)}, \left(F_{\text{total}}\right)^{(5)}, \left(F_{\text{total}}\right)^{(6)}\right]
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

(Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

\[
\text{Output2} := \text{augment}\left[\text{ID2, LC2, } \frac{P_2}{\text{lbf}}, \frac{V_2}{\text{lbf}}, \frac{M_2}{\text{in-lbf}}\right]
\]

Size of the "Output2" Array:  \(\text{rows(Output2)} = 768\)

(6 bolts x 64 load cases) x 2 joints = 768 load cases

\[
\text{WRITEPRN("output_forces_keelbolts_r2_nomland_fs.txt") := Output2}
\]

**Bolt Fail-safe Results**

The array from the text file above is read:

\[
data_fs := \text{READPRN("output_forces_keelbolts_r2_nomland_fs.txt")}
\]

\[s := 1..\text{rows(data_fs)}\]
Fail-safe Loads, nominal landing

<table>
<thead>
<tr>
<th>Applied load</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>$P_{FS,s} := \text{data}_{fs,s,3}\ lbf$</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>$V_{FS,s} := \text{data}_{fs,s,4}\ lbf$</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>$M_{FS,s} := \text{data}_{fs,s,5}\ in\ lbf$</td>
</tr>
</tbody>
</table>

Joint separation load $\max(P_{sep_{FS}}) = 2766.612\ lbf$ and $\max(P_{FS}) = 2766.612\ lbf$

Max. load on the bolt (ultimate) $\max(P_{b_{FS}}) = 24395.6\ lbf$ and $\max(V_{FS}) = 2104.709\ lbf$

Summary of fail-safe Margins for bolt:

| Joint separation | $MS_{minFS_{1,1}} = 2.893$ | Total Thread shear Ultimate | $MS_{minFS_{5,1}} = 0.067$ |
| Direct Tension Ultimate | $MS_{minFS_{2,1}} = 8.479$ | Shear Ultimate | $MS_{minFS_{6,1}} = 6.08$ |
| Total Tension Ultimate | $MS_{minFS_{3,1}} = 0.236$ | Bending Ultimate | $MS_{minFS_{7,1}} = 10$ |
| Direct Thread shear Ultimate | $MS_{minFS_{4,1}} = 7.18$ | Combined shear, tension and bending ultimate | $MS_{minFS_{8,1}} = 0.2351$ |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

$MS_{bolt_{FS}} := \min(MS_{FS})$

$MS_{bolt_{FS}} = 0.067$ Failure Mode $FS = \text{"Total Thread Shear Ultimate"}$

$MS_{min_ID} = 66045003$ Element Identification (66045) and Bolt Number (2) for Minimum Margin

$MS_{min_{LC}} = 4015$ Load Case Number for Minimum Margin

$MS_{min_{P}} = 2766.6$ Applied Tensile Load for Minimum Margin

$MS_{min_{V}} = 1490.7$ Applied Shear Load for Minimum Margin

$MS_{min_{M}} = 0$ Applied Bending Moment for Minimum Margin
2.4.3.2 Keel Retainer to Keel Trunnion and Keel Block
Keel Retainer to Keel Trunnion and Keel Block Bolt Analysis

The Keel Assembly consists of one keel retainer to keel trunnion interface. There are a total of 8 fasteners attaching the Keel Retainer to the Keel Trunnion. These 8 fasteners are NAS8103PU8 (160 ksi), 0.190-32 UNF. The Keel Assembly also consists of one keel retainer to keel block interface. There are a total of 8 fasteners attaching the Keel Retainer to the Keel Block. These 8 fasteners are HTH1978-3-3 (200 ksi), 0.190-32 UNJF. The drawing number for the Keel Assembly is SEG39135768.

ISO View of USS-02 Keel Assembly - SDG39135768

ISO View of the components for USS-02 Keel Assembly - SDG39135768
NASPOST Results

The following NASPOST results were sorted for maximum forces in the y-direction for all trunnions. The keel trunnion has element ID 5 in the loads model (Ref. Appendix A2 for NASPOST sort):

++ MAX Y LAUNCH TRUNNION FORCES ++

ID  SUBCASE  FX  FY  FZ

5  1060  0.000000E+00  2.411519E+04  0.000000E+00

++ MAX Y ABORT LANDING TRUNNION FORCES ++

ID  SUBCASE  FX  FY  FZ

5  2017  0.000000E+00  9.118636E+03  0.000000E+00

++ MAX Y NOMLANDING TRUNNION FORCES ++

ID  SUBCASE  FX  FY  FZ

5  4051  0.000000E+00  1.559590E+04  0.000000E+00

Maximum Load for Keel Retainer to Keel Trunnion Interface:

Due to temperature and friction, a percent of the normal load (Pr) is used for calculating the axial load (Pf) to the trunnion.

The launch case 1060 from above, has an normal load of 24115.9 lbf at a minimum temperature of 40F. At 40F this gives a coeffient of friction of .100, per the table in Appendix C7. The axial load is then 10% of the 24115.9 lbf normal load. The axial load is then 2411.59 lbf.

The launch case 4051 from above, has an normal load of 15595.9 lbf at a minimum temperature of -56F. At -56F this gives a coeffient of friction of .168, per the table in Appendix C7. The axial load is then 16.8% of the 15595.9 lbf normal load. The axial load is then 2620.1 lbf. Therefore the nominal landing case is used in this analysis. Reference section 2.3.4 "Keel Trunnion" for the keel trunnion analysis.

Normal load in y direction  Pr := 15595.9-lbf  (Ref.AMS-02, loads model 2-04, Load case 4051, element ID 5, data file: maxtrunnionforces4000.lis)

Axial Friction load 16.8% of load  Pf := Pr-0.168  Pf = 2620.1-lbf

The 8 bolts attaching the keel retainer to the keel trunnion share an equal amount of the axial load due to friction.

Number of Bolts  nb := 8

Applied tensile load on each bolt  P := Pf / nb  P = 328-lbf

2.4.3.2-3  ESCG-4005-05-AMS-0039
CHECK BOLTS: Keel Retainer to Keel Trunnion (NAS8103PU8 Material-A-286 CRES), Tapped hole .190-32UNJF-3B, Washer NAS1149E0332R

Flange 1: Keel Retainer
Part number: SDG39135773
Material: CRES 15-5PH H1025

Flange 2: Keel Trunnion
Part number SDG39135772
Material: Custom 455 H1000

Loads - 4051 Nominal Landing Case
Applied tensile load \( P = 328 \text{-lbf} \)

Applied shear load \( V = 0 \text{-lbf} \)

Applied bending moment: \( M = 0 \text{-in-lbf} \)

Factors of Safety

| Ultimate | SFu := 1.4 | Yield | SFy := 1.1 |
| Joint Separation | SFsep := 1.2 | Fitting factor | FF := 1.15 |

Temperature Data (Ref Appendix C2), Nominal Landing Case

| Assembly | Temp\_initial := 70 deg |
| Maximum | Temp\_max := 181 deg |
| Minimum | Temp\_min := \(-56\) deg |

Bolt and tapped hole Data

| Nominal diameter of bolt | \( D := 0.190 \text{-in} \) |
| Total length of bolt | \( L := 0.5 \text{-in} \) |
| Threaded length | \( L_t := L \) |

(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

\( T \)ue Feb 15 10:29:25 AM 2005
Bolts from Keel Retainer to Keel Trunnion and Keel Block

**Washer Data**

- Thickness of washers: \( t_w := 0.032 \text{ in} \)
- Outer Diameter of washer: \( D_w := 0.438 \text{ in} \)
- Inner Diameter of washer: \( D_{wi} := 0.203 \text{ in} \)
- Bolt head dia. across flats: \( d_w := 0.357 \text{ in} \)

**Flange data**

- Thickness of flange 1: \( t_f1 := 0.125 \text{ in} \)
- Thickness of flange 2: \( t_f2 := 0.375 \text{ in} \)
- Diameter of hole: \( D_{hole} := 0.213 \text{ in} \)

Note: If there is no washer, \( t_w, D_w \) and \( D_{wi} \) should be zero.
(used only if there is no washer)

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
  \[ T_{Su\_bolt} := .97 \]
  \[ T_{Sy\_bolt} := .97 \]
- Bolt ultimate tensile allowable stress
  \[ F_{tu\_bolt} := 160000 \text{ psi} \] (Ref. AMS 5726)
- Bolt ultimate shear allowable stress
  \[ F_{su\_bolt} := 0.6 \times F_{tu\_bolt} \]
- Bolt yield tensile allowable stress
  \[ F_{ty\_bolt} := 120000 \text{ psi} \] (Ref. AMS 5726)
- Temperature correction factor for bolt modulus
  \[ T_{E\_bolt} := .97 \] (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

- Modulus of elasticity of bolt
  \[ E_{\_bolt} := 29.1 \times 10^6 \text{ psi} \] (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt
  \[ \beta_{\_bolt\_hot} := 9.1 \times 10^{-6} \text{ in}\text{in}^{-6} \text{deg}^{-1} \]
  \[ \beta_{\_bolt\_cold} := 8.6 \times 10^{-6} \text{ in}\text{in}^{-6} \text{deg}^{-1} \]

**Washer**

- Temperature correction factor for washer modulus
  \[ T_{E\_washer} := .97 \] (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

- Modulus of elasticity of washer
  \[ E_{\_washer} := 29.1 \times 10^6 \text{ psi} \] (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 modulus \( T_{f1E} := .99 \) (Ref. MIL-HDBK-5J, fig. 2.6.7.1.4)

Temperature correction factor for flange 2 modulus \( T_{f2E} := .99 \) (Ref. MIL-HDBK-5J, fig. 2.6.7.1.4 and Appendix C11)

Modulus of elasticity for the parts in the joint
(Ref. MIL-HDBK-5J, table 2.6.7.0(c) and table 2.6.4.0 (b))

\[ E_{\text{flange}1} := \left(28.5 \cdot 10^6 \text{ psi}\right) \quad E_{\text{flange}2} := \left(28.9 \cdot 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges
(For flange 1 Ref. MIL-HDBK-5J, table 2.6.7.0(H1075) and Appendix C12)

\[ \beta_{\text{flange1}_{\text{hot}}} := 6.3 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \quad \beta_{\text{flange2}_{\text{hot}}} := 5.8 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \]

(For flange 2 Ref. MIL-HDBK-5J, table 2.6.4.0 (H950) and Appendix C11)

\[ \beta_{\text{flange1}_{\text{cold}}} := 5.9 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \quad \beta_{\text{flange2}_{\text{cold}}} := 5.5 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \]

Flange with tapped hole

Temperature correction factor for flange with tapped hole strength
(Ref. MIL-HDBK-5J, fig. 2.6.4.2.1)

\( TS_{f2} := .97 \)

Tension allowable ultimate \( F_{tu_{f2}} := 200000 \) psi (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

Shear allowable \( F_{su_{f2}} := 124000 \) psi (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

Torque/Preload data

Maximum torque (60% of yield) \( T_{\text{max}} := 41.0 \) in-lbf

Loading plane factor \( n := 0.5 \)

Minimum torque (95% of max. torque) \( T_{\text{min}} := 39.0 \) in-lbf

Preload Uncertainty \( u := 0.25 \)

Torque coefficient \( k := 0.15 \)

This file uses the calculations shown in \escfl02\2i11\mathcad\8307_bolts\bolt_stiffness_tap_RevC

Mon Feb 14 12:25:48 2005
Bolt Load data

Bolt/joint stiffness factor = 0.104 Preload due to temperature \( p_{\text{thr, pos}} = 261.6 \text{ lbf} \)

Max. preload \( \text{PLD}_{\text{max}} = 2059.8 \text{ lbf} \)

Min. preload \( \text{PLD}_{\text{min}} = 692.6 \text{ lbf} \)

Joint separation load \( P_{\text{sep}} = 393.017 \text{ lbf} \)

Max. load on the bolt (ultimate) \( P_b = 2087.2 \text{ lbf} \)

Max. load on the bolt (yield) \( P_{by} = 2081.4 \text{ lbf} \)

Bolt ultimate tensile strength \( P_{At} = 2987.4 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

- Joint separation \( MS_1 = 0.616 \)
- Direct Tension Ultimate \( MS_2 = 4.67 \)
- Direct Tension Yield \( MS_3 = 4.41 \)
- Total Tension Ultimate \( MS_4 = 0.431 \)
- Total Tension Yield \( MS_5 = 0.076 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[
MS_{\text{b Bolt}} := \min(\text{MS})
\]

\[
MS_{\text{b Bolt}} = 0.076 \quad \text{Failure Mode} = "\text{Total Tension Yield}"\]
### Fail-safe Analysis

Total Number of bolts for fail-safe  
\[ n_{fs} := 7 \]

Applied tensile load  
\[ P_{FS} := \frac{P_f}{n_{fs}} \]

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
</table>
| Applied tensile load \( P_{FS} = 374.302 \text{ lbf} \) | Applied tensile load  
| Applied shear load \( V_{FS} := 0 \text{ lbf} \) | Ultimate  
| Applied bending moment \( M_{FS} := 0 \text{ in-lbf} \) | Joint Separation  
| SFu_{FS} := 1.0 | SFsep_{FS} := 1.0 |

This file uses the calculations shown in \textbackslash escf\textbackslash 02\textbackslash 11\textbackslash mathcad\8307\bolts\bolt\stiffness\tap\FS\RevC

### Bolt Fail-safe Load data

Joint separation load  
\[ P_{sep_{FS}} = 374.302 \text{ lbf} \]

Max. load on the bolt (ultimate)  
\[ P_{b_{FS}} = 2082.2 \text{ lbf} \]

### Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margins</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{FS1} = 0.697 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{FS2} = 5.94 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{FS3} = 0.435 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{FS4} = 18.78 )</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( MS_{FS5} = 3.09 )</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>( MS_{FS6} = 10 )</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( MS_{FS7} = 10 )</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>( MS_{FS8} = 0.435 )</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt_{FS}} := \min(MS_{FS}) \]

\[ MS_{bolt_{FS}} = 0.435 \]

Failure Mode_{FS} = "Combined Shear Tension Bending Ultimate"
Free Body Diagram and Hand Calculations for Keel Retainer to Keel Block Interface:

**Geometry:**
(Ref. SDG39135773 and SDG39135770)

- Inner Diameter of Trunnion Block: $\text{IDbl} := 3.001\text{-in}$
- Outer Diameter of Trunnion Retainer: $\text{ODtr} := 4.00\text{-in}$
- Diameter of Retainer to Block Bolt Pattern: $\text{ODbbp} := 3.50\text{-in}$
- Diameter of Retainer to Trunnion Bolt Pattern: $\text{ODtbp} := 2.698\text{-in}$

**Cross Sectional View of USS-02 Keel Assembly - SDG39135768**

**Summation of Moments with a Downward Motion of Trunnion**

$$
\text{Pt1} := \frac{\text{Pf} \cdot \left( \text{IDbl} - \text{ODtbp} \right)}{2 \cdot \left( \text{ODbbp} - \text{IDbl} \right)} = 1591\text{-lbf}
$$

$$
\text{P2} := \frac{\text{Pt1}}{\text{nb}} = 199\text{-lbf}
$$

**Summation of Moments with an Upward Motion of Trunnion**

$$
\text{Pt2} := \frac{\text{Pf} \cdot \left( \text{ODtr} - \text{ODtbp} \right)}{2 \cdot \left( \text{ODtr} - \text{ODbbp} \right)} = 6823\text{-lbf}
$$

$$
\text{P3} := \frac{\text{Pt2}}{\text{nb}} = 853\text{-lbf}
$$
Finite Element Analysis for Keel Retainer to Keel Block Interface:

A finite element analysis was performed on the keel retainer plate in order to extract loads for the bolts at the keel retainer to keel block interface. One load case was performed for the keel trunnion’s upward motion. See free body diagram above. MSC/NASTRAN v.2005 was used as a solver for analyzing the keel plate. The keel retainer plate is machined from CRES 15-5PH H1025.

Description of Model

A FEM model was built for the keel retainer plate using FEMAP.

1. The plate was modeled as CQUAD4 elements.
2. Z-direction constraints were added to the outside diameter of the plate to represent the outer contact between the plate and the keel block. See ODtr variable above.
3. X, Y, and Z direction constraints were added to the bolt locations for the keel retainer to keel block. Constraints lay on the diameter of the bolt circle for keel retainer to keel plate. See ODbbp variable from above.
4. A force of 328 lbf was applied at 8 bolt locations (grid IDs 1 thru 8) for the keel retainer to keel trunnion interface. These loads simulate the upward motion of the trunnion. Grid IDs 1 thru 8 are also constrained in the X and Y direction. See Pf and ODtbp variable from above.
Model Checks

Rigid body checks were performed using MSC/NASTRAN. The KGG, KNN and KFF matrices all pass with low strain energies. Reference file, keelretainerck06.f06, for additional information.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.584249E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.793968E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>6.693881E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>2.263432E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.801301E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.189150E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

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<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
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</thead>
<tbody>
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<td>1</td>
<td>1.584249E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.793968E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>6.693881E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>2.263432E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.801301E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.189150E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
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<td>5</td>
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<td>PASS</td>
</tr>
<tr>
<td>6</td>
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<td>PASS</td>
</tr>
</tbody>
</table>
## Real Eigenvalues

<table>
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<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>-6.43E-05</td>
<td>8.02E-03</td>
<td>1.28E-03</td>
<td>1.00E+00</td>
<td>-6.43E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<tr>
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<tr>
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<tr>
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<td>5.73E-05</td>
<td>7.57E-03</td>
<td>1.21E-03</td>
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<tr>
<td>6</td>
<td>6</td>
<td>1.44E-04</td>
<td>1.20E-02</td>
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<td>1.00E+00</td>
<td>1.44E-04</td>
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<td>7</td>
<td>5.30E+07</td>
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<td>5.30E+07</td>
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<tr>
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<td>8</td>
<td>5.30E+07</td>
<td>7.28E+03</td>
<td>1.16E+03</td>
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<td>5.30E+07</td>
</tr>
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<td>9</td>
<td>3.83E+08</td>
<td>1.96E+04</td>
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<td>1.00E+00</td>
<td>3.83E+08</td>
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<tr>
<td>10</td>
<td>10</td>
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<td>1.98E+04</td>
<td>3.16E+03</td>
<td>1.00E+00</td>
<td>3.93E+08</td>
</tr>
</tbody>
</table>

### Loads from FEA:

SPC Force Resultant is **2624.0 lbf**

Forces at the 8 single point constraints are -818.65 lbf

Total Axial load from FEM in z-direction: \( P_t := 6549.2 \text{ lbf} \)

Number of Bolts: \( nb := 8 \)

Applied tensile load on each bolt from FEM: \( P := \frac{P_t}{nb} \quad P = 818.65 \text{ lbf} \)
CHECK BOLTS: Keel Retainer to Keel Block (SDG39135892-817 - HTH1978-3-3 Material-A-286 CRES), Insert MS124775, Washer NAS1587A3C

Flange 1: Keel Retainer
Part number: SDG39135773
Material: CRES 15-5PH H1025

Flange 2: Keel Block
Part number SDG39135770
Material: Al 7050-T7451

Loads - 4051 Nominal Landing Case

Applied tensile load \( P = 818.65 \text{lbf} \)

Applied shear load \( V := 0 \text{lbf} \)

Applied bending moment \( M := 0 \text{in-lbf} \)

Factors of Safety

Ultimate \( SF_u := 1.4 \)

Yield \( SF_y := 1.1 \)

Assembly \( Temp_{initial} := 70 \text{deg} \)

Joint Separation \( SF_{sep} := 1.2 \)

Fitting factor \( FF := 1.15 \)

Maximum \( Temp_{max} := 181 \text{deg} \)

Minimum \( Temp_{min} := -56 \text{deg} \)

Bolt and Insert Data

Nominal diameter of bolt \( D := 0.190 \text{in} \)

Number of threads/inch \( N_t := 32 \frac{1}{in} \)

Total length of bolt \( L := .5955 \text{in} \)

Length of insert \( L_{ins} := 0.475 \text{in} \)

(Based on 2.5 Diameter)

Threaded length \( L_t := .408 \text{in} \)

Min. external diameter of insert \( F_{min} := 0.236 \text{in} \)

Depth of recess for insert \( l_r := 0.02 \text{in} \)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
**Washer Data**

- Thickness of washers: \( t_w = 0.062\text{-in} \)
- Outer Diameter of washer: \( D_w = 0.469\text{-in} \)
- Inner Diameter of washer: \( D_{wi} = 0.192\text{-in} \)
- Bolt head dia. across flats: \( d_w = 0.345\text{-in} \)

Note: If there is no washer, \( t_w, D_w \) and \( D_{wi} \) should be zero.
(used only if there is no washer)

**Flange data**

- Thickness of flange 1:
  - Ref. SDG39135773
- Thickness of flange 2:
  - Ref. SDG39135770
- Diameter of hole: \( D_{hole} = 0.213\text{-in} \)

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate: \( T_{Su\_bolt} = 0.97 \)
- Bolt ultimate tensile allowable stress: \( F_{tu\_bolt} = 200000\text{ psi} \)
- Bolt ultimate shear allowable stress: \( F_{su\_bolt} = 0.6 \times F_{tu\_bolt} \)
- Bolt yield tensile allowable: \( F_{ty\_bolt} = 180000\text{ psi} \)
- Temperature correction factor for bolt modulus: \( T_{E\_bolt} = 0.97 \)
- Modulus of elasticity of bolt: \( E_{bolt} = (29.1 \times 10^6\text{ psi}) \)
- Thermal coefficient for bolt:
  - \( \beta_{bolt\_hot} = 9.1 \times 10^{-6}\text{ in}^{-1}\text{ deg}^{-1} \)
  - \( \beta_{bolt\_cold} = 8.6 \times 10^{-6}\text{ in}^{-1}\text{ deg}^{-1} \)

**Insert**

- Temperature correction factor for insert strength: \( T_{S_{ins}} = 0.97 \)
- Ultimate tensile allowable stress: \( F_{tu\_ins} = 150000\text{ psi} \)
- Ultimate shear allowable stress: \( F_{su\_ins} = 0.6 \times F_{tu\_ins} \)

**Washer**

- Temperature correction factor for washer modulus: \( T_{E\_washer} = 0.97 \)
- Modulus of elasticity of washer: \( E_{washer} = (29.1 \times 10^6\text{ psi}) \)
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1}E := 0.99 \text{ (modulus)} \quad \text{(Ref. page 2.4.3.2-6)} \]

Temperature correction factor for flange 2

\[ T_{f2}E := 0.97 \text{ (modulus)} \]

\[ T_{f2}s := 0.88 \text{ (strength)} \quad \text{(Ref. Fig. 3.7.3.2.1 MIL-HDBK-5H)} \]

\[ F_{su,f2} := 44000 \text{-psi} \]

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange}1} := 28.5 \cdot 10^6 \text{-psi} \quad E_{\text{flange}2} := 10.3 \cdot 10^6 \text{-psi} \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange}1,\text{hot}} := 6.3 \cdot 10^{-6} \text{ in-deg} \quad \beta_{\text{flange}2,\text{hot}} := 13.0 \cdot 10^{-6} \text{ in-deg} \]

\[ \beta_{\text{flange}1,\text{cold}} := 5.9 \cdot 10^{-6} \text{ in-deg} \quad \beta_{\text{flange}2,\text{cold}} := 12.1 \cdot 10^{-6} \text{ in-deg} \]

Torque/Preload data

Maximum torque (60% of Yield)

\[ T_{\text{max}} := 61.5 \text{-in-lbf} \quad \text{Loading plane factor:} \quad n := 0.5 \]

Minimum torque (95% of max. torque)

\[ T_{\text{min}} := 58.5 \text{-in-lbf} \quad \text{Preload Uncertainty:} \quad u := 0.25 \]

Torque coefficient:

\[ k := 0.15 \]

This file uses the calculations shown in \texttt{escf02\211_mathcad\8307\bolts\bolt\stiffness\insert\RevC}

Mon Feb 06 3:57:46 PM 2006 ———— 2.4.3.2 -15 ESCG-4005-05-AMS-0039
Bolt Load data

Bolt/joint stiffness factor = 0.178

Preload due to temperature Pthr_pos = 180.6-lbf

Max. preload PLDmax = 2878-lbf

Pthr_neg = −180.2-lbf

Min. preload PLDmin = 1224.4-lbf

Uncertainty factor u = 0.25

Joint separation load Psep = 982.38-lbf

Torque coefficient k = 0.15

Max. load on the bolt(ultimate) Pb = 2995.5-lbf

Loading plane factor n = 0.5

Max. load on the bolt(yield) Pby = 2970.3-lbf

Thread shear pullout load of bolt or insert Pths = 9040.8-lbf

Bolt ultimate tensile strength PAt = 3734.3-lbf

Thread shear pullout load in parent metal Ppths = 6818.1-lbf

Length_check = "Bolt length is sufficient"

(Note: Insert length is based on 2.5 times the nominal bolt diameter. Bolt length is sufficient.)

Summary of Margins for bolt:

Joint separation MS1 = 0.190 Direct Thread shear Ultimate MS6 = 4.17

Direct Tension Ultimate MS2 = 1.83 Total Thread shear Ultimate MS7 = 1.28

Direct Tension Yield MS3 = 2.25 Shear Ultimate MS8 = 10

Total Tension Ultimate MS4 = 0.25 Bending Ultimate MS9 = 10

Total Tension Yield MS5 = 0.131 Combined shear, tension and bending ultimate MS10 = 0.247

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

MSbolt = 0.131 Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

Total Number of bolts for fail-safe \( n_{fs} := 7 \)

Applied tensile load \( P_{FS} := \frac{P_t}{n_{fs}} \)

Fail-safe Loads

- Applied tensile load \( P_{FS} = 935.6 \text{-lbf} \)
- Applied shear load \( V_{FS} := 0 \text{-lbf} \)
- Applied bending moment \( M_{FS} := 0 \text{-in-lbf} \)

Fail-safe Factors of Safety

- Ultimate factor of safety \( SF_u_{FS} := 1.0 \)
- Joint Separation factor of safety \( SF_{sep}_{FS} := 1.0 \)

This file uses the calculations shown in \Escfil02\2111_mathcad\8307\bolts\bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

- Joint separation load \( P_{sep}_{FS} = 935.6 \text{-lbf} \)
- Max. load on the bolt(ultimate) \( P_{b,FS} = 2973.9 \text{-lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th></th>
<th>( MS_{FS} )</th>
<th>( SF_u_{FS} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{FS1} = 0.249 )</td>
<td>1.0</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{FS2} = 2.47 )</td>
<td>10</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{FS3} = 0.256 )</td>
<td>10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{FS4} = 5.34 )</td>
<td>0.256</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( MS_{FS5} = 1.29 )</td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt}_{FS} := \min(\text{MS}_{FS}) \)

\( MS_{bolt}_{FS} = 0.249 \)

Failure\_Mode\_FS = "Joint Separation"
2.5 USS-02 Rivet Strength Assessment
2.5.1 Upper USS-02 Riveted Joints
Upper USS-02 Riveted Joints

The Upper USS-02 Rivet Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.1.1</td>
<td>Upper Vacuum Case Joint to Upper Trunnion Bridge</td>
</tr>
<tr>
<td>2.5.1.2</td>
<td>Lower Trunnion Bridge Beam Elbow to Sill Joint</td>
</tr>
<tr>
<td>2.5.1.3</td>
<td>Sill Bracket to Sill Tube</td>
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<tr>
<td>2.5.1.4</td>
<td>Diagonal Sill Bracket to Sill Tube</td>
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<td>2.5.1.5</td>
<td>Diagonal Strut Tube to Diagonal Strut End Fitting</td>
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<td>2.5.1.6</td>
<td>Upper Trunnion Bridge Beam to Sill Joint</td>
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<tr>
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<td>Lower Trunnion Bridge Beam to Lower Trunnion Bridge Beam Elbow</td>
</tr>
<tr>
<td>2.5.1.8</td>
<td>Lower Trunnion Bridge Beam to Lower Vacuum Case Joint</td>
</tr>
</tbody>
</table>
2.5.1.1 Upper Vacuum Case Joint to Upper Trunnion Bridge
Upper Vacuum Case Joint to Upper Trunnion Bridge Beam Rivet Analysis

The Upper Vacuum Case Joint SDG39135727 connects to the Upper Trunnion Bridge Beam SDG39135728 in 4 locations. The upper vacuum case is fastened to the upper bridge beam, with NAS1398M8, 0.25 in rivets. The upper vacuum case is machined from 7050-T7451 plate and the upper trunnion bridge beam is extruded from 7075-T73511. CBEAM elements 1121, 1122, 1123, and 1124 in the loads model represents the portion of the vacuum case joint that interfaces with the bridge beam.

Material Strength for Rivets:
Rivets are NAS1398 type M, 0.25 in. blind protruding head Monel rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength $F_s = 2840 \text{ lbf}$

Material Strength for Upper Trunnion Bridge Beam:
Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))
Allowable bearing strength $F_{bru} = 119000 \text{ psi}$
Allowable shear strength $F_{su} = 35000 \text{ psi}$

Factors of safety:
Ultimate Factor of Safety: $F_{Su} := 1.4$
Fitting Factor: $F_{F} := 1.15$

Temperature:
Maximum Temperature $T_{max} := 150 \text{ deg}$
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For Fs) $c_{f} := 0.98$
(Ref. Appendix C5)
Temperature Correction Factor (For Fsu) $c_{d} := 0.99$
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For Fbru) $c_{b} := 0.92$
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "upperVCJtoUTBB.dat" for elements 1121, 1122, 1123, and 1124.
**Beam Section Properties:**

- Thickness of tube: $t := 0.25\text{\text{in}}$ (Ref. SDG39135728)
- Width of tube: $ap := 5.062\text{\text{in}}$ (Ref. SDG39135728)
- Depth of tube: $bp := 6.312\text{\text{in}}$ (Ref. SDG39135728)
- Enclosed area of mean width and mean height: $Am := (ap - t) \cdot (bp - t) \quad Am = 29.17\text{\text{in}^2}$

**Figure 2.5.1.1-1 Rivet Pattern Dimensions for Beam Element End A.**

Note: Figure is for reference only.

Note: The A and B ends of the beam elements that lay inside of the socket of the Vacuum Case Joint are tied to RBE elements that are "spidered" out to shell elements. This modeling technique stiffens the beam element inside of the socket allowing for lower loads at ends A and B. Therefore, loads are taken from end A of elements 1121, 1122, 1123, and 1124. A moment extrapolation from End A is performed to locate the moments at the center of the rivet pattern.

**Reading in Data File:**

```
data := READPRN("upperVCJtoUTBB.dat")  
ORIGIN := 1  
i := 1..rows(data)
```
Loads at End A of the Rivet Pattern:

Axial Load: \[ F_{xa} := \text{data}_{i,7} \text{lbf} \]
Shear in Y axis: \[ F_{ya} := \text{data}_{i,5} \text{lbf} \]
Shear in Z axis: \[ F_{za} := \text{data}_{i,6} \text{lbf} \]
Torsion: \[ M_{xa} := \text{data}_{i,8} \text{in-lbf} \]
Moment about Y axis: \[ M_{ya} := -\text{data}_{i,4} \text{in-lbf} \]
Moment about Z axis: \[ M_{za} := \text{data}_{i,3} \text{in-lbf} \]
Element Identification: \[ \text{ID}_{i} := \text{data}_{i,1} \]
Load Case Number: \[ \text{LC}_{i} := \text{data}_{i,2} \]

Extrapolation of Moments:

A moment extrapolation from End A is performed to locate moments at the center of the rivet pattern.

Distance from beam end A to the center of the rivet pattern: \[ \text{dist} := 2.27 \text{in} \] (Ref. Figure 2.5.1.1-1 and Appendix C4)

Extrapolation of My Moment: \[ M_{yi} := M_{ya} + F_{za} \cdot \text{dist} \]
Extrapolation of Mz Moment: \[ M_{zi} := M_{za} + F_{ya} \cdot \text{dist} \]
Load in Rivets at Upper Bridge Beam to Vacuum Case Joint:

Total Number of rivets in beam end:

\( N_{sp} := 80 \)

Number of rivets reacting \( F_z \) shear load:

\( p_{sz} := 40 \)

Number of rivets reacting \( F_y \) shear loads:

\( p_{sy} := 40 \)

Shear load/rivet due to \( F_y \)

\[ F_{sry} := \frac{F_y}{p_{sy}} \]

\( \text{max}(F_{sry}) = 45.9 \text{ lbf} \)

Shear load/rivet due to \( F_z \)

\[ F_{srz} := \frac{F_z}{p_{sz}} \]

\( \text{max}(F_{srz}) = 63.6 \text{ lbf} \)

Shear flow due to torsion
(Ref. Bruhn section A6.8)

\[ F_{srt} := \frac{M_x}{2 \cdot Am} \]

\( \text{max}(F_{srt}) = 361 \text{ lbf/in} \)

Note: The shear load (\( F_{srt} \)) is used to calculate the torsional load (\( P_{srt} \)) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.1-2.
Upper Vacuum Case Joint to Upper Trunnion Bridge Beam Rivet Analysis

Figure 2.5.1.1-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
**Calculation of Rivet Pitch:**

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

- **Perimeter of rivet pattern**
  
  \[ \text{per} := 2 \cdot \text{ap} + 2 \cdot \text{bp} \quad \text{per} = 22.7 \, \text{in} \]

- **Loads in rivet due to torsion**
  
  \[ \text{Psrt} := \frac{\text{Fsr} \cdot \text{per}}{\text{Nsp}} \quad \text{max}(\text{Psrt}) = 102.7 \, \text{lbf} \]

- **Shear load in rivets due to beam axial load**
  
  \[ \text{Prta} := \frac{\text{Fxa}}{\text{Nsp}} \quad \text{max}(\text{Prta}) = 443.8 \, \text{lbf} \]
Rivet Dimension Variables:
(Ref. SDG39135728)

\[
\begin{align*}
z_1 & := .500\text{-in} \\
z_2 & := 1.500\text{-in} \\
z_3 & := 2.531\text{-in} \\
y_1 & := .750\text{-in} \\
y_2 & := 1.500\text{-in} \\
y_3 & := 3.156\text{-in}
\end{align*}
\]

Eccentrically Loaded Rivets due to My and Mz Moments:

- **Rivet Coordinate System Data**

\[
j := 1..\text{rows(coord)} \quad \text{Counter for Coordinate Points}
\]

\[
x_{j} := \text{coord}_{j,2} \quad \text{Rivet Coordinate Points for x-direction}
\]

\[
y_{j} := \text{coord}_{j,3} \quad \text{Rivet Coordinate Points for y-direction}
\]

\[
z_{j} := \text{coord}_{j,4} \quad \text{Rivet Coordinate Points for z-direction}
\]

Note: Figure is for reference only.
Upper Vacuum Case Joint to Upper Trunnion Bridge Beam Rivet Analysis

For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

Cross-Section A-A
(Row 1, 20 rivets)

Cross-Section B-B
(Row 2, 20 rivets)

Cross-Section C-C
(Represents both sides, 40 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[
\text{sigry} := \frac{1}{\sum_{j=1}^{\text{rows(coord)}} (r_y)_j^2}
\]

Sum of the radial directions for all rivets in the rivet pattern

\[
\beta_{y_j} := \arctan2(x_j, z_j)
\]

Angle between resultant vector and tension or shear vectors

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section D-D
(Row 1, 20 rivets)

Cross-Section E-E
(Row 2, 20 rivets)

Cross-Section F-F
(Represents top and bottom, 40 rivets)

Note: Figure is for reference only.
\[ r_{z_j} := \left( x_j^2 + y_j^2 \right)^{1/2} \]
Radial distance to each rivet from the centroid of the rivet pattern

\[ \sigma_{rz} := \sum_{j=1}^{\text{rows(coord)}} (r_{z_j})^2 \]
Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_{z_j} := \arctan(\frac{y_j}{x_j}) \]
Angle between resultant vector and tension or shear vectors

\[ F_{zm_{i,j}} := \frac{M_z \cdot r_{z_j}}{\sigma_{rz}} \]
Resultant Load at Each Rivet

(Note: The angle \( \theta \) is defined off of the x-axis.
See below.)

\[ F_{y_mz_{i,j}} := F_{zm_{i,j}} \cdot \sin\left( \frac{\beta_{z_j}}{2} \right) \]
y - component of \( F_{zm_{i,j}} \)

\[ F_{x_mz_{i,j}} := F_{zm_{i,j}} \cdot \cos\left( \frac{\beta_{z_j}}{2} \right) \]
x - component of \( F_{zm_{i,j}} \)

\[ F_{i,j} := \begin{cases} F_{zm_{i,j}} & \text{if } \text{rivet_counter}_j \leq 40 \\ F_{y_mz_{i,j}} & \text{otherwise} \end{cases} \]
Total Axial Load due to \( M_y \) and \( M_z \) Moments

\[ \max(F) = 449.8 \text{ lbf} \]
Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.2 for beam and socket analysis.
Total Rivet Shear Load:

\[
P_{tij} := \begin{cases} 
\sqrt{(Pr_{t1} + Fx_{my_{i,j}} + Fx_{mz_{i,j}})^2 + (Ps_{rt_{i}} + Fs_{ry_{i}} + Fy_{my_{i,j}})^2} & \text{if } j \leq 40 \\
\sqrt{(Pr_{t1} + Fx_{my_{i,j}} + Fx_{mz_{i,j}})^2 + (Ps_{rt_{i}} + Fs_{rz_{i}} + Fz_{my_{i,j}})^2} & \text{otherwise}
\end{cases}
\]

\[
\text{max}(P_t) = 1476.8\text{-lbf}
\]

Margin of safety for Total Rivet Load:

\[
MS_{1t} := \frac{F_{sc-f}}{F_{t-FS} \cdot FF} - 1
\]

\[
\text{min}(MS_{1t}) = 0.171 \quad \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)}
\]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment(ID, LC, MS}_{1t})
\]

\[
\text{rows(output)} = 768 \quad \text{Number of rows in the "output" array}
\]

\[
\text{cols(output)} = 82 \quad \text{Number of columns in the "output" array}
\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{match(min(MS}_{1t}), MS_{1t}) = \begin{bmatrix} 575 \\ 40 \end{bmatrix}
\]

\[
\text{min}_{-LC} := \text{output}_{575,2}
\]

\[
\text{min}_{-ID} := \text{output}_{575,1}
\]

Load Case for Minimum Margin of Safety

Element ID for Minimum Margin of Safety

Rivet number 40 is the rivet with the minimum margins of safety of 0.171.
Minimum Margin of Safety:

Minimum Margin of Safety \( \min(MS1t) = 0.171 \)

Element ID for Minimum Margin of Safety \( \min_{ID} = 1123 \)

Load Case for Minimum Margin of Safety \( \min_{LC} = 4016 \)

Maximum Rivet Load for Minimum Margin of Safety \( \max(P_t) = 1476.8 \text{ lbf} \)

Rivets with Minimum Margin of Safety

Rivet number 40

(See figure 2.5.1.1 - 6 for rivet location)
**Bearing on Hole Wall:**

Hole diameter \( dh := 0.257 \text{ in} \)  
(Ref. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25 \text{ in} \)  
(Ref. SDG39135728)

Bearing area \( Ab := dh \cdot tp \)  
\( Ab = 0.06425 \text{ in}^2 \)

Max. load per rivet \( \max(P_t) = 1476.8 \text{ lbf} \)

Max. bearing stress \( b := \frac{\max(P_t)}{Ab} \)  
\( b = 22985.8 \text{ psi} \)

Margin of safety \( MSb := \frac{F_{bru} - cb}{b \cdot F_{Su} \cdot F_F} - 1 \)  
\( MSb = 1.96 \)

**Shear tear out:**

Edge distance \( e := 0.520 \text{ in} \)  
(Ref. SDG39135727)

Note: Using this e is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257 \text{ in} \)

\( E \) over D ratio \( \frac{e}{dh} = 2.023 \)

Tube thickness \( tp := 0.25 \text{ in} \)

Shear out area \( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40\text{-deg}) \right) \cdot tp \)  
\( As = 0.2108 \text{ in}^2 \)

Max. load per rivet \( \max(P_t) = 1476.8 \text{ lbf} \)

Max. shear tear out stress \( s := \frac{\max(P_t)}{As} \)  
\( s = 7006.5 \text{ psi} \)

Margin of safety \( MSsh := \frac{F_{Su} \cdot cd}{s \cdot F_{Su} \cdot F_F} - 1 \)  
\( MSsh = 2.072 \)
2.5.1.2  Lower Trunnion Bridge Beam Elbow to Sill Joint
Lower Trunnion Bridge Beam Elbow to Sill Joint Rivet Analysis

The elbow joint SDG39135734 connects the sill joint SDG39135730 to the lower trunnion bridge beam, SDG39135735 in 4 locations. The upper end of the elbow joint is fastened to the sill joint, with NAS1398M8, 0.25 in rivets. The elbow joint and the sill joint are machined from 7050-T7451 plate. CBEAM elements 1217, 1218, 1219, and 1220 in the loads model represent the portion of the elbow joint that interfaces with the sill joint. The rivet pattern centroid is 2.250 in from end A of the beam element. Element length is 7.164 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:
Rivets are NAS1398 type M, 0.25 in. blind protruding head Monel rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength $F_s := 2840$ lbf

Material Strength for Lower Trunnion Bridge Beam Elbow:
Joint material is 7050-T7451 with $e/D=2.0$
(Ref. MIL-HDBK-5J, Table 3.7.4.0(b1))
Allowable bearing strength $F_{bru} := 132000$ psi
Allowable shear strength $F_{su} := 44000$ psi

Factors of safety:
Ultimate Factor of Safety: $F_{su} := 1.4$
Fitting Factor: $FF := 1.15$

Loads model 2-06 was run in NASTRAN for 128 load cases, launch and abort landing. Beam element forces were recovered, and given in the data file "ElbowtoTSillJoint_launch_abort.dat" for elements 1217, 1218, 1219, and 1220.

Temperature:
Maximum Temperature $T_{max} := 150$ deg
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For $F_s$) $cf := .99$
(Ref. Appendix C5)
Temperature Correction Factor (For $F_{su}$) $cd := .94$
(Ref. MIL-HDBK-5J, Figure 3.7.4.2.1)
Temperature Correction Factor (For $F_{bru}$) $cb := .94$
(Ref. MIL-HDBK-5J, Figure 3.7.4.2.1)
**Loads from Beam End A:**

- **Axial Load**
  \[ F_{xa,i} := \text{data}_{i,7} \text{lbf} \]

- **Shear in Y axis**
  \[ F_{ya,i} := \text{data}_{i,5} \text{lbf} \]

- **Shear in Z axis**
  \[ F_{za,i} := \text{data}_{i,6} \text{lbf} \]

- **Torsion**
  \[ M_{xa,i} := \text{data}_{i,8} \text{in-lbf} \]

- **Moment about Y axis**
  \[ M_{ya,i} := -\text{data}_{i,4} \text{in-lbf} \]

- **Moment about Z axis**
  \[ M_{za,i} := \text{data}_{i,3} \text{in-lbf} \]

- **ID**: \[ i \]
- **LC**: \[ i \]

**Loads from Beam End B:**

- **Axial Load**
  \[ F_{xb,i} := \text{data}_{i,13} \text{lbf} \]

- **Shear in Y axis**
  \[ F_{yb,i} := \text{data}_{i,11} \text{lbf} \]

- **Shear in Z axis**
  \[ F_{zb,i} := \text{data}_{i,12} \text{lbf} \]

- **Torsion**
  \[ M_{xb,i} := \text{data}_{i,14} \text{in-lbf} \]

- **Moment about Y axis**
  \[ M_{yb,i} := -\text{data}_{i,10} \text{in-lbf} \]

- **Moment about Z axis**
  \[ M_{zb,i} := \text{data}_{i,9} \text{in-lbf} \]

**Beam Section Properties:**

- **Thickness of tube**
  \[ t := 0.25 \text{in} \] (Ref. SDG39135734)

- **Width of tube**
  \[ a := 5.938 \text{in} \] (Ref. SDG39135734)

- **Depth of tube**
  \[ b := 5.938 \text{in} \] (Ref. SDG39135734)

- **Enclosed area of mean width and mean height**
  \[ A_m := (a - t) \times (b - t) \]
  \[ A_m = 32.35 \text{in}^2 \]

---

**Figure 2.5.1.2-1** Rivet Pattern Dimensions for Beam Element Ends A and B.

*Note: Figure is for reference only.*
Bending Moment Interpolation:

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern \( c := 2.250\text{-in} \)
Total length of beam element \( d := 7.164\text{-in} \)

Moment My:

Difference \( My_{diff} := (My_a - My_b) \)
Linerally interpolate at centroid of rivets

\[
My_1 := \frac{c}{d} \cdot My_{diff} \quad My_2 := \frac{d - c}{d} \cdot My_{diff}
\]

Moment My interpolated at centroid of rivets \( My := My_b + My_2 \)

Moment Mz:

Difference \( Mz_{diff} := (Mz_a - Mz_b) \)
Linerally interpolate at centroid of rivets

\[
Mz_1 := \frac{c}{d} \cdot Mz_{diff} \quad Mz_2 := \frac{d - c}{d} \cdot Mz_{diff}
\]

Moment Mz interpolated at centroid of rivets \( Mz := Mz_b + Mz_2 \)

Free Body Diagram for Moment Distribution for My Interpolation
(Note: Similar moment distribution is used for Mz interpolation.)
Beam and Socket

Assume Beam and Socket takes 5% of the entire load. Therefore moments $M_y$ and $M_z$ have been reduced to 95%.

- Moment $M_y$ \[ M_y := M_y \cdot 0.95 \]
- Moment $M_z$ \[ M_z := M_z \cdot 0.95 \]

**Load in Rivets at Lower Bridge Beam to Elbow Joint:**

- Total Number of rivets in beam end:
  \[ N_{ps} := 96 \]

  Number of rivets reacting $F_z$ shear load:
  \[ n_{sz} := 48 \]

  Number of rivets reacting $F_y$ shear loads:
  \[ n_{sy} := 48 \]

\[
\text{Shear load/rivet due to } F_y = \frac{F_{ya}}{n_{sy}} \quad \text{max}(F_{sry}) = 34.9 \text{ lbf}
\]

\[
\text{Shear load/rivet due to } F_z = \frac{F_{za}}{n_{sz}} \quad \text{max}(F_{srz}) = 698.2 \text{ lbf}
\]

Note: The $F_{ya}$ and $F_{za}$ forces have the same magnitude as the $F_{yb}$ and $F_{zb}$ forces. The end A forces are used above.

\[
\text{Shear flow due to torsion} \quad \text{(Ref. Bruhn section A6.8)}
\]

\[
F_{srt} = \frac{M_{xa}}{2 \cdot A_m} \quad \text{max}(F_{srt}) = 234.2 \text{ lbf in}
\]

Note: The shear load ($F_{srt}$) is used to calculate the torsional load ($P_{srt}$) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.2-2.
Figure 2.5.1.2-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \]

\[ \text{per} = 23.8 \text{-in} \]

Loads in rivet due to torsion

\[ \text{Psrt} := \frac{\text{per}}{\text{Nsps}} \]

\[ \max(\text{Psrt}) = 57.9 \text{-lbf} \]

Shear load in rivets due to beam axial load

\[ \text{Prta} := \frac{\text{Nxa}}{\text{Nsps}} \]

\[ \max(\text{Prta}) = 347 \text{-lbf} \]
Rivet Dimension Variables:
(Ref. SDG39135735 and SDG39135734)

\[ z_1 := 0.500 \text{ in} \]
\[ z_2 := 1.375 \text{ in} \]
\[ z_3 := 2.250 \text{ in} \]
\[ z_4 := 2.969 \text{ in} \]
\[ y_1 := 0.500 \text{ in} \]
\[ y_2 := 1.375 \text{ in} \]
\[ y_3 := 2.250 \text{ in} \]
\[ y_4 := 2.969 \text{ in} \]

Note: Figure is for reference only.

**Eccentrically Loaded Rivets due to My and Mz Moments:**

- \( j \) := 1..rows(coord)  Counter for Coordinate Points
- \( x_j := \text{coord}_{j,2} \)  Rivet Coordinate Points for x-direction
- \( y_j := \text{coord}_{j,3} \)  Rivet Coordinate Points for y-direction
- \( z_j := \text{coord}_{j,4} \)  Rivet Coordinate Points for z-direction
For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

Cross-Section A-A
(Row 1, 20 rivets)

Cross-Section B-B
(Row 2, 16 rivets)

Cross-Section C-C
(Row 3, 12 rivets)

Cross-Section D-D
(Represents both sides, 24 rivets)

Note: Figure is for reference only.
\[ r_y \; := \; \left[ \left( x_j \right)^2 + \left( z_j \right)^2 \right]^{\frac{1}{2}} \]

radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sigry} \; := \; \sum_{j = 1}^{\text{rows(coord)}} \left( r_y \right)^2 \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_y \; := \; \text{atan2}(x_j, z_j) \]

Angle between resultant vector and tension or shear vectors

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

\[ F_{ym_{i,j}} \; := \; \frac{(-M_y)_i \cdot r_y}{\text{sigry}} \]

Resultant Load at Each Rivet

\[ F_{z_{my_{i,j}}} \; := \; F_{ym_{i,j}} \cdot \sin \left( \frac{u}{2} - \beta_y \right) \]

z - component of \( F_{ym} \)

\[ F_{x_{my_{i,j}}} \; := \; F_{ym_{i,j}} \cdot \cos \left( \frac{u}{2} - \beta_y \right) \]

x - component of \( F_{ym} \)
For Moment $M_z$:

Eccentrically Loaded Rivet Pattern about $M_z$

Cross-Section E-E
(Row 1, 20 rivets)

Cross-Section F-F
(Row 2, 16 rivets)

Cross-Section G-G
(Row 3, 12 rivets)

Cross-Section H-H
(Represents both sides, 24 rivets)

Note: Figure is for reference only.
rz_j :=[(x_j)^2 + (y_j)^2]^{-1/2}

Radial distance to each rivet from the centroid of the rivet pattern along the z-axis

\[ \text{sigrz := \sum_{j=1}^{\text{rows(coord)}} (rz_j)^2} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_z := \text{atan2}(x_j, y_j) \]

Angle between resultant vector and tension or shear vectors

\[ F_{zm_{i,j}} := \frac{(M_z)_i \cdot rz_j}{\text{sigrz}} \]

Resultant Load at Each Rivet

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

\[
F_{zm_{i,j}} := F_{zm_{i,j}} \cdot \sin \left( \frac{\theta}{2} - \beta_z \right) \quad \text{y - component of Fzm}
\]

\[
F_{x_{mz_{i,j}}} := F_{zm_{i,j}} \cdot \cos \left( \frac{\theta}{2} - \beta_z \right) \quad \text{x - component of Fzm}
\]

\[
F_{i,j} := \begin{cases} 
F_{zm_{i,j}} & \text{if } \text{rivet_counter}_{j} \leq 48 \\
F_{y_{mz_{i,j}}} & \text{otherwise}
\end{cases}
\]

Total Axial Load due to My and Mz Moments

\[
\max(F_{i,j}) = 635.2 \text{ lbf}
\]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.8 for beam and socket analysis.
Total Rivet Shear Load:

\[ P_{t_{i,j}} := \begin{cases} \left( \sqrt{\left( P_{r t_{i}} + F_{x_{m y_{i,j}}} + F_{x_{m z_{i,j}}} \right)^2 + \left( P_{s r t_{i}} + F_{s r y_{i}} + F_{y_{m z_{i,j}}} \right)^2} \right) & \text{if } j \leq 48 \\ \sqrt{\left( P_{r t_{i}} + F_{x_{m y_{i,j}}} + F_{x_{m z_{i,j}}} \right)^2 + \left( P_{s r t_{i}} + F_{s r z_{i}} + F_{z_{m y_{i,j}}} \right)^2} & \text{otherwise} \end{cases} \]

\[ \text{max}(P_t) = 1703.1 \text{ lbf} \]

Margin of safety for Total Rivet Load:

\[ M_{S1t} := \frac{F_{scf}}{P_{t} \cdot F_{Su} \cdot FF} - 1 \]

min(MS1t) = 0.025 \hspace{1cm} \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)}

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment}(\text{ID}, \text{LC}, M_{S1t})
\]

\[
\text{rows(output)} = 512 \hspace{1cm} \text{Number of rows in the "output" array}
\]

\[
\text{cols(output)} = 98 \hspace{1cm} \text{Number of columns in the "output" array}
\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[ \text{match(min(MS1t), MS1t)} = \begin{bmatrix} 313 \\ 49 \end{bmatrix} \]

\[ \text{min_LC} := \text{output}_{313,2} \hspace{1cm} \text{Load Case for Minimum Margin of Safety} \]

\[ \text{min_ID} := \text{output}_{313,1} \hspace{1cm} \text{Element ID for Minimum Margin of Safety} \]

Rivet number 49 is the rivets with the minimum margin of safety of 0.025
Minimum Margin of Safety:

Minimum Margin of Safety

\[ \text{min}(MS_{1t}) = 0.025 \]

Element ID for Minimum Margin of Safety

\[ \text{min}_\text{ID} = 1217 \]

Load Case for Minimum Margin of Safety

\[ \text{min}_\text{LC} = 2015 \]

Maximum Rivet Load for Minimum Margin of Safety

\[ \text{max}(P_t) = 1703.1 \text{ lbf} \]

Rivets with Minimum Margin of Safety

Rivet number 49

(See figure 2.5.1.2 - 2 for rivet location)
**Bearing on Hole Wall:**

Hole diameter \( dh := 0.257\text{-in} \)  
(Ref. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25\text{-in} \)  
(Ref. SDG39135734)

Bearing area \( Ab := dh \cdot tp \)  
\( Ab = 0.06425\text{-in}^2 \)

Max. load per rivet \( \max(P_t) = 1703.1\text{-lbf} \)

Max. bearing stress \( b := \frac{\max(P_t)}{Ab} \)  
\( b = 26507.2\text{-psi} \)

Margin of safety \( MS_b := \frac{F_{bru-cb}}{b \cdot F_{Su-cF}} - 1 \)  
\( MS_b = 1.91 \)

**Shear tear out:**

Edge distance \( e := 0.500\text{-in} \)  
(Ref. SDG39135730)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257\text{-in} \)

\( E \) over \( D \) ratio \( \frac{e}{dh} = 1.946 \)

Tube thickness \( tp := 0.25\text{-in} \)

Shear out area \( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40\text{-deg}) \right) \cdot tp \)  
\( As = 0.2008\text{-in}^2 \)

Max. load per rivet \( \max(P_t) = 1703.1\text{-lbf} \)

Max. shear tear out stress \( s := \frac{\max(P_t)}{As} \)  
\( s = 8482.3\text{-psi} \)

Margin of safety \( MS_{sh} := \frac{F_{su-cd}}{s \cdot F_{Su-cF}} - 1 \)  
\( MS_{sh} = 2.029 \)
2.5.1.3 Sill Bracket to Sill Tube
Sill Bracket to Sill Tube Rivet Analysis

The sill bracket SDG39135738 connects to the sill tube SDG39135739 in 2 locations. The sill bracket is fastened to the sill tube, with NAS1398DFC8, 0.25 in rivets. The sill bracket is machined from 7050-T7451 plate and the sill tube is extruded from 7075-T73511. CBEAM elements 1705 and 1706 in the loads model represents the portion of the sill bracket that interfaces with the sill tube. The rivet pattern centroid is 3.918 in from end A of the beam element. Element length is 5.750 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:

Rivets are NAS1398 type D, 0.25 in. blind protruding head 2017 Aluminum rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength \( F_s = 1970 \text{ lbf} \)

Material Strength for Sill Tube:

Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))
Allowable bearing strength \( F_{bru} = 119000 \text{ psi} \)
Allowable shear strength \( F_{su} = 35000 \text{ psi} \)

Factors of safety:

Ultimate Factor of Safety: \( F_{Su} = 1.4 \)
Fitting Factor: \( FF = 1.15 \)

Temperature:

Maximum Temperature \( T_{max} = 150 \text{ deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For \( F_s \)) \( cf := 0.98 \)
(Ref. Appendix C13)
Temperature Correction Factor (For \( F_{su} \)) \( cd := 0.99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For \( F_{bru} \)) \( cb := 0.92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "SjointtoStube.dat" for elements 1705 and 1706.

```
data := READPRN("SjointtoStube.dat")
ORIGIN := 1
i := 1..rows(data)
```
Loads from Beam End A:

Axial Load \( F_{xa,i} := \text{data}_{i,7}\text{lbf} \)
Shear in Y axis \( F_{ya,i} := \text{data}_{i,5}\text{lbf} \)
Shear in Z axis \( F_{za,i} := \text{data}_{i,6}\text{lbf} \)
Torsion \( M_{xa,i} := \text{data}_{i,8}\text{in-lbf} \)
Moment about Y axis \( M_{ya,i} := -\text{data}_{i,4}\text{in-lbf} \)
Moment about Z axis \( M_{za,i} := \text{data}_{i,3}\text{in-lbf} \)
ID \( i \) := data_{i,1} \quad LC \( i \) := data_{i,2}

Beam Section Properties:

Thickness of tube \( t := 0.25\text{in} \) (Ref. SDG39135739)
Width of tube \( a := 4.0\text{in} \) (Ref. SDG39135739)
Depth of tube \( b := 4.0\text{in} \) (Ref. SDG39135739)
Enclosed area of mean width and mean height \( A_m := (a - t) \cdot (b - t) \quad A_m = 14.06\text{in}^2 \)

Figure 2.5.1.3-1 Rivet Pattern Dimensions for Beam Element Ends A and B.

Note: Figure is for reference only.
**Bending Moment Interpolation:**

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern

\[ c := 3.918 \text{ in} \]  

(See Figure 2.5.1.3-1 and Ref. Appendix C4)

Total length of beam element

\[ d := 5.750 \text{ in} \]

Moment My:

\[
\text{Difference} \quad My_{diff,i} := \left(My_i - My_{b,i}\right)
\]

Linearly interpolate at centroid of rivets

\[
My_1 := \frac{c}{d} \cdot My_{diff} \\
My_2 := \frac{d - c}{d} \cdot My_{diff}
\]

Moment My interpolated at centroid of rivets

\[ My := My_b + My_2 \]

Moment Mz:

\[
\text{Difference} \quad Mz_{diff,i} := \left(Mz_i - Mz_{b,i}\right)
\]

Linearly interpolate at centroid of rivets

\[
Mz_1 := \frac{c}{d} \cdot Mz_{diff} \\
Mz_2 := \frac{d - c}{d} \cdot Mz_{diff}
\]

Moment Mz interpolated at centroid of rivets

\[ Mz := Mz_b + Mz_2 \]
**Sill Bracket to Sill Tube Rivet Analysis**

Load in Rivets at Lower Bridge Beam to Elbow Joint:

Total Number of rivets in beam end:

Nsps := 48

Number of rivets reacting Fz shear load:

psz := 24

Number of rivets reacting Fy shear loads:

psy := 24

Shear load/rivet due to Fy

\[ F_{sry} := \frac{F_{ya}}{psy} \]

\[ \text{max}(F_{sry}) = 21.5 \text{ lbf} \]

Shear load/rivet due to Fz

\[ F_{srz} := \frac{F_{za}}{psz} \]

\[ \text{max}(F_{srz}) = 35.4 \text{ lbf} \]

Note: The Fya and Fza forces have the same magnitude as the Fyb and Fzb forces. The end A forces are used above.

Shear flow due to torsion

(Ref. Bruhn section A6.8)

\[ F_{sr} := \frac{M_{xa}}{2 \cdot A_m} \]

\[ \text{max}(F_{sr}) = 20.2 \text{ lbf/in} \]

Note: The shear load (Fsr) is used to calculate the torsional load (Psrt) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.3-2.
Figure 2.5.1.3-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \quad \text{per} = 16 \text{-in} \]

Loads in rivet due to torsion

\[ \text{Psrt} := \text{Fsrt} \left( \frac{\text{per}}{\text{Nsps}} \right) \quad \text{max(Psrt)} = 6.7 \text{-lbf} \]

Shear load in rivets due to beam axial load

\[ \text{Prta} := \frac{\text{Fx}_a}{\text{Nsps}} \quad \text{max(Prta)} = 100.9 \text{-lbf} \]
Eccentrically Loaded Rivets due to My and Mz Moments:

Rivet Dimension Variables:
(Ref. SDG39135738)

\[
\begin{align*}
    z_1 & := 0.875 \text{ in} \\
    z_2 & := 2.00 \text{ in} \\
    z_3 & := 4.00 \text{ in} \\
    y_1 & := 0.875 \text{ in} \\
    y_2 & := 2.00 \text{ in} \\
    y_3 & := 4.00 \text{ in}
\end{align*}
\]

Note: Figure is for reference only.

Rivet Coordinate System Data

\[
\begin{align*}
    j & := 1..\text{rows(coord)} & \text{Counter for Coordinate Points} \\
    x_j & := \text{coord}_{j,2} & \text{Rivet Coordinate Points for x-direction} \\
    y_j & := \text{coord}_{j,3} & \text{Rivet Coordinate Points for y-direction} \\
    z_j & := \text{coord}_{j,4} & \text{Rivet Coordinate Points for z-direction}
\end{align*}
\]
For Moment My:

Eccentrically Loaded Rivet Pattern about My

Cross-Section A-A
(Row 1 and Row 2, 8 rivets ea.)

Cross-Section B-B
(Represents both sides, 12 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

Sum of the radial directions for all rivets in the rivet pattern

Angle between resultant vector and tension or shear vectors

(Notes: The angle θ is defined off of the x-axis. See below.)

Resultant Load at Each Rivet

z-component of Fym

x-component of Fym
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section C-C
(Row 1 and Row 2, 8 rivets ea.)

Cross-Section D-D
(Represents both sides, 12 rivets)

Note: Figure is for reference only.
\[ r_{z_j} := \left[ (x_j)^2 + (y_j)^2 \right]^{1/2} \]
Radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sig}_{rz} := \sum_{j=1}^{\text{rows(coord)}} (r_{z_j})^2 \]
Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_{z_j} := \arctan(\frac{x_j}{y_j}) \]
Angle between resultant vector and tension or shear vectors

\[ F_{z_{m_i,j}} := \frac{(-M_z) \cdot r_{z_j}}{\text{sig}_{rz}} \]
Resultant Load at Each Rivet

(\text{Note: The angle } \theta \text{ is defined off of the x-axis. See below.})

\[ F_{y_{mz_{i,j}}} := F_{z_{m_{i,j}}} \cdot \sin\left(\frac{\theta}{2} - \beta_{z_j}\right) \]
\( y \)-component of \( F_{zm} \)

\[ F_{x_{mz_{i,j}}} := F_{z_{m_{i,j}}} \cdot \cos\left(\frac{\theta}{2} - \beta_{z_j}\right) \]
\( x \)-component of \( F_{zm} \)

\[ F_{i,j} := \begin{cases} F_{z_{my_{i,j}}} & \text{if } \text{rivet_counter}_{j} \leq 24 \\ F_{y_{mz_{i,j}}} & \text{otherwise} \end{cases} \]
Total Axial Load due to \( M_y \) and \( M_z \) Moments

\[ \max\left| F \right| = 210.9 \text{-lbf} \]

\text{Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.11 for beam and socket analysis.}
Total Rivet Shear Load:

\[
Pt_{i,j} := \begin{cases} 
\sqrt{\left(P_{rt_{i}} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}}\right)^2 + \left(P_{sr_{i}} + F_{sry_{i}} + F_{y_{mz_{i,j}}}\right)^2} & \text{if } j \leq 24 \\
\sqrt{\left(P_{rt_{i}} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}}\right)^2 + \left(P_{sr_{i}} + F_{srx_{i}} + F_{z_{mz_{i,j}}}\right)^2} & \text{otherwise}
\end{cases}
\]

\[
\max(P_t) = 532.2 \text{ lbf}
\]

Margin of safety for Total Rivet Load:

\[
MS_{1t} := \frac{F_s \cdot cf}{P_t \cdot FSu \cdot FF} - 1
\]

\[
\min(MS_{1t}) = 1.253
\]

(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment(ID, LC, MS}_{1t})
\]

\[
\text{rows(output)} = 384 \quad \text{Number of rows in the "output" array}
\]

\[
\text{cols(output)} = 50 \quad \text{Number of columns in the "output" array}
\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{match(min(MS}_{1t}, MS_{1t}) = \begin{bmatrix} 40 \\ 13 \end{bmatrix}}
\]

\[
\text{min}_{LC} := \text{output}_{40,2} \quad \text{Load Case for Minimum Margin of Safety}
\]

\[
\text{min}_{ID} := \text{output}_{40,1} \quad \text{Element ID for Minimum Margin of Safety}
\]

Rivet numbers 13 are the rivets with the minimum margin of safety of 1.253.
Minimum Margin of Safety:

Minimum Margin of Safety
\[ \text{min}(MS1t) = 1.253 \]

Element ID for Minimum Margin of Safety
\[ \text{min\_ID} = 1706 \]

Load Case for Minimum Margin of Safety
\[ \text{min\_LC} = 1020 \]

Maximum Rivet Load for Minimum Margin of Safety
\[ \text{max}(Pt) = 532.2 \text{lbf} \]

Rivets with Minimum Margin of Safety
Rivet numbers 13
(See figure 2.5.1.3 - 2 for rivet location)
**Bearing on Hole Wall:**

- **Hole diameter** $dh := 0.257\text{-in}$ (Ref. SEG39135726, Flag Note 2)
- **Tube thickness** $tp := 0.25\text{-in}$ (Ref. SDG39135739)
- **Bearing area** $Ab := dh \cdot tp$ $\quad Ab = 0.064\text{-in}^2$

Max. load per rivet $\quad \text{max}(Pt) = 532.2\text{lbf}$

Max. bearing stress $\quad b := \frac{\text{max}(Pt)}{Ab}$ $\quad b = 8282.6\text{ psi}$

Margin of safety $\quad \text{MSb} := \frac{F_{b\text{ru}-cb}}{b \cdot F_{Su} \cdot F_{F}} - 1$ $\quad \text{MSb} = 7.21$

**Shear tear out:**

- **Edge distance** $e := 0.520\text{-in}$ (Ref. SDG39135738)  
  Note: Using this $e$ is conservative, since actual rivet force is in general at some angle.

- **Hole diameter** $dh := 0.257\text{-in}$
- **E over D ratio** $\quad \frac{e}{dh} = 2.023$

- **Tube thickness** $tp := 0.25\text{-in}$
- **Shear out area** $\quad As := 2 \left( e - \frac{dh}{2} \cos(40\text{-deg}) \right) \cdot tp$ $\quad As = 0.2108\text{-in}^2$

Max. load per rivet $\quad \text{max}(Pt) = 532.2\text{lbf}$

Max. shear tear out stress $\quad s := \frac{\text{max}(Pt)}{As}$ $\quad s = 2524.7\text{ psi}$

Margin of safety $\quad \text{MSsh} := \frac{F_{s\text{u}-cd}}{s \cdot F_{Su} \cdot F_{F}} - 1$ $\quad \text{MSsh} = 7.525$
2.5.1.4 Diagonal Sill Bracket to Sill Tube
Diagonal Sill Bracket to Sill Tube Rivet Analysis

The diagonal sill bracket SDG39135740 connects to the sill tube SDG39135739 in 2 locations. The diagonal sill bracket is fastened to the sill tube, with NAS1398DF08, 0.25 in rivets. The diagonal sill bracket is machined from 7050-T7451 plate and the sill tube is extruded from 7075-T73511. CBEAM elements 1711 and 1712 in the loads model represents the portion of the diagonal sill bracket that interfaces with the sill tube. The rivet pattern centroid is 2.667 in from end A of the beam element. Element length is 4.500 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:
Rivets are NAS1398 type D, 0.25 in. blind protruding head 2017 Aluminum rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength \( F_s = 1970 \text{ lbf} \)

Material Strength for Sill Tube:
Tube material is extruded 7075-T73511 with \( e/D=2.0 \)
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))
Allowable bearing strength \( F_{bru} = 119000 \text{ psi} \)
Allowable shear strength \( F_{s} = 35000 \text{ psi} \)

Factors of safety:
Ultimate Factor of Safety: \( F_{su} = 1.4 \)
Fitting Factor: \( F_{F} = 1.15 \)

Temperature:
Maximum Temperature \( T_{max} = 150 \text{ deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For Fs) \( c_f = 0.98 \)
(Ref. Appendix C13)
Temperature Correction Factor (For Fsu) \( c_d = 0.99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For Fbru) \( c_b = 0.92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "SjointtoStube.dat" for elements 1711 and 1712.

data := READPRN("diagStoStube.dat")
Diagonal Sill Bracket to Sill Tube Rivet Analysis

** Loads from Beam End A:**

Axial Load \( F_{xa_i} := \text{data}_{i,7} \text{lbf} \)

Shear in Y axis \( F_{ya_i} := \text{data}_{i,5} \text{lbf} \)

Shear in Z axis \( F_{za_i} := \text{data}_{i,6} \text{lbf} \)

Torsion \( M_{xa_i} := \text{data}_{i,8} \text{in-lbf} \)

Moment about Y axis \( M_{ya_i} := -\text{data}_{i,4} \text{in-lbf} \)

Moment about Z axis \( M_{za_i} := \text{data}_{i,3} \text{in-lbf} \)

Total Torsional Moment due to y direction offset

\[ M_{xa} := M_{xa_i} + (F_{za_i} \cdot y_{cg}) \]

** Loads from Beam End B:**

Axial Load \( F_{xb_i} := \text{data}_{i,13} \text{lbf} \)

Shear in Y axis \( F_{yb_i} := \text{data}_{i,11} \text{lbf} \)

Shear in Z axis \( F_{zb_i} := \text{data}_{i,12} \text{lbf} \)

Torsion \( M_{xb_i} := \text{data}_{i,14} \text{in-lbf} \)

Moment about Y axis \( M_{yb_i} := -\text{data}_{i,10} \text{in-lbf} \)

Moment about Z axis \( M_{zb_i} := \text{data}_{i,9} \text{in-lbf} \)

** Beam Section Properties:**

Thickness of tube \( t := 0.25 \text{in} \) (Ref. SDG39135739)

Width of tube \( a := 4.0 \text{in} \) (Ref. SDG39135739)

Depth of tube \( b := 4.0 \text{in} \) (Ref. SDG39135739)

Enclosed area of mean width and mean height \( A_m := (a-t)(b-t) \quad A_m = 14.06 \text{in}^2 \)

** Figure 2.5.1.4-1** Rivet Pattern Dimensions for Beam Element Ends A and B.

Note: Figure is for reference only.
Bending Moment Interpolation:

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern
Total length of beam element
Moment My:

\[ \text{Difference } \text{Mydiff}_i := (\text{Mya}_i - \text{Myb}_i) \]

Linearly interpolate at centroid of rivets

\[ \text{My}_1 := \frac{c}{d} \cdot \text{Mydiff}_i, \quad \text{My}_2 := \frac{d - c}{d} \cdot \text{Mydiff}_i \]

Moment My interpolated at centroid of rivets

\[ \text{My} := \text{Myb} + \text{My2} \]

Moment Mz:

\[ \text{Difference } \text{Mzdiff}_i := (\text{Mza}_i - \text{Mzb}_i) \]

Linearly interpolate at centroid of rivets

\[ \text{Mz}_1 := \frac{c}{d} \cdot \text{Mzdiff}_i, \quad \text{Mz}_2 := \frac{d - c}{d} \cdot \text{Mzdiff}_i \]

Moment Mz interpolated at centroid of rivets

\[ \text{Mz} := \text{Mzb} + \text{Mz2} \]

Free Body Diagram for Moment Distribution for My Interpolation
(Note: Similar moment distribution is used for Mz interpolation.)
Load in Rivets at Diagonal Sill Bracket:

Total Number of rivets in beam end:
\[ N_{sp} := 44 \]

Number of rivets reacting \( F_z \) shear load:
\[ p_z := 20 \]

Number of rivets reacting \( F_y \) shear loads:
\[ p_y := 24 \]

Shear load/rivet due to \( F_y \)
\[ F_{sry} := \frac{F_y}{p_y} \quad \text{max}(F_{sry}) = 17.9\text{-lbf} \]

Shear load/rivet due to \( F_z \)
\[ F_{srz} := \frac{F_z}{p_z} \quad \text{max}(F_{srz}) = 33.9\text{-lbf} \]

Note: The \( F_y \) and \( F_z \) forces have the same magnitude as the \( F_y \) and \( F_z \) forces. The end \( A \) forces are used above.

Shear flow due to torsion
(Ref. Bruhn section A6.8)
\[ F_{srt} := \frac{M_x}{2A_m} \quad \text{max}(F_{srt}) = 17.6\text{-lbf/in} \]

Note: The shear load \( (F_{srt}) \) is used to calculate the torsional load \( (P_{srt}) \) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.4-2.
Figure 2.5.1.4-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:
It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern  
\[ \text{per} = 2 \cdot a + 2 \cdot b \quad \text{per} = 16\text{-in} \]

Loads in rivet due to torsion  
\[ P_{\text{sr}} := F_{\text{sr}} \left( \frac{\text{per}}{N_{\text{sp}}} \right) \quad \text{max}(P_{\text{sr}}) = 6.4\text{-lbf} \]

Shear load in rivets due to beam axial load  
\[ P_{\text{ta}} := \frac{F_{\text{xa}}}{N_{\text{sp}}} \quad \text{max}(P_{\text{ta}}) = 113.6\text{-lbf} \]
Diagonal Sill Bracket to Sill Tube Rivet Analysis

Rivet Dimension Variables:
(Ref. SDG39135738)

\[
\begin{align*}
z_1 & := 0.875 \text{ in} \\
z_2 & := 2.00 \text{ in} \\
z_3 & := 4.00 \text{ in} \\
y_1 & := 0.875 \text{ in} \\
y_2 & := 2.00 \text{ in} \\
y_3 & := 4.00 \text{ in}
\end{align*}
\]

Note: Figure is for reference only.

Eccentrically Loaded Rivets due to My and Mz Moments:

- **Rivet Coordinate System Data**
  - \( j := 1 \ldots \text{rows}(	ext{coord}) \) Counter for Coordinate Points
  - \( x_j := \text{coord}_{j,2} \) Rivet Coordinate Points for x-direction
  - \( y_j := \text{coord}_{j,3} \) Rivet Coordinate Points for y-direction
  - \( z_j := \text{coord}_{j,4} \) Rivet Coordinate Points for z-direction

\[
\text{rivet\_counter}_j := \frac{\text{coord}_{j,1}}{\text{in}}
\]
For Moment $M_y$: 

Eccentrically Loaded Rivet Pattern about $M_y$

Cross-Section A-A

Cross-Section B-B

Note: Figure is for reference only.
diagStoStube.mcd

Title: Diagonal Sill Bracket to Sill Tube Rivet Analysis

Radial distance to each rivet from the centroid of the rivet pattern

\[ r_{y_j} := \left( x_j^2 + z_j^2 \right)^{\frac{1}{2}} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \text{sigry} := \sum_{j=1}^{\text{rows(coord)}} (r_{y_j})^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_{y_j} := \frac{\text{atan2}(x_j, z_j)}{2 \pi} \]

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

Resultant Load at Each Rivet

\[ \text{Fym}_{i,j} := \frac{-\text{My}_{i,j} \cdot r_{y_j}}{\text{sigry}} \]

\[ \text{Fz}_{\text{my}, i,j} := \text{Fym}_{i,j} \cdot \sin \left( \frac{u}{2} - \beta_{y_j} \right) \]

\[ \text{Fx}_{\text{my}, i,j} := \text{Fym}_{i,j} \cdot \cos \left( \frac{u}{2} - \beta_{y_j} \right) \]

\[ \text{My}_{1,1} = 2016.9 \text{ in-lbf} \]
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section C-C
(Row 1, 6 rivets ea.)

Cross-Section D-D
(Row 2, 8 rivets ea.)

Cross-Section E-E
(Represents both sides, 24 rivets)

Note: Figure is for reference only.
Diagonal Sill Bracket to Sill Tube Rivet Analysis

\[ M_{z_i} := M_{z_i} + \left( F_{x_i} \cdot y_{cg} \right) \]

Radial distance to each rivet from the centroid of the rivet pattern

\[ r_{z_j} := \left[ \left( x_j \right)^2 + \left( y_j \right)^2 \right]^{\frac{1}{2}} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \Sigma_{\text{rows(coord)}} r_{z_j} := \sum_{j=1}^{\text{rows(coord)}} \left( r_{z_j} \right)^2 \]

Sum of the linear directions for all rivets in the rivet pattern

\[ \beta_{z_j} := \arctan \left( \frac{x_j}{y_j} \right) \]

Angle between resultant vector and tension or shear vectors

\[ F_{z_{i,j}} := \frac{M_{z_i} \cdot r_{z_j}}{\Sigma_{\text{rows(coord)}} r_{z_j}} \]

Resultant Load at Each Rivet

(Note: The angle \( \phi \) is defined off of the x-axis. See below.)

\[ F_{y_{mz_{i,j}}} := F_{z_{i,j}} \cdot \sin \left( \frac{u}{2} - \beta_{z_j} \right) \]

y - component of Fzm

\[ F_{x_{mz_{i,j}}} := F_{z_{i,j}} \cdot \cos \left( \frac{u}{2} - \beta_{z_j} \right) \]

x - component of Fzm

\[ F_{i,j} := \begin{cases} F_{z_{my_{i,j}}} & \text{if rivet_counter}_{j} \leq 24 \\ F_{y_{mz_{i,j}}} & \text{otherwise} \end{cases} \]

Total Axial Load due to My and Mz Moments

\[ \max \left( |F| \right) = 112.5 \text{-lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.11 for beam and socket analysis.
**Total Rivet Shear Load:**

\[
P_{t_{i,j}} := \begin{cases} \sqrt{(P_{rt_{i}} + F_{x_{my_{i,j}}})^2 + (P_{sr_{i}} + F_{y_{my_{i,j}}})^2} & \text{if } j \leq 24 \\ \sqrt{(P_{rt_{i}} + F_{x_{my_{i,j}}})^2 + (P_{sr_{i}} + F_{y_{my_{i,j}}})^2} & \text{otherwise} \end{cases}
\]

\[
\text{max}(P_t) = 319.9 \text{ lbf}
\]

**Margin of safety for Total Rivet Load:**

\[
MS_{1t} := \frac{F_{scf}}{P_{t_{FSu}}FF} - 1
\]

\[
\min(MS_{1t}) = 2.75 \quad \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)}
\]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

output := augment(ID, LC, MS1t)

rows(output) = 384 \quad \text{Number of rows in the "output" array}
cols(output) = 46 \quad \text{Number of columns in the "output" array}

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

match(min(MS1t), MS1t) = \begin{bmatrix} 32 \\ 4 \end{bmatrix}

\[
\text{min}_{-\text{LC}} := \text{output}_{32,2} \quad \text{Load Case for Minimum Margin of Safety}
\]

\[
\text{min}_{-\text{ID}} := \text{output}_{32,1} \quad \text{Element ID for Minimum Margin of Safety}
\]

Rivet number 4 is the rivet with the minimum margin of safety of 2.75.
**Minimum Margin of Safety:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Margin of Safety</td>
<td>min(MS1t) = 2.75</td>
</tr>
<tr>
<td>Element ID for Minimum Margin of Safety</td>
<td>min_ID = 1712</td>
</tr>
<tr>
<td>Load Case for Minimum Margin of Safety</td>
<td>min_LC = 1016</td>
</tr>
<tr>
<td>Maximum Rivet Load for Minimum Margin of Safety</td>
<td>max(Pt) = 319.9 lbf</td>
</tr>
<tr>
<td>Rivets with Minimum Margin of Safety</td>
<td>Rivet numbers 4 (See figure 2.5.1.4 - 2 for rivet location)</td>
</tr>
</tbody>
</table>
**Bearing on Hole Wall:**

Hole diameter \( dh := 0.257 \, \text{in} \)  
(Ref. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25 \, \text{in} \)  
(Ref. SDG39135739)

Bearing area \( Ab := dh \cdot tp \)  
\[ Ab = 0.064 \, \text{in}^2 \]

Max. load per rivet \( \max(P_t) = 319.9 \, \text{lbf} \)

Max. bearing stress \( b := \frac{\max(P_t)}{Ab} \)  
\[ b = 4978.5 \, \text{psi} \]

Margin of safety \( \text{MSb} := \frac{\text{Fb}-\text{cb}}{b \cdot \text{FSu} \cdot \text{FF}} - 1 \)  
\[ \text{MSb} = 12.66 \]

**Shear tear out:**

Edge distance \( e := 0.520 \, \text{in} \)  
(Ref. SDG39135740)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257 \, \text{in} \)

\( \frac{e}{dh} = 2.023 \)

 Tube thickness \( tp := 0.25 \, \text{in} \)

Shear out area \( \text{As} := 2 \left( e - \frac{dh}{2} \cos(40\,\text{deg}) \right) \cdot tp \)  
\[ \text{As} = 0.211 \, \text{in}^2 \]

Max. load per rivet \( \max(P_t) = 319.9 \, \text{lbf} \)

Max. shear tear out stress \( s := \frac{\max(P_t)}{\text{As}} \)  
\[ s = 1517.5 \, \text{psi} \]

Margin of safety \( \text{MSsh} := \frac{\text{Fsu} \cdot \text{cd}}{s \cdot \text{FSu} \cdot \text{FF}} - 1 \)  
\[ \text{MSsh} = 13.18 \]
2.5.1.5 Diagonal Strut Tube to Diagonal Strut End Fitting
Diagonal Strut Tube to Diagonal Strut Endfitting Rivet Analysis

The diagonal strut tube SDG39135742 connects to the diagonal strut endfitting SDG39135743 on both ends of the tube. There are a total of two diagonal struts in the USS-02 assembly. The diagonal strut tube is fastened to the endfitting, with NAS1398M8, 0.25 in rivets. The diagonal strut endfitting is machined from 7075-T7351 bar and the diagonal strut tube is extruded from 6061-T6511. CBEAM elements 1801 and 1803 in the loads model represents the portion of the diagonal strut tube that interfaces with the diagonal strut endfitting.

Material Strength for Rivets:

Rivets are NAS1398 type M, 0.25 in. blind protruding head Monel rivets
(Ref. NAS1400, sheet 5)

Max. rivet shear strength  $F_s := 2840 \text{ lbf}$

Material Strength for Diagonal Strut Tube:

Tube material is extruded 6061-T6511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.6.2.0(g))

Allowable bearing strength  $F_{bru} := 82000 \text{ psi}$
Allowable shear strength  $F_{sud} := 26000 \text{ psi}$

Factors of safety:

Ultimate Factor of Safety:  $F_{Su} := 1.4$
Fitting Factor:  $FF := 1.15$

Temperature:

Maximum Temperature  $T_{max} := 150 \text{ deg}$
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For Fs)  $cf := .98$
(Ref. Appendix C5)

Temperature Correction Factor (For Fsu)  $cd := .94$
(Ref. MIL-HDBK-5J, Figure 3.6.2.2.1(a))

Temperature Correction Factor (For Fbru)  $cb := .94$
(Ref. MIL-HDBK-5J, Figure 3.6.2.2.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Maximum axial beam element forces were recovered, and given in the data file "diagstrutloads.dat" for elements 1801 and 1803.

data := READPRN("diagstrutloads.dat")

ORIGIN := 1
i := 1..rows(data)

2.5.1.5-2
ESCG-4005-05-AMS-0039
Loads from Beam End A:

Axial Load

\[ F_{xa, i} := \text{data}_{i, 3} \text{ lbf} \quad \text{max}(F_{xa}) = 34094.6 \text{ lbf} \]

Load Case

\[ LC_{i} := \text{data}_{i, 2} \]

Element ID

\[ ID_{i} := \text{data}_{i, 1} \]

Number of Rivets:

Total Number of rivets in beam:

\[ N_{sp} := 54 \]

Number of rivets reacting Fx axial load in beam end:

\[ p_{sx} := 27 \]

Total Rivet Shear Load:

The Fxa axial load is distributed equally to all 27 rivets in the beam end.

\[ \text{Shear load/rivet due to Fxa} \quad P_{t} := \frac{|F_{xa}|}{p_{sx}} \quad \text{max}(P_{t}) = 1262.8 \text{ lbf} \]
**Margin of safety for Total Rivet Load:**

\[
MS1t := \frac{F_{s\cdot cf}}{Pt\cdot FSu\cdot FF} - 1
\]

\[
\min(MS1t) = 0.37
\]

(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment}(\text{ID}, \text{LC}, MS1t)
\]

rows(output) = 9 \quad \text{Number of rows in the "output" array}

cols(output) = 3 \quad \text{Number of columns in the "output" array}

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{min}_\text{LC} := \text{output}_{9,2} \quad \text{Load Case for Minimum Margin of Safety}
\]

\[
\text{match}(\text{min}(MS1t), MS1t) = (9)
\]

\[
\text{min}_\text{ID} := \text{output}_{9,1} \quad \text{Element ID for Minimum Margin of Safety}
\]

**Minimum Margin of Safety Summary:**

Minimum Margin of Safety \( \min(MS1t) = 0.37 \)

Element ID for Minimum Margin of Safety \( \min_{ID} = 1803 \)

Load Case for Minimum Margin of Safety \( \min_{LC} = 1020 \)

Maximum Rivet Load for Minimum Margin of Safety \( \max(Pt) = 1262.8 \text{ lbf} \)
Bearing on Hole Wall:

Hole diameter \( dh := 0.257 \text{ in} \) \( \text{(Ref. SEG39135726, Flag Note 2)} \)

Tube thickness (with counterbore) \( tp := 0.174 \text{ in} \) \( \text{(Ref. SDG39135742)} \)

Bearing area \( Ab := dh \cdot tp \) \( Ab = 0.045 \text{ in}^2 \)

Max. load per rivet \( \max(Pr) = 1262.8 \text{ lbf} \)

Max. bearing stress \( \beta b := \frac{\max(Pr)}{Ab} \) \( \beta b = 28238.4 \text{ psi} \)

Margin of safety \( MSb := \frac{Fb \cdot cd}{\beta b \cdot FSu \cdot FF} - 1 \) \( MSb = 0.70 \)

Shear tear out:

Edge distance \( e := 0.520 \text{ in} \) \( \text{(Ref. SDG39135742)} \)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257 \text{ in} \)

\( E \) over \( D \) ratio \( \frac{e}{dh} = 2.023 \)

Tube thickness \( tp := 0.25 \text{ in} \)

Shear out area \( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40 \text{ deg}) \right) \cdot tp \) \( As = 0.211 \text{ in}^2 \)

Max. load per rivet \( \max(Pr) = 1262.8 \text{ lbf} \)

Max. shear tear out stress \( us := \frac{\max(Pr)}{As} \) \( us = 5990.9 \text{ psi} \)

Margin of safety \( MSsh := \frac{Fs \cdot cd}{us \cdot FSu \cdot FF} - 1 \) \( MSsh = 1.53 \)
2.5.1.6 Upper Trunnion Bridge Beam to Sill Joint
Upper Trunnion Bridge Beam to Sill Joint Rivet Analysis

The Upper Trunnion Bridge Beam SDG39135728 connects to the Sill Joint SDG39135730 in 4 locations. The upper bridge beam is fastened to the sill joint, with NAS1398M8, 0.25 in rivets. The sill joint is machined from 7050-T7451 plate and the upper trunnion bridge beam is extruded from 7075-T73511. CBEAM elements 1113, 1114, 1115, and 1116 in the loads model represents the portion of the sill joint that interfaces with the bridge beam. The rivet pattern centroid is 2.989 in from end A of the beam element. Element length is 4.977 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:
Rivets are NAS1398 type M, 0.25 in. blind protruding head Monel rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength $F_s := 2840$-lbf

Material Strength for Upper Trunnion Bridge Beam:
Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))
Allowable bearing strength $F_{bru} := 119000$-psi
Allowable shear strength $F_{su} := 35000$-psi

Factors of safety:
Ultimate Factor of Safety: $F_{Su} := 1.4$
Fitting Factor: $FF := 1.15$

Temperature:
Maximum Temperature $T_{max} := 150$-deg
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For $F_s$) $cf := .98$
(Ref. Appendix C5 )
Temperature Correction Factor (For $F_{su}$) $cd := .99$
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For $F_{bru}$) $cb := .92$
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "UTBBtoTSillJoint.dat" for elements 1113, 1114, 1115, and 1116.
**Title**: Upper Trunnion Bridge Beam to Sill Joint Rivet Analysis

**Loads from Beam End A:**

- **Axial Load**
  \[ F_x,_{i} = \text{data},_{1,7} \text{lb} \]

- **Shear in Y axis**
  \[ F_y,_{i} = \text{data},_{1,5} \text{lb} \]

- **Shear in Z axis**
  \[ F_z,_{i} = \text{data},_{1,6} \text{lb} \]

- **Torsion**
  \[ M_x,_{i} = \text{data},_{1,8} \text{in-lb} \]

- **Moment about Y axis**
  \[ M_y,_{i} = \text{data},_{1,4} \text{in-lb} \]

- **Moment about Z axis**
  \[ M_z,_{i} = \text{data},_{1,3} \text{in-lb} \]

\[ \text{ID},_{i} = \text{data},_{1,1} \quad \text{LC},_{i} = \text{data},_{1,2} \]

**Beam Section Properties:**

- **Thickness of tube**
  \[ t := 0.25 \text{ in} \]

- **Width of tube**
  \[ a := 5.062 \text{ in} \]

- **Depth of tube**
  \[ b := 6.312 \text{ in} \]

- **Enclosed area of mean width and mean height**
  \[ A_m := (a - t) \cdot (b - t) \quad A_m = 29.17 \text{ in}^2 \]

**Loads from Beam End B:**

- **Axial Load**
  \[ F_x,_{i} = \text{data},_{1,13} \text{lb} \]

- **Shear in Y axis**
  \[ F_y,_{i} = \text{data},_{1,11} \text{lb} \]

- **Shear in Z axis**
  \[ F_z,_{i} = \text{data},_{1,12} \text{lb} \]

- **Torsion**
  \[ M_x,_{i} = \text{data},_{1,14} \text{in-lb} \]

- **Moment about Y axis**
  \[ M_y,_{i} = \text{data},_{1,10} \text{in-lb} \]

- **Moment about Z axis**
  \[ M_z,_{i} = \text{data},_{1,9} \text{in-lb} \]

**Figure 2.5.1.6-1** Rivet Pattern Dimensions for Beam Element Ends A and B.

Note: Figure is for reference only.
Bending Moment Interpolation:

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern

Total length of beam element

Moment My:

Difference \[ \text{My}_{\text{diff}} := (\text{My}_a - \text{My}_b) \]

Linearly interpolate at centroid of rivets

\[ \text{My}_1 := \frac{c}{d} \text{My}_{\text{diff}} \quad \text{My}_2 := \frac{d - c}{d} \text{My}_{\text{diff}} \]

Moment My interpolated at centroid of rivets

\[ \text{My} := \text{My}_b + \text{My}_2 \]

Moment Mz:

Difference \[ \text{Mz}_{\text{diff}} := (\text{Mz}_a - \text{Mz}_b) \]

Linearly interpolate at centroid of rivets

\[ \text{Mz}_1 := \frac{c}{d} \text{Mz}_{\text{diff}} \quad \text{Mz}_2 := \frac{d - c}{d} \text{Mz}_{\text{diff}} \]

Moment Mz interpolated at centroid of rivets

\[ \text{Mz} := \text{Mz}_b + \text{Mz}_2 \]
Load in Rivets at Upper Bridge Beam to Sill Joint:

Total Number of rivets in beam end:

\[ N_{sp} := 70 \]

Number of rivets reacting Fz shear load:

\[ p_{sz} := 32 \]

Number of rivets reacting Fy shear loads:

\[ p_{sy} := 38 \]

Shear load/rivet due to Fy

\[ F_{sry} := \frac{F_{ya}}{p_{sy}} \quad \text{max}(F_{sry}) = 80\text{-lbf} \]

Shear load/rivet due to Fz

\[ F_{srz} := \frac{F_{za}}{p_{sz}} \quad \text{max}(F_{srz}) = 227.1\text{-lbf} \]

Note: The Fya and Fza forces have the same magnitude as the Fyb and Fzb forces. The end A forces are used above.

Shear flow due to torsion (Ref. Bruhn section A6.8)

\[ F_{srt} := \frac{M_{xa}}{2\cdot A_m} \quad \text{max}(F_{srt}) = 787.6 \frac{	ext{lbft}}{	ext{in}} \]

Note: The shear load (F_{srt}) is used to calculate the torsional load (P_{srt}) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.6-2.
Figure 2.5.1.6-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \quad \text{per} = 22.7 \text{-in} \]

Loads in rivet due to torsion

\[ P_{\text{sr}} := F_{\text{sr}} \left( \frac{\text{per}}{N_{\text{sp}}} \right) \quad \text{max}(P_{\text{sr}}) = 256 \text{-lbf} \]

Shear load in rivets due to beam axial load

\[ P_{\text{ra}} := \frac{F_{\text{xa}}}{N_{\text{sp}}} \quad \text{max}(P_{\text{ra}}) = 521.7 \text{-lbf} \]
Upper Trunnion Bridge Beam to Sill Joint Rivet Analysis

Rivet Dimension Variables:
(Ref. SDG39135730)

- \( z_1 := 0.766 \text{ in} \)
- \( z_2 := 2.266 \text{ in} \)
- \( z_3 := 3.156 \text{ in} \)
- \( y_1 := 0.758 \text{ in} \)
- \( y_2 := 1.516 \text{ in} \)
- \( y_3 := 2.813 \text{ in} \)

Note: Figure is for reference only.

Eccentrically Loaded Rivets due to My and Mz Moments:

- \( j := 1 \ldots \text{rows(coord)} \) Counter for Coordinate Points
- \( x_{j} := \text{coord}_{j,2} \) Rivet Coordinate Points for x-direction
- \( y_{j} := \text{coord}_{j,3} \) Rivet Coordinate Points for y-direction
- \( z_{j} := \text{coord}_{j,4} \) Rivet Coordinate Points for z-direction

\[
\text{rivet\_counter}_j := \frac{\text{coord}_{j,1}}{\text{in}}
\]
For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

**Cross-Section A-A**
(Row 1, 16 rivets)

**Cross-Section B-B**
(Row 2, 16 rivets)

**Cross-Section C-C**
(Row 3, 6 rivets)

**Cross-Section D-D**
(Represents both sides, 32 rivets)

Note: Figure is for reference only.
\[ r_{y,j} := \left[ \left( x_j \right)^2 + \left( z_j \right)^2 \right]^{\frac{1}{2}} \]

Radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sigry} := \sum_{j=1}^{\text{rows(coord)}} (r_{y,j})^2 \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_{y,j} := \text{atan2}(x_j, z_j) \]

Angle between resultant vector and tension or shear vectors

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

![Diagram](image)

\[ F_{ym_{i,j}} := \frac{-M_y \cdot r_{y,j}}{\text{sigry}} \]

Resultant Load at Each Rivet

\[ F_{z_{my_{i,j}}} := F_{ym_{i,j}} \cdot \sin \left( \frac{u}{2} - \beta_{y,j} \right) \]

\( z \)-component of \( F_{ym} \)

\[ F_{x_{my_{i,j}}} := F_{ym_{i,j}} \cdot \cos \left( \frac{u}{2} - \beta_{y,j} \right) \]

\( x \)-component of \( F_{ym} \)
For Moment $M_z$:

Eccentrically Loaded Rivet Pattern about $M_z$

**Cross-Section E-E**  
(Row 1, 16 rivets)

**Cross-Section F-F**  
(Row 2, 16 rivets)

**Cross-Section G-G**  
(Represents top and bottom, 38 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[ r_{z_j} := \left[ (x_j)^2 + (y_j)^2 \right]^{\frac{1}{2}} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \text{sigr}_z := \sum_{j=1}^{\text{rows(coord)}} (r_{z_j})^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_{z_j} := \arctan2(x_j, y_j) \]

Resultant Load at Each Rivet

\[ F_{z_{m_{i,j}}} := \frac{M_z \cdot r_{z_j}}{\text{sigr}_z} \]

Total Axial Load due to My and Mz Moments

\[ F_{i,j} := \begin{cases} F_{z_{m_{y_{i,j}}}} & \text{if } \text{rivet\_counter}_{j} \leq 38 \\ F_{z_{m_{z_{i,j}}}} & \text{otherwise} \end{cases} \]

\[ \max(F_{i,j}) = 256.6 \text{ lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.2 for beam and socket analysis.
Total Rivet Shear Load:

\[ P_{t_{i,j}} := \begin{cases} \left(Pr_{a_i} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}}\right)^2 + \left(P_{sr_{i}} + F_{sr_{y_{i}}} + F_{y_{mz_{i,j}}}\right)^2 & \text{if } j \leq 38 \\ \left(Pr_{a_i} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}}\right)^2 + \left(P_{sr_{i}} + F_{sr_{z_{i}}} + F_{z_{mz_{i,j}}}\right)^2 & \text{otherwise} \end{cases} \]

\[ \text{max}(P_t) = 1355.6 \text{ lbf} \]

Margin of safety for Total Rivet Load:

\[ MS_{1t} := \frac{F_{scf}}{P_t \cdot FSu \cdot FF} - 1 \]

\[ \min(MS_{1t}) = 0.275 \quad \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)} \]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[ \text{output} := \text{augment}(\text{ID}, \text{LC}, MS_{1t}) \]

\[ \text{rows(output)} = 768 \quad \text{Number of rows in the "output" array} \]
\[ \text{cols(output)} = 72 \quad \text{Number of columns in the "output" array} \]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[ \text{match}(\min(MS_{1t}), MS_{1t}) = \begin{bmatrix} 573 \\ 4 \end{bmatrix} \]

\[ \min_{-LC} := \text{output}_{573,2} \quad \text{Load Case for Minimum Margin of Safety} \]
\[ \min_{-ID} := \text{output}_{573,1} \quad \text{Element ID for Minimum Margin of Safety} \]

Rivet number 4 is the rivet with the minimum margin of safety of 0.275.
Minimum Margin of Safety:

Minimum Margin of Safety

\[ \text{min}(MS_{1t}) = 0.275 \]

Element ID for Minimum Margin of Safety

\[ \text{min}_\text{ID} = 1113 \]

Load Case for Minimum Margin of Safety

\[ \text{min}_\text{LC} = 4016 \]

Maximum Rivet Load for Minimum Margin of Safety

\[ \text{max}(P_t) = 1355.6 \text{lbf} \]

Rivets with Minimum Margin of Safety

Rivet number 4
(See figure 2.5.1.6 - 6 for rivet location)
Bearing on Hole Wall:

Hole diameter \( dh := 0.257\text{-in} \) (Ref. SEG39135726, Flag Note 2)
Tube thickness \( tp := 0.25\text{-in} \) (Ref. SDG39135728)
Bearing area \( Ab := dh\cdot tp \) \( Ab = 0.06425\text{-in}^2 \)

Max. load per rivet \( \max(Pt) = 1355.6\text{-lbf} \)
Max. bearing stress \( b := \frac{\max(Pt)}{Ab} \) \( b = 21098.2\text{-psi} \)
Margin of safety \( MSb := \frac{Fru\cdot cb}{b\cdot FSu\cdot FF} - 1 \) \( MSb = 2.22 \)

Shear tear out:

Edge distance \( e := 0.520\text{-in} \) (Ref. SDG39135730)
Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257\text{-in} \)
E over D ratio \( \frac{e}{dh} = 2.023 \)
Tube thickness \( tp := 0.25\text{-in} \)
Shear out area \( As := 2\left(\frac{e - \frac{dh}{2}\cdot \cos(40\text{-deg})}{2}\right)\cdot tp \) \( As = 0.2108\text{-in}^2 \)

Max. load per rivet \( \max(Pt) = 1355.6\text{-lbf} \)
Max. shear tear out stress \( s := \frac{\max(Pt)}{As} \) \( s = 6431.1\text{-psi} \)
Margin of safety \( MSsh := \frac{Fsu\cdot cd}{s\cdot FSu\cdot FF} - 1 \) \( MSsh = 2.347 \)
2.5.1.7 Lower Trunnion Bridge Beam to Lower Trunnion Bridge Beam Elbow
Lower Trunnion Bridge Beam to Lower Trunnion Bridge Beam Elbow Rivet Analysis

The elbow joint SDG39135734 connects the sill joint SDG39135730 to the lower trunnion bridge beam, SDG39135735 in 4 locations. The lower end of the elbow joint is fastened to the lower trunnion bridge, with NAS1398M8, 0.25 in rivets. The elbow joint is machined from 7050-T7451 plate and the lower trunnion bridge beam is extruded from 7075-T73511. CBEAM elements 1221, 1222, 1223, and 1224 in the loads model represents the portion of the elbow joint that interfaces with the bridge beam. The rivet pattern centroid is 4.484 in from end A of the beam element. Element length is 6.316 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:

Rivets are NAS1398 type M, 0.25 in. blind protruding head Monel rivets
(Ref. NAS1400, sheet 5)

Max. rivet shear strength \( F_s := 2840 \text{ lbf} \)

Material Strength for Lower Trunnion Bridge Beam:

Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))

Allowable bearing strength \( F_{bru} := 119000 \text{ psi} \)
Allowable shear strength \( F_{su} := 35000 \text{ psi} \)

Factors of safety:

Ultimate Factor of Safety: \( F_{su} := 1.4 \)
Fitting Factor: \( FF := 1.15 \)

Temperature:

Maximum Temperature \( T_{max} := 150\text{ deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For Fs) \( cf := .98 \)
(Ref. Appendix C5 )
Temperature Correction Factor (For Fsu) \( cd := .99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For Fbru) \( cb := .92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "ElbowtoLTBB.dat" for elements 1221, 1222, 1223, and 1224.

data := READPRN("ElbowtoLTBB.dat")
 Loads from Beam End A:  
- Axial Load: $F_{xa,i} := \text{data}_{i,7} \cdot \text{lbf}$
- Shear in Y axis: $F_{ya,i} := \text{data}_{i,5} \cdot \text{lbf}$
- Shear in Z axis: $F_{za,i} := \text{data}_{i,6} \cdot \text{lbf}$
- Torsion: $M_{xa,i} := \text{data}_{i,8} \cdot \text{in-lbf}$
- Moment about Y axis: $M_{ya,i} := -\text{data}_{i,4} \cdot \text{in-lbf}$
- Moment about Z axis: $M_{za,i} := \text{data}_{i,3} \cdot \text{in-lbf}$

 Beam Section Properties:  
- Thickness of tube: $t := 0.25\text{in}$ (Ref. SDG39135735)
- Width of tube: $a := 4.938\text{in}$ (Ref. SDG39135735)
- Depth of tube: $b := 4.938\text{in}$ (Ref. SDG39135735)
- Enclosed area of mean width and mean height: $A_m := (a - t) \cdot (b - t) \quad A_m = 21.98\text{in}^2$

 Loads from Beam End B:  
- Axial Load: $F_{xb,i} := \text{data}_{i,13} \cdot \text{lbf}$
- Shear in Y axis: $F_{yb,i} := \text{data}_{i,11} \cdot \text{lbf}$
- Shear in Z axis: $F_{zb,i} := \text{data}_{i,12} \cdot \text{lbf}$
- Torsion: $M_{xb,i} := \text{data}_{i,14} \cdot \text{in-lbf}$
- Moment about Y axis: $M_{yb,i} := -\text{data}_{i,10} \cdot \text{in-lbf}$
- Moment about Z axis: $M_{zb,i} := \text{data}_{i,9} \cdot \text{in-lbf}$

Figure 2.5.1.7-1 Rivet Pattern Dimensions for Beam Element Ends A and B.
Note: Figure is for reference only.
Bending Moment Interpolation:

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern \( c := 4.484 \text{ in} \) (See Figure 2.5.1.7-1 and Ref. Appendix C4)

Total length of beam element \( d := 6.316 \text{ in} \)

Moment \( M_y \):

\[
\text{Difference } \quad M_{\text{y diff}} := \left( M_{yA} - M_{yB} \right)
\]

Linearily interpolate at centroid of rivets

\[
M_{y1} := \frac{c}{d} \cdot M_{\text{y diff}} \quad M_{y2} := \frac{d-c}{d} \cdot M_{\text{y diff}}
\]

Moment \( M_y \) interpolated at centroid of rivets

\[
M_y := M_{yB} + M_{y2}
\]

Moment \( M_z \):

\[
\text{Difference } \quad M_{\text{z diff}} := \left( M_{zA} - M_{zB} \right)
\]

Linearily interpolate at centroid of rivets

\[
M_{z1} := \frac{c}{d} \cdot M_{\text{z diff}} \quad M_{z2} := \frac{d-c}{d} \cdot M_{\text{z diff}}
\]

Moment \( M_z \) interpolated at centroid of rivets

\[
M_z := M_{zB} + M_{z2}
\]
Load in Rivets at Lower Bridge Beam to Elbow Joint:

Total Number of rivets in beam end:
Nsps := 60

Number of rivets reacting $F_z$ shear load:
psz := 28

Number of rivets reacting $F_y$ shear loads:
psy := 32

Shear load/rivet due to $F_y$
\[ F_{sry} := \frac{F_y}{psy} \quad \text{max}(F_{sry}) = 41.1\text{-lbf} \]

Shear load/rivet due to $F_z$
\[ F_{srz} := \frac{F_z}{psz} \quad \text{max}(F_{srz}) = 87.6\text{-lbf} \]

Note: The $F_y$ and $F_z$ forces have the same magnitude as the $F_y$ and $F_z$ forces. The end A forces are used above.

Shear flow due to torsion
(Ref. Bruhn section A6.8)
\[ F_{srt} := \frac{M_x}{2Am} \quad \text{max}(F_{srt}) = 351.1\frac{\text{lbf}}{\text{in}} \]

Note: The shear load ($F_{srt}$) is used to calculate the torsional load ($P_{sr}$) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.7-2.
Figure 2.5.1.7-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \]

\[ \text{per} = 19.8 \text{ in} \]

Loads in rivet due to torsion

\[ \text{Psrt} := F_{sr t} \left( \frac{\text{per}}{N_{sp s}} \right) \]

\[ \max(\text{Psrt}) = 115.6 \text{ lbf} \]

Shear load in rivets due to beam axial load

\[ \text{Prta} := \frac{F_{xa}}{N_{sp s}} \]

\[ \max(\text{Prta}) = 1000.7 \text{ lbf} \]
Eccentrically Loaded Rivets due to My and Mz Moments:

- Rivet Coordinate System Data
  
  \[
  j := 1..\text{rows}(\text{coord}) 
  \]
  Counter for Coordinate Points

  \[
  x_j := \text{coord}_{j,2} 
  \]
  Rivet Coordinate Points for x-direction

  \[
  y_j := \text{coord}_{j,3} 
  \]
  Rivet Coordinate Points for y-direction

  \[
  z_j := \text{coord}_{j,4} 
  \]
  Rivet Coordinate Points for z-direction

Rivet Dimension Variables:
(Ref. SDG39135735 and SDG39135734)

- \(z_1 := 0.625\text{ in}\)
- \(z_2 := 1.50\text{ in}\)
- \(z_3 := 2.469\text{ in}\)
- \(y_1 := 0.758\text{ in}\)
- \(y_2 := 1.515\text{ in}\)
- \(y_3 := 2.469\text{ in}\)
For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

Cross-Section A-A  
(Row 1, 16 rivets)

Cross-Section B-B  
(Row 2, 12 rivets)

Cross-Section C-C  
(Row 3, 4 rivets)

Cross-Section D-D  
(Represents both sides, 28 rivets)

Note: Figure is for reference only.
\[ r_y_j := \left[ \left( x_j \right)^2 + \left( z_j \right)^2 \right]^{\frac{1}{2}} \]

Radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sigry} := \frac{\text{rows(coord)}}{\sum_{j=1}^{\text{rows(coord)}} \left( r_y_j \right)^2} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \beta y_j := \text{atan2}(x_j, z_j) \]

Angle between resultant vector and tension or shear vectors

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

Resultant Load at Each Rivet

\[ F_{ym_{i,j}} := \frac{-M_y \cdot r_y_j}{\text{sigry}} \]

\[ F_{z_{my_{i,j}}} := F_{ym_{i,j}} \cdot \sin\left(\frac{u}{2} - \beta y_j\right) \]

z - component of \( F_{ym} \)

\[ F_{x_{my_{i,j}}} := F_{ym_{i,j}} \cdot \cos\left(\frac{u}{2} - \beta y_j\right) \]

x - component of \( F_{ym} \)
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section E-E
(Row 1, 16 rivets)

Cross-Section F-F
(Row 2, 12 rivets)

Cross-Section G-G
(Represents top and bottom, 32 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[ rz_j = \left( x_j^2 + y_j^2 \right)^{1/2} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \text{sig}_{rz} = \sum_{j=1}^{\text{rows(coord)}} \left( rz_j \right)^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_{z_j} = \arctan2(x_j, y_j) \]

Resultant Load at Each Rivet

\[ F_{z_{i,j}} := \frac{M_z \cdot rz_j}{\text{sig}_{rz}} \]

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

\[ F_{z_{i,j}} := \begin{cases} F_{z_{my_{i,j}}} & \text{if } \text{rivet_counter}_j \leq 32 \\ F_{z_{mx_{i,j}}} & \text{otherwise} \end{cases} \]

Total Axial Load due to \( M_y \) and \( M_z \) Moments

\[ \max(F_i) = 299.3 \text{ lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.8 for beam and socket analysis.
Total Rivet Shear Load:

\[
P_{t,ij} := \begin{cases} 
\sqrt{(P_{ta, i} + F_{x_{my}, i,j} + F_{x_{mz}, i,j})^2 + (P_{srt, i} + F_{sry, i} + F_{y_{mz}, i,j})^2} & \text{if } j \leq 32 \\
\sqrt{(P_{ta, i} + F_{x_{my}, i,j} + F_{x_{mz}, i,j})^2 + (P_{srt, i} + F_{srz, i} + F_{y_{mz}, i,j})^2} & \text{otherwise}
\end{cases}
\]

Margin of safety for Total Rivet Load:

\[
MS_{1t} := \frac{F_{scf}}{P_{t FSu \cdot FF}} - 1
\]

\[
\text{min}(MS_{1t}) = 0.213 \quad \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)}
\]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment(ID, LC, MS}_{1t})
\]

\[
\text{rows(output)} = 768 \quad \text{Number of rows in the "output" array}
\]

\[
\text{cols(output)} = 62 \quad \text{Number of columns in the "output" array}
\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{match(min(MS}_{1t}), MS}_{1t}) = \begin{pmatrix} 569 \\ 2 \end{pmatrix}
\]

\[
\text{min}_{LC} := \text{output}_{569,2} \quad \text{Load Case for Minimum Margin of Safety}
\]

\[
\text{min}_{ID} := \text{output}_{569,1} \quad \text{Element ID for Minimum Margin of Safety}
\]

Rivet number 1 is the rivet with the minimum margin of safety of 0.213.
Minimum Margin of Safety:

Minimum Margin of Safety  
min(MS1t) = 0.213

Element ID for Minimum Margin of Safety  
min_ID = 1221

Load Case for Minimum Margin of Safety  
min_LC = 4015

Maximum Rivet Load for Minimum Margin of Safety  
max(Pt) = 1425.2 lbf

Rivets with Minimum Margin of Safety  
Rivet number 1  
(See figure 2.5.1.7 - 2 for rivet location)
Bearing on Hole Wall:

Hole diameter \( \text{dh} := 0.257\text{-in} \)  
(Ref. SEG39135726, Flag Note 2)

Tube thickness \( \text{tp} := 0.25\text{-in} \)  
(Ref. SDG39135735)

Bearing area \( \text{Ab} := \text{dh} \cdot \text{tp} \)  
\( \text{Ab} = 0.064\text{in}^2 \)

Max. load per rivet \( \text{max(Pt)} = 1425.2\text{lbf} \)

Max. bearing stress \( \text{b} := \frac{\text{max(Pt)}}{\text{Ab}} \)  
\( \text{b} = 22181.7\text{psi} \)

Margin of safety \( \text{MSb} := \frac{\text{Fbru-b}}{\text{b-FSu-FF}} - 1 \)  
\( \text{MSb} = 2.07 \)

Shear tear out:

Edge distance \( e := 0.520\text{-in} \)  
(Ref. SDG39135734)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( \text{dh} := 0.257\text{-in} \)

\( \dfrac{e}{\text{dh}} = 2.023 \)

Tube thickness \( \text{tp} := 0.25\text{-in} \)

Shear out area \( \text{As} := 2\left(e - \dfrac{\text{dh}}{2} \cdot \cos(40\text{-deg})\right) \cdot \text{tp} \)  
\( \text{As} = 0.211\text{in}^2 \)

Max. load per rivet \( \text{max(Pt)} = 1425.2\text{lbf} \)

Max. shear tear out stress \( \text{s} := \frac{\text{max(Pt)}}{\text{As}} \)  
\( \text{s} = 6761.4\text{psi} \)

Margin of safety \( \text{MSsh} := \frac{\text{Fsu-cd}}{\text{s-FSu-FF}} - 1 \)  
\( \text{MSsh} = 2.18 \)
2.5.1.8 Lower Trunnion Bridge Beam to Lower Vacuum Case Joint
Lower Trunnion Bridge Beam to Lower Vacuum Case Joint Rivet Analysis

The lower vacuum case joint SDG39135737 connects to the lower trunnion bridge beam SDG39135735, in 4 locations. The lower vacuum case joint is fastened to the lower trunnion bridge beam, with NAS1398M8, 0.25 in rivets. The lower vacuum case joint is machined from 7050-T7451 plate and the lower trunnion bridge beam is extruded from 7075-T73511. CBEAM elements 1203, 1206, 1209, and 1212 in the loads model represents the portion of the elbow joint that interfaces with the bridge beam. The rivet pattern centroid is 1.832 in from end A of the beam element outside of the joint. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:
Rivets are NAS1398 type M, 0.25 in. blind protruding head Monel rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength  \( F_s = 2840 \text{ lbf} \)

Material Strength for Lower Trunnion Bridge Beam:
Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))
Allowable bearing strength  \( F_{bru} = 119000 \text{-psi} \)
Allowable shear strength  \( F_{su} = 35000 \text{-psi} \)

Temperature:
Maximum Temperature  \( T_{max} = 150 \text{-deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For Fs)  \( cf = 0.98 \)
(Ref. Appendix C5)
Temperature Correction Factor (For Fsu)  \( cd = 0.99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For Fbru)  \( cb = 0.92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "LTBBtowerrVCJ.dat" for elements 1203, 1206, 1209, and 1212.

```
data := READPRN("LTBBtowerrVCJ.dat")
ORIGIN := 1
i := 1..rows(data)
```

2.5.1.8-2  ESCG-4005-05-AMS-0039
Beam Section Properties:

Thickness of tube \( t := 0.25 \text{ in} \) (Ref. SDG39135735)
Width of tube \( a := 4.938 \text{ in} \) (Ref. SDG39135735)
Depth of tube \( b := 4.938 \text{ in} \) (Ref. SDG39135735)

Enclosed area of mean width and mean height
\[ A_m := (a - t)(b - t) \]
\[ A_m = 21.98 \text{ in}^2 \]

Figure 2.5.1.8-1 Rivet Pattern Dimensions for Beam Element Ends A and B.
Note: Figure is for reference only.

Note: The A and B ends of the beam elements that lay inside of the socket of the Vacuum Case Joint are tied to RBE elements that are "spidered" out to shell elements. This modeling technique stiffens the beam element inside of the socket allowing for lower loads at ends A and B. Therefore, loads are taken from end A of elements 1203, 1206, 1209, and 1212. A moment extrapolation from End A is performed to locate the moments at the center of the rivet pattern.

Reading in Data File:

\[ \text{data} := \text{READPRN}("LTBBtolowerVCJ.dat") \]
\[ \text{ORIGIN} := 1 \]
\[ i := 1 \ldots \text{rows(data)} \]
Loads from Beam End A:

Axial Load \( F_{xa_i} := \text{data}_i,7 \text{lbf} \)

Shear in Y axis \( F_{ya_i} := \text{data}_i,5 \text{lbf} \)

Shear in Z axis \( F_{za_i} := \text{data}_i,6 \text{lbf} \)

Torsion \( M_{xa_i} := \text{data}_i,8 \text{in-lbf} \)

Moment about Y axis \( M_{ya_i} := \text{data}_i,4 \text{in-lbf} \)

Moment about Z axis \( M_{za_i} := \text{data}_i,3 \text{in-lbf} \)

\( ID_i := \text{data}_i,1 \quad \text{LC}_i := \text{data}_i,2 \)

Extrapolation of Moments:

A moment extrapolation from End A is performed to locate moments at the center of the rivet pattern.

Distance from beam end A to the center of the rivet pattern:

\( \text{dist} := 1.832 \text{in} \)

Extrapolation of My Moment:

\( M_{y_i} := M_{ya_i} + F_{za_i} \cdot \text{dist} \)

Extrapolation of Mz Moment:

\( M_{z_i} := M_{za_i} + F_{ya_i} \cdot \text{dist} \)
Load in Rivets at Lower Bridge Beam to Elbow Joint:

Total Number of rivets in beam end:

\[ N_{sp} := 64 \]

Number of rivets reacting Fz shear load:

\[ p_{sz} := 32 \]

Number of rivets reacting Fy shear loads:

\[ p_{sy} := 32 \]

Shear load/rivet due to Fy

\[ F_{sry} := \frac{F_{ya}}{p_{sy}} \quad \text{max}(F_{sry}) = 62 \text{ lbf} \]

Shear load/rivet due to Fz

\[ F_{srz} := \frac{F_{za}}{p_{sz}} \quad \text{max}(F_{srz}) = 99.9 \text{ lbf} \]

Note: The \( F_{ya} \) and \( F_{za} \) forces have the same magnitude as the \( F_{yb} \) and \( F_{zb} \) forces. The end A forces are used above.

Shear flow due to torsion
(Ref. Bruhn section A6.8)

\[ F_{srt} := \frac{M_{xa}}{2 \cdot A m} \quad \text{max}(F_{srt}) = 206.3 \frac{\text{lbf}}{\text{in}} \]

Note: The shear load (\( F_{srt} \)) is used to calculate the torsional load (\( P_{srt} \)) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.1.8-2.
Figure 2.5.1.8-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \]

\[ \text{per} = 19.8 \text{ in} \]

Loads in rivet due to torsion

\[ \text{Psrt} := \frac{\text{per}}{\text{Nsps}} \]

\[ \text{max}(\text{Psrt}) = 63.7 \text{ lbf} \]

Shear load in rivets due to beam axial load

\[ \text{Prta} := \frac{\text{Fxa}}{\text{Nsps}} \]

\[ \text{max}(\text{Prta}) = 919.4 \text{ lbf} \]
Rivet Dimension Variables:  
(Ref. SDG39135735 and SDG39135734)

\[ \begin{align*} 
    z_1 &:= 0.500 \text{ in} \\
    z_2 &:= 1.50 \text{ in} \\
    z_3 &:= 2.469 \text{ in} \\
    y_1 &:= 0.500 \text{ in} \\
    y_2 &:= 1.50 \text{ in} \\
    y_3 &:= 2.469 \text{ in} 
\end{align*} \]

Eccentrically Loaded Rivets due to My and Mz Moments:

\[ \begin{align*} 
    j &:= 1..\text{rows(coord)} \quad \text{Counter for Coordinate Points} \\
    x_j &= \text{coord}_{j.2} \quad \text{Rivet Coordinate Points for x-direction} \\
    y_j &= \text{coord}_{j.3} \quad \text{Rivet Coordinate Points for y-direction} \\
    z_j &= \text{coord}_{j.4} \quad \text{Rivet Coordinate Points for z-direction} \\
\end{align*} \]
For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

Cross-Section A-A
(Row 1, 16 rivets)

Cross-Section B-B
(Row 2, 16 rivets)

Cross-Section C-C
(Represents both sides, 32 rivets)

Note: Figure is for reference only.
\[ r_{y_j} := \left[ \left( x_{j} \right)^2 + \left( z_{j} \right)^2 \right]^{1/2} \]
Radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sigry} := \sum_{j=1}^{\text{rows(coord)}} \left( r_{y_j} \right)^2 \]
Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_{y_j} := \text{atan2}(x_{j}, z_{j}) \]
Angle between resultant vector and tension or shear vectors

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

![Diagram](Image)

\[ F_{ym_{i,j}} := \frac{M_y \cdot r_{y_j}}{\text{sigry}} \]
Resultant Load at Each Rivet

\[ F_{z_{my_{i,j}}} := F_{ym_{i,j}} \cdot \sin\left( \frac{\theta_{y_j}}{2} - \beta_{y_j} \right) \]
z-component of \( F_{ym} \)

\[ F_{x_{my_{i,j}}} := F_{ym_{i,j}} \cdot \cos\left( \frac{\theta_{y_j}}{2} - \beta_{y_j} \right) \]
x-component of \( F_{ym} \)
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section D-D
(Row 1, 16 rivets)

Cross-Section E-E
(Row 2, 16 rivets)

Cross-Section F-F
(Represents both sides, 32 rivets)

Note: Figure is for reference only.
Lower Trunnion Bridge Beam to Lower Vacuum Case Joint Rivet Analysis

\[ rz_j := \left( \frac{x_j}{y_j} \right)^2 \]
Radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sigrz} := \sum_{j=1}^{\text{rows(coord)}} (rz_j)^2 \]
Sum of the radial directions for all rivets in the rivet pattern

\[ \beta z_j := \text{atan2}(x_j, y_j) \]
Angle between resultant vector and tension or shear vectors

\[ Fz_{m,i,j} := \frac{(-M_z)_j \cdot rz_j}{\text{sigrz}} \]
Resultant Load at Each Rivet

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

\[ Fy_{mz,i,j} := Fz_{m,i,j} \cdot \sin \left( \frac{\theta}{2} - \beta z_j \right) \]
y - component of Fzm

\[ Fx_{mz,i,j} := Fz_{m,i,j} \cdot \cos \left( \frac{\theta}{2} - \beta z_j \right) \]
x - component of Fzm

\[ F_{i,j} := \begin{cases} Fz_{my,i,j} & \text{if rivet_counter}_j \leq 32 \\ Fy_{mz,i,j} & \text{otherwise} \end{cases} \]
Total Axial Load due to My and Mz Moments

\[ \max(F_{i,j}) = 271.8 \text{ lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.8 for beam and socket analysis.
Total Rivet Shear Load:

\[
Pt_{i,j} := \begin{cases} 
\sqrt{(\text{Prt}_{i,j} + \text{Fx}_{my_{i,j}} + \text{Fx}_{mz_{i,j}})^2 + (\text{Ps}_{i,j} + \text{Fs}_{y_{i}} + \text{Fy}_{mz_{i,j}})^2} & \text{if } j \leq 32 \\
\sqrt{(\text{Prt}_{i,j} + \text{Fx}_{my_{i,j}} + \text{Fx}_{mz_{i,j}})^2 + (\text{Ps}_{i,j} + \text{Fs}_{r_{z_{i}}} + \text{Fz}_{my_{i,j}})^2} & \text{otherwise}
\end{cases}
\]

\[
\text{max}(Pt) = 1520.2 \text{ lbf}
\]

Margin of safety for Total Rivet Load:

\[
\text{MS}_{1t} := \frac{\text{Fs}_{cf}}{P_{t} \cdot \text{F}_{S_{u}} \cdot \text{FF}} - 1
\]

\[
\text{min}(\text{MS}_{1t}) = 0.137
\]

(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment}(\text{ID}, \text{LC}, \text{MS}_{1t})
\]

\[
\text{rows(output)} = 768 \quad \text{cols(output)} = 66
\]

Number of rows in the "output" array

Number of columns in the "output" array

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{match}(\text{min}(\text{MS}_{1t}), \text{MS}_{1t}) = \left[ \begin{array}{c} 570 \\ 45 \end{array} \right]
\]

\[
\text{min}_{LC} := \text{output}_{570,2}
\]

Load Case for Minimum Margin of Safety

\[
\text{min}_{ID} := \text{output}_{570,1}
\]

Element ID for Minimum Margin of Safety

Rivet number 45 is the rivet with the minimum margin of safety of 0.137.
**Minimum Margin of Safety:**

Minimum Margin of Safety

\[ \text{min}(MS1t) = 0.137 \]

Element ID for Minimum Margin of Safety

\[ \text{min}_\text{ID} = 1206 \]

Load Case for Minimum Margin of Safety

\[ \text{min}_\text{LC} = 4015 \]

Maximum Rivet Load for Minimum Margin of Safety

\[ \text{max}(Pt) = 1520.2 \text{ lbf} \]

Rivets with Minimum Margin of Safety

Rivet number 45

(See figure 2.5.1.8 - 2 for rivet location)
Bearing on Hole Wall:

Hole diameter \( dh := 0.257 \text{-in} \)  
(Tab. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25 \text{-in} \)  
(Ref. SDG39135735)

Bearing area  
\( Ab := dh \cdot tp \)  
\( Ab = 0.064 \text{in}^2 \)

Max. load per rivet  
\( \text{max}(Pt) = 1520.2 \text{lbf} \)

Max. bearing stress  
\( b := \frac{\text{max}(Pt)}{Ab} \)  
\( b = 23660.1 \text{psi} \)

Margin of safety  
\( MS_b := \frac{F_{bu-cb}}{b \cdot FSu \cdot FF} - 1 \)  
\( MS_b = 1.87 \)

Shear tear out:

Edge distance  
\( e := 0.520 \text{-in} \)  
(Ref. SDG39135737)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter  
\( dh := 0.257 \text{-in} \)

\( E \) over D ratio  
\( \frac{e}{dh} = 2.023 \)

Tube thickness  
\( tp := 0.25 \text{-in} \)

Shear out area  
\( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40 \text{-deg}) \right) \cdot tp \)  
\( As = 0.211 \text{in}^2 \)

Max. load per rivet  
\( \text{max}(Pt) = 1520.2 \text{lbf} \)

Max. shear tear out stress  
\( \Rightarrow := \frac{\text{max}(Pt)}{As} \)  
\( \Rightarrow = 7212 \text{psi} \)

Margin of safety  
\( MS_{sh} := \frac{F_{su-cd}}{\Rightarrow \cdot FSu \cdot FF} - 1 \)  
\( MS_{sh} = 1.98 \)
2.5.2 Lower USS-02 Riveted Joints


Lower USS-02 Riveted Joints

The Lower USS-02 Rivet Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.2.1</td>
<td>Lower USS-02 to Upper USS-02 to Lower Angle Beam</td>
</tr>
<tr>
<td>2.5.2.2</td>
<td>Lower Angle Beam to Lower Angle Flange Beam Flange</td>
</tr>
<tr>
<td>2.5.2.3</td>
<td>EMC Box Tubes to Centerbody Joints</td>
</tr>
<tr>
<td>2.5.2.4</td>
<td>RICH Bracket to EMC Box Tubes</td>
</tr>
<tr>
<td>2.5.2.5</td>
<td>RICH PAS Brackets to EMC Box Tubes</td>
</tr>
</tbody>
</table>
2.5.2.1 Lower USS-02 to Upper USS-02 to Lower Angle Beam
Lower Angle Beam to Lower to Upper USS-02 Joint Rivet Analysis

The Lower Angle Beam SDG39135764 connects to the Lower to Upper USS-02 Joint SDG39135762 in 4 locations. The lower angle beam is fastened to the lower to upper joint, with NAS1398DFC, 0.25 in rivets. The lower to upper joint is machined from 7050-T7451 plate and the lower angle beam is extruded from 7075-T73511. CBEAM elements 1604, 1609, 1614, and 1619 in the loads model represents the portion of the lower to upper joint that interfaces with the lower angle beam. The rivet pattern centroid is 2.688 in from end A of the beam element. Element length is 5.375 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:

Rivets are NAS1398 type D, 0.25 in. blind protruding head 2017 Aluminum rivets
(Ref. NAS1400, sheet 5)
Max. rivet shear strength \( F_s := 1970 \text{ lbf} \)

Material Strength for Lower Angle Beam:

Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))
Allowable bearing strength \( F_{bru} := 119000 \text{ psi} \)
Allowable shear strength \( F_{su} := 35000 \text{ psi} \)

Factors of safety:

<table>
<thead>
<tr>
<th></th>
<th>Fs := 1.4</th>
<th>FF := 1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Factor of Safety:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fitting Factor:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Factors of safety:

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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fitting Factor:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Temperature:

Maximum Temperature \( T_{max} := 161 \text{ deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)
Temperature Correction Factor (For Fs) \( cf := .97 \)
(Ref. Appendix C13 )
Temperature Correction Factor (For Fs) \( cd := .99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))
Temperature Correction Factor (For Fbru) \( cb := .92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "uppertolowertoLAB.dat" for elements 1604, 1609, 1614, and 1619.

\[ \text{data := READPRN("uppertolowertoLAB.dat") \quad \text{ORIGIN := 1 \quad \text{i := 1..rows(data)}} \]
### Loads from Beam End A:

- **Axial Load**
  \[ F_{xa} := \text{data}_{i,7} \text{lbf} \]

- **Shear in Y axis**
  \[ F_{ya} := \text{data}_{i,5} \text{lbf} \]

- **Shear in Z axis**
  \[ F_{za} := \text{data}_{i,6} \text{lbf} \]

- **Torsion**
  \[ M_{xa} := \text{data}_{i,8} \text{in-lbf} \]

- **Moment about Y axis**
  \[ M_{ya} := \text{-data}_{i,4} \text{in-lbf} \]

- **Moment about Z axis**
  \[ M_{za} := \text{data}_{i,3} \text{in-lbf} \]

- **ID**
  \[ := \text{data}_{i,1} \]

- **LC**
  \[ := \text{data}_{i,2} \]

### Loads from Beam End B:

- **Axial Load**
  \[ F_{xb} := \text{data}_{i,13} \text{lbf} \]

- **Shear in Y axis**
  \[ F_{yb} := \text{data}_{i,11} \text{lbf} \]

- **Shear in Z axis**
  \[ F_{zb} := \text{data}_{i,12} \text{lbf} \]

- **Torsion**
  \[ M_{xb} := \text{data}_{i,14} \text{in-lbf} \]

- **Moment about Y axis**
  \[ M_{yb} := \text{-data}_{i,10} \text{in-lbf} \]

- **Moment about Z axis**
  \[ M_{zb} := \text{data}_{i,9} \text{in-lbf} \]

### Beam Section Properties:

- **Thickness of tube**
  \[ t := 0.25 \text{ in} \] 
  (Ref. SDG39135764)

- **Width of tube**
  \[ a := 4.062 \text{ in} \] 
  (Ref. SDG39135764)

- **Depth of tube**
  \[ b := 4.062 \text{ in} \] 
  (Ref. SDG39135764)

- **Enclosed area of mean width and mean height**
  \[ A_m := (a - t) \cdot (b - t) \]
  \[ Am = 14.53 \text{ in}^2 \]

---

**Figure 2.5.2.1-1** Rivet Pattern Dimensions for Beam Element Ends A and B.

*Note: Figure is for reference only.*
Bending Moment Interpolation:
NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern
Total length of beam element
Moment My:
Difference
Linearity interpolate at centroid of rivets
Moment My interpolated at centroid of rivets
Moment Mz:
Difference
Linearity interpolate at centroid of rivets
Moment Mz interpolated at centroid of rivets
Load in Rivets at Lower Angle Beam to Lower USS-02 to Upper USS-02 Joint:

Total Number of rivets in beam end:
\[ N_{sp} := 88 \]

Number of rivets reacting Fz shear load:
\[ p_{sz} := 44 \]

Number of rivets reacting Fy shear loads:
\[ p_{sy} := 44 \]

Shear load/rivet due to Fy
\[ F_{sry} := \frac{F_{ya}}{p_{sy}} \quad \text{max}(F_{sry}) = 128 \text{lbf} \]

Shear load/rivet due to Fz
\[ F_{srz} := \frac{F_{za}}{p_{sz}} \quad \text{max}(F_{srz}) = 136.4 \text{lbf} \]

Note: The Fya and Fza forces have the same magnitude as the Fyb and Fzb forces. The end A forces are used above.

Shear flow due to torsion
(Ref. Bruhn section A6.8)
\[ F_{sr} := \frac{M_{xa}}{2 \cdot A_{m}} \quad \text{max}(F_{sr}) = 331.5 \frac{\text{lbf}}{\text{in}} \]

Note: The shear load (Fsr) is used to calculate the torsional load (Psrt) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.2.1-2.
Figure 2.5.2.1-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[
\text{per} := 2 \cdot a + 2 \cdot b \\
\text{per} = 16.2 \text{ in}
\]

Loads in rivet due to torsion

\[
\text{Psrt} := \frac{\text{Fsr}}{\text{Nsp}} \\
\text{max(Psrt)} = 61.2 \text{ lbf}
\]

Shear load in rivets due to beam axial load

\[
\text{Prta} := \frac{\text{Fxa}}{\text{Nsp}} \\
\text{max(Prta)} = 299.8 \text{ lbf}
\]
**Title:** Lower Angle Beam to Lower to Upper USS-02 Joint Rivet Analysis

---

**Rivet Dimension Variables:**

(Ref. SDG39135764)

\[
\begin{align*}
z_1 & := 0.500 \text{ in} \\
z_2 & := 1.250 \text{ in} \\
z_3 & := 2.281 \text{ in} \\
y_1 & := 0.500 \text{ in} \\
y_2 & := 1.250 \text{ in} \\
y_3 & := 2.281 \text{ in}
\end{align*}
\]

**Eccentrically Loaded Rivets due to My and Mz Moments:**

- \( j := 1 \ldots \text{rows}(\text{coord}) \) Counter for Coordinate Points
- \( x_j := \text{coord}_{j,2} \) Rivet Coordinate Points for x-direction
- \( y_j := \text{coord}_{j,3} \) Rivet Coordinate Points for y-direction
- \( z_j := \text{coord}_{j,4} \) Rivet Coordinate Points for z-direction
For Moment My:

Eccentrically Loaded Rivet Pattern about My

Cross-Section A-A
(Row 1, 24 rivets)

Cross-Section B-B
(Row 2, 20 rivets)

Cross-Section C-C
(Represents both sides, 44 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[ r_y_j := \left( \frac{1}{\sqrt{x_j^2 + z_j^2}} \right) \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \text{sigry} := \sum_{j = 1}^{\text{rows(coord)}} (r_y_j)^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_y_j := \text{atan2}(x_j, z_j) \]

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

Resultant Load at Each Rivet

\[ F_{ym_{i,j}} := -\frac{\text{My} \cdot r_{y_j}}{\text{sigry}} \]

\[ F_{z_{my_{i,j}}} := F_{ym_{i,j}} \cdot \sin \left( \frac{\theta}{2} - \beta_y_j \right) \]

z - component of Fym

\[ F_{x_{my_{i,j}}} := F_{ym_{i,j}} \cdot \cos \left( \frac{\theta}{2} - \beta_y_j \right) \]

x - component of Fym
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section D-D
(Row 1, 24 rivets)

Cross-Section E-E
(Row 2, 20 rivets)

Cross-Section F-F
(Represents both sides, 44 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[ r_{z_j} := \left( (x_j)^2 + (y_j)^2 \right)^{\frac{1}{2}} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \sigma_{rz} := \sum_{j=1}^{\text{rows(coord)}} (r_{z_j})^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_{z_j} := \arctan^2 \left( x_j \cdot y_j \right) \]

Resultant Load at Each Rivet

\[ F_{z_{m_i,j}} := \frac{M_z \cdot r_{z_j}}{\sigma_{rz}} \]

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

\[ F_{y_{mz_{i,j}}} := F_{z_{m_i,j}} \cdot \sin \left( \frac{\pi}{2} - \beta_{z_j} \right) \]

\[ F_{x_{mz_{i,j}}} := F_{z_{m_i,j}} \cdot \cos \left( \frac{\pi}{2} - \beta_{z_j} \right) \]

Total Axial Load due to My and Mz Moments

\[ F_{i,j} := \begin{cases} F_{z_{my_{i,j}}} & \text{if } \text{rivet_counter}_j \leq 44 \\ F_{y_{mz_{i,j}}} & \text{otherwise} \end{cases} \]

\[ \max \left( F_{i,j} \right) = 269.4 \text{ lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.2.6 for beam and socket analysis.
Total Rivet Shear Load:

\[ P_{t_{i,j}} := \begin{cases} \sqrt{(P_{ra_i} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}})^2 + (P_{sr_{i}} + F_{sr_{y_{i}}} + F_{y_{mz_{i,j}}})^2} & \text{if } j \leq 44 \\ \sqrt{(P_{ra_i} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}})^2 + (P_{sr_{i}} + F_{sr_{z_{i}}} + F_{y_{mz_{i,j}}})^2} & \text{otherwise} \end{cases} \]

Maximum of safety for Total Rivet Load:

\[ P_{t_{569,50}} = 601.9 \text{ lbf} \]

Margin of safety for Total Rivet Load:

\[ MS_{1t} := \frac{F_{scf}}{P_{t} F_{Su} FF} - 1 \]

\[ \min(\text{MS}_{1t}) = 0.972 \]

(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

```
output := augment(ID, LC, MS_{1t})
```

```
rows(output) = 768
```

```
cols(output) = 90
```

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

```
\begin{pmatrix} 569 \\ 50 \end{pmatrix}
```

\[ \text{min}_{LC} := \text{output}_{569,2} \]

Load Case for Minimum Margin of Safety

\[ \text{min}_{ID} := \text{output}_{569,1} \]

Element ID for Minimum Margin of Safety

Rivet number 50 is the rivet with the minimum margin of safety of 0.972.
**Minimum Margin of Safety:**

- Minimum Margin of Safety: \( \text{min}(MS_{1t}) = 0.972 \)
- Element ID for Minimum Margin of Safety: \( \text{min}_\text{ID} = 1604 \)
- Load Case for Minimum Margin of Safety: \( \text{min}_\text{LC} = 4015 \)
- Maximum Rivet Load for Minimum Margin of Safety: \( \text{max}(P_t) = 601.9 \text{ lbf} \)
- Rivets with Minimum Margin of Safety: Rivet number 50
  (See figure 2.5.2.1 - 2 for rivet location)
Bearing on Hole Wall:

Hole diameter \( dh := 0.257 \text{-in} \)  
(Ref. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25 \text{-in} \)  
(Ref. SDG39135764)

Bearing area \( Ab := dh \cdot tp \)  
\( Ab = 0.064 \text{ in}^2 \)

Max. load per rivet \( \max(Pt) = 601.9 \text{ lbf} \)

Max. bearing stress \( b := \frac{\max(Pt)}{Ab} \)  
\( b = 9367.4 \text{ psi} \)

Margin of safety \( MSb := \frac{Fbru-ch}{b \cdot FSu \cdot FF} - 1 \)  
\( MSb = 6.26 \)

Shear tear out:

Edge distance \( e := 0.500 \text{-in} \)  
(Ref. SDG39135764)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257 \text{-in} \)

\( e \) over \( D \) ratio \( \frac{e}{dh} = 1.946 \)

Tube thickness \( tp := 0.25 \text{-in} \)

Shear out area \( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40 \text{-deg}) \right) \cdot tp \)  
\( As = 0.2008 \text{ in}^2 \)

Max. load per rivet \( \max(Pt) = 601.9 \text{ lbf} \)

Max. shear tear out stress \( \sigma := \frac{\max(Pt)}{As} \)  
\( \sigma = 2997.6 \text{ psi} \)

Margin of safety \( MSsh := \frac{Fsu \cdot cd}{\sigma \cdot FSu \cdot FF} - 1 \)  
\( MSsh = 6.18 \)
2.5.2.2  Lower Angle Beam to Lower Angle Flange
Beam Flange
Lower Angle Beam to Lower Angle Beam Flange Rivet Analysis

The Lower Angle Beam SDG39135764 connects to the Lower Angle Beam Flange SDG39135767 in 4 locations. The lower angle beam is fastened to the lower angle beam flange, with NAS1398DFC, 0.25 in rivets. The lower angle beam flange is machined from 7050-T7451 plate and the lower angle beam is extruded from 7075-T73511. CBEAM elements 1601, 1606, 1611, and 1616 in the loads model represents the portion of the lower angle beam flange that interfaces with the lower angle beam. The rivet pattern centroid is 2.615 in from end A of the beam element. Element length is 4.885 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:

Rivets are NAS1398 type D, 0.25 in. blind protruding head 2017 Aluminum rivets
(Ref. NAS1400, sheet 5)

Max. rivet shear strength \( F_s \) := 1970 lbf

Material Strength for Lower Angle Beam:

Tube material is extruded 7075-T73511 with e/D=2.0
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))

 Allowable bearing strength \( F_{bru} \) := 119000 psi

 Allowable shear strength \( F_{s-u} \) := 35000 psi

Factors of safety:

Ultimate Factor of Safety: \( F_{su} := 1.4 \)
Fitting Factor: \( F_F := 1.15 \)

Temperature:

Maximum Temperature \( T_{max} := 150\text{ deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)

Temperature Correction Factor (For \( F_s \)) \( cf := .97 \)
(Ref. Appendix C13)

Temperature Correction Factor (For \( F_{s-u} \)) \( cd := .99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))

Temperature Correction Factor (For \( F_{bru} \)) \( cb := .92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "LABtolowerflange.dat" for elements 1601, 1606, 1611, and 1616.

data := READPRN("LABtolowerflange.dat") ORIGIN := 1 i := i..rows(data)

2.5.2.2-2 ESCG-4005-05-AMS-0039
Loads from Beam End A:

Axial Load \( F_{xa} := \text{data}_{i,7} \) lbf
Shear in Y axis \( F_{ya} := \text{data}_{i,5} \) lbf
Shear in Z axis \( F_{za} := \text{data}_{i,6} \) lbf
Torsion \( M_{xa} := \text{data}_{i,8} \) in-lbf
Moment about Y axis \( M_{ya} := \text{data}_{i,4} \) in-lbf
Moment about Z axis \( M_{za} := \text{data}_{i,3} \) in-lbf

ID \( := \text{data}_{i,1} \) LC \( := \text{data}_{i,2} \)

Loads from Beam End B:

Axial Load \( F_{xb} := \text{data}_{i,13} \) lbf
Shear in Y axis \( F_{yb} := \text{data}_{i,11} \) lbf
Shear in Z axis \( F_{zb} := \text{data}_{i,12} \) lbf
Torsion \( M_{xb} := \text{data}_{i,14} \) in-lbf
Moment about Y axis \( M_{yb} := \text{data}_{i,10} \) in-lbf
Moment about Z axis \( M_{zb} := \text{data}_{i,9} \) in-lbf

Beam Section Properties:

Thickness of tube \( t := 0.25 \) in (Ref. SDG39135764)
Width of tube \( a := 4.062 \) in (Ref. SDG39135764)
Depth of tube \( b := 4.062 \) in (Ref. SDG39135764)
Enclosed area of mean width and mean height

\[ Am := (a - t) \times (b - t) \quad Am = 14.53\text{in}^2 \]

---

Figure 2.5.2.2-1 Rivet Pattern Dimensions for Beam Element Ends A and B.

Note: Figure is for reference only.
Bending Moment Interpolation:

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern $c := 2.615\text{-in}$ (See Figure 2.5.2.2-1 and Ref. Appendix C4)

Total length of beam element $d := 4.885\text{-in}$

Moment My:

Difference $\text{Mydiff}_i := (\text{My}_a - \text{My}_b)$

Linearly interpolate at centroid of rivets

$\text{My}_1 := \frac{c}{d} \cdot \text{Mydiff}$

$\text{My}_2 := \frac{d - c}{d} \cdot \text{Mydiff}$

Moment My interpolated at centroid of rivets

$\text{My} := \text{My}_b + \text{My}_2$

Moment Mz:

Difference $\text{Mzdiff}_i := (\text{Mz}_a - \text{Mz}_b)$

Linearly interpolate at centroid of rivets

$\text{Mz}_1 := \frac{c}{d} \cdot \text{Mzdiff}$

$\text{Mz}_2 := \frac{d - c}{d} \cdot \text{Mzdiff}$

Moment Mz interpolated at centroid of rivets

$\text{Mz} := \text{Mz}_b + \text{Mz}_2$
Load in Rivets at Lower Angle Beam to Lower Angle Beam Flange:

Total Number of rivets in beam end:

\[ N_{sp} := 80 \]

Number of rivets reacting \( F_z \) shear load:

\[ p_{sz} := 40 \]

Number of rivets reacting \( F_y \) shear loads:

\[ p_{sy} := 40 \]

Shear load/rivet due to \( F_y \)

\[ F_{sry} := \frac{F_y}{p_{sy}} \quad \text{max}(F_{sry}) = 128.7 \text{lbf} \]

Shear load/rivet due to \( F_z \)

\[ F_{srz} := \frac{F_z}{p_{sz}} \quad \text{max}(F_{srz}) = 149.4 \text{lbf} \]

Note: The \( F_y \) and \( F_z \) forces have the same magnitude as the \( F_y \) and \( F_z \) forces. The end A forces are used above.

Shear flow due to torsion

(Ref. Bruhn section A6.8)

\[ F_{srt} := \frac{M_x}{2 \cdot A_m} \quad \text{max}(F_{srt}) = 322.6 \text{ lbf/in} \]

Note: The shear load \((F_{srt})\) is used to calculate the torsional load \((P_{srt})\) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.2.2-2.
Figure 2.5.2.2-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \]
\[ \text{per} = 16.2 \text{ in} \]

Loads in rivet due to torsion

\[ P_{srt} := F_{srt} \left( \frac{\text{per}}{N_{sps}} \right) \]
\[ \max(P_{srt}) = 65.5 \text{ lbf} \]

Shear load in rivets due to beam axial load

\[ P_{rta} := \frac{F_{xa}}{N_{sps}} \]
\[ \max(P_{rta}) = 326.8 \text{ lbf} \]
**Title**: Lower Angle Beam to Lower to Lower Angle Beam Flange Rivet Analysis

---

**Rivet Dimension Variables:**
(Ref. SDG39135764)

- \( z_1 := 0.500\text{-in} \)
- \( z_2 := 1.250\text{-in} \)
- \( z_3 := 2.281\text{-in} \)
- \( y_1 := 0.500\text{-in} \)
- \( y_2 := 1.250\text{-in} \)
- \( y_3 := 2.281\text{-in} \)

---

**Eccentrically Loaded Rivets due to My and Mz Moments:**

- \( j := 1..\text{rows(coord)} \) Counter for Coordinate Points
- \( x_j := \text{coord}_{j,2} \) Rivet Coordinate Points for x-direction
- \( y_j := \text{coord}_{j,3} \) Rivet Coordinate Points for y-direction
- \( z_j := \text{coord}_{j,4} \) Rivet Coordinate Points for z-direction

---

**Note:** Figure is for reference only.
For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

**Cross-Section A-A**
(Row 1, 20 rivets)

**Cross-Section B-B**
(Row 2, 20 rivets)

**Cross-Section C-C**
(Represents both sides, 40 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern
\[ r_y, := \left[ (x_y)^2 + (z_y)^2 \right]^{\frac{1}{2}} \]

Sum of the radial directions for all rivets in the rivet pattern
\[ \Sigma r_y := \sum_{j=1}^{\text{rows(coord)}} (r_y)^2 \]

Angle between resultant vector and tension or shear vectors
\[ \beta_y := \arctan\left(\frac{x_y}{z_y}\right) \]

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

Resultant Load at Each Rivet
\[ \text{Fym,} := \frac{\text{My,} \cdot r_y}{\Sigma r_y} \]

\[ \text{Fz_my,} := \text{Fym,} \cdot \sin\left(\frac{\pi}{2} - \beta_y\right) \]
\[ \text{Fx_my,} := \text{Fym,} \cdot \cos\left(\frac{\pi}{2} - \beta_y\right) \]
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section D-D
(Row 1, 20 rivets)

Cross-Section E-E
(Row 2, 20 rivets)

Cross-Section F-F
(Represents both sides, 40 rivets)

Note: Figure is for reference only.
\[ r_{z_j} := \left( x_j^2 + y_j^2 \right)^{\frac{1}{2}} \] Radial distance to each rivet from the centroid of the rivet pattern

\[ \sigma_{rz} := \sum_{j=1}^{\text{rows(coord)}} (r_{z_j})^2 \] Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_{z_j} := \arctan \left( \frac{x_j}{y_j} \right) \] Angle between resultant vector and tension or shear vectors

\[ F_{zm_{i,j}} := \frac{(-M_z)_i r_{z_j}}{\sigma_{rz}} \] Resultant Load at Each Rivet

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

\[ F_{mz_{i,j}} := F_{zm_{i,j}} \sin \left( \frac{\theta}{2} - \beta_{z_j} \right) \] y - component of Fzm

\[ F_{mx_{i,j}} := F_{zm_{i,j}} \cos \left( \frac{\theta}{2} - \beta_{z_j} \right) \] x - component of Fzm

\[ F_{i,j} := \begin{cases} F_{mz_{i,j}} & \text{if } \text{rivet-counter}_j \leq 40 \\ F_{my_{i,j}} & \text{otherwise} \end{cases} \] Total Axial Load due to My and Mz Moments

\[ \max \left( |F_i| \right) = 468 \text{-lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.2.6 for beam and socket analysis.
**Total Rivet Shear Load:**

\[
Pt_{i,j} := \begin{cases} 
\sqrt{\left(Pr_{ta_i} + F_{x_my_{i,j}} + F_{z_my_{i,j}}\right)^2 + \left(P_{sr_{i}} + F_{sr_{y_i}} + F_{y_my_{i,j}}\right)^2} & \text{if } j \leq 40 \\
\sqrt{\left(Pr_{ta_i} + F_{x_my_{i,j}} + F_{z_my_{i,j}}\right)^2 + \left(P_{sr_{i}} + F_{sr_{z_i}} + F_{y_my_{i,j}}\right)^2} & \text{otherwise}
\end{cases}
\]

\[
\text{max}(Pt) = 835.1\text{-lbf}
\]

**Margin of safety for Total Rivet Load:**

\[
MS1t := \frac{F_{scf}}{Pt \cdot F_{Su} \cdot FF} - 1
\]

\[
\text{min}(MS1t) = 0.421 \quad \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...)}
\]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment(}ID,LC,MS1t)\]

\[
\text{rows(output)} = 768 \quad \text{Number of rows in the "output" array}
\]

\[
\text{cols(output)} = 82 \quad \text{Number of columns in the "output" array}
\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{match(min(MS1t),MS1t)} = \begin{bmatrix} 569 \\ 20 \end{bmatrix}
\]

\[
\text{min}_LC := \text{output}_{569,2} \quad \text{Load Case for Minimum Margin of Safety}
\]

\[
\text{min}_ID := \text{output}_{569,1} \quad \text{Element ID for Minimum Margin of Safety}
\]

Rivet number 20 is the rivet with the minimum margin of safety of 0.421
Minimum Margin of Safety:

Minimum Margin of Safety \[ \text{min}(MS1t) = 0.421 \]

Element ID for Minimum Margin of Safety \[ \text{min\_ID} = 1601 \]

Load Case for Minimum Margin of Safety \[ \text{min\_LC} = 4015 \]

Maximum Rivet Load for Minimum Margin of Safety \[ \text{max}(Pt) = 835.1 \text{ lbf} \]

Rivets with Minimum Margin of Safety

Rivet number 20

(See figure 2.5.2.2 - 2 for rivet location)
**Bearing on Hole Wall:**

Hole diameter \( dh := 0.257 \text{-in} \) (Ref. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25 \text{-in} \) (Ref. SDG39135764)

Bearing area \( Ab := dh \cdot tp \) \( Ab = 0.064 \text{-in}^2 \)

Max. load per rivet \( \max(P_t) = 835.1 \text{-lbf} \)

Max. bearing stress \( b := \frac{\max(P_t)}{Ab} \) \( b = 12998.4 \text{-psi} \)

Margin of safety \( MS_b := \frac{F_{b\cdot\text{ru} \cdot \text{cb}}}{b \cdot F_{\text{Su} \cdot FF}} - 1 \) \( MS_b = 4.23 \)

**Shear tear out:**

Edge distance \( e := 0.938 \text{-in} \) (Ref. SDG39135764)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257 \text{-in} \)

\( \frac{e}{dh} = 3.65 \)

Tube thickness \( tp := 0.25 \text{-in} \)

Shear out area \( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40\text{-deg}) \right) \cdot tp \) \( As = 0.42 \text{-in}^2 \)

Max. load per rivet \( \max(P_t) = 835.1 \text{-lbf} \)

Max. shear tear out stress \( s := \frac{\max(P_t)}{As} \) \( s = 1989.5 \text{-psi} \)

Margin of safety \( MS_{sh} := \frac{F_{\text{su} \cdot \text{cd}}}{s \cdot F_{\text{Su} \cdot FF}} - 1 \) \( MS_{sh} = 9.82 \)
2.5.2.3  EMC Box Tubes to Centerbody Joints
EMC Box Tube to Centerbody Joint Rivet Analysis

The base of the lower USS is square with a centerbody at each corner and tubes connecting them at 8 joints. The centerbody box joints SDG39135759-001 and -002 are machined from 7050-T7451 plate. They are fastened to the EMC box tubes SDG39135761-301 and-303, with NAS1398M8, 0.25 in monel rivets. The tubes can only be riveted to the joint on three sides, the top, bottom and one side of the tubes. There are 33 rivets per side on each centerbody joint.

Material Strength for Rivets:
Rivets are NAS1398M8, 0.25 in. blind protruding head locked spindle Monel rivets

(Ref. NAS1400, sheet 5)

Max. rivet shear strength $F_s := \frac{2840}{\text{lbf}}$

Material Strength for EMC Box Tube:
Tube material is extruded 7075-T73511 with $e/D = 2.0$

(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))

Allowable bearing strength $F_{bru} := 119000$-psi

Allowable shear strength $F_{su} := 35000$-psi

Temperature:
Maximum Temperature (launch) $T_{launch} := 120$-deg

Maximum Temperature (abort) $T_{abort} := 150$-deg

(Ref. Appendix C2, AMS-02 Temperature Table)

Factors of safety:
Ultimate Factor of Safety: $F_{Su} := 1.4$

Fitting Factor: $FF := 1.15$

Loads model 2-06 was run in NASTRAN for 128 load cases. These 128 load cases include launch and abort landing. Beam element forces were recovered, and given in the input file "emcboxtoLowerCBJ2.dat" for elements 1501, 1503, 1504, 1508, 1509, 1513, 1514, 1517.
**Beam Section Properties:** (Ref. SDG39135761)

- Thickness of tube: \( t := 0.25 \text{-in} \)
- Width of tube: \( a := 4.0 \text{-in} \)
- Depth of tube: \( b := 4.0 \text{-in} \)
- Enclosed area of mean width and mean height: \( A_m := (a - t) \cdot (b - t) \quad A_m = 14.06 \text{-in}^2 \)

**Applies for Elements:** 1501, 1503, 1504, 1508, 1509, 1513, 1514, 1517

![Figure 2.5.2.3-3 Rivet Pattern Dimensions for Beam Element End A.](image)

**Note:** Figure is for reference only.

Note: The A and B ends of the beam elements that lay inside of the socket of the Centerbody Box Joint are tied to RBE elements that are "spidered" out to shell elements. This modeling technique stiffens the beam element inside of the socket allowing for lower loads at ends A and B. Therefore, loads are taken from end A of elements 1501, 1503, 1504, 1508, 1509, 1513, 1514, and 1517. A moment extrapolation from End A is performed to locate the moments at the center of the rivet pattern.

**Reading in Data File:**

\[
data := \text{READPRN}(\text{"emcboxtoLowerCBJ2.dat"}) \quad \text{ORIGIN} := 1 \quad i := 1 \ldots \text{rows(data)}
\]
Loads from Beam End A:

Axial Load

\[ F_{x_i} := \begin{cases} 
\text{data}_{i,7} & \text{if data}_{i,1} = 1501 \ \text{lbf} \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1503 \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1504 \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1508 \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1509 \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1513 \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1514 \\
\text{data}_{i,7} & \text{if data}_{i,1} = 1517 
\end{cases} \]

Shear in Y axis

\[ F_{y_i} := \begin{cases} 
\text{data}_{i,5} & \text{if data}_{i,1} = 1501 \ \text{lbf} \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1503 \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1504 \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1508 \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1509 \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1513 \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1514 \\
\text{data}_{i,5} & \text{if data}_{i,1} = 1517 
\end{cases} \]

Shear in Z axis

\[ F_{z_i} := \begin{cases} 
\text{data}_{i,6} & \text{if data}_{i,1} = 1501 \ \text{lbf} \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1503 \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1504 \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1508 \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1509 \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1513 \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1514 \\
\text{data}_{i,6} & \text{if data}_{i,1} = 1517 
\end{cases} \]

Torsion

\[ M_{x_i} := \begin{cases} 
\text{data}_{i,8} & \text{if data}_{i,1} = 1501 \ \text{in-lbf} \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1503 \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1504 \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1508 \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1509 \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1513 \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1514 \\
\text{data}_{i,8} & \text{if data}_{i,1} = 1517 
\end{cases} \]
Moment about Y axis

\[
M_{ya_i} := 
\begin{align*}
&- \text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1501 \text{ in-lbf} \\
&- \text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1503 \\
&\text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1504 \\
&\text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1508 \\
&\text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1509 \\
&\text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1513 \\
&- \text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1514 \\
&- \text{data}_{i,4} \text{ if } \text{data}_{i,1} = 1517
\end{align*}
\]

\[
y_{cg} := 0.667 \text{ in}
\]

\[
M_{xa_i} := M_{ya_i} + F_{za_i} \cdot y_{cg}
\]

Total Torsional Moment due to y direction offset

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1501 \text{ in-lbf}
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1503
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1504
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1508
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1509
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1513
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1514
\]

\[
M_{za_i} := \text{data}_{i,3} \text{ if } \text{data}_{i,1} = 1517
\]

\[
\text{Element Identification: } \ ID_i := \text{data}_{i,1}
\]

\[
\text{Load Case Number: } \ LC_i := \text{data}_{i,2}
\]

\[
\text{Temperature Correction Factor}
\]

Temperature Correction Factor (For Fsu)

\[
(\text{Ref. Appendix C5})
\]

\[
c_f := \begin{cases} 
.99 & \text{if } LC_i \leq 1064 \\
.98 & \text{otherwise}
\end{cases}
\]

Temperature Correction Factor (For Fs)

\[
(\text{Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b)})
\]

\[
c_d := .99
\]

Temperature Correction Factor (For Fbru)

\[
(\text{Ref. MIL-HDBK-5J, Figure 3.7.6.1(a)})
\]

\[
c_b := .92
\]

\[
\text{Extrapolation of Moments:}
\]

A moment extrapolation from End A is performed to locate moments at the center of the rivet pattern.

Distance from beam end A to the center of the rivet pattern:

\[
\text{dist} := 2.40 \text{ in} \quad (\text{Ref. Appendix C4})
\]

Extrapolation of My Moment

\[
M_{ya_i} := M_{ya_i} + F_{za_i} \cdot \text{dist}
\]

Extrapolation of Mz Moment

\[
M_{za_i} := M_{za_i} + F_{ya_i} \cdot \text{dist}
\]
Load in Rivets at EMC Box Tube to Centerbody Box Joint:

Total Number of rivets in beam end:
\[ N_{sp} := 33 \]

Number of rivets reacting Fz shear load:
\[ p_{sz} := 11 \]

Number of rivets reacting Fy shear loads:
\[ p_{sy} := 22 \]

Shear load/rivet due to Fy
\[ F_{sry} := \frac{F_{ya}}{p_{sy}} \]
\[ \text{max}(F_{sry}) = 114.4 \text{lbf} \]

Shear load/rivet due to Fz
\[ F_{srz} := \frac{F_{za}}{p_{sz}} \]
\[ \text{max}(F_{srz}) = 427.9 \text{lbf} \]

Shear flow due to torsion
(Ref. Bruhn section A6.8)
\[ F_{sr} := \frac{M_{xa}}{2 \cdot Am} \quad \text{max}(F_{sr}) = 456.7 \frac{\text{lbf}}{\text{in}} \]

Note: The shear load (F_{sr}) is used to calculate the torsional load (P_{sr}) in the rivet due to the pitch on the rivet pattern. See Figures 2.5.2.3-4 and 2.5.2.3-5.
Figure 2.5.2.3-4 Side 1 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Figure 2.5.2.3-5 Side 2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
**Calculation of Rivet Pitch:**

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

- **Perimeter of rivet pattern**
  \[ \text{per} := 2 \cdot a + b \quad \text{per} = 12 \cdot \text{in} \]

- **Loads in rivet due to torsion**
  \[ \text{Psrt} := \frac{\text{Fsrt} \cdot \text{per}}{\text{Nsp}} \]
  \[ \text{max}(\text{Psrt}) = 166.1 \text{-lbf} \]

- **Shear load in rivets due to beam axial load**
  \[ \text{Prta} := \frac{\text{Fxa}}{\text{Nsp}} \]
  \[ \text{max}(\text{Prta}) = 296.1 \text{-lbf} \]

**Rivet Dimension Variables:**
(Ref. SDG39135759)

- \[ z_1 := 1.0 \text{-in} \]
- \[ z_2 := 2.0 \text{-in} \]
- \[ y_1 := 1.0 \text{-in} \]
- \[ y_2 := 2.0 \text{-in} \]
Eccentrically Loaded Rivets due to My and Mz Moments:

```
Rivet Coordinate System Data

j := 1..rows(coord)  Counter for Coordinate Points

x_j := coord_j,2    Rivet Coordinate Points for x-direction

y_j := coord_j,3    Rivet Coordinate Points for y-direction

z_j := coord_j,4    Rivet Coordinate Points for z-direction

rivet_counter_j := coord_j,1 / in
```
For Moment $M_y$:

Eccentrically Loaded Rivet Pattern about $M_y$

Cross-Section A-A
(Row 1, 16 rivets)

Cross-Section B-B
(Row 2, 6 rivets)

Cross-Section C-C
(Represents side, 11 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[ r_y_j := \left( \left( x_j \right)^2 + \left( z_j \right)^2 \right)^{\frac{1}{2}} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \text{sigry} := \sum_{j=1}^{\text{rows(coord)}} \left( r_y_j \right)^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_{y_j} := \begin{cases} 0 & \text{if } (x_j = 0) \land (z_j = 0) \\ \text{atan2}(x_j, z_j) & \text{otherwise} \end{cases} \]

(Note: The angle \( \theta \) is defined off of the x-axis. See below.)

Resultant Load at Each Rivet

\[ \text{max}(\text{Fym}) = 891 \text{ lbf} \]

- \( Fz_{my,i,j} := Fym_{i,j} \cdot \sin\left( \beta_{y,j} - \frac{u}{2} \right) \) - component of Fym

- \( Fx_{my,i,j} := Fym_{i,j} \cdot \cos\left( \beta_{y,j} - \frac{u}{2} \right) \) - component of Fym
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section D-D
(Row 1, 8 rivets)

Cross-Section E-E
(Row 2, 3 rivets)

Cross-Section F-F
(Represents both sides, 22 rivets)

Note: Figure is for reference only.
Mz_i := Mz_i + (Fx_{ai} \cdot yc) 

Total Mz Moment due to unsymmetrical rivet pattern in y direction

rz_j := \left(\frac{1}{\sum_{j=1}^{rows(coord)} (rz_j)^2}\right)^{1/2} 

Radial distance to each rivet from the centroid of the rivet pattern

sigrz := \sum_{j=1}^{rows(coord)} (rz_j)^2 

Sum of the radial directions for all rivets in the rivet pattern

\beta_z_j := \arctan2(x_j, y_j) 

Angle between resultant vector and tension or shear vectors

Fzm_i,j := \frac{(Mz_i \cdot rz_j)}{sigrz} 

Resultant Load at Each Rivet

max(Fzm) = 953.2 lbf

(Note: The angle $\theta$ is defined off of the x-axis. See below.)

\[ Fy_{mz_{i,j}} := Fzm_{i,j} \cdot \sin\left(\frac{u}{2} + \beta_z_j\right) \] 

y - component of Fzm

\[ Fx_{mz_{i,j}} := Fzm_{i,j} \cdot \cos\left(\frac{u}{2} + \beta_z_j\right) \] 

x - component of Fzm

\[ F_{i,j} := \begin{cases} 
Fz_{my_{i,j}} & \text{if } \text{rivet_counter}_j \leq 22 \\
Fy_{mz_{i,j}} & \text{otherwise} 
\end{cases} \] 

Total Axial Load due to My and Mz Moments

max(F) = 637.6 lbf

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.2.3 for beam and socket analysis.
Total Rivet Shear Load:

\[ P_{t,ij} := \begin{cases} \sqrt{\left(P_{rt} + F_{x_{my}} + F_{x_{mz}}\right)^2 + \left(P_{srt} + F_{sry} + F_{x_{mz}}\right)^2} & \text{if } j \leq 22 \\ \sqrt{\left(P_{rt} + F_{x_{my}} + F_{x_{mz}}\right)^2 + \left(P_{srt} + F_{sry} + F_{x_{mz}}\right)^2} & \text{otherwise} \end{cases} \]

\[ \max(P_t) = 1523.9 \text{ lbf} \]

Margin of safety for Total Rivet Load:

\[ MS_{t,1} := \frac{F_{s-cf} - 1}{P_{t,1} \cdot F_{Su} \cdot FF} \]

\[ \min(MS_{t,1}) = 0.146 \quad \text{(Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. . . .)} \]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[ \text{output} := \text{augment(ID, LC, MS1t)} \]

\[ \text{rows(output)} = 1024 \quad \text{Number of rows in the "output" array} \]

\[ \text{cols(output)} = 35 \quad \text{Number of columns in the "output" array} \]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[ \text{match(min(MS1t), MS1t)} = \left[ \begin{array} \{157\} \\ 8 \end{array} \right] \]

Load Case for Minimum Margin of Safety

\[ \text{min\_LC} := \text{output} \left( \text{match(min(MS1t), MS1t)}_{1,1} \right)^2 \]

Element ID for Minimum Margin of Safety

\[ \text{min\_ID} := \text{output} \left( \text{match(min(MS1t), MS1t)}_{1,1} \right)^1 \]

Rivet number 8 is the one with the minimum margin of safety of 0.146.
Shear Minimum Margin of Safety:

Minimum Margin of Safety
\[ \text{min}(\text{MSlt}) = 0.146 \]

Element ID for Minimum Margin of Safety
\[ \text{min\_ID} = 1509 \]

Load Case for Minimum Margin of Safety
\[ \text{min\_LC} = 1020 \]

Maximum Rivet Load for Minimum Margin of Safety
\[ \text{max}(Pt) = 1524 \text{lbf} \]

Rivet with Minimum Margin of Safety
Rivet number 8
(See Figures 2.5.2.3-4 and 2.5.2.3-5 for rivet location)
Bearing on Hole Wall:

Hole diameter \( dh := 0.257\text{-in} \)  
(Ref. SEG39135758, Flag Note 1)
Tube thickness \( tp := 0.25\text{-in} \)  
(Ref. SDG39135761)
Bearing area \( Ab := dh \cdot tp \)  
\[ Ab = 0.06425\text{-in}^2 \]

Max. load per rivet \[ \text{max}(Pt) = 1523.9\text{-lbf} \]
Max. bearing stress \[ b := \frac{\text{max}(Pt)}{Ab} \]  
\[ b = 23718.7\text{-psi} \]
Margin of safety \[ MSb := \frac{F_{bru\cdot cb}}{b \cdot F_{Su\cdot FF}} - 1 \]  
\[ MSb = 1.87 \]

Shear tear out:

Edge distance \( e := (0.588 + 0.312)\text{-in} \)  
(Ref. SDG39135759)
Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257\text{-in} \)

\[ \frac{e}{dh} = 3.502 \]

Tube thickness \( tp := 0.25\text{-in} \)
Shear out area \[ As := 2\left(\frac{e}{2} \cdot \cos(40\text{-deg})\right) \cdot tp \]  
\[ As = 0.4008\text{-in}^2 \]

Max. load per rivet \[ \text{max}(Pt) = 1523.9\text{-lbf} \]
Max. shear tear out stress \[ s := \frac{\text{max}(Pt)}{As} \]  
\[ s = 3802.4\text{-psi} \]
Margin of safety \[ MS_{sh} := \frac{F_{su\cdot cd}}{s \cdot F_{Su\cdot FF}} - 1 \]  
\[ MS_{sh} = 4.66 \]
2.5.2.4 RICH Bracket to EMC Box Tubes
Margins of Safety

Table 2.5.2.4-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1398M8-9</td>
<td>RICH Rivets</td>
<td>Monel ALY 400</td>
<td>Landing</td>
<td>Shear</td>
<td>3.36 (u)</td>
<td>2.5.2.4-13</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 1.4 for Ultimate and 1.1 for Yield.
2. Boundary condition is at five Trunnion locations.
3. All 192 load cases of Launch and Landing are applied.
4. $u =$ ultimate, $y =$ yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing.

Description of Structure

Figure 2.5.2.4-1 below shows the location of six RICH Brackets in AMS-02. The Brackets were machined out of 7050-T7451 Aluminum Alloy plate. They were riveted to Centerbody Tubes. Part of a Bracket was bolted to Ring Imaging Cherenkov Counter (RICH).

Figure 2.5.2.4-1: Location of RICH Brackets in AMS-02

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built of the RICH Brackets using FEMAP software.

1. Parts were mainly modeled as CQUAD4 and CTRIA3 plate elements.
2. Section of Centerbody Tube, which was coupled with Brackets, was CQUAD4 plate elements.
3. All rivets was modeled as RBE2 rigid elements with DOF’s 1&2, 1&3, or 2&3. (see Figure 2.5.2.4-3)
4. Continuation of Centerbody Tube beam elements and plate elements was represented by RBE2 rigid elements with DOF’s 1-6.
5. Bar elements were found at intersection between two plates.

The model of RICH Brackets was then imported into USS2-04 load model. A built PAS model was also integrated into the load model.

Figure 2.5.2.4-2: FEMAP Model of RICH Brackets
Figure 2.5.2.4-3: FEMAP Model of Rivets

The model was constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.5.2.4-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5.

All 192 load cases for Launch and Landing were applied.

MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02.

Forces at rivet location were requested.
Table below shows details of model inputs.

### Table 2.5.2.4-2: Inputs of Finite Element Model of RICH Brackets

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>TYPE</th>
<th>COLOR</th>
<th>PROP</th>
<th>MAT'L</th>
<th>LC#</th>
<th>SPC#</th>
<th>COORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>rich bracket</td>
<td>200,001 - 212,802</td>
<td>200,001 - 202,424</td>
<td>plate</td>
<td>124</td>
<td>200,001 - 0.25&quot; TK</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centerbody tube at rich</td>
<td>215,001</td>
<td>215,840</td>
<td>plate</td>
<td>85</td>
<td>200,011 - tube</td>
<td>200,001</td>
<td>200001</td>
<td>1001001</td>
<td></td>
</tr>
<tr>
<td>rivets</td>
<td>215,001 - 215,504</td>
<td>200,001 - 220,464</td>
<td>bar</td>
<td>24</td>
<td>200,003 - dummy</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>misc</td>
<td>215,001 - 215,504</td>
<td>200,001 - 220,464</td>
<td>rbe2</td>
<td>13</td>
<td>200,003 -</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAS</td>
<td>300,001 - 303,474</td>
<td>300,001 - 304,504</td>
<td></td>
<td>300,001 - 300,023</td>
<td>300,001 - 300,066</td>
<td>300,001</td>
<td>300,001</td>
<td>300,001 - 300,002</td>
<td></td>
</tr>
</tbody>
</table>
### Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Strain Energy</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.273202E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.420144E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.633816E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.057998E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.047791E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.609049E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Results of Rigid Body Checks of Matrix KGG (G-Set)**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Strain Energy</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.263888E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.129834E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.326043E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.075881E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.044385E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.661979E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Results of Rigid Body Checks of Matrix KNN (N-Set)**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Strain Energy</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.263888E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.129834E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.326043E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.075881E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.044385E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.661979E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Results of Rigid Body Checks of Matrix KFF (F-Set)**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Strain Energy</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.263888E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.129834E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.326043E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.075881E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.044385E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.661979E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>
*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  1.000000E-02
DIRECTION    STRAIN ENERGY   PASS/FAIL
          ---------    -------------    ---------
            1         1.263888E-07        PASS
            2         4.129834E-08        PASS
            3         1.326043E-08        PASS
            4         5.075881E-05        PASS
            5         1.044385E-04        PASS
            6         1.661979E-04        PASS

A further check is that of rigid body modes. The first 10 unconstrained modes are shown below.
There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 2.5.2.4-3: Eigenvalue Summary of RICH Brackets Model

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-5.53E-06</td>
<td>2.35E-03</td>
<td>3.74E-04</td>
<td>1.00E+00</td>
<td>-5.53E-06</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3.02E-06</td>
<td>1.74E-03</td>
<td>2.76E-04</td>
<td>1.00E+00</td>
<td>3.02E-06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>5.91E-06</td>
<td>2.43E-03</td>
<td>3.87E-04</td>
<td>1.00E+00</td>
<td>5.91E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1.21E-05</td>
<td>3.47E-03</td>
<td>5.53E-04</td>
<td>1.00E+00</td>
<td>1.21E-05</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2.89E-05</td>
<td>5.38E-03</td>
<td>8.56E-04</td>
<td>1.00E+00</td>
<td>2.89E-05</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>3.10E-05</td>
<td>5.56E-03</td>
<td>8.86E-04</td>
<td>1.00E+00</td>
<td>3.10E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3.56E+07</td>
<td>5.97E+03</td>
<td>9.50E+02</td>
<td>1.00E+00</td>
<td>3.56E+07</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>5.44E+07</td>
<td>7.37E+03</td>
<td>1.17E+03</td>
<td>1.00E+00</td>
<td>5.44E+07</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>7.79E+07</td>
<td>8.83E+03</td>
<td>1.41E+03</td>
<td>1.00E+00</td>
<td>7.79E+07</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.61E+08</td>
<td>1.27E+04</td>
<td>2.02E+03</td>
<td>1.00E+00</td>
<td>1.61E+08</td>
</tr>
</tbody>
</table>

Additional check is comparison of the Strap loads between the load model and the detail model.
The loads are picked randomly. Loads in both models are closely matched.
### Table 2.5.2.4-4: Strap Loads (lbf) in Load Model 2-04

<table>
<thead>
<tr>
<th>Case</th>
<th>90001</th>
<th>90002</th>
<th>90003</th>
<th>90004</th>
<th>90005</th>
<th>90006</th>
<th>90007</th>
<th>90008</th>
<th>90009</th>
<th>90010</th>
<th>9011</th>
<th>9012</th>
<th>9013</th>
<th>9014</th>
<th>9015</th>
<th>9016</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>1186.6</td>
<td>1615.3</td>
<td>1495.4</td>
<td>2128.4</td>
<td>1241.3</td>
<td>3808.0</td>
<td>1382.5</td>
<td>5331.2</td>
<td>5259.6</td>
<td>1683.6</td>
<td>10097.9</td>
<td>2054.3</td>
<td>7952.9</td>
<td>3314.8</td>
<td>9044.1</td>
<td>3929.6</td>
</tr>
<tr>
<td>1023</td>
<td>1171.3</td>
<td>2245.6</td>
<td>1605.7</td>
<td>6899.0</td>
<td>1013.3</td>
<td>1511.8</td>
<td>1670.6</td>
<td>3157.0</td>
<td>7264.3</td>
<td>4582.4</td>
<td>6207.3</td>
<td>3965.4</td>
<td>6681.8</td>
<td>1678.2</td>
<td>10078.1</td>
<td>1914.3</td>
</tr>
<tr>
<td>2031</td>
<td>3923.0</td>
<td>6907.2</td>
<td>1444.7</td>
<td>2837.3</td>
<td>1555.9</td>
<td>2975.5</td>
<td>5887.1</td>
<td>4599.8</td>
<td>3987.8</td>
<td>1216.2</td>
<td>6181.0</td>
<td>8787.8</td>
<td>1481.6</td>
<td>1652.1</td>
<td>7512.9</td>
<td>5265.2</td>
</tr>
<tr>
<td>2040</td>
<td>2119.5</td>
<td>1696.3</td>
<td>5485.8</td>
<td>2655.9</td>
<td>2756.3</td>
<td>2103.0</td>
<td>7067.2</td>
<td>3734.3</td>
<td>4950.0</td>
<td>1586.5</td>
<td>1980.6</td>
<td>2141.0</td>
<td>1433.5</td>
<td>2698.7</td>
<td>1621.3</td>
<td>4952.3</td>
</tr>
<tr>
<td>4050</td>
<td>1896.4</td>
<td>2100.0</td>
<td>3024.5</td>
<td>3905.9</td>
<td>5116.4</td>
<td>1178.1</td>
<td>6429.4</td>
<td>1281.8</td>
<td>882.7</td>
<td>1133.1</td>
<td>2774.4</td>
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<td>682.0</td>
<td>1087.4</td>
<td>1612.9</td>
<td>2519.9</td>
</tr>
<tr>
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<td>7657.7</td>
<td>3755.7</td>
<td>1663.0</td>
<td>1556.5</td>
<td>10633.2</td>
<td>1494.6</td>
<td>2604.4</td>
<td>1236.1</td>
<td>5487.6</td>
<td>10488.8</td>
<td>593.2</td>
<td>852.8</td>
<td>2100.1</td>
<td>7849.4</td>
<td>479.6</td>
<td>947.1</td>
</tr>
</tbody>
</table>

Note: 1. Negative sign in Table 2.5.2.4-6 means load in Detail model greater than in Load model.

### Table 2.5.2.4-5: Strap Loads (lbf) in RICH Brackets Model

<table>
<thead>
<tr>
<th>Case</th>
<th>90001</th>
<th>90002</th>
<th>90003</th>
<th>90004</th>
<th>90005</th>
<th>90006</th>
<th>90007</th>
<th>90008</th>
<th>90009</th>
<th>90010</th>
<th>9011</th>
<th>9012</th>
<th>9013</th>
<th>9014</th>
<th>9015</th>
<th>9016</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>1195.5</td>
<td>1626.4</td>
<td>1487.0</td>
<td>2103.9</td>
<td>1243.4</td>
<td>3955.8</td>
<td>1377.0</td>
<td>5313.0</td>
<td>5456.3</td>
<td>1695.6</td>
<td>9916.7</td>
<td>2040.5</td>
<td>8043.0</td>
<td>3343.1</td>
<td>9093.3</td>
<td>3917.9</td>
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<tr>
<td>1023</td>
<td>1169.8</td>
<td>2238.5</td>
<td>1606.0</td>
<td>6878.7</td>
<td>1014.5</td>
<td>1513.0</td>
<td>1674.1</td>
<td>3197.3</td>
<td>7269.8</td>
<td>4497.9</td>
<td>6255.0</td>
<td>3913.6</td>
<td>6651.4</td>
<td>1685.5</td>
<td>10027.4</td>
<td>1920.5</td>
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<tr>
<td>2031</td>
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<td>6885.9</td>
<td>1446.3</td>
<td>1556.1</td>
<td>2993.2</td>
<td>6918.0</td>
<td>1390.2</td>
<td>1620.2</td>
<td>6171.0</td>
<td>8757.8</td>
<td>1481.3</td>
<td>1653.5</td>
<td>7487.3</td>
<td>5279.0</td>
<td>1562.3</td>
<td>1500.0</td>
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<td>2040</td>
<td>2119.5</td>
<td>1696.3</td>
<td>5485.2</td>
<td>2655.8</td>
<td>2756.4</td>
<td>2103.1</td>
<td>7067.2</td>
<td>3734.8</td>
<td>1495.0</td>
<td>1586.5</td>
<td>1980.6</td>
<td>2141.0</td>
<td>1433.5</td>
<td>2698.7</td>
<td>1621.2</td>
<td>4952.8</td>
</tr>
<tr>
<td>4050</td>
<td>1896.4</td>
<td>2098.6</td>
<td>3021.5</td>
<td>3883.5</td>
<td>5118.2</td>
<td>1179.8</td>
<td>6366.9</td>
<td>1281.3</td>
<td>884.2</td>
<td>1135.0</td>
<td>2761.4</td>
<td>6589.3</td>
<td>685.4</td>
<td>1089.2</td>
<td>1609.6</td>
<td>2492.2</td>
</tr>
<tr>
<td>4064</td>
<td>7685.5</td>
<td>3754.2</td>
<td>1662.9</td>
<td>1556.4</td>
<td>10634.0</td>
<td>1494.7</td>
<td>2604.8</td>
<td>1236.2</td>
<td>5487.8</td>
<td>10489.4</td>
<td>593.2</td>
<td>852.9</td>
<td>2100.0</td>
<td>7847.2</td>
<td>479.6</td>
<td>947.1</td>
</tr>
</tbody>
</table>

### Table 2.5.2.4-6: Load Differences (lbf) between Two Models

<table>
<thead>
<tr>
<th>Case</th>
<th>90001</th>
<th>90002</th>
<th>90003</th>
<th>90004</th>
<th>90005</th>
<th>90006</th>
<th>90007</th>
<th>90008</th>
<th>90009</th>
<th>90010</th>
<th>9011</th>
<th>9012</th>
<th>9013</th>
<th>9014</th>
<th>9015</th>
<th>9016</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>-8.9</td>
<td>-11.1</td>
<td>8.3</td>
<td>24.6</td>
<td>-2.0</td>
<td>-147.8</td>
<td>5.5</td>
<td>18.2</td>
<td>-196.7</td>
<td>-12.0</td>
<td>181.3</td>
<td>13.8</td>
<td>-90.1</td>
<td>-28.3</td>
<td>-49.2</td>
<td>11.6</td>
</tr>
<tr>
<td>1023</td>
<td>1.5</td>
<td>7.2</td>
<td>-0.3</td>
<td>20.3</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-3.6</td>
<td>-40.4</td>
<td>-5.5</td>
<td>84.5</td>
<td>47.7</td>
<td>51.8</td>
<td>30.3</td>
<td>-7.3</td>
<td>50.6</td>
<td>-6.2</td>
</tr>
<tr>
<td>2031</td>
<td>-9.2</td>
<td>21.3</td>
<td>-1.6</td>
<td>-0.2</td>
<td>-17.8</td>
<td>-30.9</td>
<td>-0.4</td>
<td>1.0</td>
<td>64.0</td>
<td>30.0</td>
<td>0.3</td>
<td>-1.4</td>
<td>25.6</td>
<td>-13.8</td>
<td>1.7</td>
<td>0.2</td>
</tr>
<tr>
<td>2040</td>
<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
<td>0.1</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>-0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>4050</td>
<td>0.0</td>
<td>1.4</td>
<td>3.0</td>
<td>22.5</td>
<td>-1.9</td>
<td>-1.7</td>
<td>62.4</td>
<td>0.4</td>
<td>-1.5</td>
<td>-1.9</td>
<td>13.0</td>
<td>28.9</td>
<td>-3.4</td>
<td>-1.9</td>
<td>3.3</td>
<td>27.7</td>
</tr>
<tr>
<td>4064</td>
<td>-0.8</td>
<td>1.5</td>
<td>0.1</td>
<td>0.2</td>
<td>-0.8</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.1</td>
<td>-0.2</td>
<td>-0.6</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>2.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: 1. Negative sign in Table 2.5.2.4-6 means load in Detail model greater than in Load model.
Material and Temperature

The Rivets are Monel Alloy 400 (UNS N04400). Material properties of Monel Alloy 400 are taken from the specification of NAS1398M8-9. Temperature limits are based upon ICD-2-19001 (Shuttle Orbiter / Cargo Standard Interfaces), Revision-L. For Launch condition, the temperature of 150°F is applied. For Landing condition, the temperature of 220°F is applied.

Analysis

All MPC forces for Rivets are compared to the shear strength of Monel Alloy 400. All margins of safety are positive.
Check of Rivets, NAS1398M8-9 at RICH Brackets to Centerbody Tubes

Rivets are NAS1398M8-9, 0.25 in., blind protruding head locked spindle; Monel Alloy 400 (UNS N04400).

Rivet diameter, \( D := 0.25\text{ in} \)

Shear area, \( A := \frac{\beta D^2}{4} \) \( A = 0.049\text{ in}^2 \)

Max. rivet shear strength @ room temperature \( F_{su} := 48500\text{ psi} \) (Ref. www.specialmetals.com, MONEL Alloy 400, Table 10)

By interpolation method, shear strength at the temperature 220°F was calculated:

\( F_{su} := 45146\text{ psi} \)

Shear allowable, \( P_{su} := F_{su} \cdot A \)

\( P_{su} = 2216\text{lbf} \)

2.5.2.4-11
Table 10 - Shear Strength of MONEL Alloy 400 Rivet Wire

<table>
<thead>
<tr>
<th>Property</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annealed</td>
</tr>
<tr>
<td>Shear Strength, ksi</td>
<td></td>
</tr>
<tr>
<td>Room</td>
<td>48.5</td>
</tr>
<tr>
<td>600&lt;sup&gt;b&lt;/sup&gt;</td>
<td>45.0</td>
</tr>
<tr>
<td>800&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.0</td>
</tr>
<tr>
<td>1000&lt;sup&gt;b&lt;/sup&gt;</td>
<td>29.0</td>
</tr>
<tr>
<td>800&lt;sup&gt;c&lt;/sup&gt;</td>
<td>38.5</td>
</tr>
<tr>
<td>1000&lt;sup&gt;c&lt;/sup&gt;</td>
<td>30.5</td>
</tr>
<tr>
<td>Tensile Strength, ksi</td>
<td>78.5</td>
</tr>
<tr>
<td>Yield Strength</td>
<td></td>
</tr>
<tr>
<td>(0.2% Offset), ksi</td>
<td>46.0</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>41</td>
</tr>
</tbody>
</table>

<sup>a</sup> Corresponds to the approximate strength of the shank of a headed rivet.
<sup>b</sup> 30 min at temperature before testing.
<sup>c</sup> 24 hr at temperature before testing.

Factor of Safety, \( \text{FSu} := 1.4 \)

**NASPOST inputs**

Read in the external datum from NASPOST results: *(see p.2.5.2.4-14 for SORT format)*

- Shear forces are retracted at GRID IDs represented location of rivets.
- All 192 load cases for Launch and Landing are included.

\[
\text{load} := \text{READPRN}("rivetR.inp")
\]

*(Reading rivet loads from Launch and Landing cases)*

\[
i := 1 \ldots \text{rows}(	ext{load})
\]

\[
\text{ID} := \text{load}^{(1)}
\]

\[
\text{LC} := \text{load}^{(2)}
\]

\[
\text{shear1} := \text{load}^{(3)}
\]

\[
\text{shear2} := \text{load}^{(4)}
\]

* Note that "rivetR.inp" was generated from NASPOST results (.LIS files) by just removing all texts and comments.
AMS-02 RICH BRACKET - RIVETS

Total shear per rivet:  \[ P_{s_i} := \sqrt{(\text{shear1})^2 + (\text{shear2})^2} \text{ lbf} \]

Margin of Safety,  \[ MS_i := \frac{P_{su}}{FS_u P_{s_i}} - 1 \]

Minimum MS,  \[ MS_{rivetR} := \text{min}(MS) \]

\[ MS_{rivetR} = 3.36 \]

*** GRID and Load Case IDs, shear forces, and margin of safety where minimum MS was calculated are shown below.

```
output := augment(ID, LC)
output := augment(output, shear1)
output := augment(output, shear2)
output := augment(output, MS)
sorted1 := csort(output, 5)

GRID  LC  Shears  MS
submatrix(sorted1, 1, 1, 1, cols(sorted1)) = (215487  4015  -264  249  3.361875)
```
REFERENCE: NASPOST SORT script

$ SELECT MPC-FORCES;IDS=215049 THRU 215060\ 
   215097 THRU 215108\ 
   215145 THRU 215156\ 
   215193 THRU 215204\ 
   215241 THRU 215252\ 
   215481 THRU 215492
 SORT VAR = MAXABS(FX);OPT=0
 PRINT 1 2;
 HEADING = 'RICH RIVETS: MPC FORCE / Fx'
$
$ $ SORT VAR = MAXABS(FY);OPT=0
$ $ PRINT 1 2;
 $ $ HEADING = 'RICH RIVETS: MPC FORCE / Fy'
$
$ SELECT MPC-FORCES;IDS=215253 THRU 215264 215493 THRU 215504
 SORT VAR = MAXABS(FX);OPT=0
 PRINT 1 3;
 HEADING = 'RICH RIVETS: MPC FORCE / Fx'
$
$ $ SORT VAR = MAXABS(FZ);OPT=0
$ $ PRINT 1 3;
 $ $ HEADING = 'RICH RIVETS: MPC FORCE / Fz'
$
$ SELECT MPC-FORCES;IDS=215061 THRU 215072\ 
   215109 THRU 215120\ 
   215157 THRU 215168\ 
   215205 THRU 215216
 SORT VAR = MAXABS(FY);OPT=0
 PRINT 2 3;
 HEADING = 'RICH RIVETS: MPC FORCE / Fy'
$
$ $ SORT VAR = MAXABS(FZ);OPT=0
$ $ PRINT 2 3;
 $ $ HEADING = 'RICH RIVETS: MPC FORCE / Fz'
$
2.5.2.5 RICH PAS Brackets to EMC Box Tubes
Margins of Safety

Table 2.5.2.5-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1398M8-9</td>
<td>PAS-RICH Rivets</td>
<td>Monel ALY 400</td>
<td>On-Orbit</td>
<td>Shear</td>
<td>0.27 (u)</td>
<td>2.5.2.5-14</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 1.4 and 1.1 for Ultimate and Yield, respectively in Launch and Landing conditions.
2. Factors of Safety are 2.0 and 1.25 for Ultimate and Yield, respectively in On-Orbit condition.
3. Boundary condition is at five Trunnion locations in Launch and Landing condition. Boundary condition is at C.G. of PAS Capture Bar and three Guide Bars in On-Orbit condition.
4. All 192 load cases of Launch and Landing and 8 load cases of On-Orbit are applied.
5. \( u \) = ultimate, \( y \) = yield
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing. It is also designed with a yield factor of 1.25 and an ultimate factor 2.0 against limit loads for On-Orbit.

Description of Structure

Figure 2.5.2.5-1 below shows the location of two PAS-RICH Brackets in AMS-02. The Brackets were machined out of 7050-T7451 Aluminum Alloy plate. They were riveted to Centerbody Tubes. Part of a Bracket was bolted to Payload Attach System (PAS). Another part was bolted to Ring Imaging Cherenkov Counter (RICH).

Figure 2.5.2.5-1: Location of PAS-RICH Brackets in AMS-02

* Note that the above figure does not show Vacuum Case for clarity.
Description of Model

A FEM model was built of the PAS-RICH Brackets using FEMAP software.

1. Parts were mainly modeled as CQUAD4 and CTRIA3 plate elements.
2. Interface of PAS-RICH brackets and PAS was CHEXA solid elements.
3. Section of Centerbody Tube, which was coupled with Brackets, was CQUAD4 plate elements.
4. All rivets was modeled as RBE2 rigid elements with DOF’s 1&2 or 1&3. (see Figure 2.5.2.5-3)
5. Continuation of Centerbody Tube beam and plate elements was represented by RBE2 rigid elements with DOF’s 1-6.
6. Bar elements were found at intersection between two plates.
7. RSSCON element was connector of plate to solid elements.

The model of PAS-RICH Brackets was then imported into USS2-04 load model. A built PAS model was also integrated into the load model.
Figure 2.5.2.5-3: FEMAP Model of Rivets

The model was constrained with DOF’s 1&3 at Trunnion 1&2 (see Figure 2.5.2.5-1), with DOF’s 3 at Trunnion 3&4, and with DOF’s 2 at Trunnion 5 for Launch and Landing conditions. The model was also constrained with DOF’s 3 at C.G. of PAS Capture Bar, with DOF’s 236 at two rear Guide Bars, and with DOF’s 136 at front Guide Bar for On-Orbit condition.

All 192 load cases for Launch and Landing, and 8 load cases for On-Orbit were applied.

MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of AMS-02.
Forces at rivet location were requested.

Table below shows details of model inputs.

**Table 2.5.2.5-2: Inputs of Finite Element Model of PAS-RICH Brackets**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>TYPE</th>
<th>PROP#</th>
<th>MAT'L#</th>
<th>LC#</th>
<th>SPC#</th>
<th>COORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>pas rich bracket</td>
<td>200,001 - 212,802</td>
<td>203,001 - 204,624</td>
<td>plate</td>
<td>200,001 - 0.25&quot; TK</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>205,001 - 206,830</td>
<td>plate</td>
<td>200,002 - 0.4375&quot; TK</td>
<td>200,021</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>solid</td>
<td>200,021 - solid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centerbody tube</td>
<td></td>
<td>210,001 - 211,920</td>
<td>plate</td>
<td>200,011 - tube</td>
<td>200,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAS</td>
<td>300,001 - 304,504</td>
<td>300,001 - 300,023</td>
<td>300,001 - 300,023</td>
<td>300,001 - 300,006</td>
<td>300,001</td>
<td>300,001</td>
<td>300,011 - 300,002</td>
<td></td>
</tr>
</tbody>
</table>
Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
------------ -------- --------
 1 5.314041E-08 PASS
 2 7.262543E-08 PASS
 3 3.534839E-08 PASS
 4 9.702608E-05 PASS
 5 4.916835E-05 PASS
 6 1.171079E-05 PASS

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
------------ -------- --------
 1 4.694130E-08 PASS
 2 7.125755E-08 PASS
 3 3.189959E-08 PASS
 4 8.980069E-05 PASS
 5 5.375610E-05 PASS
 6 2.025928E-05 PASS

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN+AUTO (N+AUTOSPC-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02
DIRECTION STRAIN ENERGY PASS/FAIL
------------ -------- --------
 1 4.694130E-08 PASS
 2 7.125755E-08 PASS
 3 3.189959E-08 PASS
 4 8.980069E-05 PASS
 5 5.375610E-05 PASS
 6 2.025928E-05 PASS
A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 2.5.2.5-3: Eigenvalue Summary of PAS-RICH Brackets Model

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.06E-05</td>
<td>3.25E-03</td>
<td>5.18E-04</td>
<td>1.00E+00</td>
<td>-1.06E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.56E-06</td>
<td>1.25E-03</td>
<td>1.99E-04</td>
<td>1.00E+00</td>
<td>-1.56E-06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>5.29E-06</td>
<td>2.30E-03</td>
<td>3.66E-04</td>
<td>1.00E+00</td>
<td>5.29E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>6.34E-06</td>
<td>2.52E-03</td>
<td>4.01E-04</td>
<td>1.00E+00</td>
<td>6.34E-06</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>8.82E-06</td>
<td>2.97E-03</td>
<td>4.73E-04</td>
<td>1.00E+00</td>
<td>8.82E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1.12E-05</td>
<td>3.34E-03</td>
<td>5.32E-04</td>
<td>1.00E+00</td>
<td>1.12E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3.58E+07</td>
<td>5.98E+03</td>
<td>9.52E+02</td>
<td>1.00E+00</td>
<td>3.58E+07</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>5.07E+07</td>
<td>7.12E+03</td>
<td>1.13E+03</td>
<td>1.00E+00</td>
<td>5.07E+07</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1.24E+08</td>
<td>1.12E+04</td>
<td>1.78E+03</td>
<td>1.00E+00</td>
<td>1.24E+08</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.69E+08</td>
<td>1.30E+04</td>
<td>2.07E+03</td>
<td>1.00E+00</td>
<td>1.69E+08</td>
</tr>
</tbody>
</table>
Additional check is comparison of the interface loads between the load model and the detail model. The loads are picked randomly. Loads in both models are closely matched.

Table 2.5.2.5-4: Interface Loads (lbf) in Load Model 2-04

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-10265.5</td>
<td>-4218.5</td>
<td>9910.0</td>
<td>7635.5</td>
<td>-785.8</td>
<td>987.6</td>
<td>-3250.9</td>
<td>1119.0</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>19044.8</td>
<td>-16676.0</td>
<td>3404.8</td>
<td>2433.2</td>
<td>-12722.8</td>
<td>7581.0</td>
<td>-11633.1</td>
<td>-519.6</td>
</tr>
<tr>
<td>2033(Fz)</td>
<td>-1601.8</td>
<td>-1942.0</td>
<td>645.2</td>
<td>437.5</td>
<td>-6117.5</td>
<td>-9489.8</td>
<td>-3363.9</td>
<td>5239.9</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-1910.6</td>
<td>1228.8</td>
<td>-2868.4</td>
<td>-4166.4</td>
<td>7219.1</td>
<td>5784.0</td>
<td>3041.0</td>
<td>6638.5</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-543.2</td>
<td>11872.4</td>
<td>8070.0</td>
<td>-3118.7</td>
<td>-1324.4</td>
<td>-7806.0</td>
<td>-6032.6</td>
<td>3874.0</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>-3360.5</td>
<td>-834.1</td>
<td>-187.7</td>
<td>1137.0</td>
<td>13878.8</td>
<td>-1881.9</td>
<td>15033.1</td>
<td>21524.6</td>
</tr>
</tbody>
</table>

Table 2.5.2.5-5: Interface Loads (lbf) in PAS-RICH Brackets Model

<table>
<thead>
<tr>
<th>Case</th>
<th>64001</th>
<th>64002</th>
<th>64003</th>
<th>64004</th>
<th>64011</th>
<th>64012</th>
<th>64013</th>
<th>64014</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005(Fx)</td>
<td>-10454.2</td>
<td>-4312.0</td>
<td>10003.4</td>
<td>7718.2</td>
<td>-876.5</td>
<td>984.5</td>
<td>-3296.8</td>
<td>1074.5</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>18937.1</td>
<td>-16619.2</td>
<td>3365.7</td>
<td>2397.4</td>
<td>-12670.1</td>
<td>7579.1</td>
<td>-11506.6</td>
<td>-520.1</td>
</tr>
<tr>
<td>2033(Fz)</td>
<td>-1601.8</td>
<td>-1942.6</td>
<td>645.1</td>
<td>434.9</td>
<td>-6112.6</td>
<td>-9495.3</td>
<td>-3371.0</td>
<td>5249.1</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-1905.3</td>
<td>1222.7</td>
<td>-2869.7</td>
<td>-4156.4</td>
<td>7248.5</td>
<td>5782.5</td>
<td>3051.6</td>
<td>6651.5</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-535.4</td>
<td>11877.4</td>
<td>8075.0</td>
<td>-3112.0</td>
<td>-1326.9</td>
<td>-7798.7</td>
<td>-6046.1</td>
<td>3858.6</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>-3361.7</td>
<td>-832.2</td>
<td>-186.9</td>
<td>1132.7</td>
<td>13894.9</td>
<td>-1891.3</td>
<td>15009.3</td>
<td>21544.4</td>
</tr>
</tbody>
</table>

Table 2.5.2.5-6: Load Differences (lbf) between Two Models

<table>
<thead>
<tr>
<th>Load</th>
<th>LOAD DIFFERENCES BETWEEN TWO MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>64001</td>
</tr>
<tr>
<td>1005(Fx)</td>
<td>188.7</td>
</tr>
<tr>
<td>1028(Fy)</td>
<td>107.7</td>
</tr>
<tr>
<td>2033(Fz)</td>
<td>0.0</td>
</tr>
<tr>
<td>2047(Fx)</td>
<td>-5.2</td>
</tr>
<tr>
<td>4040(Fy)</td>
<td>-7.8</td>
</tr>
<tr>
<td>4061(Fz)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Note: 1. Negative sign in Table 2.5.2.5-6 means load in Detail model greater than in Load model.
Material and Temperature

The Rivets are Monel Alloy 400 (UNS N04400). Material properties of Monel Alloy 400 are taken from the specification of NAS1398M8-9. Temperature limits are based upon ICD-2-I9001 (Shuttle Orbiter / Cargo Standard Interfaces), Revision-L. For Launch condition, the temperature of 150°F is applied. For Landing condition, the temperature of 220°F is applied. For On-Orbit condition, the temperature of 200°F is applied.

Analysis

All MPC forces for Rivets are compared to the shear strength of Monel Alloy 400. All margins of safety are positive.
Check of Rivets, NAS1398M8-9 at PAS RICH Brackets to Centerbody Tubes

Rivets are NAS1398M8-9, 0.25 in., blind protruding head locked spindle; Monel Alloy 400 (UNS N04400).

Rivet diameter,  \[ D := 0.25 \text{ in} \]

Shear area,  \[ A := \frac{\beta \cdot D^2}{4} \]

\[ A = 0.049 \text{ in}^2 \]
Max. rivet shear strength
@ room temperature

\[ F_{su} = 48500 \text{ psi} \quad (\text{Ref. www.specialmetals.com, MONEL Alloy 400, Table 10}) \]

### Table 10 - Shear Strength of MONEL Alloy 400 Rivet Wire

<table>
<thead>
<tr>
<th>Property</th>
<th>Condition</th>
<th>Annealed</th>
<th>B &amp; S No. 1(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Strength, ksi</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Room</td>
<td></td>
<td>48.5</td>
<td>54.5</td>
</tr>
<tr>
<td>600(^b)</td>
<td></td>
<td>45.0</td>
<td>52.0</td>
</tr>
<tr>
<td>800(^b)</td>
<td></td>
<td>37.0</td>
<td>47.5</td>
</tr>
<tr>
<td>1000(^b)</td>
<td></td>
<td>29.0</td>
<td>38.0</td>
</tr>
<tr>
<td>800(^c)</td>
<td></td>
<td>38.5</td>
<td>49.5</td>
</tr>
<tr>
<td>1000(^c)</td>
<td></td>
<td>30.5</td>
<td>38.5</td>
</tr>
<tr>
<td>Tensile Strength, ksi</td>
<td></td>
<td>78.5</td>
<td>88.0</td>
</tr>
<tr>
<td>Yield Strength (0.2% Offset), ksi</td>
<td></td>
<td>46.0</td>
<td>75.5</td>
</tr>
<tr>
<td>Elongation, %</td>
<td></td>
<td>41</td>
<td>18</td>
</tr>
</tbody>
</table>

\(^a\)Corresponds to the approximate strength of the shank of a headed rivet.

\(^b\)30 min at temperature before testing.

\(^c\)24 hr at temperature before testing.

By interpolation method, shear strengths at specific temperatures below were calculated:

\[ @ 220^\circ F: \quad F_{su1} := 45146 \text{ psi} \]

\[ @ 200^\circ F: \quad F_{su2} := 45594 \text{ psi} \]

Shear allowables,

\[ @ 220^\circ F: \quad Psu1 := F_{su1} \times A \quad Psu1 = 2216 \text{ lbf} \]

\[ @ 200^\circ F: \quad Psu2 := F_{su2} \times A \quad Psu2 = 2238 \text{ lbf} \]
Factor of Safety,

+ For Launch and Landing: \( F_{Su1} := 1.4 \)

+ For On-Orbit: \( F_{Su2} := 2.0 \)

**NASPOST inputs**

Read in the external datum from NASPOST results: *(see p.2.5.2.5-15 for SORT format)*

- Shear forces are retracted at GRID IDs represented location of rivets.

- All 192 load cases for Launch and Landing, and 8 cases for On-Orbit are included.

\[
\text{load1} := \text{READPRN}("rivetPR.inp") \quad \text{(Reading rivet loads from Launch and Landing cases)}
\]

\[
i := 1 \ldots \text{rows(load1)} \quad \text{ID1} := \text{load1}^{(1)} \quad \text{LC1} := \text{load1}^{(2)}
\]

\[
\text{shear1} := \text{load1}^{(3)} \quad \text{shear2} := \text{load1}^{(4)}
\]

\[
\text{load2} := \text{READPRN}("rivetPR-or.inp") \quad \text{(Reading rivet loads from On-Orbit cases)}
\]

\[
j := 1 \ldots \text{rows(load2)} \quad \text{ID2} := \text{load2}^{(1)} \quad \text{LC2} := \text{load2}^{(2)}
\]

\[
\text{shear3} := \text{load2}^{(3)} \quad \text{shear4} := \text{load2}^{(4)}
\]

* Note that "rivetPR.inp" and "rivetPR-or.inp" were generated from NASPOST results (.LIS files) by just removing all texts and comments.

\[
+ \text{ For Launch and Landing:} \quad \text{Total shear per rivet:}
\]

\[
Ps_1 := \sqrt{(\text{shear1})^2 + (\text{shear2})^2} \text{-lbf}
\]

\[
Ps_2 := \sqrt{(\text{shear3})^2 + (\text{shear4})^2} \text{-lbf}
\]
Margin of Safety,

\[
MS_1 := \frac{P_{s1}}{F_{s1} \cdot P_{s1}} - 1
\]

\[
MS_2 := \frac{P_{s2}}{F_{s2} \cdot P_{s2}} - 1
\]

Minimum MS,

\[
MS_{rivetPR} := \min(\text{MS1})
\]

\[
MS_{rivetPRor} := \min(\text{MS2})
\]

\[
MS_{rivetPR} = 0.73
\]

\[
MS_{rivetPRor} = 0.27
\]

-------------------------------

*** GRID and Load Case IDs, shear forces, and margin of safety where minimum MS was calculated are shown below.

+ Launch and Landing:

\[
\text{output} := \text{augment(ID1, LC1)} \quad \text{output} := \text{augment(output, shear1)} \quad \text{output} := \text{augment(output, shear2)}
\]

\[
\text{output} := \text{augment(output, MS1)} \quad \text{sorted1 := csort(output, 5)}
\]

\[
\text{GRID} \quad \text{LC} \quad \text{Shears} \quad \text{MS}
\]

\[
\text{submatrix(sorted1, 1, 1, 1, cols(sorted1))} = (215315 \quad 1019 \quad -760 \quad -512 \quad 0.727379)
\]

+ On-Orbit:

\[
\text{output} := \text{augment(ID2, LC2)} \quad \text{output} := \text{augment(output, shear3)} \quad \text{output} := \text{augment(output, shear4)}
\]

\[
\text{output} := \text{augment(output, MS2)} \quad \text{sorted1 := csort(output, 5)}
\]

\[
\text{GRID} \quad \text{LC} \quad \text{Shears} \quad \text{MS}
\]

\[
\text{submatrix(sorted1, 1, 1, 1, cols(sorted1))} = (215311 \quad 200008 \quad -489 \quad 736 \quad 0.266406)
\]
REFERENCE: NASPOST SORT script

```
$ SELECT MPC-FORCES;IDS=215265 THRU 215282 215373 THRU 215390
   SORT VAR = MAXABS(FX);OPT=0
   PRINT 1 2;
   HEADING = 'PAS RICH RIVETS: MPC FORCE / Fx'
$
$ SELECT MPC-FORCES;IDS=215283 THRU 215318 215391 THRU 215426
   SORT VAR = MAXABS(FX);OPT=0
   PRINT 1 3;
   HEADING = 'PAS RICH RIVETS: MPC FORCE / Fx'
$
```
2.5.3 Keel Assembly Riveted Joints
Keel Assembly Riveted Joints

The Keel Assembly Rivet Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>2.5.3.1</th>
<th>Keel Angle Joint to Keel Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.3.2</td>
<td>Keel Tube to Keel Block</td>
</tr>
</tbody>
</table>
2.5.3.1 Keel Angle Joint to Keel Tube
Keel Angle Joint to Keel Tube Rivet Analysis

The keel angle joint SDG39135769 connects to the keel tube SDG39135771 in 2 locations. The keel angle joint is fastened to the keel tube, with NAS1398DFC8, 0.25 in rivets. The keel angle joint is machined from 7050-T7451 plate and the keel tube is extruded from 7075-T73511. CBEAM elements 1305 and 1306 in the loads model represents the portion of the keel tube that interfaces with the keel angle joint. The rivet pattern centroid is 5.498 in from end A of the beam element. Element length is 7.595 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:

Rivets are NAS1398 type D, 0.25 in. blind protruding head 2017 Aluminum rivets
(Ref. NAS1400, sheet 5)

Max. rivet shear strength \( F_s = 1970 \text{ lbf} \)

Material Strength for Keel Tube:

Tube material is extruded 7075-T73511 with \( e/D = 2.0 \)
(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))

Allowable bearing strength \( F_{bru} = 119000 \text{ psi} \)
Allowable shear strength \( F_{s u} = 35000 \text{ psi} \)

Factors of safety:

Ultimate Factor of Safety: \( F_{su} = 1.4 \)
Fitting Factor: \( F_{f} = 1.15 \)

Temperature:

Maximum Temperature \( T_{max} = 150 \text{ deg} \)
(Ref. Appendix C2, AMS-02 Temperature Table)

Temperature Correction Factor (For Fs) \( c_f : = .98 \)
(Ref. Appendix C13)

Temperature Correction Factor (For Fsu) \( c_d : = .99 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))

Temperature Correction Factor (For Fbru) \( c_b : = .92 \)
(Ref. MIL-HDBK-5J, Figure 3.7.6.1(a))

Loads model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "keeljntoekeltube.dat" for elements 1305 and 1306.

\[ \text{data} \rightarrow \text{READPRN("keeljntoekeltube.dat")} \]

ORIGIN := 1
i := 1..rows(data)
Prepared By: B. Dyer 05/03/06
Revised By: G. Reyes 06/23/09
Checked By: C. Bala

Title: Keel Angle Joint to Keel Tube Rivet Analysis

Loads from Beam End A:
Axial Load: \( F_{xA} \) := data\(_{i,7}\) lbf
Shear in Y axis: \( F_{yA} \) := data\(_{i,5}\) lbf
Shear in Z axis: \( F_{zA} \) := data\(_{i,6}\) lbf
Torsion: \( M_{xA} \) := data\(_{i,8}\) in-lbf
Moment about Y axis: \( M_{yA} \) := data\(_{i,4}\) in-lbf
Moment about Z axis: \( M_{zA} \) := data\(_{i,3}\) in-lbf
ID \(_i\) := data\(_{i,1}\)
LC \(_i\) := data\(_{i,2}\)

Loads from Beam End B:
Axial Load: \( F_{xB} \) := data\(_{i,13}\) lbf
Shear in Y axis: \( F_{yB} \) := data\(_{i,11}\) lbf
Shear in Z axis: \( F_{zB} \) := data\(_{i,12}\) lbf
Torsion: \( M_{xB} \) := data\(_{i,14}\) in-lbf
Moment about Y axis: \( M_{yB} \) := data\(_{i,10}\) in-lbf
Moment about Z axis: \( M_{zB} \) := data\(_{i,9}\) in-lbf

Beam Section Properties:
Thickness of tube: \( t = 0.25\) in (Ref. SDG39135771)
Width of tube: \( a = 4.0\) in (Ref. SDG39135771)
Depth of tube: \( b = 4.0\) in (Ref. SDG39135771)
Enclosed area of mean width and mean height: \( A_m := (a - t) \cdot (b - t) \)
\( A_m = 14.06\) in\(^2\)

Figure 2.5.3.1-1 Rivet Pattern Dimensions for Beam Element Ends A and B.
Note: Figure is for reference only.
Bending Moment Interpolation:
NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B, therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern
Total length of beam element

Moment My:
Difference \[ \text{Mydiff}_i := (\text{My}_i - \text{My}_j) \]
Linearily interpolate at centroid of rivets
\[ \text{My}_1 := \frac{c}{d} \cdot \text{Mydiff}_i \]
\[ \text{My}_2 := \frac{d - c}{d} \cdot \text{Mydiff}_i \]

Moment My interpolated at centroid of rivets
\[ \text{My} := \text{My}_b + \text{My}_2 \]

Moment Mz:
Difference \[ \text{Mzdiff}_i := (\text{Mz}_i - \text{Mz}_j) \]
Linearily interpolate at centroid of rivets
\[ \text{Mz}_1 := \frac{c}{d} \cdot \text{Mzdiff}_i \]
\[ \text{Mz}_2 := \frac{d - c}{d} \cdot \text{Mzdiff}_i \]

Moment Mz interpolated at centroid of rivets
\[ \text{Mz} := \text{Mz}_b + \text{Mz}_2 \]
Load in Rivets at Diagonal Sill Bracket:

Total Number of rivets in beam end:
Nsps := 36

Number of rivets reacting Fz shear load:
psz := 18

Number of rivets reacting Fy shear loads:
psy := 18

Shear load/rivet due to Fy
Fsr := \frac{Fya}{psy}
max(Fsr) = 30.3 \text{ lbf}

Shear load/rivet due to Fz
Fsz := \frac{Fza}{psz}
max(Fsz) = 35.3 \text{ lbf}

Note: The Fya and Fza forces have the same magnitude as the Fyb and Fzb forces. The end A forces are used above.

Shear flow due to torsion (Ref. Bruhn section A6.8)
Fsrt := \frac{Mxa}{2 \cdot Am}
max(Fsrt) = 93.1 \text{ lbf/in}

Note: The shear load (Fsrt) is used to calculate the torsional load (Psrt) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.3.1-2.
Figure 2.5.3.1-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:

It is assumed that all rivets share the torsion load equally. Therefore, each column of rivets has the same maximum load per rivet due to torsion.

Perimeter of rivet pattern

\[ \text{per} := 2 \cdot a + 2 \cdot b \quad \text{per} = 16\text{-in} \]

Loads in rivet due to torsion

\[ \text{Psrt} := \text{Fsrt} \left( \frac{\text{per}}{\text{Nsps}} \right) \quad \text{max(Psrt)} = 41.4\text{-lbf} \]

Shear load in rivets due to beam axial load

\[ \text{Prta} := \frac{\text{Fx}_a}{\text{Nsps}} \quad \text{max(Prta)} = 523.7\text{-lbf} \]
Rivet Dimension Variables:
(Ref. SDG39135769)

\[ z_1 := 1.00\text{-in} \]
\[ z_2 := 2.00\text{-in} \]
\[ z_3 := 4.00\text{-in} \]
\[ y_1 := 1.00\text{-in} \]
\[ y_2 := 2.00\text{-in} \]
\[ y_3 := 4.00\text{-in} \]

Note: Figure is for reference only.

**Eccentrically Loaded Rivets due to My and Mz Moments:**

**Rivet Coordinate System Data**

\[ j := 1..\text{rows(coord)} \]  
Counter for Coordinate Points

\[ x_{j} := \text{coord}_{j,2} \]  
Rivet Coordinate Points for x-direction

\[ y_{j} := \text{coord}_{j,3} \]  
Rivet Coordinate Points for y-direction

\[ z_{j} := \text{coord}_{j,4} \]  
Rivet Coordinate Points for z-direction
For Moment $M_y$:

![Diagram showing eccentrically loaded rivet pattern about $M_y$]

**Eccentrically Loaded Rivet Pattern about $M_y$**

**Cross-Section A-A**
- (Row 1, 6 rivets)
- (Row 2, 6 rivets)

**Cross-Section B-B**
- (Represents both sides, 18 rivets)

Note: Figure is for reference only.
Prepared By: B. Dyer 05/03/06
Revised By: G. Reyes 06/23/09
Title: Keel Angle Joint to Keel Tube Rivet Analysis

\[
ry_j := \left[ (x_j)^2 + (z_j)^2 \right]^{\frac{1}{2}} \quad \text{Radial distance to each rivet from the centroid of the rivet pattern}
\]

\[
\text{sigry} := \sum_{j=1}^{\text{rows(coord)}} (ry_j)^2 \quad \text{Sum of the radial directions for all rivets in the rivet pattern}
\]

\[
\beta y_j := \tan^{-1}(x_j, z_j) \quad \text{Angle between resultant vector and tension or shear vectors}
\]

(Note: The angle \(\theta\) is defined off of the x-axis.

See below.)

\[
F_{ym_{i,j}} := \frac{M_{y_i} \cdot ry_j}{\text{sigry}} \quad \text{Resultant Load at Each Rivet}
\]

\[
F_{z_{my_{i,j}}} := F_{ym_{i,j}} \cdot \sin \left( \frac{u}{2} - \beta y_j \right) \quad \text{z - component of } F_{ym_{i,j}}
\]

\[
F_{x_{my_{i,j}}} := F_{ym_{i,j}} \cdot \cos \left( \frac{u}{2} - \beta y_j \right) \quad \text{x - component of } F_{ym_{i,j}}
\]
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section C-C
(Row 1, 6 rivets
Row 2, 6 rivets)

Cross-Section D-D
(Represents both sides, 18 rivets)

Note: Figure is for reference only.
rz_j := \left[ (x_j)^2 + (y_j)^2 \right]^{\frac{1}{2}} \quad \text{Radial distance to each rivet from the centroid of the rivet pattern}

\text{sig}_{rz} := \sum_{j = 1}^{\text{rows(coord)}} (rz_j)^2 \quad \text{Sum of the radial directions for all rivets in the rivet pattern}

\beta_{z_j} := \text{atan2}(x_j, y_j) \quad \text{Angle between resultant vector and tension or shear vectors}

F_{zm, i, j} := \frac{(-M_z) \cdot rz_j}{\text{sig}_{rz}} \quad \text{Resultant Load at Each Rivet}

\max(F_{zm}) = 243.4 \text{ lbf}

(Note: The angle \( \phi \) is defined off of the x-axis. See below.)

\begin{align*}
F_{y_{mz}, i, j} & := F_{zm, i, j} \cdot \sin \left( \frac{\pi}{2} - \beta_{z_j} \right) \quad \text{y - component of Fzm} \\
F_{x_{mz}, i, j} & := F_{zm, i, j} \cdot \cos \left( \frac{\pi}{2} - \beta_{z_j} \right) \quad \text{x - component of Fzm}
\end{align*}

F_{i, j} := \begin{cases} 
F_{zm, i, j} \quad \text{if rivet_counter}_j \leq 18 \\
F_{y_{mz}, i, j} \quad \text{otherwise}
\end{cases} \quad \text{Total Axial Load due to My and Mz Moments}

\max(F_i) = 207.8 \text{ lbf}

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.3.3 for beam and socket analysis.
Total Rivet Shear Load:

\[
Pt_{i,j} := \begin{cases} \sqrt{(P_{ta_{i}} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}})^2 + (P_{sr_{i}} + F_{sry_{i}} + F_{uy_{i,j}})^2} & \text{if } j \leq 18 \\ \sqrt{(P_{ta_{i}} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}})^2 + (P_{sr_{i}} + F_{sry_{i}} + F_{uz_{i,j}})^2} & \text{otherwise} \end{cases}
\]
\[\text{max}(Pt) = 681.7\text{-lbf}\]

Margin of safety for Total Rivet Load:

\[
MS_{1t} := \frac{F_{scf}}{Pt \times F_{Su} \times F_{F}} - 1
\]
\[\text{min}(MS_{1t}) = 0.76 \quad (\text{Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...})\]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment(ID,LC,MS_{1t})}
\]
\[\text{rows(output)} = 384 \quad \text{Number of rows in the "output" array}\]
\[\text{cols(output)} = 38 \quad \text{Number of columns in the "output" array}\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\text{match(min(MS_{1t}), MS_{1t})} = \left[ \begin{array}{c} 29 \\ 19 \end{array} \right]
\]
\[\text{min}_LC := \text{output}_{29,2} \quad \text{Load Case for Minimum Margin of Safety}\]
\[\text{min}_ID := \text{output}_{29,1} \quad \text{Element ID for Minimum Margin of Safety}\]

Rivet number 19 is the rivet with the minimum margin of safety of 0.76.
Minimum Margin of Safety:

Minimum Margin of Safety \( \text{min}(MS1t) = 0.76 \)

Element ID for Minimum Margin of Safety \( \text{min}_\text{ID} = 1305 \)

Load Case for Minimum Margin of Safety \( \text{min}_\text{LC} = 1015 \)

Maximum Rivet Load for Minimum Margin of Safety \( \max(P_t) = 681.7\text{lbf} \)

Rivets with Minimum Margin of Safety Rivet numbers 19
(See figure 2.5.3.1 - 2 for rivet location)
Bea ring on Hole Wall:

Hole diameter \( d_h := 0.257 \text{ in} \)  
(Ref. SEG39135768)

Tube thickness \( t_p := 0.25 \text{ in} \)  
(Ref. SDG3913571)

Bearing area \( A_b := d_h \cdot t_p \)  
\[ A_b = 0.064 \text{ in}^2 \]

Max. load per rivet \( \max(P_t) = 681.7 \text{ lbf} \)

Max. bearing stress \( b := \frac{\max(P_t)}{A_b} \)  
\[ b = 10610.7 \text{ psi} \]

Margin of safety \( MS_b := \frac{F_b - c_b}{b \cdot F_{Su} \cdot F_{F}} - 1 \)  
\[ MS_b = 5.41 \]

Shear tear out:

Edge distance \( c := 0.750 \text{ in} \)  
(Ref. SDG39135769)

Note: Using this \( c \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( d_h := 0.257 \text{ in} \)

\( \frac{e}{d_h} = 2.918 \)

Tube thickness \( t_p := 0.25 \text{ in} \)

Shear out area \( A_s := 2 \left( \frac{e - d_h}{2} \cos(40 \text{ deg}) \right) \cdot t_p \)  
\[ A_s = 0.326 \text{ in}^2 \]

Max. load per rivet \( \max(P_t) = 681.7 \text{ lbf} \)

Max. shear tear out stress \( s := \frac{\max(P_t)}{A_s} \)  
\[ s = 2092.6 \text{ psi} \]

Margin of safety \( MS_{sh} := \frac{F_{Su} \cdot c_d}{s \cdot F_{Su} \cdot F_{F}} - 1 \)  
\[ MS_{sh} = 9.28 \]
2.5.3.2 Keel Tube to Keel Block
Keel Block to Keel Tube Rivet Analysis

The Keel Block SDG39135770-301 attaches to the Keel Tube SDG39135771-301 with 9 rivets (SDG39135768) per side on all four sides, with NAS1398DFC8-9, 0.25 in Aluminum alloy rivets. There are a total of 36 rivets.

The Keel Block is machined from 7050-T7451 plate and the Keel Tube is extruded from 7075-T73511. CBEAM elements 1307 and 1308 in the loads model 2-06 represents the portion of the Keel Block that interfaces with the Keel Tube. The rivet pattern centroid is 1.395 in from end B of the beam element Figure 2.5.3.2-1. Element length is 3.577 in. See Appendix C4 for AMS Rivet Pattern Location Table.

Material Strength for Rivets:
Rivets are NAS1398DFC8-9, 0.25 in. blind protruding head Aluminum rivets

(Ref. MIL-HDBK-5H, Table 8.1.3.1.2(d1))

Max. rivet shear strength \( F_s := 1970 \text{ lbf} \)

Material Strength for Keel Tube:
Tube material is extruded 7075-T7351 with e/D=2.0

(Ref. MIL-HDBK-5J, Table 3.7.6.0(g2))

Allowable bearing strength \( F_{bru} := 119000 \text{ psi} \)

Allowable shear strength \( F_{su} := 35000 \text{ psi} \)

Temperature:
Maximum Temperature \( T_{max} := 150 \text{ deg} \)

(Ref. Appendix C2, AMS-02 Temperature Table)

Temperature Correction Factor (For Fs) \( cf := .98 \)

(Ref. Appendix C13 )

Temperature Correction Factor (For Fs) \( cd := .99 \)

(Ref. MIL-HDBK-5J, Figure 3.7.6.1.2(b))

Temperature Correction Factor (For Fbru) \( cb := .92 \)

(Ref. MIL-HDBK-5J, Figure 3.7.6.1.3(a))

Load model 2-06 was run in NASTRAN for 192 load cases. Beam element forces were recovered, and given in the data file "keeltubetokeelblock.dat" for elements 1307 and 1308.

data := READPRN("keeltubetokeelblock.dat")
ORN := 1
i := 1..rows(data)

2.5.3.2-2

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**Loads from Beam End A:**

- Axial Load $F_{xa_i} := \text{data}_{i,7} \text{lbf}$
- Shear in Y axis $F_{ya_i} := \text{data}_{i,5} \text{lbf}$
- Shear in Z axis $F_{za_i} := \text{data}_{i,6} \text{lbf}$
- Torsion $M_{xa_i} := \text{data}_{i,8} \text{in-lbf}$
- Moment about Y axis $M_{ya_i} := -\text{data}_{i,4} \text{in-lbf}$
- Moment about Z axis $M_{za_i} := \text{data}_{i,3} \text{in-lbf}$

$ID_i := \text{data}_{i,1}$  $LC_i := \text{data}_{i,2}$

**Beam Section Properties:**

- Thickness of tube $t := 0.25 \text{ in}$ (Ref. SDG39135771)
- Width of tube $a := 4.0 \text{ in}$ (Ref. SDG39135771)
- Depth of tube $b := 4.0 \text{ in}$ (Ref. SDG39135771)
- Enclosed area of mean width and mean height $Am := (a-t)(b-t) \quad Am = 14.06 \text{in}^2$

**Loads from Beam End B:**

- Axial Load $F_{xb_i} := \text{data}_{i,13} \text{lbf}$
- Shear in Y axis $F_{yb_i} := \text{data}_{i,11} \text{lbf}$
- Shear in Z axis $F_{zb_i} := \text{data}_{i,12} \text{lbf}$
- Torsion $M_{xb_i} := \text{data}_{i,14} \text{in-lbf}$
- Moment about Y axis $M_{yb_i} := -\text{data}_{i,10} \text{in-lbf}$
- Moment about Z axis $M_{zb_i} := \text{data}_{i,9} \text{in-lbf}$

**Figure 2.5.3.2-1** Rivet Pattern Dimensions for Beam Element Ends A and B.

Note: Figure is for reference only.
Bending Moment at Center of Rivet Pattern:

NASTRAN gives beam moments at ends A and B of the beam element. The center of gravity of the rivet pattern falls between nodes A and B; therefore, the moment at the center of the rivet pattern needs to be interpolated.

Distance from end A to the center of the rivet pattern \( c := (3.577 - 1.395) \text{ in} \) (See Figure 2.5.3.2-1 and Ref. Appendix C4)

Total length of beam element \( d := 3.577 \text{ in} \)

**Moment My:**

Difference \( \text{Mydiff}_i := (\text{My}_a - \text{My}_b) \)

Linearly interpolate at centroid of rivets \( \text{My}_1 := \frac{c}{d} \cdot \text{Mydiff} \)

\( \text{My}_2 := \frac{d - c}{d} \cdot \text{Mydiff} \)

Moment My interpolated at centroid of rivets \( \text{My} := \text{My}_b + \text{My}_2 \)

**Moment Mz:**

Difference \( \text{Mzdiff}_i := (\text{Mz}_a - \text{Mz}_b) \)

Linearly interpolate at centroid of rivets \( \text{Mz}_1 := \frac{c}{d} \cdot \text{Mzdiff} \)

\( \text{Mz}_2 := \frac{d - c}{d} \cdot \text{Mzdiff} \)

Moment Mz interpolated at centroid of rivets \( \text{Mz} := \text{Mz}_b + \text{Mz}_2 \)

Free Body Diagram for Moment Distribution for My Interpolation
(Note: Similar moment distribution is used for Mz interpolation.)
Load in Rivets at Keel Tube to Keel Block:

Total Number of rivets at beam end:

\[ N_{sp} = 36 \]

Number of rivets reacting \( F_z \) shear load:

\[ ps_z = 18 \]

Number of rivets reacting \( F_y \) shear loads:

\[ ps_y = 18 \]

Shear load/rivet due to \( F_y \)

\[ F_{sry} = \frac{F_y}{ps_y} \quad \text{max}(F_{sry}) = 24.4 \text{-lbf} \]

Shear load/rivet due to \( F_z \)

\[ F_{srz} = \frac{F_z}{ps_z} \quad \text{max}(F_{srz}) = 33.9 \text{-lbf} \]

Note: The \( F_y \) and \( F_z \) forces have the same magnitude as the \( F_y \) and \( F_z \) forces. The end A forces are used above.

Shear flow due to torsion

(Ref. Bruhn section A6.8)

\[ Fsrt := \frac{M_x}{2 \cdot Am} \quad \text{max}(Fsrt) = 93 \text{-lbf} / \text{in} \]

Note: The shear load \( (Fsrt) \) is used to calculate the torsional load \( (Psrt) \) in the rivet due to the pitch on the rivet pattern. See Figure 2.5.3.2-2.
Figure 2.5.3.2-2 Layout of Rivet Patterns used to Calculate Rivet Pitch for Torsional Load
Calculation of Rivet Pitch:  (All rivets share the torsion load equally)

Perimeter of rivet pattern
\[ \text{per} := 2 \cdot a + 2 \cdot b \]
\[ \text{per} = 16\text{-in} \]

Loads in rivet due to torsion
\[ P_{\text{sr}} := F_{\text{sr}} \cdot \frac{\text{per}}{N_{\text{sp}}} \]
\[ \text{max}(P_{\text{sr}}) = 41.3\text{-lbf} \]

Shear load in rivets due to beam axial load
\[ P_{\text{ra}} := \frac{F_{\text{xa}}}{N_{\text{sp}}} \]
\[ \text{max}(P_{\text{ra}}) = 523.5\text{-lbf} \]

Rivet Dimension Variables:  
(Ref. SDG39135735 and SDG39135734)

- \[ z_1 := .875\text{-in} \]
- \[ z_2 := 2.0\text{-in} \]
- \[ y_1 := .875\text{-in} \]
- \[ y_2 := 2.0\text{-in} \]

Note: Figure is for reference only.
Eccentrically Loaded Rivets due to My and Mz Moments:

Rivet Coordinate System Data

\[ j := 1..\text{rows(coord)} \]  
Counter for Coordinate Points

\[ x_j := \text{coord}_{j,2} \]  
Rivet Coordinate Points for x-direction

\[ y_j := \text{coord}_{j,3} \]  
Rivet Coordinate Points for y-direction

\[ z_j := \text{coord}_{j,4} \]  
Rivet Coordinate Points for z-direction

For Moment My:

Eccentrically Loaded Rivet Pattern about My

Cross-Section A-A
(Rows 1&2, 18 rivets)

Cross-Section B-B
(Represents both sides, 18 rivets)

Note: Figure is for reference only.
Keel Block to Keel Tube Rivet Analysis

\[ r_j := \left( x_j^2 + z_j^2 \right)^{\frac{1}{2}} \]
Radial distance to each rivet from the centroid of the rivet pattern

\[ \text{sigry} := \sum_{j=1}^{\text{rows(coord)}} \left( r_j \right)^2 \]
Sum of the radial directions for all rivets in the rivet pattern

\[ \beta_{ij} := \begin{cases} 0 & \text{if } (x_j = 0) \land (z_j = 0) \\ \frac{\arctan2(x_j, z_j)}{\pi} & \text{otherwise} \end{cases} \]
Angle between resultant vector and tension or shear vectors

(Note: The angle \( \beta \) is defined off of the x-axis. See below.)

![Diagram of Keel Block to Keel Tube Rivet Analysis]

\[ \text{My}_{1,1} = -1362.7 \text{ in-lbf} \]

\[ x_{18} = -0.9 \text{ in} \quad y_{18} = -0.9 \text{ in} \quad z_{18} = 2 \text{ in} \]

\[ F_{ym,ij} := \frac{\text{My}_{ij} \cdot r_j}{\text{sigry}} \]
Resultant Load at Each Rivet

\[ F_{z,my_{ij}} := F_{ym,ij} \cdot \sin \left( \frac{\pi}{2} - \beta_{ij} \right) \]
\( z \)-component of \( F_{ym} \)

\[ F_{x,my_{j}} := F_{ym,ij} \cdot \cos \left( \frac{\pi}{2} - \beta_{ij} \right) \]
\( x \)-component of \( F_{ym} \)

\[ F_{z,my_{1,10}} = -12 \text{ lbf} \]

\[ F_{x,my_{1,10}} = 27.4 \text{ lbf} \]
For Moment Mz:

Eccentrically Loaded Rivet Pattern about Mz

Cross-Section C-C
(Rows 1&2, 18 rivets)

Cross-Section D-D
(Represents both sides, 18 rivets)

Note: Figure is for reference only.
Radial distance to each rivet from the centroid of the rivet pattern

\[ rz_j := \left( x_j^2 + y_j^2 \right)^{1/2} \]

Sum of the radial directions for all rivets in the rivet pattern

\[ \text{sig}_z := \sum_{j=1}^{\text{rows}(\text{coord})} (rz_j)^2 \]

Angle between resultant vector and tension or shear vectors

\[ \beta_z_j := \begin{cases} 0 & \text{if } (x_j = 0) \land (y_j = 0) \\ \text{atan2}(x_j, y_j) & \text{otherwise} \end{cases} \]

Resultant Load at Each Rivet

\[ F_{z_{1,j}} := \frac{(-M_z)_{i,j} \cdot rz_j}{\text{sig}_z} \]

(Notes: The angle \( \theta \) is defined off of the x-axis. See below.)

Total Axial Load due to My and Mz Moments

\[ F \_{i,j} := \begin{cases} F_{z_{my,ij}} & \text{if } \text{rivet\_counter}_{ij} \leq 18 \\ F_{z_{mj,ij}} & \text{otherwise} \end{cases} \]

\[ \max(F) = 54.7 \text{ lbf} \]

Note: The axial loading is reacted by the beam and socket and not taken by the rivet. See section 2.1.8 for beam and socket analysis.
Total Rivet Shear Load:

\[ P_{t_{i,j}} := \begin{cases} \sqrt{\left( Pr_{i} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}} \right)^2 + \left( Ps_{rt_{i}} + F_{sry_{i}} + F_{y_{mz_{i,j}}} \right)^2} & \text{if } j \leq 18 \\ \sqrt{\left( Pr_{i} + F_{x_{my_{i,j}}} + F_{x_{mz_{i,j}}} \right)^2 + \left( Ps_{rt_{i}} + F_{srz_{i}} + F_{z_{my_{i,j}}} \right)^2} & \text{otherwise} \end{cases} \]

\[ \max(P_t) = 633.4 \text{ lbf} \]

Margin of safety for Total Rivet Load:

\[ MS_{1t} := \frac{F_{scf}}{P_{t_{FSu-FF}}} - 1 \quad \min(MS_{1t}) = 0.893 \quad (\text{Note: Fitting Factor (FF) included for misalignment, different shim thicknesses, etc. ...}) \]

The following will output an array for each row of rivets with element identity, load case, load, and margin of safety from left to right.

\[
\text{output} := \text{augment(ID,LC,MS_{1t})}
\]

\[
\text{rows} (\text{output}) = 384 \quad \text{Number of rows in the "output" array}
\]

\[
\text{cols} (\text{output}) = 38 \quad \text{Number of columns in the "output" array}
\]

The "output" array is then searched for the location of the minimum margin. The match function is used to locate the minimum margin of safety and the element identity, load case, rivet location, and maximum load are pulled from the array.

\[
\min_{LC} := \text{output}_{39,2} \quad \text{Load Case for Minimum Margin of Safety}
\]

\[
\min_{ID} := \text{output}_{39,1} \quad \text{Element ID for Minimum Margin of Safety}
\]

Rivet number 34 is the rivet with the minimum margin of safety of 0.893.
**Minimum Margin of Safety:**

Minimum Margin of Safety \( \min(MS_t) = 0.893 \)

Element ID for Minimum Margin of Safety \( \min_{ID} = 1307 \)

Load Case for Minimum Margin of Safety \( \min_{LC} = 1020 \)

Maximum Rivet Load for Minimum Margin of Safety \( \max(P_t) = 633.4 \text{ lbf} \)

Rivets with Minimum Margin of Safety
Rivet number 34
(See figure 2.5.3.2-2 for rivet location)
Keel Block to Keel Tube Rivet Analysis

**Bearing on Hole Wall:**

Hole diameter \( dh := 0.257\text{-in} \)  
(Ref. SEG39135726, Flag Note 2)

Tube thickness \( tp := 0.25\text{-in} \)  
(Ref. SDG39135771)

Bearing area \( Ab := dh \times tp \)  
\( Ab = 0.06425\text{-in}^2 \)

Max. load per rivet \( \max(P_t) = 633.4\text{-lbf} \)

Max. bearing stress \( b := \frac{\max(P_t)}{Ab} \)  
\( b = 9858\text{-psi} \)

Margin of safety \( MS_b := \frac{F_{bru-cb}}{b \cdot FSu \cdot FF} - 1 \)  
\( MS_b = 5.9 \)

**Shear tear out:**

Edge distance \( e := 0.520\text{-in} \)  
(Ref. SDG39135770)

Note: Using this \( e \) is conservative, since actual rivet force is in general at some angle.

Hole diameter \( dh := 0.257\text{-in} \)

\( e \) over \( D \) ratio \( \frac{e}{dh} = 2.023 \)

Tube thickness \( tp := 0.25\text{-in} \)

Shear out area \( As := 2 \left( e - \frac{dh}{2} \cdot \cos(40\text{-deg}) \right) \times tp \)  
\( As = 0.2108\text{-in}^2 \)

Max. load per rivet \( \max(P_t) = 633.4\text{-lbf} \)

Max. shear tear out stress \( \sigma := \frac{\max(P_t)}{As} \)  
\( \sigma = 3004.9\text{-psi} \)

Margin of safety \( MS_{sh} := \frac{FSu \cdot cd}{\sigma \cdot FSu \cdot FF} - 1 \)  
\( MS_{sh} = 6.162 \)
3.0 Strength and Stability Assessment of Vacuum Case Assembly
3.1 Upper and Lower Conical Flange Assembly
3.1.1 Conical Flange Assembly Strength Assessment
The Stress Analysis of the Conical Flanges

1. Introduction of the Conical Flanges

Figure 3.1.1-1 shows the Conical Flanges. The section view of the assembly in Figure 3.1.1-2 shows how the Conical flanges are assembled within the Vacuum Case System.

![Figure 3.1.1-1: Conical Flange](image)
Conical Flanges - AMS-02

Figure 3.1.1-2: Conical Flange Assembly in Vacuum Case
The design of the Flange Skin is 0.095 inch thick. The Radial Ribs are 0.983 inch high with the thickness of 0.14 inch. The Circumferential Ribs are 0.491 inch high with the thickness of 0.135 inch. Some of the details show in Figure 3.1.1-3.

Figure 3.1.1-3: Some Details of Conical Flange
2. The Method Used to Perform the Stress Analysis of the Conical Flanges

The FEA math models of the Flanges were made using FEMAP software. The FEA models of the Flanges consist of the CQUAD4, CTRIA3, and also RBE's of SPC/MPC. Then, the models of the Flanges were connected to the whole FEA model of AMS02 by RBE2s. The solutions of the Flange FEA math models are obtained from running the NASTRAN model. The modifications, design changes, and engineering judgments were made based on these solutions. The NASTRAN was run several times when a final solution was reached.

3. The information of the Flange FEA models and assumptions

When the NASTRAN was run for the Flange FEA models, the assumptions were made that the rest of the FEA math models are correct; the connections, which put the Flange math models on the Support Rings and Inner Cylinder are correct; all the boundary conditions including the constrains and loading cases are correct. In other words, the stress analysis of the Conical Flanges only focuses on the Flange FEA math model itself.

Figures 3.1.1-4 and 3.1.1-5 show how the Flange math models are within the Vacuum Case FEA models. Figure 3.1.1-6 shows the FEA models of the Conical Flanges by hiding the math models of the Outer Cylinder, Inner Cylinder, and Support Rings.
Figure 3.1.1-4: Top Conical Flange Shown
Conical Flanges - AMS-02

Figure 3.1.1-5: Bottom Conical Flange Shown
### Conical Flanges - AMS-02

![Conical Flanges](image)

**Figure 3.1.1-6: Conical Flanges**
The NASTRAN data file of the Conical Flanges is put under the directory:
/hsm/bsommer/ams/bulk/3-01, and named as "vc-hifi.dat" on May 7, 2001.

The results of the Flange model check for the KGG, KNN, KAA and Six Rigid Body Modes are listed below. The math model has nothing to do with the A-set reduction. Therefore, the KNN shall be same as the KAA. The results give confidence that the flange model is correct because the underlined translation values of each matrix are less than E-05, and the underlined rotation values of each matrix are less than E-03. The first six modes are very close to zero and transition modes are well separated. The more details of the output for the model check of the flanges are attached in Appendix A4. The output file of NASTRAN for the flange model check is put under the directory:
/hsm/bsommer/ams/checks/3-01, and named as "checkamsflanges.f06" on May 7, 2001.

### MATRIX CHECK KGG - 6 X 6 SQUARE MATRIX

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### MATRIX CHECK KNN - 6 X 6 SQUARE MATRIX

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3.1.1-9                      ESCG-4005-05-AMS-0039
**Engineering and Science Contract Group**  
**Structural Analysis Section**

**Conical Flanges - AMS-02**

**MATRIX CHECK**  
KAA - 6 X 6 SQUARE MATRIX.

\[-8.2943D-07 \quad -1.2442D-07 \quad 4.4710D-08 \quad 1.6216D-05 \quad -3.5647D-05 \quad 4.4811D-05\]

\[6.7537D-07 \quad 2.3723D-07 \quad 6.8612D-09 \quad 2.5061D-05 \quad -8.0928D-06 \quad -1.4793D-05\]

\[-3.5929D-09 \quad -1.6223D-08 \quad 2.1329D-08 \quad -1.0320D-05 \quad -1.9622D-05 \quad 1.1193D-05\]

\[-9.7322D-06 \quad 3.4268D-05 \quad -2.1670D-06 \quad -8.0765D-05 \quad -7.2146D-04 \quad -2.4835D-04\]

\[-2.7887D-05 \quad -1.6477D-05 \quad -1.8767D-05 \quad 3.1161D-03 \quad -2.4291D-03 \quad -2.4835D-04\]

\[7.9334D-06 \quad -2.6788D-05 \quad 8.5138D-06 \quad -8.3960D-04 \quad -5.5407D-04 \quad -3.5242D-03\]

**EIGENVALUE ANALYSIS SUMMARY** (READ MODULE)

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<td>1.000000E+00</td>
<td>7.302433E+02</td>
<td></td>
</tr>
</tbody>
</table>

**WEIGHT SUMMARY**

<table>
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<tr>
<th>DIRECTION</th>
<th>MASS</th>
<th>X-C.G.</th>
<th>Y-C.G.</th>
<th>Z-C.G.</th>
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<td>X</td>
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<td>-4.980716E-17</td>
<td>3.396014E-02</td>
<td>-3.702117E-02</td>
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<td>Y</td>
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<td>4.677141E-17</td>
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<td>Z</td>
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<td>3.396527E-02</td>
<td>-7.414474E-17</td>
</tr>
</tbody>
</table>

\[I(S)\]

\[9.223871E+04 \quad -2.808297E+02 \quad 2.212755E+02\]

\[-2.808297E+02 \quad 6.513497E+04 \quad 8.145423E+02\]

\[2.212755E+02 \quad 8.145423E+02 \quad 8.321372E+04\]

\[I(Q)\]

\[6.509564E+04 \quad 8.324427E+04 \quad 9.224748E+04\]

\[Q\]

\[9.972480E-03 \quad -2.595862E-02 \quad 9.996133E-01\]

\[-9.989467E-01 \quad 4.451689E-02 \quad 1.112187E-02\]

\[-4.478838E-02 \quad -9.967138E-02 \quad -2.548733E-02\]

Total weight = 386.0886 x Mass = 14200 lbf  
The actual hardware is 14187 lbf (ref. VC 3-01)

3.1.1-10      ESCG-4005-05-AMS-0039
4. The Loads and Constrains.

The VC FEA assembly math model is connected with the USS-02 FEA math models. The entire AMS02 FEA math model is constrained at the five Trunion locations.

A number of load cases under the launch and landing conditions were investigated in order to identify the worst load cases. Based on these investigation, the worst ones were Load Cases R1016, R1032 and R2016 under the landing cold condition.

The Load Factors for R1016, R1032 and R2016 are listed below. The Load Factors are applied at the C.G. of the entire AMS02 math model when we run NASTRAN. The Load Factors are taken from Table 4.1 of Page 16 in AMS02 Structural Verification Plan for STS and ISS (JSC-28792, Rev.B). The data files of NASTRAN for these load cases are put under directory:

/hsms/swang/ams02/nonlin/flange-new/1000, and named as "R1016.dat" on June 5, 2002.
/hsms/swang/ams02/nonlin/flange-new/1000, and named as "R1032.dat" on June 5, 2002.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Event</th>
<th>Nx</th>
<th>Ny</th>
<th>Nz</th>
<th>Rx</th>
<th>Ry</th>
<th>Rz</th>
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<tr>
<td>R1016</td>
<td>Liftoff</td>
<td>5.7</td>
<td>1.6</td>
<td>-5.9</td>
<td>-10.0</td>
<td>-25.0</td>
<td>-18.0</td>
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<tr>
<td>R1032</td>
<td>Liftoff</td>
<td>5.7</td>
<td>-1.6</td>
<td>-5.9</td>
<td>-10.0</td>
<td>-25.0</td>
<td>-18.0</td>
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<tr>
<td>R2016</td>
<td>Landing</td>
<td>4.5</td>
<td>2.0</td>
<td>-6.5</td>
<td>-20.0</td>
<td>-35.0</td>
<td>-15.0</td>
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</table>

5. The results

The maximum stresses of the elements for each of the Load Cases R1016, 1032 and 2016 are listed below. The NASPOST was used to sort out these information from the f06 and pch data files of the three load cases. A part of the sorted data for the three cases is attached in Appendix A4. The f06 data files of NASTRAN for these load cases are put under directory:

/hsms/swang/ams02/nonlin/flange-new/1000/6-02, and named as "R2053.pch" on June 8, 2002.
/hsms/swang/ams02/nonlin/flange-new/1000/6-02, and named as "R2020.pch" on June 8, 2002.
/hsms/swang/ams02/nonlin/flange-new/2000/6-02, and named as "R2016.pch" on June 8, 2002.

The sorted file of NASPOST from these pch files are put under same directories above.
The maximum stress on the Conical Flanges is located at the intersection of the first ring and a radial rib. The details of the geometric area with this stress level are shown in Figure 3.1.1-7.

\[
\begin{align*}
\sigma_t &= 28711 \text{ psi} \quad \text{(max. tensile)} \\
\sigma_y &= 27853 \text{ psi} \quad \text{(max. yield)} \\
\tau & = 15139 \text{ psi} \quad \text{(max. shear)}
\end{align*}
\]

Note: The Von Mises stress distribution for each of the load cases R1016, R1032 and R2016 is attached from Appendix A4. The worst stresses 43.02 KSI and 35.28 KSI on Page A4-15, 42.78 KSI, 34.98 KSI on Page A4-24, 42.53 KSI and 34.86 KSI on Page A4-33 are located at the top tips of the radial ribs, which are artificially high due to the sharp corner of the tips. Therefore, they will not be used to perform the stress analysis for the Conical Flanges.
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saike Wang</td>
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<tr>
<td>Checked By</td>
<td>C. Bala</td>
<td>01/14/03</td>
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<tr>
<td>Title</td>
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<td></td>
</tr>
</tbody>
</table>

Figure 3.1.1-7: Stress Contour Plot
6. The stress analysis


$F_{tu} := 54000 \text{psi}$  
$F_{ty} := 36000 \text{psi}$  
$F_{su} := 31000 \text{psi}$  
$\eta_{ult} := 0.97$  
$\eta_{yld} := 0.97$

Ultimate  
$M_{Su} := \frac{\eta_{ult} \cdot F_{tu}}{\sigma_y \cdot F_{su}} - 1$  
$M_{Su} = 0.303$  

Yield  
$M_{Sy} := \frac{\eta_{yld} \cdot F_{ty}}{\sigma_y \cdot F_{Sy}} - 1$  
$M_{Sy} = 0.14$  

Shear  
$M_{Ss} := \frac{\eta_{ult} \cdot F_{su}}{\tau_s \cdot F_{Su}} - 1$  
$M_{Ss} = 0.419$  

Margins of Safety
3.1.2 Conical Flange Stability Assessment
Conical Flange Stability Analysis

The Vacuum Case Conical Flange is subjected to an external pressure for the internal pressure condition of 11.76 psi Limit. Under this load, the Conical Flange undergoes hoop compression and must be analyzed for general stability. The problem of an orthotropic conical shell subjected to lateral pressure is approached by the application of a Knock Down Factor (based on W. T. Koiter's asymptotic theory) to the bifurcation buckling capability obtained from a modified Finite Element model of the Vacuum Case. The modifications applied to the original model increased substantially the Conical Flange mesh definition in order to obtain a converged eigenvalue. Although not as sensitive to initial imperfections as the extreme case of a cylinder under axial compression, the shell is still sensitive to initial imperfections in this failure mode. The actual boundary conditions are accounted for by the use of the FE model resulting load distribution due to the applied pressure. Strap preloads and a gasket line load are used to obtain subparametric prebuckling stress distributions. The internal pressure is then applied and a linear elastic bifurcation buckling eigenvalue is obtained relative to the applied internal pressure. A Safety Factor of 1.10 is specified for this loading.
Conical Flange Knock Down Factor for Hydrostatic Pressure

Geometry and Material Properties. (ribs OUTSIDE)

E := 10.8 \cdot 10^6 \text{ (1.0)} \quad \text{Modulus of elasticity, psi}

\beta := 0.31 \quad \text{Poisson's ratio}

t_{mn} := 0.095 \quad \text{Skin nominal thickness, in}

tol_s := 0.01 \quad \text{Skin minimum thickness tolerance, in}

H_s := 1.062 \quad \text{Overall stringer height, in}

t_{snm} := 0.14 \quad \text{Axial rib nominal thickness, in}

tol_a := 0.01 \quad \text{Axial minimum thickness tolerance, in}

l_s := 1 \quad \text{+/−1: negative for inside rib}

b_s := 8.364 \quad \text{Axial rib spacing, in}

H_f := 0.571 \quad \text{Overall ring height, in}

t_{mn} := 0.135 \quad \text{Circumferential rib nominal thickness, in}

tol_c := 0.01 \quad \text{Circumferential rib low side tolerance, in}

l_r := 1 \quad \text{+/−1: negative for inside rib}

d_r := 4.5 \quad \text{Circumferential rib spacing, in}

R_{rr} := 0.375 \quad \text{Rib to rib fillet radius, in}

R_{rs} := 0.125 \quad \text{Rib to skin fillet radius, in}

l' := 0 \quad \text{Hole depth as a fraction of the rib clear height (set to zero for no hole)}

Constitutive Equations

\[ \begin{pmatrix} C_{11} & \beta C_m & 0 & C_{14} & 0 & 0 \\ \beta C_m & C_{22} & 0 & 0 & C_{25} & 0 \\ 0 & 0 & C_{33} & 0 & 0 & 0 \\ C_{14} & 0 & 0 & C_{44} & \beta D_b & 0 \\ 0 & C_{25} & 0 & \beta D_b & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \]

Thickness used in stability analysis:

( Note: \(1.05 \ast t_{\text{mn}}\) or \(t_{\text{nom}}\) whichever is less)

\[ \begin{align*}
  t &= 0.089 \quad \text{Skin, in} \\
  t_s &= 0.137 \quad \text{Axial rib, in} \\
  l_r &= 0.131 \quad \text{Circumferential rib, in}
\end{align*} \]
Numerically, the coefficients are:

\[
C = \begin{pmatrix}
126490.953 & 330577.498 & 0 & 91669.483 & 0 & 0 \\
330577.498 & 1234225.412 & 0 & 0 & 44492.684 & 0 \\
0 & 0 & 367900.763 & 0 & 0 & 0 \\
91669.483 & 0 & 0 & 62620.723 & 219.436 & 0 \\
0 & 44492.684 & 0 & 219.436 & 16105.608 & 0 \\
0 & 0 & 0 & 0 & 0 & 428.966 \\
\end{pmatrix}
\]

**Imperfection Amplitude**

Compute neutral-axis based coefficients

\[
Cb44 := \frac{C_{4,4}}{C_{1,1}} \quad Cb55 := \frac{C_{5,5}}{C_{2,2}}
\]

Cb44 = 55879.163 \quad Cb55 = 14501.688

For specially orthotropic wall construction. Radius of curvature (to the skin CL) is given by:

\[
R = 93.832 \text{ (in)}
\]

\[
\sigma := \frac{1}{29.8} \sqrt{\frac{R}{\frac{Cb44-Cb55}{C_{1,1}C_{2,2}}^{0.25}}}
\]

\[
\sigma = 0.835
\]

For monocoque (NASA SP-8007)

\[
m := \frac{1}{16} \sqrt{\frac{R}{t}}
\]

For equivalent monocoque, then:

\[
\sigma = \frac{1}{16} \sqrt{\frac{R}{t_e}}
\]

Solve for \(t_e\)

\[
t_e := \frac{1}{256} \frac{R}{\sigma^2}
\]

\[
t_e = 0.526 \text{ (in)}
\]

Compute KDF, as a cylinder under axial bending compression using NASA SP-8007 equation. This is used ONLY to get a TYPICAL imperfection. The higher bending KDF is used to reflect better manufacturing.

\[
\varepsilon_b := 1 - 0.731 \left(1 - e^{-\sigma}\right)
\]

\[
\varepsilon_b = 0.586
\]
Use the KDF factor above, and the relation of relative imperfection amplitude vs. the KDF for an isotropic cylinder under axial compression to get a TYPICAL imperfection.

\[
y(\cdot) := -8.231558521307306 - 84.98842544713989 \cdot \alpha^2 - 1060.73887874186 \cdot \alpha^3 + 1665.239629380405 \cdot \alpha^4 - 1539.81680162251 \cdot \alpha^5 + 774.7616151347756 \cdot \alpha^6 - 163.5857306811959 \cdot \alpha^7
\]

This relation was obtained by fitting a polynomial to W.T. Koiter's asymptotic theory results for monocoque unpressurized cylinders under axial compression. Used here to get a TYPICAL imperfection ONLY.

\[
y' := y\left(\frac{\theta}{b}\right) \quad \text{... Using axial bending compression KDF}
\]
\[
y' = 0.096 \quad \text{... Relative imperfection amplitude ( % of } t_c\text{)}
\]

Using the previously computed equivalent thickness to get

\[
y'_{eq} := y' t_c
\]
\[
y'_{eq} = 0.05 \quad \text{... TYPICAL Physical Imperfection amplitude, in. Note this is as well the specified Design Value.}
\]

KDF for (Local Cylindrical) Configuration

Imperfection Analysis : Hydrostatic Load Equivalent monocoque shell
\[
\beta_{21} := \frac{C_{1,2}}{C_{1,1}} \quad \beta_{12} := \frac{C_{2,1}}{C_{2,2}} \quad Z_L := \frac{L^2}{R_{eq}} \sqrt{1 - \beta_{21} \beta_{12}}
\]
\[
\beta_{21} = 0.265 \quad \beta_{12} = 0.268 \quad Z_L = 11.259
\]

Lateral or Hydrostatic Pressure

From the curve
\[
A_2 = -0.612 \quad \text{Design is imperfection sensitive for } A_2 < 0.0
\]

Figure 3.1.2-1 Imperfection parameter \(a_2\) vs. parameter \(Z_L\) for cylinders subjected to lateral or hydrostatic pressure. The dot marks the current design.
Imperfection parameter (imperfection sensitive for $a_2 < 0.$)

$$a_2 := A_2 \left( 1 - \beta_{2T} \beta_{1T} \right)$$

Design is imperfection sensitive for $a_2 < 0.$

$$a_2 = -0.56875$$

With the initial guess: $\alpha = 0.75$

Solve the following asymptotic theory equation by iteration:

$$\frac{3}{2} \sqrt{-3 \cdot a_2 \cdot c_r \cdot |y|} - \left( 1 - \alpha \cdot c_r \right)^{\frac{3}{2}} = 0$$

To get

$H = 0.7333$  KDF for lateral or hydrostatic pressure. Used here since lateral stability behavior controls.

Compute Margin of Safety

$p_{cl} := 1.369045 \cdot p_{ref}$  From MSC/NASTRAN FE model, after convergence. See Figure 3.1.2-2

$p_{cl} = 20.125$

$p_{cr} := \frac{p_{cl}}{H \cdot p_{cl}}$

$p_{cr} = 14.758$

Then

$$MS := \frac{p_{cr}}{p} - 1$$

$MS = 0.14$  General Lateral Stability

$SF = 1.1$
Figure 3.1.2-2 From NASTRAN (Current Eigenvalue analysis includes 1950.0 lb strap preload, circumferential rib taper, additional thickness in outer pocket, gasket spring load, 2 in fillet in o/c end ring, all current model definitions, and latest o/c design. Also includes conical flange axial rib modification at the outer radius end and high resolution outer case discrete rib model)
KDF vs. Relative Imperfection Curve For Conical Flange

To aid in the assessment of off-design conditions (larger imperfections), the following curve have been computed. This curve relates the KDF to the **Relative Imperfection** for the specific configuration of the inner cylinder. Applies only to small off-design imperfection deviations, not to off-design thickness.

To use, follow the **Example** below:

For a **physical imperfection** amplitude of \( \varepsilon = .075 \) in, and the **design stability thickness** of \( t_e = 0.526 \) in,

Compute the **relative imperfection** from

\[
y' = \frac{\varepsilon}{t_e} = 0.143
\]

From the curve, obtain : \( y = y'(y') \), \( y = 0.6719 \)

With \( p_{cl} = 20.125 \) (psi), obtained previously, we have \( p_{cr} := \frac{p_{cr}}{p_{cl}} \)

\( p_{cr} = 13.523 \) (psi)

The new Margin of Safety is then computed from

\[
MS := \frac{p_{cr}}{p} - 1
\]

\( MS = 0.05 \)  
**Conical Flange General Stability**  
**SF = 1.1**
# References

[1] **Buckling of Bars, Plates, and Shells**
B.O. Almroth and D.O. Brush, McGraw-Hill
3.2 Outer Cylinder
3.2.1 Outer Cylinder Strength Assessment
3.2.1 Outer Cylinder Strength Analysis

Introduction

The Outer Cylinder, shown in Figure 3.2.1-1, is a 109.256-inch outer diameter and a 46.578-inch length cylinder manufactured from a 7050-T7451 Aluminum Rolled Ring Forging. The outer skin thickness varies from 0.265-inch at the bottom to 0.152-inch at ring 10, located just above the middle of the cylinder. A total of fourteen 0.1-inch thick evenly spaced circumferential ribs help stabilize the skin of the Outer Cylinder under buckling loads. A detailed view of the outer cylinder profile is shown in Figure 3.2.1-2.
Figure 3.2.1-1: Side View of Vacuum Case Outer Cylinder
Figure 3.2.1-2: Profile of Outer Cylinder (Dimensions are in Inches)
Analysis Method Used to Perform Strength Analysis for the Outer Cylinder

MSC NASTRAN v2001 is used for the finite element analysis of the Outer Cylinder. The pre/post processing software used in building and analyzing the NASTRAN input and output is FEMAP version 8.1. The hi-fi Outer Cylinder model is composed of CQUAD4, HEXA, PENTA and RSSCON elements. The ends of the cylinder are connected to the top and bottom Support Rings with RBE2, CBUSH and Linear Gap elements. The entire Vacuum Case model, including the high fidelity Outer Cylinder, is integrated with the USS-02 and various other experiment models to make up the total AMS-02 payload. The results from this model were used to determine the critical stresses for this component.

The linear gap elements are used to simulate the behavior at the bolt interface that attaches the Outer Cylinder to the top and bottom Support Rings. Non-linear analysis was not possible since the gap elements were limited to linear static analysis only. Taking the resultant case specific strap loads and applying them to the Vacuum Case with FORCE cards simulated the nonlinear portion of the loads model.

Outer Cylinder Finite Element Model Checks

Strain energy and rigid body modes were checked using the high fidelity Outer Cylinder Vacuum Case model combined with the remaining components to make up the full payload model. The overall payload model used in the analysis is version 6-02a found in the /hsm/bsommer/ams/bulk/6-02a directory. The Vacuum Case model used for the Outer Cylinder analysis is located in the /hsm/bsommer/ams/bulk/stressmods/outercylinder directory and titled outer-stress.dat. Figure 3.2.1-3 shows the fine meshed Outer Cylinder model.
The strain energy and rigid body modes checks for this model are found in the /hsm/bsommer/ams/checks/6-02 directory entitled checkamsouter.f06. The strain energy check limits that are acceptable are for values of 1.0E-5 for translations and 1.0E-3 for rotations. The results for the strain energy checks for the KGG, KNN, KFF matrices are found in Tables 3.2.1-1 through 3.2.1-3. Only the diagonal terms of the 6x6 matrix are listed. The results for the rigid body modes, listed in Table 3.2.1-4 shows six rigid body modes with a good separation between the last rigid body mode 6 and the first real mode mode 7. The total model Mass and CG location is shown in Table 3.2.1-5. The mass units are in slinches and the z coordinate is in the orbiter coordinate system.

Figure 3.2.1-3: Outer Cylinder Stress Model
### Table 3.2.1-1: KGG for Outer Cylinder Model

RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.276314E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.189297E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.845768E-08</td>
<td>PASS</td>
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<tr>
<td>4</td>
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</tr>
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<td>6</td>
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### Table 3.2.1-2: KNN for Outer Cylinder Model

RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

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<tr>
<td>2</td>
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<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>4.857794E-07</td>
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<td>PASS</td>
</tr>
<tr>
<td>6</td>
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### Table 3.2.1-3: KFF for Outer Cylinder Model

RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

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<tr>
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<td>PASS</td>
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Table 3.2.1-4: Rigid Body Modes for Outer Cylinder Model

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<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RAD:ANS</th>
<th>CYCLES (Hz)</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
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<td>-3.50E-08</td>
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<tr>
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<td>2</td>
<td>7.34E-08</td>
<td>2.71E-04</td>
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<td>7.34E-08</td>
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<tr>
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<td>3</td>
<td>2.12E-07</td>
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<tr>
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<td>4</td>
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<td>5.24E-04</td>
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<td>2.74E-07</td>
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<td>5</td>
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<td>7</td>
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<td>5.99E+01</td>
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<td>1.00E+00</td>
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</tr>
</tbody>
</table>

Table 3.2.1-5: Mass for Stress and Loads Model and CG For Outer Cylinder Model

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>2.6301E+01</td>
<td>2.09E-15</td>
<td>1.24E+00</td>
<td>-3.08E+00</td>
</tr>
<tr>
<td>Y</td>
<td>2.6301E+01</td>
<td>-1.29E-01</td>
<td>-1.62E-15</td>
<td>-3.08E+00</td>
</tr>
<tr>
<td>Z</td>
<td>2.6301E+01</td>
<td>-1.29E-01</td>
<td>1.24E+00</td>
<td>-6.33E-17</td>
</tr>
</tbody>
</table>

Loads Model Mass = 3.8851E+01

The cg coordinates for Table 3.2.1-5 are defined around a fully loaded AMS model. The mass differential between the loads model and the stress model is due to the fact that the cold mass and nonlinear straps are not included in the model. These components have been replaced with concentrated forces applied at the strap attachment locations. The strap forces used in the model are the case consistent strap loads calculated in the nonlinear static analysis using the loads model. To more closely match the overall loads behavior the rotational load factors are still applied around the CG for the entire payload.

Table 3.2.1-6: CG Location for AMS-02 in the Orbiter Z location

<table>
<thead>
<tr>
<th>X (in)</th>
<th>Y (in)</th>
<th>Z (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.46E-01</td>
<td>2.58E+00</td>
<td>3.86E+02</td>
</tr>
</tbody>
</table>
Loads and Constraints

The AMS-02 payload model is constrained at five trunnion locations. A total of 256 load cases for multiple launch/landing scenarios were run using NASTRAN. The critical load cases for the Outer Cylinder were determined by sorting the element stresses from the Outer Cylinder loads model. The high fidelity Outer Cylinder model is incorporated into the loads Vacuum Case model for use in determining the peak stresses. A total of five load cases were chosen as the critical load cases.

The list of the critical load cases with the corresponding load factors is shown in Table 3.2.1-7. Note that the 2### load cases are for landing with a full helium tank. 1### are launch load cases. The Load Factors used for this analysis are listed in Table 4-1, Page 17 of the AMS-02 Structural Verification Plan for STS and ISS(JSC-28792, Rev.C). The NASTRAN run streams for these load cases can be found in the /hsm/bsomer/ams/nonlin/outercylinder/2000 directory and labeled R20##.dat or /hsm/bsommer/ams/nonlin/outercylinder/1000 with the titles R10##.dat.

Table 3.2.1-7: Critical Load Case Load Factors for Outer Cylinder Model

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Event</th>
<th>Nx (g)</th>
<th>Ny (g)</th>
<th>Nz (g)</th>
<th>Rx (rad/s²)</th>
<th>Ry (rad/s²)</th>
<th>Rz (rad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1028</td>
<td>Launch</td>
<td>5.7</td>
<td>-1.6</td>
<td>-5.9</td>
<td>10</td>
<td>-25</td>
<td>-18</td>
</tr>
<tr>
<td>1030</td>
<td>Launch</td>
<td>5.7</td>
<td>-1.6</td>
<td>-5.9</td>
<td>-10</td>
<td>25</td>
<td>-18</td>
</tr>
<tr>
<td>2031</td>
<td>Landing Full</td>
<td>4.5</td>
<td>-2</td>
<td>-6.5</td>
<td>-20</td>
<td>-35</td>
<td>15</td>
</tr>
<tr>
<td>2057</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>-2</td>
<td>-6.5</td>
<td>20</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>2058</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>-2</td>
<td>-6.5</td>
<td>20</td>
<td>35</td>
<td>-15</td>
</tr>
</tbody>
</table>

An interface loads comparison between the stress and loads model, shown in Table 3.2.1-8 shows total mass vs. trunnion reaction load. Only one load case is shown in the tables to illustrate the similarities between the two models.

Table 3.2.1-8: Mass Calculated from Trunnion Forces vs. Mass of Stress Model

<table>
<thead>
<tr>
<th>Axis</th>
<th>Total Trunnion Load</th>
<th>Load Factor</th>
<th>Mass from Trunnion Reaction Load LC 1028</th>
<th>Mass Stress Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-84870.26</td>
<td>5.7</td>
<td>1.4890E+04</td>
<td>1.4998E+04</td>
</tr>
<tr>
<td>Y</td>
<td>23831.41</td>
<td>1.6</td>
<td>1.4895E+04</td>
<td>1.4998E+04</td>
</tr>
<tr>
<td>Z</td>
<td>88007.75</td>
<td>5.9</td>
<td>1.4917E+04</td>
<td>1.4998E+04</td>
</tr>
</tbody>
</table>
The discrepancies in the mass/force comparison are due to the fact that the Vacuum Case is attached to the USS-02 before the pressure load is applied. The trunnion loads due to pressure are shown in Table 3.2.1-9.

**Table 3.2.1-9: Trunnion Loads Due to 1 atm Pressure Only**

<table>
<thead>
<tr>
<th>Trunnion Location</th>
<th>Fx (lbf)</th>
<th>Fy (lbf)</th>
<th>Fz (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>2.09E+02</td>
<td>0</td>
<td>5.20E+01</td>
</tr>
<tr>
<td>Primary</td>
<td>1.47E+02</td>
<td>0</td>
<td>-1.38E+02</td>
</tr>
<tr>
<td>Secondary</td>
<td>0</td>
<td>0</td>
<td>-7.08E+01</td>
</tr>
<tr>
<td>Secondary</td>
<td>0</td>
<td>0</td>
<td>2.39E+01</td>
</tr>
<tr>
<td>Keel</td>
<td>0</td>
<td>-8.94E+01</td>
<td>0</td>
</tr>
</tbody>
</table>

The values shown in Table 3.2.1-9 would be subtracted from the Mass calculation shown in column four of Table 3.2.1-8.
Strength Analysis Results for Outer Cylinder

The maximum stresses for the Outer Cylinder are shown below. NASPOST was used to sort the maximum stresses from the load cases listed in Table 3.2.1-6. The punch files containing the analysis results are found in the /hsm/bsommer/ams/stress/outer/6-02 directory. The files are named according to the load case. (i.e.: gap1030.pch, gap2031.pch, etc.....) The NASPOST list file can be found in /hsm/bsommer/ams/naspost/outer/6-02/ directory. A copy of this list file is located in Appendix A1. The load case containing the highest stress for principle, VonMises and shear are shown below in Table 3.2.1-10. Contour plots of the highest principal stress are shown in Figures 3.2.1-4 through 3.2.1-5.

Table 3.2.1-10: Highest Stresses for Outer Cylinder Model

<table>
<thead>
<tr>
<th>Load Case ID</th>
<th>Elem. ID</th>
<th>Elem. Type</th>
<th>Stress Type</th>
<th>MAX Stress (ksi)</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2031</td>
<td>2000330</td>
<td>Quad4-plate</td>
<td>Max Principal</td>
<td>-18.97</td>
<td>A1-2</td>
</tr>
<tr>
<td>2031</td>
<td>2000330</td>
<td>Quad4-plate</td>
<td>Max Vonm</td>
<td>17.23</td>
<td>A1-3</td>
</tr>
<tr>
<td>2031</td>
<td>2000330</td>
<td>Quad4-plate</td>
<td>Max Shear</td>
<td>9.48</td>
<td>A1-4</td>
</tr>
</tbody>
</table>
Figure 3.2.1-4: Outer Cylinder Stress Contour for Load Case 2031
Figure 3.2.1-5: Outer Cylinder Stress Contour Detail for Load Case 2031
Margin of Safety for Outer Cylinder Strength

OUTER CYLINDER, VACUUM CASE, AMS-02 7050-T7451 (AMS 4108) Rolled Ring Forging

Material allowables are from MIL-HB-5H Table 3.7.3.0(d) for 2.0" to 4.0" thick Hand forging

- $F_{tu} : 67,000 \text{psi}$: Ultimate tensile strength
- $F_{ty} : 55,000 \text{psi}$: Compressive yield strength
- $F_{su} : 41,000 \text{psi}$: Ultimate shear strength
- $F_{sy} : 1.1$: Yield Factor of Safety
- $F_{su} : 1.4$: Ultimate Factor of Safety
- $\gamma_u : 0.92$: Thermal reduction factor at 140 F from MIL-HB-5H Figure 3.7.3.2.1.
- $\gamma_y : 0.98$

The maximum stresses for the Outer Cylinder occur in load case 2031. Margins for the Outer Cylinder will be calculated based on the stress values shown below.

- $\sigma_{ult} : 18,969.97 \text{psi}$ (max. principal) Element 2000330
- $\sigma_{yield} : 17,231.25 \text{psi}$ (max. Von-Mises) Element 2000330
- $\tau_{shear} : 9,484.98 \text{psi}$ (max. shear) Element 2000330

Margins of Safety

\[
\text{Ultimate} \quad MSu := \frac{\gamma_u \cdot F_{tu}}{\sigma_{ult} \cdot F_{su}} - 1 \quad \text{MSu} = 1.321
\]

\[
\text{Yield} \quad MSy := \frac{\gamma_y \cdot F_{ty}}{\sigma_{yield} \cdot F_{sy}} - 1 \quad \text{MSy} = 1.844
\]

\[
\text{Shear} \quad MSs := \frac{\gamma_u \cdot F_{su}}{\tau_{shear} \cdot F_{su}} - 1 \quad \text{MSs} = 1.841
\]

The Outer Cylinder is acceptable for both vacuum and maximum expected flight loads using a temperature reduction factor of 0.92 ultimate and 0.98 for yield.
Outer Cylinder Analysis Conclusions

The outer Cylinder for the AMS-02 Vacuum Case is acceptable for the loading conditions defined in the AMS-02 Structural Verification Plan for STS and ISS (JSC-28792, Rev.C) and for a total payload weight of 14809lbs. There are several factors that could change the analysis for the Outer Cylinder. Among them is an increase in the mass of the magnet, helium tank or tracker. Other possible impacts to the current analysis, such as changes in inertial load factors due to updated transient analysis, will have to be assessed when they occur.
Open Action Item from Phase II Safety Review

**Purpose of analysis:**

Analyze the Vacuum Case Outer Cylinder to a pressure of 0.8 bar. A conservative approach will be taken when calculating the hoop stress. The ribs that help stabilize the skin of the outer cylinder will be ignored and the smallest wall thickness of the outer cylinder will be used to calculate the hoop stress. The following figure shows the Vacuum Case Assembly.

![Vacuum Case Assembly Diagram](image-url)

*Figure 3.2.1-6: Vacuum Case Assembly*
Figure 3.2.1-7 shows the dimensions of the Outer Cylinder. The overall diameter of the Outer Cylinder is 109.256 inches.

Figure 3.2.1-7: Section View of Vacuum Case Outer Cylinder (Dimensions shown are in inches)
A detailed view of the outer cylinder profile is shown in Figure 3.2.1-8. This figure shows the various wall thicknesses of the Outer Cylinder. The smallest Outer Cylinder wall thickness is 0.152 inches.

Figure 3.2.1-8: Profile of Outer Cylinder (Dimensions shown are in inches)
Material Properties:

AL Alloy 7050-T7451 Rolled Ring Forging (AMS 4108) - Material allowables are from MIL-HBK-5H Table 3.7.3.0(d) for 2.0” to 4.0” thick hand forging

\[ F_{tu} := 67000 \text{ psi} \quad \text{(Ultimate Tensile Strength)} \]

Specification:

\[ t := 0.152 \text{ in} \quad \text{(Smallest wall thickness of Outer Cylinder)} \]

\[ d := 109.256 \text{ in} \quad \text{(Diameter of Outer Cylinder)} \]

\[ R := \frac{d}{2} \quad R = 54.628 \text{ in} \quad \text{(Radius)} \]

The applied pressure will be defined as,

\[ q := 0.8 \text{ bar} \]

Recall that 1 bar = 14.504 psi, therefore,

\[ q = 11.603 \text{ psi} \quad \text{(Pressure)} \]

Calculate Stress: (Per Roark's Formulas, 7th ed., Table 13.1)

\[ \beta := \frac{q \cdot R}{t} \quad \beta = 4170.064 \text{ psi} \quad \text{(Hoop Stress)} \]

Factor of Safety:

\[ F_{Su} := 2.0 \]

Margin of Safety:

\[ MS_{u} := \frac{F_{tu}}{\beta \cdot F_{Su}} - 1 \quad MS_{u} = 7.033 \quad \text{(Ultimate Margin of Safety)} \]
3.2.2 Outer Cylinder Stability Assessment
3.2.2 Outer Cylinder Stability Assessment

Introduction

The Outer Cylinder, shown in Figure 3.2.2-1, is a 109.256 inch outer diameter and a 46.578 inch length cylinder manufactured from a 7050-T7451 Aluminum Rolled Ring Forging. The outer skin thickness varies from 0.265 inch at the bottom to 0.152 inch between rings 10 and 11, located just above the middle of the cylinder. A total of fourteen 0.1 inch thick evenly spaced circumferential ribs help stabilize the skin of the Outer Cylinder under buckling loads. A section view of the Vacuum Case Outer Cylinder is shown in Figure 3.2.2.-2.
Figure 3.2.2-2  Section View of Vacuum Case Outer Cylinder (Dimensions shown are in inches)
A detailed view of the outer cylinder profile is shown in Figure 3.2.2-3. This figure shows the various wall thicknesses of the Outer Cylinder. The Outer Cylinder rings have been numbered to correspond to the Point-by-Point analysis results shown in Table 3.2.2-1.

![Profile of Outer Cylinder](image)

**Figure 3.2.2-3  Profile of Outer Cylinder (Dimensions shown are in inches)**
The following analysis is the stability assessment of the Vacuum Case Outer Cylinder. Figure 3.2.2-4 depicts bifurcation points and limit points (as in "limiting") via geometrically nonlinear analysis. The presence of unavoidable initial imperfections will cause the structure to fail at a limit point E. Point E may be approximated by computing the "classical" Linear bifurcation load at point G with the subsequent application of semi-empirical Knock-Down-Factor (KDF). This is the NASA-SP8007 document approach. It does not include the effects of prebuckling rotations and the effect of imperfections is assumed to be accounted for by the application of the KDF.

The effect of prebuckling rotations may be accounted for by solving the nonlinear buckling problem, and obtaining point B, or by performing a nonlinear perfect structure analysis. This may lead to unstable behavior at point B or stable behavior at point A, which does not include the effect of imperfections. A KDF may be applied to the nonlinear bifurcation point B but may result in an overconservative design since KDF are derived to be applied to the linear bifurcation results. Point E may also be approximated by applying W.T. Koiter's asymptotic theory. This is a linear theory that includes the effects of initial imperfections in the shape of the lowest buckling mode. It originally neglected the effects of prebuckling rotations; however this theory has been extended to include prebuckling nonlinearity, and has also been found to explain the behavior of imperfection-sensitive structures even if the prebuckling rotations are effective. Point E may be also approximated by a Finite Element geometrically nonlinear analysis that follows path OE and includes initial imperfections with the shape of the lowest buckling modes and of a magnitude that can be related to an empirical KDF.

To identify critical cases, a point-by-point analysis is performed. This point-by-point analysis uses both NASA SP8007 and W.T. Koiter's asymptotic theory and assumes local conditions of loading from the FE model and that the local geometry is the same everywhere in the cylinder. This analysis is applied to all elements in the model and for every load condition.
The point-by-point analysis is performed for all cases for both local and general modes of failure. It accounts for interaction of axial compression, hydrostatic pressure and shear at both, the local and general level. It also accounts for the effects of eccentricity, and uses the geometry and results from a FE model where the stiffener rings have been "smeared" out. It does not account for possible interaction between local and general stability failure modes.

The point-by-point analysis corresponds to computing the classical linear elastic bifurcation buckling load followed by the application of a Knock-Down-Factor per NASA SP-8007, to approximate point E, or to the analytical determination of the limit point load at point E per W.T. Koiter's asymptotic theory. Note that a thickness of 1.05*t_{\text{min}} or t_{\text{nominal}} - whichever is less - is used in all stability computations, and t_{\text{min}} is used in all strength calculation.

A margin of safety summary from the point-by-point analysis is presented in Table 3.2.2-1. Note that a safety factor of 1.4 is used on all loads, pressure, misalignment, strap preload, and inertia. The key to the Margin of Safety types is as follows:

**Type Failure Mode**
1) Skin stability at ULTIMATE load
2) General stability at ULTIMATE load
3) Rib stability at ULTIMATE load
4) Skin maximum principal stress - YIELD
5) Skin minimum principal stress - YIELD
6) Skin maximum shear stress - YIELD
7) Skin maximum principal stress - ULTIMATE
8) Skin minimum principal stress - ULTIMATE
9) Skin maximum shear stress - ULTIMATE
10) Axial rib lesser of YIELD or ULTIMATE combined stress (does not apply for Outer Cylinder)
11) Circumferential rib lesser of YIELD or ULTIMATE combined stress

The margins of safety shown in Table 3.2.2-1 represent the minimum margin of safety for any failure mode type and load case.
### Table 3.2.2.1 - Point-by-Point Margin of Safety Summary

<table>
<thead>
<tr>
<th>Ring</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ang/Sta</td>
<td>2.76</td>
<td>2.28</td>
<td>3.81</td>
<td>5.35</td>
<td>6.89</td>
<td>8.43</td>
<td>9.97</td>
<td>11.51</td>
<td>13.05</td>
<td>14.59</td>
<td>16.13</td>
<td>17.67</td>
<td>19.22</td>
<td>20.76</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- OC_buckling.mcd
- AMS-02 VACUUM CASE - OUTER CYLINDER BUCKLING ANALYSIS
- file: ring 2 22334455667788

---

**Checked By:** William Torres

**Prepared By:** William Torres

**Date:** 03/05/03

**Engineering and Science Concert Group**

**Structural Analysis Section**

**Drawing No.:** SDG39135761-001

**File Name:** OC_buckling.mcd

---

**Title:** AMS-02 VACUUM CASE - OUTER CYLINDER BUCKLING ANALYSIS
Prepared
By

Name

William Torres

Checked
By

File Name

03/05/03

OC_buckling.mcd
Engineering and Science Contract Group

Draw ing No.

Structural Analysis Section

SDG39135761-001

AMS-02 VACUUM CASE - OUTER CYLINDER BUCKLING ANALYSIS

Title

Ring
Ang/Sta
1.406
4.219
7.031
9.844
12.656
15.469
18.281
21.094
23.906
26.719
29.531
32.344
35.156
37.969
40.781
43.594
46.406
49.219
52.031
54.844
57.656
60.469
63.281
66.094
68.906
71.719
74.531
77.344
80.156
82.969
85.781
88.594
91.406
94.219
97.031
99.844
102.656
105.469
108.281
111.094
113.906
116.719
119.531
122.344
125.156
127.969
130.781
133.594
136.406
139.219
142.031
144.844
147.656
150.469
153.281
156.094
158.906
161.719
164.531
167.344
170.156
172.969
175.781
178.594
t_nom

Date

9
22.30
3.95
3.57
3.15
2.82
2.23
1.71
1.41
1.16
0.95
0.84
0.73
0.68
0.67
0.67
0.67
0.68
0.65
0.63
0.64
0.67
0.73
0.82
0.95
1.14
1.42
1.68
1.76
1.96
2.15
2.40
2.73
3.09
3.39
3.58
3.45
2.82
2.35
2.05
1.81
1.47
1.15
0.90
0.72
0.60
0.53
0.49
0.49
0.52
0.54
0.55
0.57
0.61
0.69
0.80
0.94
1.09
1.28
1.50
1.76
2.16
2.77
3.59
4.44
4.42
0.163

9
23.84
1.69
3.55
3.12
2.81
2.27
1.76
1.46
1.13
0.92
0.78
0.69
0.66
0.68
0.72
0.75
0.81
0.78
0.76
0.75
0.75
0.77
0.83
0.93
1.09
1.32
1.64
1.83
2.02
2.20
2.46
2.79
3.13
3.40
3.55
3.51
2.91
2.46
2.17
1.71
1.38
1.15
0.92
0.76
0.66
0.60
0.58
0.59
0.62
0.63
0.63
0.62
0.63
0.68
0.76
0.89
1.06
1.25
1.52
1.77
2.16
2.75
3.56
4.39
4.35
0.163

10
25.38
1.61
1.62
2.80
2.52
2.08
1.60
1.25
0.93
0.73
0.58
0.52
0.51
0.56
0.63
0.70
0.79
0.79
0.75
0.67
0.62
0.61
0.64
0.71
0.84
1.03
1.32
1.68
1.86
2.06
2.30
2.61
2.93
3.16
3.27
3.22
2.75
2.34
1.89
1.40
1.11
0.93
0.79
0.66
0.59
0.55
0.55
0.57
0.60
0.60
0.58
0.54
0.53
0.54
0.59
0.68
0.83
1.04
1.30
1.57
1.92
2.46
3.19
4.00
4.22
0.157

Table 3.2.2-1 Point-by-Point Margin of Safety Summary ( Cont'd )
10
11
11
12
12
13
13
14
14
26.92 28.46 30.00 31.54 33.08 34.62 36.16 37.70 39.24
1.60
1.71
1.75
1.58
1.67
1.69
1.72
1.70
1.80
1.60
1.72
1.74
1.59
1.67
1.69
1.75
1.72
1.83
2.81
2.58
1.75
1.61
1.69
1.72
1.78
1.76
1.88
2.54
2.34
2.40
2.69
2.82
3.19
3.18
3.04
3.05
2.15
2.03
2.15
2.45
2.59
2.95
2.98
2.91
3.03
1.66
1.54
1.56
1.72
1.77
2.07
2.20
2.71
2.90
1.23
1.04
1.02
1.10
1.09
1.27
1.29
1.72
1.87
0.88
0.71
0.66
0.70
0.66
0.75
0.71
0.96
0.98
0.66
0.49
0.43
0.45
0.39
0.45
0.38
0.51
0.44
0.53
0.37
0.31
0.33
0.27
0.31
0.23
0.32
0.21
0.47
0.33
0.28
0.30
0.25
0.29
0.22
0.31
0.21
0.48
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3.2.2- 8

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ESCG-4005-05-AMS-0039


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**Table 3.2.1-1 Point-by-Point Margin of Safety Summary (Cont'd)**

*Engineering and Science Contract Group*

**Drawing No.**

*SDG39135761-001*

*Title*

**AMS-02 VACUUM CASE - OUTER CYLINDER BUCKLING ANALYSIS**

*Prepared By*  
William Torres  
03/05/03

*Checked By*  
03/09/03

*File Name*  
OC_buckling.mcd
Finite Element Analysis

Once the critical cases are identified using the point-by-point analysis, a nonlinear FE analysis is performed for these cases. At this level, the stiffeners are modeled as discrete elements. The internal loads are obtained from nonlinear runs that follow specified loading sequences. The two critical cases identified by the Point-by-Point analysis are load case 2031 and load case 2063.

Both nonlinear perfect and nonlinear geometrically imperfect structure analyses are performed using the FE approach. The imperfect structure includes imperfections in the shape of the +/- lowest buckling modes of the critical cases and with amplitudes typical of cylinders with a KDF corresponding to a structure with equivalent R/t ratio. The refined mesh used was determined as that capable to model a half-wave between stiffener rings. This analysis represents path OE in Figure 1. The mechanical loads were increased until a Factor of Safety of 2.0 was attained. No unstable points were encountered, and the stresses computed remain within acceptable linear limits, the structure is then deemed stable and safe.

The following Figures summarize the Finite Element nonlinear analysis for the two critical cases treated. This analysis is based on 6-02 loads.

![Figure 3.2.2-2. Eigenshape for Outer Cylinder refined model. Pressure only case, \( \lambda = 5.726894 \). Other structure removed from picture for clarity.](image-url)
Figure 3.2.2-3. Eigenshape for Outer Cylinder refined model. Case 2031, $\lambda = 4.421158$. 
Table 3.2.2-13

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Output Set: Case 2063 Eig.=4.953587
Deformed (1): Total Translation
Contour: Total Translation

Figure 3.2.2-4. Eigenshape for Outer Cylinder refined model. Case 2063, $\lambda = 4.953587$. 
Case 2031 w/2031 Imperfection
Top Major SF=2.0

Figure 3.2.2-5. Top major principal stresses for Case 2031, with imperfection corresponding to same case. Maximum stress is 13606.0 psi.
### AMS-02 VACUUM CASE - OUTER CYLINDER BUCKLING ANALYSIS

**Case 2031 w/2031 Imperfection**  
**Top Minor SF=2.0**

![Graph showing stress distribution](image)

Figure 3.2.2-6. Top minor principal stresses for Case 2031, with imperfection corresponding to same case. Minimum stress is -24431.0 psi
Figure 3.2.2-7. Bottom major principal stresses for Case 2031, with imperfection corresponding to same case. Maximum stress is 17934.0 psi.
Case 2031 w/2031 Imperfection
Bottom Minor SF=2.0

Figure 3.2.2-8. Bottom minor principal stresses for Case 2031, with imperfection corresponding to same case. Minimum stress is -26373.0 psi.
The following Figures summarize the Finite Element nonlinear analysis for the critical case 2063. This analysis is based on 6-02 loads.

Figure 3.2.2-9. Top major principal stresses for Case 2063, with imperfection corresponding to same case. Maximum stress is 6300.0 psi. SF = 2.0.
Figure 3.2.2-10. Top minor principal stresses for Case 2063, with imperfection corresponding to same case. Minimum stress is -20071.0 psi. SF = 2.0.
Figure 3.2.2-11. Bottom major principal stresses for Case 2063, with imperfection corresponding to same case. Maximum stress is 6912.0 psi. SF = 2.0.
Figure 3.2.2-12. Bottom minor principal stresses for Case 2063, with imperfection corresponding to same case. Minimum stress is -24318.0 psi. SF = 2.0.
**Review Item Disposition (RID)**  
**ALPHA MAGNETIC SPECTROMETER – 02**  
**AMS-CDR-1-13**

**Type of Review**  
**CDR**

**Vehicle/Other**  
AMS-02

**Date of Review**  
MAY 13 – 16, 2003

**Initiator/Org**  
H.C. Lo/Lockheed Martin

**Mail Code/Phone/Extension**  
B25/333-7047

**Team Tracking No.**

**Team No./System Title**

**Structural Design**

**Subteam No./Subsystem Title**

**Team 1**

**RID Title:** Safety Factor for Buckling Analysis

**Description of Problem:**

Current safety factor for buckling (stability in general) is 1.4. The static test does not cover the non-linearity nature of the buckling phenomena, especially the helium tank casing. Test/analysis correlation covers the linearity prediction only.

**Recommendation:**

Use a safety factor of 2.0 for all stability analysis.

**Impact if Recommendation Not Implemented:**

Possible unexpected under-designed structure.

---

**Initiator’s Signature**

**NASA Team Leader**

**Contractor’s (or NASA’s) Comment:**

Analysis for the outer cylinder buckling was done to a factor of safety of 2.0. And the results were discussed in a telecon with William Torres at LM Michoud. On 9/3/2004. Dr. H.C. Lo and Paul Romine were present during the telecon and were satisfied with the results of the analysis. Others present during the meeting were C. Balasubramanian, Chris Tutt, Howard Carter and Bruce Sommer.

---

**Project Engineer (Contractor or NASA)**

**Team Leader (Contractor or NASA)**

---

**Dispositioned By:**

- [ ] NASA Team Leader
- [ ] Preboard
- [ ] Board

**Type Action:**

- [X] Open
- [ ] Contractor Action Required
- [ ] NASA Action Required
- [ ] Closed
- [ ] Contractor (or NASA) Explanation Satisfactory
- [ ] Disapproved
- [ ] Withdrawn

**Actionee:** C. BALAS  
**Org:** LMSO  
**Due Date:** 11/30/03

**Description of Action:**

The analysis successfully demonstrates that the AMS-02 vacuum case satisfies a safety factor 2.0 for buckling analysis and obtains a positive safety margin.

**Contractor or NASA Representative:**

**Date:** 06-12-07

---

JSC Form 1491 (Rev Oct 93) (AMS Apr 03)  
3.2.2-22
Balas, Chittur

Lo, Hung C (X-LM OPERATIONS SUPPORT)
Friday, September 03, 2004 10:52 AM
Balas, Chittur
RE: cdr rid 1-13 closure

Bala,

The analysis successfully demonstrates that the AMS-02 vacuum case satisfies a safety factor 2.0 for buckling analysis and obtains a positive safety margin.

I agree that the red 1-13 can be closed.

HC LO/Lockheed Martin
281-483-8950

-----Original Message-----
From: Balas, Chittur [mailto:chittur.balas@lmco.com]
Sent: Friday, September 03, 2004 9:53 AM
To: Lo, Hung C (X-LM OPERATIONS SUPPORT)
Cc: Tutt, Chris
Subject: cdr rid 1-13 closure

H.C.,

I am enclosing the RID1-13 on the buckling of the Outer cylinder for the AMS-02 Vacuum case. Please disposition the RID by accepting the analysis which we showed you in the telecon this morning.

<<1-13.doc>>

C. Balasubramanian (Bala)
Mechanical Systems Analysis Department
Structural Analysis Section
Lockheed Martin Space Operations
2400 NASA Road 1, B25
Houston, TX. 77058-3799

Phone: 281-333-7518
Fax: 281-333-8038
e-mail: chittur.balas@lmco.com
Chittur Balan

From: " McDonald, Patrick D" <Patrick.McDonald@escg.jacobs.com>
To: "Chittur Balan" <balas@hal-pc.org>
Cc: "Lauritzen, Carl A" <Carl.Lauritzen@escg.jacobs.com>
Sent: Monday, June 11, 2007 11:27 AM
Attach: FW PDR RID closure.msg
Subject: AMS VC buckling analysis

Bala,

For the buckling analysis on the VC case I do feel that I need to have something a little more formal than an email documenting ES approval of the buckling analysis.

In Dr. Lo's email, he mentions closing the PDR RID on buckling of the VC and opening a new RID requiring a buckling analysis using a factor of safety of 2.0.

Did Dr. Lo open a new RID and, if so, has the new RID been closed out? If so, his signature on the new RID concurring with the buckling analysis could serve as documentation of ES approval of the VC buckling analysis. Could you provide me with documentation of the RID closure, if there was one?

Thanks,

Patrick D. McDonald
Jacobs ESCG
2224 Bay Area Blvd.
Houston, TX, 77058
281-461-5583
patrick.mcdonald@escg.jacobs.com
3.3 Inner Cylinder
3.3.1 Inner Cylinder Strength Assessment
3.3.1 Stress Analysis for Vacuum Case Inner Cylinder

Introduction

The Inner Cylinder, shown in Figure 3.3.1-1, is the central core of the Vacuum Case. The 43.898-inch outer diameter x 32.306-inch length cylinder is manufactured from 2219-T852 hand-forged aluminum. The thickness for the majority of the cylinder’s length is 0.125 inch thick, which tapers to 0.25 inch for the final 0.961 inches at each end shown in Figure 3.3.1-2. The 0.25 inch thickness at the ends is needed to provide the proper cross sectional dimensions necessary to weld the Inner Cylinder to the top and bottom Conical Flanges of the Vacuum Case.

![Figure 3.3.1-1: Side View of Vacuum Case Inner Cylinder](image-url)
Analysis Method Used to Perform the Stress Analysis for the Inner Cylinder

MSC NASTRAN v2001 is used for the finite element analysis of the Inner Cylinder. The pre/post processing software used in building and analyzing the NASTRAN input and output is FEMAP version 8.2. The hi-fi Inner Cylinder model is built entirely out of CQUAD4 and CTRIA3 elements. The ends of the cylinder are connected to the top and bottom Conical Flanges with RBE2 elements. The entire Vacuum Case model, including the high fidelity Inner Cylinder, is integrated with the USS and magnet assembly model to make up the total AMS-02 payload as shown on Figure 3.3.1-3. The results from this model were used to determine the critical stresses for this component.

Stability analysis for the Inner Cylinder is located in section 3.3.2.

Figure 3.3.1-2: End Detail of Inner Cylinder
Figure 3.3.1-3: AMS-02 Model 2-03

Inner Cylinder Finite Element Model Checks

Strain energy and rigid body modes were checked using the high fidelity Inner Cylinder Vacuum Case model combined with the remaining components to make up the full payload model. The overall payload model used in the analysis is version 2-03 found in the /hsm/bsommer/ams/bulk/2-03 directory. The Vacuum Case model used for the Inner Cylinder analysis is located in the /hsm/bsommer/ams/bulk/stressmods/innercylinder directory and titled vc-inner.dat. Figure 3.3.1-4 shows the fine meshed Inner Cylinder model. The top and bottom of the Inner Cylinder contains rigid elements that attach the cylinder, with all six degrees of freedom (DOF), to the Conical Flanges. This simulates a full penetration welded joint. The weld interface is meshed with CQUAD4 elements rotated about the z-axis every 0.9375° and spaced 0.125" apart along the vertical z-axis. A second ring of rigid
elements, 0.75” below the weld and constrained only in the radial direction, simulates the last point of contact that the Inner Cylinder makes with the conical flanges.

Figure 3.3.1-4: Inner Cylinder Stress Model

Figure 3.3.1-5 shows a schematic of the Inner Cylinder to Conical Flange weld interface. The rigid element attachment details are shown in Figure 3.3.1-6.
WELD LOCATION MOVED DOWN (-Z) .250 INCHES AND WELD WILL NOW BE FLUSH WITH THE INNER DIAMETER.

Closeout Weld Location

Figure 3.3.1-5: Inner Cylinder to Conical Flange Weld Detail
Top ring of rigid elements simulate full penetration weld. Transfers all six degrees of freedom to conical flange.

Simulates contact with the conical flange in the radial direction only. Not used for internal pressure case.

**Figure 3.3.1-6: Finite Element Model Detail for Conical Flange to Inner Cylinder Attachment**
The strain energy and rigid body modes checks for this model are found in the /hsm/bsommer/ams/checks/2-03 directory entitled checkIC.f06. The strain energy check limits that are acceptable are for values of 1.0E-5 for translations and 1.0E-3 for rotations. The results for the strain energy checks for the KGG, KNN, KFF matrices are found in Tables 3.3.1-1 through 3.3.1-3. Only the diagonal terms of the 6x6 matrix are listed. The results for the rigid body modes, listed in Table 3.3.1-4 shows six rigid body modes with a good separation between the last rigid body mode 6 and the first real mode mode 7. The total model Mass and CG location is shown in Table 3.3.1-5. The mass units are in slinches and the z coordinate is in the orbiter coordinate system.

Table 3.3.1-1: KGG for Inner Cylinder Model

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</tr>
<tr>
<td>6</td>
<td>2.930787E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Table 3.3.1-2: KNN for Inner Cylinder Model

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.012086E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>6.367055E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.797336E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>3.891126E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>5.230546E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.930787E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>
Table 3.3.1-3: KFF for Inner Cylinder Model

RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.012086E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>6.367055E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.797336E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>3.891126E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>5.230546E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.930787E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Table 3.3.1-4: Rigid Body Modes for Inner Cylinder Model

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES (Hz)</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-3.73E-05</td>
<td>6.11E-03</td>
<td>9.72E-04</td>
<td>1.00E+00</td>
<td>-3.73E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-2.04E-05</td>
<td>4.52E-03</td>
<td>7.19E-04</td>
<td>1.00E+00</td>
<td>-2.04E-05</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-1.04E-05</td>
<td>3.22E-03</td>
<td>5.13E-04</td>
<td>1.00E+00</td>
<td>-1.04E-05</td>
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<tr>
<td>4</td>
<td>4</td>
<td>1.32E-05</td>
<td>3.64E-03</td>
<td>5.79E-04</td>
<td>1.00E+00</td>
<td>1.32E-05</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.75E-05</td>
<td>4.19E-03</td>
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<td>1.00E+00</td>
<td>1.75E-05</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>3.54E-05</td>
<td>5.95E-03</td>
<td>9.47E-04</td>
<td>1.00E+00</td>
<td>3.54E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>2.33E+03</td>
<td>4.82E+01</td>
<td>7.68E+00</td>
<td>1.00E+00</td>
<td>2.33E+03</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>2.33E+03</td>
<td>4.82E+01</td>
<td>7.68E+00</td>
<td>1.00E+00</td>
<td>2.33E+03</td>
</tr>
</tbody>
</table>

Table 3.3.1-5: Mass for Stress and Loads Model and CG For Inner Cylinder Model

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1.6391E-01</td>
<td>1.63E-16</td>
<td>-4.71E+01</td>
<td>1.87E+01</td>
</tr>
<tr>
<td>Y</td>
<td>1.6391E-01</td>
<td>4.65E+00</td>
<td>3.24E-16</td>
<td>1.87E+01</td>
</tr>
<tr>
<td>Z</td>
<td>1.6391E-01</td>
<td>4.65E+00</td>
<td>-4.71E+01</td>
<td>-6.34E-18</td>
</tr>
</tbody>
</table>

- The cg coordinates for Table 3.3.1-5 should be close to zero since the cg is defined around node 999999
Table 3.3.1-6: CG Location for AMS-02 in the Orbiter Z location

<table>
<thead>
<tr>
<th>X (in)</th>
<th>Y (in)</th>
<th>Z (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.46E-01</td>
<td>2.58E+00</td>
<td>3.86E+02</td>
</tr>
</tbody>
</table>

Loads and Constraints

The AMS-02 payload model is constrained at five trunnion locations. A total of 256 load cases for multiple launch/landing scenarios were run using NASTRAN. The critical load cases for the Inner Cylinder were determined by sorting the element stresses from the Inner Cylinder loads model. The high fidelity Inner Cylinder model is incorporated into the loads Vacuum Case model for use in determining the peak stresses. A total of seventeen load cases were chosen as the critical load cases, which included a contingency load case for an internal pressure of 0.8 atmospheres.

The list of the critical load cases with the corresponding load factors is shown in Table 3.3.1-7. Note that the R2### load cases are for landing with a full helium tank. R1### are launch load cases. The Load Factors used for this analysis are listed in Table 1, Page 14 of the AMS-02 Structural Verification Plan for STS and ISS(JSC-28792, Rev.B). The NASTRAN run streams for these load cases can be found in the /hsm/bsommer/ams/nonlin/innercylinder/2000 directory and labeled R20##.dat or /hsm/bsommer/ams/nonlin/innercylinder/1000 with the titles R10##.dat.
Table 3.3.1-7: Critical Load Case Load Factors for Inner Cylinder Model

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Event</th>
<th>Nx (g)</th>
<th>Ny (g)</th>
<th>Nz (g)</th>
<th>Rx (rad/s²)</th>
<th>Ry (rad/s²)</th>
<th>Rz (rad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1008</td>
<td>Launch</td>
<td>5.7</td>
<td>1.6</td>
<td>5.9</td>
<td>-10.0</td>
<td>-25.0</td>
<td>-18.0</td>
</tr>
<tr>
<td>1041</td>
<td>Launch</td>
<td>-5.7</td>
<td>1.6</td>
<td>-5.9</td>
<td>10.0</td>
<td>25.0</td>
<td>18.0</td>
</tr>
<tr>
<td>1045</td>
<td>Launch</td>
<td>-5.7</td>
<td>1.6</td>
<td>-5.9</td>
<td>-10.0</td>
<td>25.0</td>
<td>18.0</td>
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<tr>
<td>1062</td>
<td>Launch</td>
<td>-5.7</td>
<td>-1.6</td>
<td>-5.9</td>
<td>-10.0</td>
<td>25.0</td>
<td>-18.0</td>
</tr>
<tr>
<td>2007</td>
<td>Landing Full</td>
<td>4.5</td>
<td>2.0</td>
<td>6.5</td>
<td>-20.0</td>
<td>-35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2008</td>
<td>Landing Full</td>
<td>4.5</td>
<td>2.0</td>
<td>6.5</td>
<td>-20.0</td>
<td>-35.0</td>
<td>-15.0</td>
</tr>
<tr>
<td>2016</td>
<td>Landing Full</td>
<td>4.5</td>
<td>2.0</td>
<td>-6.5</td>
<td>-20.0</td>
<td>-35.0</td>
<td>-15.0</td>
</tr>
<tr>
<td>2019</td>
<td>Landing Full</td>
<td>4.5</td>
<td>-2.0</td>
<td>6.5</td>
<td>20.0</td>
<td>-35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2020</td>
<td>Landing Full</td>
<td>4.5</td>
<td>-2.0</td>
<td>6.5</td>
<td>20.0</td>
<td>-35.0</td>
<td>-15.0</td>
</tr>
<tr>
<td>2027</td>
<td>Landing Full</td>
<td>4.5</td>
<td>-2.0</td>
<td>-6.5</td>
<td>20.0</td>
<td>-35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2033</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>2.0</td>
<td>6.5</td>
<td>20.0</td>
<td>35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2037</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>2.0</td>
<td>6.5</td>
<td>-20.0</td>
<td>35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2041</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>2.0</td>
<td>-6.5</td>
<td>20.0</td>
<td>35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2042</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>2.0</td>
<td>-6.5</td>
<td>20.0</td>
<td>35.0</td>
<td>-15.0</td>
</tr>
<tr>
<td>2053</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>-2.0</td>
<td>6.5</td>
<td>-20.0</td>
<td>35.0</td>
<td>15.0</td>
</tr>
<tr>
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<td>Landing Full</td>
<td>-4.5</td>
<td>-2.0</td>
<td>6.5</td>
<td>-20.0</td>
<td>35.0</td>
<td>-15.0</td>
</tr>
<tr>
<td>2061</td>
<td>Landing Full</td>
<td>-4.5</td>
<td>-2.0</td>
<td>-6.5</td>
<td>-20.0</td>
<td>35.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

An interface loads comparison between the stress and loads model, shown on Tables 3.3.1-8 and 3.3.1-9, show a close correlation between strap forces and reaction forces at the trunnion attachment points. Only one load case is shown in the tables to illustrate the similarities between the two models.
Table 3.3.1-8: Strap Force Loads Comparison of 2-03 Loads Model vs. Inner Cylinder Stress Model for Load Case 1045

<table>
<thead>
<tr>
<th>Strap ID</th>
<th>Strap Forces (lbs) Loads Model 2-03</th>
<th>Strap Forces (lbs) Stress Model 2-03</th>
<th>Abs Difference (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90001</td>
<td>21536.22</td>
<td>21550.31</td>
<td>14.090</td>
</tr>
<tr>
<td>90002</td>
<td>1720.04</td>
<td>1725.90</td>
<td>5.862</td>
</tr>
<tr>
<td>90003</td>
<td>5393.09</td>
<td>5166.23</td>
<td>226.858</td>
</tr>
<tr>
<td>90004</td>
<td>1443.65</td>
<td>1444.44</td>
<td>0.789</td>
</tr>
<tr>
<td>90005</td>
<td>10944.35</td>
<td>10950.03</td>
<td>5.680</td>
</tr>
<tr>
<td>90006</td>
<td>7309.97</td>
<td>7300.49</td>
<td>9.477</td>
</tr>
<tr>
<td>90007</td>
<td>4253.01</td>
<td>4258.97</td>
<td>5.960</td>
</tr>
<tr>
<td>90008</td>
<td>5133.97</td>
<td>5135.07</td>
<td>1.109</td>
</tr>
<tr>
<td>90009</td>
<td>1818.36</td>
<td>1823.44</td>
<td>5.081</td>
</tr>
<tr>
<td>90010</td>
<td>6046.60</td>
<td>6056.24</td>
<td>9.633</td>
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<tr>
<td>90011</td>
<td>1070.62</td>
<td>1074.43</td>
<td>3.809</td>
</tr>
<tr>
<td>90012</td>
<td>1432.79</td>
<td>1432.66</td>
<td>0.130</td>
</tr>
<tr>
<td>90013</td>
<td>1822.22</td>
<td>1821.27</td>
<td>0.952</td>
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<tr>
<td>90014</td>
<td>8667.13</td>
<td>8678.48</td>
<td>11.344</td>
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<tr>
<td>90015</td>
<td>1408.19</td>
<td>1411.33</td>
<td>3.133</td>
</tr>
<tr>
<td>90016</td>
<td>1803.96</td>
<td>1808.75</td>
<td>4.782</td>
</tr>
</tbody>
</table>

Table 3.3.1-9: Mass Calculated from Trunnion Forces vs. Mass of Stress Model

<table>
<thead>
<tr>
<th>Axis</th>
<th>Total Trunnion Load</th>
<th>Load Factor</th>
<th>Mass from Trunnion Reaction Load LC 1045</th>
<th>Mass Stress Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>85517.79</td>
<td>-5.7</td>
<td>1.5003E+04</td>
<td>1.4995E+04</td>
</tr>
<tr>
<td>Y</td>
<td>-23998.60</td>
<td>1.6</td>
<td>1.4999E+04</td>
<td>1.4991E+04</td>
</tr>
<tr>
<td>Z</td>
<td>88511.16</td>
<td>-5.9</td>
<td>1.5002E+04</td>
<td>1.4993E+04</td>
</tr>
</tbody>
</table>

The discrepancies in strap loads are not seen as a problem for the Inner Cylinder model itself. The differences in the resultant mass at the trunnions and the actual model mass is due to a slight imbalance in the pressure load. The imbalance primarily occurs in the support rings and not at the Inner Cylinder itself. The bulk of the imbalanced force is transferred directly to the USS-02 by way of the interface plates and diagonal strut attachments and not through the Inner Cylinder.
Stress Analysis Results for Inner Cylinder

The maximum stresses for the Inner Cylinder are shown below. NASPOST was used to sort the maximum stresses from the load cases listed in Table 3.3.1-7. The punch files containing the analysis results are found in the /hsm/bsommer/ams/nonlin/innercylinder/2000/2-03/ directory. The files are named according to the load case. (i.e., R2019.pch, R2020.pch, etc.....) The NASPOST list file can be found in /hsm/bsommer/ams/naspost/inner/2-03/ directory. A copy of this list file is located in Appendix A3. The load case containing the highest stress for principle, VonMises and shear are shown below in Table 3.3.1-10. Contour plots of the highest principal stress are shown in Figures 3.3.1-7 through 3.3.1-9.

Table 3.3.1-10: Highest Stresses for Inner Cylinder Model

<table>
<thead>
<tr>
<th>Load Case ID</th>
<th>Elem. ID</th>
<th>Elem. Type</th>
<th>Stress Type</th>
<th>MAX Stress (ksi)</th>
<th>Appendix A3 Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1045</td>
<td>202937</td>
<td>Quad4-plate</td>
<td>Max Principal</td>
<td>-31.39</td>
<td>A3-5</td>
</tr>
<tr>
<td>R1045</td>
<td>202937</td>
<td>Quad4-plate</td>
<td>Max VonM</td>
<td>29.13</td>
<td>A3-7</td>
</tr>
<tr>
<td>R1045</td>
<td>202937</td>
<td>Quad4-plate</td>
<td>Max Shear</td>
<td>15.7</td>
<td>A3-8</td>
</tr>
</tbody>
</table>
Figure 3.3.1-7: Inner Cylinder Stress Contour for Load Case 1045
Figure 3.3.1-8: Max Absolute Principal Stress of 31393psi in Element ID 202937
Figure 3.3.1-9: Max Tensile Stress of 21390 psi in Element ID 202939
Margins of Safety

INNER CYLINDER, VACUUM CASE, AMS-02 2219-T852 (AMS 4144)

Material allowables are from MIL-HDBK-5H Table 3.2.7.0(c) for 2.0” to 4.0” thick Hand forging

\[ \begin{align*}
F_{tu} & := 60000 \text{psi} & \text{Ultimate tensile strength} & \quad F_{sy} & := 1.1 & \text{Yield Factor of Safety} \\
F_{ty} & := 46000 \text{psi} & \text{Compressive yield strength} & \quad F_{su} & := 1.4 & \text{Ultimate Factor of Safety} \\
F_{su} & := 32000 \text{psi} & \text{Ultimate shear strength} & \quad \gamma & := 0.96 & \text{Thermal reduction factor at 140 F}
\end{align*} \]

The maximum stresses for the inner cylinder occur in load case 1045. Margins for the inner cylinder will be calculated based on the stress values shown below.

\[ \begin{align*}
\sigma_{ult} & := 31393.48 \text{psi} \\
\sigma_{yield} & := 29130.16 \text{psi} \\
\tau_{shear} & := 15696.74 \text{psi}
\end{align*} \]

Margins of Safety

\[ \begin{align*}
\text{Ultimate} & \quad MSu := \frac{\gamma \cdot F_{tu}}{\sigma_{ult} \cdot F_{su}} - 1 & \quad MSu = 0.311 \\
\text{Yield} & \quad MSy := \frac{\gamma \cdot F_{ty}}{\sigma_{yield} \cdot F_{sy}} - 1 & \quad MSy = 0.378 \\
\text{Shear} & \quad MSs := \frac{\gamma \cdot F_{su}}{\tau_{shear} \cdot F_{su}} - 1 & \quad MSs = 0.398
\end{align*} \]
Inner Cylinder Weld Analysis

The stresses for the welded interface between the Inner Cylinder to Conical Flange is calculated using the edge stresses for the Quad4-plate elements located at each end of the conical flanges. The critical weld load cases were determined by sort for the max positive principal stress at the Inner Cylinder to conical flange interface. All 256 load cases were sorted using the loads model to determine the worst load cases for the weld. The worst load cases for the weld coincided with the worst load cases for the Inner Cylinder. The critical weld load case is shown in Table 3.3.1-11. The highest weld stress is shown in Table 3.3.1-12. The stress contour plot for the weld is shown on Figure 3.3.1-10.

Table 3.3.1-11: Critical Load Case Load Factor Combinations for Inner Cylinder to Conical Flange Weld

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Event</th>
<th>Nx (g)</th>
<th>Ny (g)</th>
<th>Nz (g)</th>
<th>Rx (rad/s^2)</th>
<th>Ry (rad/s^2)</th>
<th>Rz (rad/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1045</td>
<td>Launch</td>
<td>-5.7</td>
<td>1.6</td>
<td>-5.9</td>
<td>-10</td>
<td>25</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.3.1.2-2: Highest Weld Stress for Inner Cylinder to Conical Flange

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Elem. ID</th>
<th>Elem. Type</th>
<th>MAX PRIN Bottom (ksi)</th>
<th>Appendix A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1045</td>
<td>300224</td>
<td>Quad4-plate</td>
<td>19666.58</td>
<td>A3-3</td>
</tr>
</tbody>
</table>
Figure 3.3.1-10: Load Case 1045 Maximum Weld Stress of 19666.58psi
INNER CYLINDER WELD

\[ F_{tu} := 32000 \text{ psi} \]

Ultimate tensile strength

Provided by Weld Testing conducted by Dan Rybicki. A copy of the weld allowables is shown on page C3-2.

\[ F_{Su} := 1.4 \]

Ultimate Factor of Safety

\[ \gamma := 0.96 \]

Thermal reduction factor at 140 °F.

\[ \sigma_{ult} := 19666.58 \text{ psi} \]

Margin of Safety for Weld

\[
\sigma_{ult} - F_{tu} = \gamma F_{tu} - 1
\]

\[ MS_{u} = 0.116 \]
Inner Cylinder Analysis Conclusions

The inner Cylinder for the AMS-02 Vacuum Case is acceptable for the loading conditions defined in the ASM-02 Structural Verification Plan for STS and ISS (JSC-28792, Rev.B) and for a total payload weight of 15000lbs. There are several factors that could change the analysis for the Inner Cylinder. Among them is an increase in the mass of the magnet, helium tank or tracker. Other possible impacts to the current analysis, such as changes in inertial load factors due to updated transient analysis, will have to be assessed when they occur.
3.3.2 Inner Cylinder Stability Assessment
This analysis computes the stability of the AMS-02 Inner Cylinder, treating it as a specially orthotropic cylinder under hydrostatic compression.

Cylinder is made of 2219-T852

\[ E := 10.4 \times 10^6 \text{ psi} \quad \beta := .33 \]

Define the geometry

\[ L := 33.307 \text{ in} \quad \text{(length of cylinder)} \]

\[ \text{Rosl := 22.074 in} \quad \text{(radius of cylinder to the surface location-nominal radius plus nominal thickness)} \]

\[ t := .13 \text{ in} \quad \text{(average thickness of cylinder - dimension is 0.125" +.010 -.000)} \]

\[ \text{dref := 0.5t} \quad \text{(reference surface location)} \]

\[ R := \text{Rosl} - \text{dref} \quad R = 22.009 \text{ in} \quad \text{(Cylinder radius to reference surface)} \]
Use the yield factor of safety for AMS-02

\[ F_{Sy} := 1.1 \]

The applied hydrostatic pressure is defined as per the AMS SVP as being .8 atmospheres:

\[ \text{pressure} := .8 \times 14.7 \text{ psi} \quad \text{pressure} = 11.76 \text{ psi} \]

Define the number of axial (m) and circumferential (n) waves. This analysis will check buckling for all combinations of these waves, and determine the minimum margin

\[ M := 10 \quad N := 20 \]

Define:

\[ u(m) := \left( \frac{m \cdot L}{L} \right)^2 \quad = (n) := \left( \frac{n}{R} \right)^2 \]

These will simplify the equations
Now, define the Constitutive coefficients as (see Almroth, eqn 5.74, noting that this case has no rings or stiffeners so the s and r terms are zero).

\[
C_{11} := \frac{E \cdot t}{1 - \beta^2} \quad C_{11} = 1517225.901 \text{ lbf/in}
\]

\[
C_{12} := \beta C_{11} \quad C_{12} = 500684.547 \text{ lbf/in}
\]

\[
C_{22} := C_{11} \quad C_{22} = 1517226 \text{ lbf/in}
\]

\[
C_{33} := \frac{E \cdot t}{2(1 + \beta)} \quad C_{33} = 508271 \text{ lbf/in}
\]

\[
C_{44} := \frac{E \cdot t^3}{12 \left(1 - \beta^2\right)} \quad C_{44} = 2137 \text{ in-lbf}
\]

\[
C_{55} := C_{44} \quad C_{55} = 2137 \text{ in-lbf}
\]

\[
C_{45} := \beta C_{44} \quad C_{54} := C_{45} \quad C_{45} = 705 \text{ in-lbf}
\]

\[
C_{66} := (1 - \beta) \frac{E \cdot t^3}{12 \left(1 - \beta^2\right)} \quad C_{66} = 1432 \text{ in-lbf}
\]

Using twice the twisting curvature based on the most common approach, the equation becomes:

\[
C_{66} := \frac{1 - \beta}{2} \frac{E \cdot t^3}{12 \left(1 - \beta^2\right)} \quad C_{66} = 715.815 \text{ in-lbf}
\]
Now, define (per Almroth, eqn 5.77)

\[
A_{11}(m, n) := C_{11} \left( \frac{m}{L} \right)^2 + C_{33} \left( \frac{n}{R} \right)^2
\]

\[
A_{11}(1, 1) = 3.949 \times 10^9 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}^2}
\]

\[
A_{12}(m, n) := (C_{12} + C_{33}) \frac{m}{L} \frac{n}{R}
\]

\[
A_{12}(1, 1) = 1.174 \times 10^9 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}^2}
\]

\[
A_{13}(m, n) := \frac{C_{12}}{R} m \frac{n}{L}
\]

\[
A_{13}(1, 1) = 5.825 \times 10^8 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}^2}
\]

\[
A_{22}(m, n) := C_{33} \left( \frac{m}{L} \right)^2 + C_{22} \left( \frac{n}{R} \right)^2
\]

\[
A_{22}(1, 1) = 2.078 \times 10^9 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}^2}
\]

\[
A_{23}(m, n) := \frac{C_{22} n}{R}
\]

\[
A_{33}(m, n) := C_{44} \left( \frac{m}{L} \right)^4 + 2 \cdot (2 \cdot C_{66} + C_{45}) \left( \frac{m}{L} \right)^2 \left( \frac{n}{R} \right)^2 + C_{55} \left( \frac{n}{R} \right)^4 + \frac{C_{22}}{R^2}
\]

Now, define the matrices

\[
a_{0}(m, n) := \begin{pmatrix} A_{11}(m, n) & A_{12}(m, n) \\ A_{12}(m, n) & A_{22}(m, n) \end{pmatrix}
\]

\[
a_{1}(m, n) := \begin{pmatrix} A_{11}(m, n) & A_{12}(m, n) & A_{13}(m, n) \\ A_{12}(m, n) & A_{22}(m, n) & A_{23}(m, n) \\ A_{13}(m, n) & A_{23}(m, n) & A_{33}(m, n) \end{pmatrix}
\]

We're dividing by the units since below we need to take the determinant of a matrix and in MathCAD the matrix must be unitless. Note that the determinant of \( a_0 \) would have units of \( (\text{lbf/\text{in}^3})^2 \) and \( a_1 \) units of \( (\text{lbf/\text{in}^3})^3 \)

Create ranges for \( m \) and \( n \), using maximum numbers defined above

\[
m := 1..M \quad n := 1..N
\]
Now, solve for the pressure as a function of $m$ and $n$. The division of determinants for $a_1$ and $a_0$ would result in units of lbf/in$^3$, so we'll multiply by this to achieve the correct pressure units.

\[
q_{cl}(m, n) := \frac{1}{R \left( \frac{1}{2} \cdot u(m) + \pm(n) \right)} \cdot \frac{|a_1(m, n)|}{|a_0(m, n)|} \left( \frac{\text{lbf}}{\text{in}^3} \right)
\]

The minimum pressure is therefore: $\min(q_{cl}) = 17.833$ psi

Now find the radial and circumferential waves that gives the minimum pressure

\[
m_{\min} := \left( \text{match}(\min(q_{cl}), q_{cl}) \right)_1 \quad m_{\min} = 1
\]

\[
n_{\min} := \left( \text{match}(\min(q_{cl}), q_{cl}) \right)_2 \quad n_{\min} = 8
\]

From Almroth, the Batdorf parameter for cylinders with simply supported ends is given as:

\[
Z := \frac{L^2}{R \cdot t} \sqrt{1 - \beta^2} \quad Z = 366.008
\]

Figure 7.19 in Almroth shows a plot of Imperfection sensitivity of cylinders subjected to lateral pressure. This plot is shown below. For $Z = 366.008$, read the graph to get $\frac{a_2}{1 - y^2}$ which we'll give as $a_{2\text{cal}} := -0.0144$
The above plot is shown again, this time zoomed in on the region we're interested in.
So, we can solve for $a_2$

$$a_2 := a_2\text{cal}\left(1 - \beta^2\right)$$

$$a_2 = -0.01283$$

If the initial imperfections are assumed to be in the form of a classical buckling mode, Almroth then gives an equation for the relationship among limiting point load, imperfection magnitude and the imperfection-sensitivity parameter $a_2$

$$\left(1 - u\right)^2 = \frac{1}{2}\left(-a_2\right)^2 \cdot u \cdot |\,|$$

Eqn 7.55, page 256, Almroth

We'll solve this for $\lambda$, the ratio of applied pressure at the limit point to corresponding classical critical pressure.

First, find $\mu$, which is the ratio of imperfection amplitude to shell wall thickness.

Define: $\varepsilon := 0.025$ in  \hspace{1cm} The maximum physical imperfection as specified in the design (see SDG39135782 tolerance on inner diameter is +.015 / tolerance on wall thickness is +.010)

So, the ratio is therefore: $\mu := \frac{\varepsilon}{t}$, \hspace{1cm} $\mu = 0.192$

Use a MathCAD solve block to find $\lambda$.

Guess: $u := .1$

Given

$$\frac{1}{2} \frac{(3) \cdot 3^2}{2} \left(-a_2\right)^2 \cdot u \cdot |\,| - \left(1 - u\right)^2 = 0$$

$u := \text{Find}(u)$

$u = 0.866$

$\lambda$ is then the Knock Down Factor to be used with the buckling pressure calculated above.

$$\text{Per} := u \cdot \text{min(qcl)}$$

$\text{Pcr} = 15.444$ psi

The margin of safety is therefore:

$$MS := \frac{\text{Per}}{\text{pressure}\cdot FSy} - 1$$

$MS = 0.194$
3.4 Upper Support Ring
Margins of Safety

Table 3.4-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135786</td>
<td>Upper Support Ring</td>
<td>AL ALY 7050-T7451</td>
<td>Launch</td>
<td>Yield</td>
<td>0.035 (u)</td>
<td>3.4-26</td>
</tr>
</tbody>
</table>
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing.

Description of Structure

Figure 3.4-1 below shows the location of Upper Support Ring in AMS-02. The Ring is machined from 7050-T7451 Aluminum Alloy Rolled Forging. It is attached to the Outer Cylinder with 192 bolts, and to the Conical Flange with 232 bolts. Eight Strap Ports are machined on the Ring to accommodate the magnet suspension straps. The Upper Support Ring has four Interface Plates for attachment of the USS-02.

* Note that the above figure does not show USS-02 for clarity.
Description of Model

High Detail USS Flight Model

The high detail USS flight model is used for the stress analysis of the Upper Support Ring. This model is used to recover On-Orbit Loads as well as the base for all detailed Flight USS models. It includes the 5-07 loads model with high fidelity models integrated into it. These models include the Sill, Elbow, Lower USS and VC Interface Joints as well as the Keel Block. These models are used in previous flight stress analysis as separate models and were created for each joint. Since computer resources have improved, we now have the ability to run larger models. These models are combined into one model. This was done to save on the number of models required which reduces the total number of runs required saving both man hours and cpu time as well as reducing the possibilities of errors. This model is shown in Figure 3.4-2. The FEA model is called uss-8-07-high.MOD and is stored in the directory \Escfil02\caduser\projects\edsug\ams\public\sangster\8-07\Flight FEMAP Models.

![Figure 3.4-2: High Detail Full Flight USS Model](image-url)
High Detail Flight Vacuum Case Model

The high detail Vacuum Case model is used for the stress analysis of the Upper Support Ring. This model is created by combining the stress models of the Upper Ring, Lower Ring, Conical Flange, Outer Cylinder, and Inner Cylinder into a single model. This model is shown in Figure 3.4-3.

![Figure 3.4-3: High Detail Flight VC](image)

Model Checks

The model checks are documented in Section 4.11.1 of the AMS-02 Fatigue and Fracture report ESCG-4450-08-STAN-DOC-0115. The model checks correspond to Configuration 13 per the AMS-02 Fatigue and Fracture report ESCG-4450-08-STAN-DOC-0115. Configuration 13 consists of the flight and landing configurations of the AMS-02.
The input files for this run are listed in Table 3.4-2. Table 3.4-3 shows the files used to check that the RBE2 elements have modeling contact and not tension as intended. Table 3.4-4 lists the different VC models used for different load cases. The different models were created depending on what portion of the RBE2 elements are used for modeling contact for that load case. Table 3.4-6 lists the model files used for each load case. Model checks for both the constrained and unconstrained models are shown in Table 3.4-7. The fixed modes run shows that when the model is constrained it is fully constrained. The Strain Energy checks shown in Table 3.4-8 show the total strain energy.

### Table 3.4 -2: Files used

<table>
<thead>
<tr>
<th>Include file directory</th>
<th>Include File name</th>
<th>Description or Description Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>/ams/transport/bulk</td>
<td>vc-high.dat *Note 1</td>
<td>This Model 2.3.2. High Detail Flight</td>
</tr>
<tr>
<td>/ams/bulk/2-07</td>
<td>trd.dat</td>
<td>2-07 Loads Model - AMS Stress Report</td>
</tr>
<tr>
<td>/ams/bulk/2-07</td>
<td>trdgas.dat</td>
<td>2-07 Loads Model - AMS Stress Report</td>
</tr>
<tr>
<td>/ams/bulk/2-07</td>
<td>trdgas-spring.dat</td>
<td>2-07 Loads Model - AMS Stress Report</td>
</tr>
<tr>
<td>/ams/bulk/2-07</td>
<td>cab.dat</td>
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<tr>
<td>/ams/bulk/2-07</td>
<td>ltof.dat</td>
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</tr>
<tr>
<td>/ams/bulk/2-07</td>
<td>ltof-bolts.dat</td>
<td>2-07 Loads Model - AMS Stress Report</td>
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<tr>
<td>/ams/bulk/2-07</td>
<td>ecal.dat</td>
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<td>/ams/bulk/2-07</td>
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<td>ramradiator.dat</td>
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<td>wakeradiator.dat</td>
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<td>rich.dat</td>
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<tr>
<td>/ams/transport/bulk</td>
<td>trdgas-high-connect.dat</td>
<td>This file contains the bracket connecting the TRD Gas to the Joint</td>
</tr>
<tr>
<td>/ams/transport/bulk</td>
<td>uss-high-rbemixed-rbe2.dat</td>
<td>Vacuum Cash Shipping Fixture Stress Report</td>
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<td>/ams/bulk/2-07</td>
<td>ip-uss-springs.dat</td>
<td>2-07 Loads Model - AMS Stress Report</td>
</tr>
</tbody>
</table>
The VC is modeled using RBE2 elements to represent the compressive contact between the Rings and Outer Cylinder as well as the Rings and conical flange. For other configurations, this is realistic since the inertia loads do not overcome the compressive pressure load. For liftoff and landing, the inertia load overcomes the compressive load in some elements. This means that the RBE2 is experiencing a tensile load when it should only be experiencing a compressive load. To correct for this, an iterative process was used in which the RBE2 elements were removed and runs were redone until all remaining RBE2 elements only carried compressive loads. This check was made using Naspost and files are listed in Table 3.4-2. The modes and frequencies shown are for the initial run with all RBE2 elements. It was found that the frequencies did not shift much with the minimal number of RBE2 elements removed.
### Table 3.4-3: Naspost RBE2 Compression Check

<table>
<thead>
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<th>Favorites</th>
<th>Tools</th>
<th>Help</th>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Address</td>
<td>Z:\Fracture\BaseAnalysis\MPCTension analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- MpcCheckFlight.nas.lis
- MpcCheckFlight-miss.nas.lis
- MpcLandingCheck.nas
- MpcLandingCheck-miss.nas
- MpcCheckFlight.nas
- MpcCheckFlight-miss.nas

### Table 3.4-4: VC Model Files

<table>
<thead>
<tr>
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<th>Favorites</th>
<th>Tools</th>
<th>Help</th>
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</table>

- vc-high-nodes3.dat
- vc-high-nodes31.dat
- vc-high-nodes32.dat
- vc-high-nodes33.dat
- vc-high-nodes34.dat
- vc-high-nodes35.dat
- vc-high-nodes36.dat
- vc-high-nodes37.dat
- vc-high-nodes38.dat
- vc-high-nodes39.dat
- vc-high-nodes40.dat
- vc-high-nodes41.dat
- vc-high-nodes42.dat
- vc-high-nodes43.dat
- vc-high-nodes44.dat
### Table 3.4-5: Configuration 13 Job File List

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<th>File Name</th>
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<td>job-flight-static-37</td>
<td>job-landing-base-41</td>
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<td>job-flight-base2-02</td>
<td>job-flight-static-39</td>
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<td>job-flight-base2-33</td>
<td>job-landing-base</td>
<td>job-landing-modal</td>
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<td>job-flight-base2-35</td>
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<td>job-landing-static</td>
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### Table 3.4-6: Configuration 13 File list

<table>
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<th>Final Run Name</th>
<th>Load Case</th>
<th>VC model</th>
<th>Final Run Name</th>
<th>Load Case</th>
<th>VC model</th>
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<tr>
<td>31.54</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>32.04</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>32.88</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>32.93</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>34.06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>34.10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Material and Temperature

The Upper Support Ring is 7050-T7451 Aluminum Alloy. Material properties of 7050-T7451 are taken from MIL-HDBK-5H, Table 3.7.3.0(d) for thickness of 5.001”-6.000”. Temperature limits are based upon Bolted Interface Temperatures worksheet provided by Thermal Group. For Launch condition, the temperature of 120°F is applied. For Abort Landing condition, the temperature of 150°F is applied.

Analysis

The critical stresses for the Upper Support Ring are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. The following stress analysis method was used in the fracture and fatigue assessment and will be incorporated in the stress analysis.
The updated model was used with data sorted for every configuration individually. The previous stress analysis that Peter Hoang performed is replaced with the stress analysis performed by Chris Sangster. Figure 3.4-4 shows the rings in relation to the VC.

Figure 3.4-4: View of Vacuum Case
VC Upper Support Ring Stress analysis

Drawing Number : SDG39135786
Material Properties : 7050-T7451 AL ALY, AMS 4108
(Ref. MIL-HDBK-5H, Table 3.7.3.0(d) for thickness of 5.001"-6.000")
Allowable tensile Stress Ftu: 66 ksi
Ultimate Factor of Safety FSu: 1.4

For each Load Condition
1.) the Max Temp. was determined.
2.) yu(temp correction factor) was obtained from MIL-HDBK-5H, Figure 3.7.3.2.1
3.) Corrected Ftu was calculated using Ftu=Ftu*yu
4.) The stress required to create a margin of zero was calculated. Zero Margin Stress=Ftu*yu/FSu
5.) Fatigue Critical Stress was calculated using Fatigue Critical Stress=Ftu*yu*.3

These calculations are shown in the below in Table 3.4-9: Zero Margin Stress.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temp</th>
<th>yu</th>
<th>Corrected Ftu</th>
<th>Zero Margin Stress</th>
<th>Fatigue Critical stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch:</td>
<td>120</td>
<td>0.95</td>
<td>62700</td>
<td>44786</td>
<td>18810</td>
</tr>
<tr>
<td>Abort Landing:</td>
<td>150</td>
<td>0.91</td>
<td>60060</td>
<td>42900</td>
<td>18018</td>
</tr>
<tr>
<td>Transportation:</td>
<td>94</td>
<td>0.98</td>
<td>6480</td>
<td>46200</td>
<td>19404</td>
</tr>
<tr>
<td>On-Orbit:</td>
<td>150</td>
<td>0.91</td>
<td>60060</td>
<td>42900</td>
<td>18018</td>
</tr>
</tbody>
</table>

Principle Stress in all elements was recovered and sorted.
1.) Max Principle stress for each element type was recovered.
2.) Elements with stress above Zero Margin Stress were recovered
3.) Elements with stress exceeding the Fatigue Critical Stress were recovered from the Nastran results using Naspost.
Table 3.4-10 shows the max principal stress for each element type, recovered from Naspost. Elements stresses that show negative margins are highlighted in yellow.

Table 3.4-10: Element Recovered Stress

<table>
<thead>
<tr>
<th>Location</th>
<th>Quad</th>
<th>Tri</th>
<th>Hex</th>
<th>Penta</th>
<th>TetA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered</td>
<td>PSI</td>
<td>PSI</td>
<td>PSI</td>
<td>PSI</td>
<td>PSI</td>
</tr>
<tr>
<td>Units</td>
<td>PSI</td>
<td>PSI</td>
<td>PSI</td>
<td>PSI</td>
<td>PSI</td>
</tr>
<tr>
<td>Max ABS Principle Stress</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launch:</td>
<td>23938</td>
<td>30860</td>
<td>112923</td>
<td>24092</td>
<td>25445</td>
</tr>
<tr>
<td>Abort Landing:</td>
<td>24507</td>
<td>31544</td>
<td>62930</td>
<td>18640</td>
<td>16535</td>
</tr>
<tr>
<td>Transportation:</td>
<td>19476</td>
<td>24678</td>
<td>67626</td>
<td>18960</td>
<td>17300</td>
</tr>
<tr>
<td>On-Orbit</td>
<td>453</td>
<td>392</td>
<td>4249</td>
<td>2029</td>
<td>984</td>
</tr>
</tbody>
</table>

The elements recovered in Naspost were imported into FEMAP and shown in Figure 3.4-4 and Figure 3.4-6. Figure 3.4-5 is a close up view showing one area of the O-ring lip with negative margins. All other areas on the O-ring lip look similar. Figure 3.4-6 shows all the elements around the ring with negative margins. These elements are shown in blue.

Figure 3.4-5: Close Up of O-ring Elements on the VC Ring with Negative Margins
Figure 3.4-6: Elements with Negative Margins, on the O-ring Lip of the VC Ring
The arrows shown in Figure 3.4-7 point to the areas of concern at locations where a RBE2 element was used to model the contact on the lip. The RBE2 element is shown in light orange with a red arrow pointing to it in Figure 3.4-8.
The following statements explain the reasons for the high stresses and the rationale for ignoring these high stresses.

1. RBE2 element can cause artificially high stresses.
2. The elements surrounding the RBE2 elements do not have high stresses or negative margins.
3. Hand calculations show that the stress due to the compressive load is much lower than the zero margin stress. Refer to Table 3.4-13.
4. The O-ring’s at these locations are being compressed and shares some of the load. This was not modeled and makes the analysis conservative.
5. If a local deformation occurred no failure would occur and the load would simply distribute to a larger portion of the ring.
Stress of Surrounding Elements

Table 3.4-11 shows elements surrounding the hexagonal element 8007579 which showed a stress of 112.923 ksi in Table 3.4-10 for the launch case. The highest element stress now is 31.4 ksi on element 8012522.

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>MAX-MAX-PRIN</th>
<th>MAX-MIN-PRIN</th>
<th>ABS MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>8007580</td>
<td>1049</td>
<td>7615</td>
<td>28919</td>
<td>28919</td>
</tr>
<tr>
<td>8012521</td>
<td>1049</td>
<td>13405</td>
<td>4129</td>
<td>13405</td>
</tr>
<tr>
<td>8012522</td>
<td>1049</td>
<td>9513</td>
<td>31401</td>
<td>31401</td>
</tr>
<tr>
<td>8023506</td>
<td>1049</td>
<td>13151</td>
<td>4593</td>
<td>13151</td>
</tr>
<tr>
<td>8023509</td>
<td>1049</td>
<td>4042</td>
<td>4283</td>
<td>4283</td>
</tr>
<tr>
<td>8023511</td>
<td>1049</td>
<td>7633</td>
<td>6179</td>
<td>7633</td>
</tr>
<tr>
<td>8070079</td>
<td>1049</td>
<td>10596</td>
<td>5599</td>
<td>10596</td>
</tr>
<tr>
<td>8070082</td>
<td>1049</td>
<td>6600</td>
<td>28870</td>
<td>28870</td>
</tr>
<tr>
<td>8070084</td>
<td>1049</td>
<td>7711</td>
<td>30332</td>
<td>30332</td>
</tr>
</tbody>
</table>
Hand Calculations Showing the Max Stress Due to the Load Recovered from the RBE2 Element.

The stress was calculated using Stress=Force/Area. Table 3.4-12 shows two red boxes each representing the area used in this calculation for the RBE2 element inside the red box.

The area used was half the area of the elements on either side of the RBE2 element. The elements were one of 4 general sizes. For each size element the area was calculated from a length and width; assuming the elements were rectangles. The calculations are shown in Table 3.4-12.

### Table 3.4-12: Element area calculations

<table>
<thead>
<tr>
<th>Width(in)</th>
<th>Length(in)</th>
<th>Area(in^2)</th>
<th>Element size</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1622</td>
<td>0.43254</td>
<td>0.070158</td>
<td>Small Top Elements</td>
</tr>
<tr>
<td>0.1622</td>
<td>0.86691</td>
<td>0.140613</td>
<td>Top Elements</td>
</tr>
<tr>
<td>0.2546</td>
<td>0.40837</td>
<td>0.103971</td>
<td>Lower small</td>
</tr>
<tr>
<td>0.2546</td>
<td>0.81665</td>
<td>0.207919</td>
<td>Bottom Elements</td>
</tr>
</tbody>
</table>

To show this more clearly the RBE2 element loads were recovered for all nodes on elements in question. The Calculations are shown in Table 3.4-13. Steps in this calculation are as follows:

1.) For each RBE2 element the Load was recovered
2.) Elements connected to RBE2 elements were found
3.) For each solid element the size was determined
4.) The area of each element was found
5.) The stress was calculated using
   \[
   \text{Stress} = \frac{\text{Load}}{\left(\frac{\text{Element 1 Area} + \text{Element 2 Area}}{2}\right)}
   \]
Table 3.4-13: Compressive stress calculations

<table>
<thead>
<tr>
<th>GRID ID</th>
<th>LoadCase</th>
<th>Load</th>
<th>Element ID 2</th>
<th>Element Area</th>
<th>Element Area</th>
<th>Max Compressive stress</th>
<th>16965</th>
</tr>
</thead>
<tbody>
<tr>
<td>8082126</td>
<td>1049</td>
<td>-3527</td>
<td>8070081</td>
<td>8007579</td>
<td>0.21</td>
<td>0.21</td>
<td>16965</td>
</tr>
<tr>
<td>8082126</td>
<td>1053</td>
<td>-3490</td>
<td>8070081</td>
<td>8007579</td>
<td>0.21</td>
<td>0.21</td>
<td>16785</td>
</tr>
<tr>
<td>8082126</td>
<td>1050</td>
<td>-3441</td>
<td>8070081</td>
<td>8007579</td>
<td>0.21</td>
<td>0.21</td>
<td>16548</td>
</tr>
<tr>
<td>8082126</td>
<td>1054</td>
<td>-3399</td>
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<td>8007579</td>
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<td>0.21</td>
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<tr>
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<td>1057</td>
<td>-3129</td>
<td>8070081</td>
<td>8007579</td>
<td>0.21</td>
<td>0.21</td>
<td>15048</td>
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<tr>
<td>704123</td>
<td>7001</td>
<td>1565</td>
<td>8025863</td>
<td>8025757</td>
<td>0.14</td>
<td>0.14</td>
<td>11130</td>
</tr>
<tr>
<td>704022</td>
<td>7007</td>
<td>1566</td>
<td>8022153</td>
<td>8022259</td>
<td>0.14</td>
<td>0.14</td>
<td>11140</td>
</tr>
<tr>
<td>704179</td>
<td>7008</td>
<td>1570</td>
<td>8081536</td>
<td>8081508</td>
<td>0.14</td>
<td>0.14</td>
<td>11164</td>
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<tr>
<td>704110</td>
<td>7004</td>
<td>1579</td>
<td>8077627</td>
<td>8077599</td>
<td>0.14</td>
<td>0.14</td>
<td>11226</td>
</tr>
<tr>
<td>704083</td>
<td>7002</td>
<td>1585</td>
<td>8085073</td>
<td>8085045</td>
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<td>0.14</td>
<td>11270</td>
</tr>
<tr>
<td>704014</td>
<td>7006</td>
<td>1586</td>
<td>8088580</td>
<td>8088608</td>
<td>0.14</td>
<td>0.14</td>
<td>11279</td>
</tr>
<tr>
<td>704110</td>
<td>7004</td>
<td>1592</td>
<td>8077627</td>
<td>8077599</td>
<td>0.14</td>
<td>0.14</td>
<td>11325</td>
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<tr>
<td>704083</td>
<td>7002</td>
<td>1594</td>
<td>8085073</td>
<td>8085045</td>
<td>0.14</td>
<td>0.14</td>
<td>11333</td>
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<tr>
<td>704022</td>
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<td>1601</td>
<td>8022153</td>
<td>8022259</td>
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<td>0.14</td>
<td>11383</td>
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<tr>
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<td>7006</td>
<td>1613</td>
<td>8088580</td>
<td>8088608</td>
<td>0.14</td>
<td>0.14</td>
<td>11474</td>
</tr>
<tr>
<td>704014</td>
<td>7006</td>
<td>1634</td>
<td>8088580</td>
<td>8088608</td>
<td>0.14</td>
<td>0.14</td>
<td>11624</td>
</tr>
</tbody>
</table>
As you can see, when applying the hand calculations, the stresses reduce significantly. In order to recover stresses from the VC Ring FE model, several elements were removed from the NASPOST sort. The reason why the elements were omitted is because if the hand calculations are applied for each of these elements, the stress would also reduce significantly. Figure 3.4-10 and Figure 3.4-11 show a picture of the location where the elements were omitted. The elements omitted are in a straight row around the ring.

Figure 3.4-10: Omitted Elements on Upper Support Ring
After omitting the elements shown in Figure 3.4-10 and 3.4-11, it was found that 3 additional elements (8035881, 8035989, 8035991) had high stresses. These elements were connected to either an RBE2 or a CBUSH. Figure 3.4-12 shows the location of the 3 elements. For the element connected to the RBE2, the stresses on all the nodes in the element were recovered. The stress on all the other nodes in the element resulted with positive margins.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8035881</td>
<td>1020</td>
<td>4.744452E+03</td>
<td>7.071944E+03</td>
<td>2.693563E+04</td>
<td>1.596904E+04</td>
<td>2.055569E+04</td>
<td>4.276148E+04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8035989</td>
<td>4.95079E+04</td>
<td>2.648401E+04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8035991</td>
<td>4.276148E+04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stress of node connected to RBE2
Stress of node with the next highest stress

Figure 3.4-11: Additional Omitted Elements on Upper Support Ring
For the 2 elements around the CBUSH, bearing calculations were performed in the Outer Cylinder to Upper Support Ring bolt analysis (Section 3.10.3). Positive margins were obtained in the bearing calculations. Therefore elements 8035881, 8035989, 8035991 were omitted in the margin of safety calculations.

Figure 3.4-12: Location of Elements 8035881, 8035989, 8035991
Check of Upper Support Ring

Material Properties: 7050-T7451 AL ALY, AMS 4108

\[ F_u := 66000 \text{ psi} \]
\[ F_y := 53000 \text{ psi} \]
\[ F_{su} := 40000 \text{ psi} \]

Factors of Safety, \( F_{su} := 1.4 \) \( F_{sy} := 1.1 \)

Temperature Reduction Factors, \( \text{Ref. MIL-HDBK-5H, Figure 3.7.3.2.1} \)

Launch: + At \( 120^\circ F \):
\[ \beta_{u1} := 0.95 \]
\[ \beta_{y1} := 0.99 \]

Abort Landing: + At \( 150^\circ F \):
\[ \beta_{u2} := 0.91 \]
\[ \beta_{y2} := 0.97 \]

Maximum Von-Mises, Principal, and Shear stresses of both plate and solid elements are selected from 64 load cases for Launch and 64 load cases for Abort Landing. NASPOST is used to sort out the maximum stresses within the load cases.

+ Launch: For Solid Elements

Maximum Principal stress, \( u_{u1} := 42867 \text{ psi} \) \( ID: 8033822 \ , \ LC: 1007 \)
(Refer to Appendix A13, p. A13-38)

Maximum Von-Mises stress, \( u_{y1} := 46108 \text{ psi} \) \( ID: 8035767 \ , \ LC: 1020 \)
(Refer to Appendix A13, p. A13-39)

Maximu Shear stress, \( u_{s1} := 25964 \text{ psi} \) \( ID: 8035767 \ , \ LC: 1020 \)
(Refer to Appendix A13, p. A13-40)

Margins of Safety:

\[ MS_{u1} := \frac{\beta_{u1} \cdot F_{u}}{F_{su} \cdot u_{u1}} - 1 \]
\[ MS_{y1} := \frac{\beta_{y1} \cdot F_{y}}{F_{sy} \cdot u_{y1}} - 1 \]
\[ MS_{s1} := \frac{\beta_{u1} \cdot F_{su}}{F_{su} \cdot u_{s1}} - 1 \]

\[ MS_{u1} = 0.045 \]
\[ MS_{y1} = 0.035 \]
\[ MS_{s1} = 0.0454 \]
- Launch: For Plate Elements

Maximum Principal stress, \( u_{1} := 30860 \text{ psi} \)  
\( \text{ID: 8100183, LC: 1028} \)  
(Refer to Appendix A13, p. A13-24)

Maximum Von-Mises stress, \( y_{1} := 31503 \text{ psi} \)  
\( \text{ID: 8100184, LC: 1028} \)  
(Refer to Appendix A13, p. A13-25)

Maximu Shear stress, \( s_{1} := 16220 \text{ psi} \)  
\( \text{ID: 8100183, LC: 1028} \)  
(Refer to Appendix A13, p. A13-26)

Margins of Safety:
\[
\text{MS}_{u1} := \frac{\beta_{u1} \cdot F_{u}}{F_{S} \cdot u_{1}} - 1 \\
\text{MS}_{y1} := \frac{\beta_{y1} \cdot F_{y}}{F_{S} \cdot y_{1}} - 1 \\
\text{MS}_{s1} := \frac{\beta_{s1} \cdot F_{s}}{F_{S} \cdot s_{1}} - 1
\]

\( \text{MS}_{u1} = 0.451 \)  
\( \text{MS}_{y1} = 0.514 \)  
\( \text{MS}_{s1} = 0.6734 \)

- Abort Landing: For Solid Elements

Maximum Principal stress, \( u_{2} := 36788 \text{ psi} \)  
\( \text{ID: 8057602, LC: 2027} \)  
(Refer to Appendix A13, p. A13-50)

Maximum Von-Mises stress, \( y_{2} := 34145 \text{ psi} \)  
\( \text{ID: 8057602, LC: 2027} \)  
(Refer to Appendix A13, p. A13-51)

Maximu Shear stress, \( s_{2} := 17405 \text{ psi} \)  
\( \text{ID: 8057602, LC: 2027} \)  
(Refer to Appendix A13, p. A13-52)

Margins of Safety:
\[
\text{MS}_{u2} := \frac{\beta_{u2} \cdot F_{u}}{F_{S} \cdot u_{2}} - 1 \\
\text{MS}_{y2} := \frac{\beta_{y2} \cdot F_{y}}{F_{S} \cdot y_{2}} - 1 \\
\text{MS}_{s2} := \frac{\beta_{s2} \cdot F_{s}}{F_{S} \cdot s_{2}} - 1
\]

\( \text{MS}_{u2} = 0.166 \)  
\( \text{MS}_{y2} = 0.369 \)  
\( \text{MS}_{s2} = 0.494 \)
+ Abort Landing: For Plate Elements

Maximum Principal stress, \( u_{u2} := 31544 \text{ psi} \)

Maximum Von-Mises stress, \( u_{y2} := 32240 \text{ psi} \)

Maximu Shear stress, \( u_{s2} := 16573 \text{ psi} \)

Margins of Safety:

\[
MS_{u2} := \frac{\beta_{u2} F_{u}}{F_{S_y} u_{u2}} - 1 \quad MS_{u2} = 0.36
\]

\[
MS_{y2} := \frac{\beta_{y2} F_{y}}{F_{S_y} u_{y2}} - 1 \quad MS_{y2} = 0.45
\]

\[
MS_{s2} := \frac{\beta_{s2} F_{u}}{F_{S_y} u_{s2}} - 1 \quad MS_{s2} = 0.569
\]
3.5 Lower Support Ring
Margins of Safety

Table 3.5-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135785</td>
<td>Lower Support Ring</td>
<td>AL ALY 7050-T7451</td>
<td>Launch</td>
<td>Yield</td>
<td>0.035 (u)</td>
<td>3.4-26 (From Upper Support Ring Analysis)</td>
</tr>
</tbody>
</table>
Factors of Safety

The hardware is designed with a yield factor of 1.1 and an ultimate factor of 1.4 against limit loads for Launch and Landing.

Description of Structure

Figure 3.5-1 below shows the location of Lower Support Ring in AMS-02. The Ring is machined from 7050-T7451 Aluminum Alloy Rolled Forging. It is attached to the Outer Cylinder with 200 bolts, and to the Conical Flange with 192 bolts. Eight Strap Ports are machined on the Ring to accommodate the magnet suspension straps. The Lower Support Ring has four Interface Plates for attachment of the USS-02.

* Note that the above figure does not show USS-02 for clarity.

Figure 3.5-1: Location of Lower Support Ring in AMS-02
Description of Model

High Detail USS Flight Model

The high detail USS flight model is used for the stress analysis of the Lower Support Ring. This model is used to recover On-Orbit Loads as well as the base for all detailed Flight USS models. It includes the 5-07 loads model with high fidelity models integrated into it. These models include the Sill, Elbow, Lower USS and VC Interface Joints as well as the Keel Block. These models are used in previous flight stress analysis as separate models and were created for each joint. Since computer resources have improved, we now have the ability to run larger models. These models are combined into one model. This was done to save on the number of models required which reduces the total number of runs required saving both man hours and cpu time as well as reducing the possibilities of errors. This model is shown in Figure 3.5-2. The FEA model is called uss-8-07-high.MOD and is stored in the directory \Escfil02\caduser\projects\edsug\ams\public\sangster\8-07\Flight FEMAP Models.

Figure 3.5-2: High Detail Full Flight USS Model
High Detail Flight Vacuum Case Model

The high detail Vacuum Case model is used for the stress analysis of the Lower Support Ring. This model is created by combining the stress models of the Lower Ring, Lower Ring, Conical Flange, Outer Cylinder, and Inner Cylinder into a single model. This model is shown in Figure 3.5-3.

![Figure 3.5-3: High Detail Flight VC](image)

Model Checks

The model checks are documented in Section 4.11.1 of the AMS-02 Fatigue and Fracture report ESCG-4450-08-STAN-Doc-0115. The model checks correspond to Configuration 13 per the AMS-02 Fatigue and Fracture report ESCG-4450-08-STAN-Doc-0115. Configuration 13 consists of the flight and landing configurations of the AMS-02.
The input files for this run are listed in Table 3.5-2. Table 3.5-3 shows the files used to check that the RBE2 elements have modeling contact and not tension as intended. Table 3.5-4 lists the different VC models used for different load cases. The different models were created depending on what portion of the RBE2 elements are used for modeling contact for that load case. Table 3.5-6 lists the model files used for each load case. Model checks for both the constrained and unconstrained models are shown in Table 3.5-7. The fixed modes run shows that when the model is constrained it is fully constrained. The Strain Energy checks shown in Table 3.5-8 show the total strain energy.

Table 3.5-2: Files used

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The VC is modeled using RBE2 elements to represent the compressive contact between the Rings and Outer Cylinder as well as the Rings and conical flange. For other configurations, this is realistic since the inertia loads do not overcome the compressive pressure load. For liftoff and landing, the inertia load overcomes the compressive load in some elements. This means that the RBE2 is experiencing a tensile load when it should only be experiencing a compressive load. To correct for this, an iterative process was used in which the RBE2 elements were removed and runs were redone until all remaining RBE2 elements only carried compressive loads. This check was made using Naspost and files are listed in Table 3.5-2. The modes and frequencies shown are for the initial run with all RBE2 elements. It was found that the frequencies did not shift much with the minimal number of RBE2 elements removed.
Table 3.5-3: Naspost RBE2 Compression Check

Table 3.5-4: VC Model Files
## Table 3.5-5: Configuration 13 Job File List

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3.5-9 ESCG-4005-05-AMS-0039
### Table 3.5-6: Configuration 13 File list

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Material and Temperature

The Lower Support Ring is 7050-T7451 Aluminum Alloy. Material properties of 7050-T7451 are taken from MIL-HDBK-5H, Table 3.7.3.0(d) for thickness of 5.001”-6.000”. Temperature limits are based upon Bolted Interface Temperatures worksheet provided by Thermal Group. For Launch condition, the temperature of 120°F is applied. For Abort Landing condition, the temperature of 150°F is applied.

Analysis

The updated model was used with data sorted for every configuration individually. The previous stress analysis that Peter Hoang performed is replaced with the stress analysis performed by Chris Sangster. The stress analysis performed for the Upper Support Ring will envelop the stress analysis for the Lower Support Ring. Stresses were much higher in the Upper Support Ring and resulted with positive margins. Therefore, margins for the Lower Support Ring will be positive. The critical stresses for the Upper Support Ring are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. Refer to Section 3.4 for details of the stress analysis.
3.6 Upper Interface Plate Assembly
Upper Interface Plate Assembly

The upper interface plate connects the Upper USS-02 Assembly to the Upper Support Ring. The upper interface plates (SDG39135788-301, -303) are machined from Aluminum 7050-T7451 plate. There are four interface plates used to bolt the Upper USS-02 Assembly to the Vacuum Case.

Material Properties: 7050-T7451 AL Alloy, AMS 4050 (Ref. Table 3.7.3.0(b), MIL-HDBK-5H)

F_{tu} := 68000\cdot\text{psi}\cdot0.92 \quad (\text{Ultimate Tensile Strength})

F_{ty} := 59000\cdot\text{psi}\cdot0.97 \quad (\text{Tensile Yield Strength})

F_{su} := 43000\cdot\text{psi}\cdot0.92 \quad (\text{Ultimate Shear Strength})

Factors of Safety

F_{Su} := 1.4 \quad (\text{Ultimate}) \quad F_{Sy} := 1.1 \quad (\text{Yield})

The expected temperature range is +40 to +150F (Ref. Appendix C2). A 92% temperature de-rating on ultimate strength and 97% temperature de-rating on yield strength is being applied to the abort landing case (Ref. Figure 3.7.3.2.1, MIL-HDBK-5H).

Part Geometry

\[ b := 10.5\text{-in} \quad (\text{Base}) \]

\[ h := 0.75\text{-in} \quad (\text{Height}) \]

\[ d_{\text{load}} := 2.0\text{-in} \quad (\text{Moment Arm Distance}) \]

\[ (\text{At section A-A}) \]

\[ I_{AA} := \frac{1}{12}b\cdot h^3 \]

\[ c_{AA} := \frac{h}{2} \]

\[ A_{AA} := b\cdot h \]
Loads were obtained from bolt analysis Section 2.4.1.1, Upper Interface Plate to USS-02, using the output file "output_forces_upperussipf_r2AbortLand.txt". The output gives an array with the element identification, load case number, applied load on the bolt, applied shear on the bolt, and applied moment on the bolt. These bolt forces will be used to calculate the force being applied on the upper interface plate. Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 66001, 66002, 66003, and 66004. These loads are read into an array and distributed out to the 8 bolts for each interface plate. This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis as well. For the purpose of this analysis, only the loads from bolt numbers 1, 2, and 3 were considered. Refer to figure below for bolt location.

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Format of Output File

The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 66001, 66002, 66003, and 66004, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66001 will have bolt numbers 1 thru 3 attached to the end for all 64 load cases. This brings the total number of load cases to 768 (4 joints x 3 bolts x 64 load cases = 768). Refer to example of output file data.

Example of Output File Data

3.6-3
The applied load, $F$, was determined using the applied load values given in output file "output_forces_upperussipf_r2_abortland.txt". Only the applied loads from bolt number 1, 2, and 3 were used for all 64 abort load cases. The maximum load being applied on bolts 1, 2, or 3 is 3728.8 lbf. A conservative approach will be taken, and the maximum load will be multiplied by a factor of 3 since there are 3 bolts along the analyzed cross section. Therefore, an applied load of 11186.4 lbf will be used for this analysis.

**Stress at Section A-A**

\[
F := 11186.4 \text{-lbf} \quad \text{(Applied Load)}
\]

\[
M := F \cdot d_{load} \quad M = 22372.8 \text{ in-lbf} \quad \text{(Bending Moment)}
\]

\[
\beta := \frac{M \cdot c_{AA}}{I_{AA}} \quad \beta = 22727.92 \text{ psi} \quad \text{(Bending Stress)}
\]

\[
u := \frac{F}{A_{AA}} \quad u = 1420.5 \text{ psi} \quad \text{(Shear Stress)}
\]

\[
u_{max} := \sqrt{\left(\frac{\beta}{2}\right)^{2} + u^{2}} \quad u_{max} = 11452.4 \text{ psi} \quad \text{(Maximum Shear Stress)}
\]

**Principal Stresses:**

\[
\beta p_1 := \frac{\beta}{2} + \left[\left(\frac{\beta}{2}\right)^{2} + u^{2}\right]^{\frac{1}{2}} \quad \beta p_1 = 22816.36 \text{ psi}
\]

\[
\beta p_2 := \frac{\beta}{2} - \left[\left(\frac{\beta}{2}\right)^{2} + u^{2}\right]^{\frac{1}{2}} \quad \beta p_2 = -88.44 \text{ psi}
\]

\[
\beta_{max} := \begin{cases} 
\beta p_1 & \text{if } |\beta p_1| \geq |\beta p_2| \\
\beta p_2 & \text{otherwise}
\end{cases} \quad \beta_{max} = 22816.36 \text{ psi} \quad \text{(Maximum Principal Stress)}
\]

\[
\beta_{vm} := \sqrt{(\beta p_1)^{2} + (\beta p_2)^{2} - \beta p_1 \beta p_2} \quad \beta_{vm} = 22860.71 \text{ psi} \quad \text{(Von Mises Stress)}
\]
Title: Upper Interface Plate Assembly

Factors of Safety

\[
MS_u := \frac{F_{tu}}{\beta_{max} \cdot F_{S_u}} - 1 \quad MS_u = 0.96 \quad \text{(Ultimate Margin of Safety)}
\]

\[
MS_y := \frac{F_{ty}}{\beta_{vm} \cdot F_{S_y}} - 1 \quad MS_y = 1.28 \quad \text{(Yield Margin of Safety)}
\]

\[
MS_s := \frac{F_{su}}{u_{max} \cdot F_{S_u}} - 1 \quad MS_s = 1.47 \quad \text{(Shear Margin of Safety)}
\]
3.7 Lower Interface Plate Assembly
Lower Interface Plate Assembly

The lower interface plate connects the Upper USS-02 Assembly to the Lower Support Ring. The lower interface plates (SDG39135789-301) are machined from Aluminum 7050-T7451 plate. There are four interface plates used to bolt the Upper USS-02 Assembly to the Vacuum Case.

Material Properties: 7050-T7451 AL Alloy, AMS 4050 (Ref. Table 3.7.3.0(b1), MIL-HDBK-5H)

- $F_{tu} = 68000$-psi-0.92 (Ultimate Tensile Strength)
- $F_{ty} = 59000$-psi-0.97 (Tensile Yield Strength)
- $F_{su} = 43000$-psi-0.92 (Ultimate Shear Strength)

Factors of Safety

FS$_u$ := 1.4  *(Ultimate)  FS$_y$ := 1.1  *(Yield)*

The expected temperature range is +40 to +150F (Ref. Appendix C2). A 92% temperature de-rating on ultimate strength and 97% temperature de-rating on yield strength is being applied to the abort landing case (Ref. Figure 3.7.3.2.1, MIL-HDBK-5H).

Part Geometry

- $b := 11.0$-in  *(Base)*
- $h := .75$-in  *(Height)*
- $d_{load} := 2.0$-in  *(Moment Arm Distance)*

*(At section A-A)*

\[ I_{AA} := \frac{1}{12}bh^3 \]

\[ c_{AA} := \frac{h}{2} \]

\[ A_{AA} := bh \]
Lower Vacuum Case Interface Plate to USS-02 Bolt Pattern

Loads were obtained from bolt analysis Section 2.4.1.2, Lower Interface Plate to USS-02, using the output file "output_forces_lowerussip_r2_abortland.txt". The output gives an array with the element identification, load case number, applied load on the bolt, applied shear on the bolt, and applied moment on the bolt. These bolt forces will be used to calculate the force being applied on the lower interface plate. Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 66011, 66012, 66013, and 66014. These loads are read into an array and distributed out to the 10 bolts for each interface plate. This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis as well. For the purpose of this analysis, only the loads from bolt numbers 1, 2, and 3 were considered. Refer to figure below for bolt location.

```
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<th>LC</th>
<th>P</th>
<th>V</th>
<th>M</th>
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<td>-205.79</td>
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<tr>
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<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>66011003</td>
<td>2064</td>
<td>1486.59</td>
<td>-2039.77</td>
<td>0</td>
</tr>
</tbody>
</table>
```

**Format of Output File**

The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 66011, 66012, 66013, and 66014, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 66011 will have bolt numbers 1 thru 3 attached to the end for all 64 load cases. This brings the total number of load cases to 768 (4 joints x 3 bolts x 64 load cases = 768). Refer to example of output file data.
The applied load, F, was determined using the applied load values given in output file "output_forces_lowerussipf_r2_abortland.txt". Only the applied loads from bolt number 1, 2, and 3 were used for all 64 abort load cases. The maximum load being applied on bolts 1, 2, or 3 is 2279.49 lbf. A conservative approach will be taken, and the maximum load will be multiplied by a factor of 3 since there are 3 bolts along the analyzed cross section. Therefore, an applied load of 6838.47 lbf will be used for this analysis.

**Stress at Section A-A**

\[
F := 6838.47 \text{ lbf} \quad \text{(Applied Load)}
\]

\[
M := F \cdot d_{load} \quad M = 13676.94 \text{ in-lbf} \quad \text{(Bending Moment)}
\]

\[
\beta := \frac{M \cdot c_{AA}}{I_{AA}} \quad \beta = 13262.49 \text{ psi} \quad \text{(Bending Stress)}
\]

\[
u := \frac{F}{A_{AA}} \quad u = 828.91 \text{ psi} \quad \text{(Shear Stress)}
\]

\[
u_{\text{max}} := \sqrt{\left(\frac{\beta}{2}\right)^2 + u^2} \quad u_{\text{max}} = 6682.85 \text{ psi} \quad \text{(Maximum Shear Stress)}
\]

**Principal Stresses:**

\[
\beta_{p1} := \frac{\beta}{2} + \left[\left(\frac{\beta}{2}\right)^2 + u^2\right]^{1/2} \quad \beta_{p1} = 13314.09 \text{ psi}
\]

\[
\beta_{p2} := \frac{\beta}{2} - \left[\left(\frac{\beta}{2}\right)^2 + u^2\right]^{1/2} \quad \beta_{p2} = -51.61 \text{ psi}
\]

\[
\beta_{\text{max}} := \begin{cases} \beta_{p1} & \text{if } |\beta_{p1}| \geq |\beta_{p2}| \\ \beta_{p2} & \text{otherwise} \end{cases} \quad \beta_{\text{max}} = 13314.09 \text{ psi} \quad \text{(Maximum Principal Stress)}
\]

\[
\beta_{\text{vm}} := \sqrt{(\beta_{p1})^2 + (\beta_{p2})^2 - \beta_{p1} \beta_{p2}} \quad \beta_{\text{vm}} = 13339.97 \text{ psi} \quad \text{(Von Mises Stress)}
\]
Factors of Safety

\[ MS_u := \frac{F_{tu}}{\beta_{\text{max}} F_{S_u}} - 1 \quad MS_u = 2.36 \quad \text{(Ultimate Margin of Safety)} \]

\[ MS_y := \frac{F_{ty}}{\beta_{\text{vm}} F_{S_y}} - 1 \quad MS_y = 2.9 \quad \text{(Yield Margin of Safety)} \]

\[ MS_s := \frac{F_{su}}{u_{\text{max}} F_{S_u}} - 1 \quad MS_s = 3.23 \quad \text{(Shear Margin of Safety)} \]
3.8 Clevis Plate
Clevis Plate, Vacuum Case

Drawings no.: SDG 39135790
Units used: in, lbf

The objective of this analysis is to demonstrate the structural strength of the Clevis Plate. The Clevis Plate (SDG 39135790) is mounted on the Upper Support Ring (SEG 39135786).

Factors of Safety and Design Factors:

FSy := 1.1 Yield factor of safety
FSu := 1.4 Ultimate factor of safety

The Expected temperature range is 40 to +120F (Ref. Appendix C2). 98% temperature de-rating is applied for launch.

Figure 3.8-1 Location of Clevis Plate
Lug Analysis

Angle of applied force: \( \beta = 69.692 \, \text{deg} \) (Ref. CAD Model)

Figure 3.8-2 Angle of applied force
Angle of applied force: \( \beta = 69.692 \, \text{deg} \)

Applied force: \( f = 34052.77 \, \text{lb} \)

**This load is the AMS 2-04 model_launch 1032**

The applied load \( f \) is acted on the pin that is supported by two lugs. Therefore, the applied load on each lug is half of the total applied load \( (f/2) \).

Axial load is: \( P_{y,\text{lug}} := \frac{f}{2} \cos(\beta) \quad P_{y,\text{lug}} = 5909 \, \text{lb} \)

Transverse load is: \( P_{z,\text{lug}} := \frac{f}{2} \sin(\beta) \quad P_{z,\text{lug}} = 15968 \, \text{lb} \)

---

**SECTION A-A**

Figure 3.8-4 Clevis Plate
Distance from centerline to outside of lug:
\[ e := (3.245 - 1.745) \text{ in} \]
\[ e = 1.5 \text{ in} \]

Diameter of hole
\[ D := 1.005 \text{ in} \]

Thickness of lug:
\[ t := .5 \text{ in} \]

Twice \( e \) is:
\[ W := 2 \cdot e \]
\[ W = 3 \text{ in} \]

**Lug Material: A286**

Tensile allowable, ultimate and yield
\[ F_{tu} := 130000 \text{ psi} \times 0.98 \quad F_{ty} := 85000 \text{ psi} \times 0.98 \]
\[ F_{tu} = 127400 \text{ psi} \quad F_{ty} = 83300 \text{ psi} \]

Shear allowable
\[ F_{su} := 85000 \text{ psi} \times 0.98 \]
\[ F_{su} = 83300 \text{ psi} \]

(Ref. MIL-HDBK-5HJ, table 6.2.1.0 (b))

The Expected temperature range is 40 to +120F (Ref. Appendix C2). 98% temperature de-rating is applied for launch.

Part number: SDG 39135790
Material: A286

Factors of Safety

\[ SF_u = 1.4 \quad SF_y = 1.1 \]

Geometry (See Figure)

\[ D = 1.005 \quad e = 1.5 \quad \beta_1 = 0 \text{ deg} \]
\[ t = 0.5 \quad W = 3 \quad \beta_2 = 0 \text{ deg} \]

Loading (See Figure)

\[ P = \frac{34052.77}{2} \quad u = 69.692 \text{ deg} \]

\[ P_{ax} = P \cdot \cos(u) \quad P_{at} = P \cdot \sin(u) \]
\[ P_{ax} = 5909.29 \quad P_{at} = 15968.033 \]

Material properties

\[ F_{uu} = 127400 \quad \text{Ultimate tension allowable stress} \]
\[ F_{uy} = 83300 \quad \text{Yield tension allowable stress} \]

Select material code number

(1 <= k <= 20, from table at right)

\[ k = 1 \]

Material

1) 4130, 4140, 4340 and 8630 steels, heat treated to 125,000 psi
2) 4130, 4140, 4340 and 8630 steels, heat treated to 150,000 psi
3) 4130, 4140, 4340 and 8630 steels, heat treated to 180,000 psi
4) 17-7PH (TH 1050), 17-4PH, PH15-7Mo
5) 2014-T6 and 7075-T6 plate <= 0.5 in (L,T)
6) 2014-T6 and 7075-T6 plate > 0.5 in, <= 1.0 in in (L,T)
   7) 2014-T6 and 7075-T6 die forging (T)
   8) 2014-T6 and 7075-T6 die forging (L)
   9) 2014-T6 hand forged billet <= 36 sq in in (T) (length < 3*width)
   10) 2014-T6 bar and extrusion (T)
   11) 2014-T6 hand forged billet <= 36 sq in in (L) (length > 3*width)
   12) 2014-T6 hand forged billet <= 36 sq in in (T) (length > 3*width)
   13) 2024-T3 and 2024-T4 plate <= 0.5 in in (L,T)
   14) 2024-T3 and 2024-T4 plate > 0.5 in, 2024-T4 (L,T)
   15) 2024-T4 and 2024-T42 extrusion (L,T), 2024-T6 plate (L,T)
   16) 2024-T6 bar (T)
   17) 7075-T6 hand forged billet <= 16 sq in in (L)
   18) 7075-T6 hand forged billet <= 16 sq in in (T)
   19) 195-T6 and 356-T6 aluminum alloy casting
   20) 220-T4 aluminum alloy casting
   21) 2014-T6 and 7075-T6 plate > 1.0 in in (L,T)
   22) 7075-T6 hand forged billet > 16 sq in in (T)
   23) 2014-T6 hand forged billet > 36 sq in in (T)
   24) 7075-T6 hand forged billet > 36 sq in in (L)
Lug coefficients are picked from charts as shown below. Data is included in the collapsed region.
Lug allowable, transverse direction

\[ \frac{A_{uv}}{A_{br}} = 1.086 \]

| \( k_{tu} = 1.384 \) | \( k_{ty} = 1.126 \) |

**Ultimate**

\[ P_{tu} := K_{tu} F_{tu} D \cdot t \]

\[ P_{tu} = 88592.817 \]

**Yield**

\[ P_{ty} := K_{ty} F_{ty} D \cdot t \]

\[ P_{ty} = 47147.251 \]

Axial direction, tenion

\[ \frac{W}{D} = 2.985 \]

| \( k_{tu} = 0.926 \) | \( k_{ty} = 0.926 \) |

**Ultimate**

\[ P_{ax} := K_{tu} F_{tu} (W - D) \cdot t \]

\[ P_{tu} = 117626.257 \]

**Yield**

\[ P_{ty} := K_{ty} F_{ty} (W - D) \cdot t \]

\[ P_{ty} = 76909.476 \]

Axial direction, shear-bearing

\[ \frac{e}{D} = 1.493 \]

| \( k_{bru} = 1.412 \) | \( k_{bry} := 1.5 \) |

**Ultimate**

\[ P_{bru} := K_{bru} F_{bru} D \cdot t \]

\[ P_{bru} = 90380.745 \]

**Yield**

\[ P_{bry} := K_{bry} F_{bry} D \cdot t \]

\[ P_{bry} = 62787.375 \]

Using the minimum axial capability

\[ \frac{D}{t} = 2.01 \]

| \( k_{axu} = 0.092 \) |

**Ultimate**

\[ P_{ax,ult} := \text{if} \left( P_{tu} < P_{bru}, P_{tu}, P_{bru} \right) \]

\[ P_{ax,ult} = 90380.745 \]

**Yield**

\[ P_{ax,yld} := \text{if} \left( P_{ty} < P_{bry}, P_{ty}, P_{bry} \right) \]

\[ P_{ax,yld} = 62787.375 \]

\[ R_{axu} := \frac{SF_{y} P_{ax}}{P_{ax,ult}} \]

\[ R_{axu} = 0.092 \]

\[ R_{axy} := \frac{SF_{y} P_{ax}}{P_{ax,yld}} \]

\[ R_{axy} = 0.104 \]

Then the margin of safety is computed as

\[ MS_{ult} := \frac{1}{\left( R_{axu}^{1.6} + R_{tru}^{1.6} \right)^{0.625}} - 1 \]

\[ MS_{ult} = 2.54 \]

\[ MS_{yld} := \frac{1}{\left( R_{axy}^{1.6} + R_{try}^{1.6} \right)^{0.625}} - 1 \]

\[ MS_{yld} = 1.49 \]
3.9 Feedthru Port Cover Plate
Section 3.9  Vacuum Case Feed-thru-port Cover Plate

Table 3.9.1-1  Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135791</td>
<td>VC Feed-thru-port Cover Plate</td>
<td>6061-T651 Al. Aly.</td>
<td>Inertia Loads (Liftoff/landing) plus pressure</td>
<td>Tension</td>
<td>25.9</td>
<td>3.9-39</td>
<td></td>
</tr>
<tr>
<td>NAS1351N3H16</td>
<td>VC Feed-thru-port Cover Plate Bolts</td>
<td>A286 0190-32 UNJF-3A</td>
<td>Inertia Loads (Liftoff/landing) plus pressure</td>
<td>Total Tension Yield</td>
<td>0.131</td>
<td>3.9-14</td>
<td></td>
</tr>
</tbody>
</table>

Notes:  Factor of Safety is 2.0 for Ultimate and 1.25 for Yield

3.9.1  Introduction

This section contains the structural verification of the feed-thru port cover plate for the AMS-02 vacuum case assembly (SDG39135791). The cover plates provide a closure and vacuum seal for the unused ports during flight operations and for ground operations during which the vacuum case has been evacuated. The ports are located on both the upper and lower support rings of the vacuum case.

The purpose of this document is to present the structural analysis and verification performed for the feed-thru port cover plate. This document describes in detail the approach taken to verify the structure and the requirements (load factors, factors of safety, material allowables, etc) taken into account when performing the analysis. The analyses will fulfill the requirements found in the AMS-02 Structural Verification Plan for the Space Transportation system and International Space Station (JSC-28792, Rev. E) and associated requirements documents.

3.9.2  Vacuum Case Feed-thru Port Fastener Analysis

The fasteners that attach components to the vacuum case feed-thru ports have loads induced by two sources: (1) differential pressure at the port and (2) inertia forces acting on the component.

The maximum differential pressure is 14.7 psi and occurs when the vacuum case has an internal vacuum and standard atmospheric pressure externally. The induced force is assumed to act normal to the plane of the feed-thru port. The diameter of the cover plate is 6.125 inches and the resultant force due to the differential pressure is 433 pounds acting normal to the plate.

The AMS-02 Structural Verification Plan provides load factors for small secondary structures. For the components that attach to a feed-thru port, the maximum weight is 34 pounds and the corresponding load factor is 31 g’s. The SVP specifies that the induced load will act simultaneously in three axes with 100% of the maximum in one axis and 25% of the maximum in the two orthogonal axes. This corresponds to a maximum load of 1054 pounds in the primary axis and 263.5 pounds in both of the other axes.
The pressure loads in the normal direction were added to the various axis combinations of inertia loads produce a set of 24 load cases as shown in Table 3.9.2-1 and Table 3.9.2-2. These load cases bound the conditions for all components that attach to the feed-thru port, including the case when only a port cover is used.

The fasteners were assessed in accordance with the requirements of NSTS-08307. The computations were performed using MathCAD. The worksheets are included in Appendix A.

For the case with eight fasteners, all margins are positive and the minimum margin is 0.131 for total tension yield. For the fail-safe case, the bolt with the largest load (bolt 7) was removed from the pattern. Again, all margins are positive and the minimum margin is 0.504 for "combined shear, tension, and bending ultimate".

### 3.9.3 Vacuum Case Feed-thru Port Cover Analysis

The cover for the vacuum case feed-thru ports must sustain loads induced by differential pressure across the port and inertia forces acting directly on the port cover.

The circular port cover has an outer diameter of 6.125 inches and a thickness of 0.5 inches. It is manufactured from 6061 aluminum plate with a T651 temper. The weight of the cover is approximately 1.44 pounds.

The maximum differential pressure of 14.7 psi is induced when there is a vacuum inside the vacuum case and standard atmospheric pressure outside.

The AMS-02 Structural Verification Plan provides load factors for small secondary structures. For the port cover, the appropriate load factor is 40 g’s and produces a resultant force of 57.8 pounds normal to the face of the port cover. To allow the inertia force to be conveniently combined with the pressure force for computational purposes, the inertia force is represented as a distributed force across the total area of the cover. The resulting distributed load is 1.96 psi.

The stress in a circular plate can be computed using a formula specified in Roark’s Formulas for Stress and Strain, Seventh Edition. The pressure force and the inertia force are combined to produce a maximum applied load of 16.66 psi across the face of the port cover. The computed maximum stress is 780 psi. The structural margins associated with this small stress are large (i.e. greater than 20). The stress computations are provided in Appendix B.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Axial (Fx)</th>
<th>Shear (Fy)</th>
<th>Shear (Fz)</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Pressure + 100% inertia</td>
<td>+25% Inertia</td>
<td>+25% Inertia</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>2</td>
<td>Pressure + 100% inertia</td>
<td>-25% Inertia</td>
<td>+25% Inertia</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>Pressure + 100% inertia</td>
<td>+25% Inertia</td>
<td>-25% Inertia</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>4</td>
<td>Pressure + 100% inertia</td>
<td>-25% Inertia</td>
<td>-25% Inertia</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>Pressure - 100% inertia</td>
<td>+25% Inertia</td>
<td>+25% Inertia</td>
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<td>0.0</td>
<td>0.0</td>
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<td>6</td>
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<td>+25% Inertia</td>
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<tr>
<td>7</td>
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<tr>
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<tr>
<td>9</td>
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<td>+25% Inertia</td>
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<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
### Table 3.9.2-2  Load Cases for Assessment of the Fasteners for Components Mounted to Vacuum Case Feed-thru Ports

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Fx (lb)</th>
<th>Fy (lb)</th>
<th>Fz (lb)</th>
<th>Mx (in-lb)</th>
<th>My (in-lb)</th>
<th>Mz (in-lb)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1487.1</td>
<td>263.5</td>
<td>263.5</td>
<td>0.0</td>
<td>0.0</td>
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</tr>
<tr>
<td>2</td>
<td>1487.1</td>
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<td>263.5</td>
<td>0.0</td>
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<td>3</td>
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<td>263.5</td>
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<tr>
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<td>1054.0</td>
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<tr>
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<tr>
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<td>-1054.0</td>
<td>0.0</td>
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<tr>
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<td>-1054.0</td>
<td>0.0</td>
<td>0.0</td>
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</tr>
</tbody>
</table>
Vacuum Case Feed-thru-port Cover Bolts

There are a total of 8 fasteners attaching the vacuum case feed-thru-port cover to the vacuum case ring. The fasteners are NAS1351N3H16 (160 ksi).

Bolt Geometry

\[
\text{size} \quad \text{thread/in} = \begin{pmatrix}
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
\end{pmatrix}
\]

\[
\text{bolt} := \begin{pmatrix}
0.19 \\
0.19 \\
0.19 \\
0.19 \\
0.19 \\
0.19 \\
0.19 \\
0.19 \\
\end{pmatrix}
\]

\[
i := 1 \text{.. rows(bolt)}
\]

\[
N_i := \text{bolt}_{i,2} \cdot \frac{1}{\text{in}}
\]

\[
D_i := \text{bolt}_{i,1} \cdot \text{in}
\]

\[
\text{pitch of bolt}
\]

\[
\text{bolt diameter}
\]

\[
A_{t_i} := \beta \left( \frac{D_i - 0.9743}{N_i} \frac{1}{2} \right)^2
\]

Tensile Area of bolt

\[
A_{s_i} := \beta \left( \frac{D_i - 1.299038}{N_i} \frac{1}{2} \right)^2
\]

Shear Area of bolt
Bolts connecting Vacuum Case Feed-thru-Port Cover Plate to Vacuum Case Ring

Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.25</td>
<td>-1.0524</td>
<td>2.5407</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>-2.5407</td>
<td>1.0524</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>-2.5407</td>
<td>-1.0524</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>-1.0524</td>
<td>-2.5407</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
<td>1.0524</td>
<td>-2.5407</td>
</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>2.5407</td>
<td>-1.0524</td>
</tr>
<tr>
<td>7</td>
<td>0.25</td>
<td>2.5407</td>
<td>1.0524</td>
</tr>
<tr>
<td>8</td>
<td>0.25</td>
<td>1.0524</td>
<td>2.5407</td>
</tr>
</tbody>
</table>
Location of applied forces and moments

\( x_{\text{force}} := 0.0 \text{in} \quad y_{\text{force}} := 0.0 \text{in} \quad z_{\text{force}} := 0.0 \text{in} \)

\[
\begin{bmatrix}
    x_{\text{force}} \\
    y_{\text{force}} \\
    z_{\text{force}}
\end{bmatrix}
\]

Center of gravity of bolt group

\[
\begin{align*}
    x_{\text{cg}} & := \frac{\sum x_i}{\text{rows}(x)} \\
    y_{\text{cg}} & := \frac{\sum y_i}{\text{rows}(y)} \\
    z_{\text{cg}} & := \frac{\sum z_i}{\text{rows}(z)}
\end{align*}
\]

\[
\begin{align*}
    x_{\text{cg}} &= 0.25 \text{in} \\
    y_{\text{cg}} &= 0 \text{in} \\
    z_{\text{cg}} &= 0 \text{in}
\end{align*}
\]

\[
\begin{bmatrix}
    x_{\text{cg}} \\
    y_{\text{cg}} \\
    z_{\text{cg}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    0.25 \\
    0 \\
    0
\end{bmatrix} \text{in}
\]

Load Vector

\[
\begin{bmatrix}
    r_{\text{load}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    -0.25 \\
    0 \\
    0
\end{bmatrix} \text{in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\begin{align*}
    r_i & := \sqrt{(z_i - z_{\text{cg}})^2 + (y_i - y_{\text{cg}})^2} \\
    r & := \begin{bmatrix}
        2.750 \\
        2.750 \\
        2.750 \\
        2.750 \\
        2.750 \\
        2.750 \\
        2.750
    \end{bmatrix} \text{in}
\end{align*}
\]

3.9-7
Reading database file

The following file reads in all loads:

```plaintext
data := READPRN("VC-port-cover-bolt-loads-v2.txt")
num_bolts := rows(bolt)
j := 1 .. rows(data)
```

Loads from PSS loads model

- **Axial Load**
  \[ F_x_j := \text{data}_{j,3} \text{lbf} \]
  \[ M_x_j := \text{data}_{j,6} \text{in-lbf} \]

- **Shear in Y axis**
  \[ F_y_j := \text{data}_{j,4} \text{lbf} \]
  \[ M_y_j := \text{data}_{j,8} \text{in-lbf} \]

- **Shear in Z axis**
  \[ F_z_j := \text{data}_{j,5} \text{lbf} \]
  \[ M_z_j := \text{data}_{j,7} \text{in-lbf} \]

- **Element Identification**
  \[ ID_j := \text{data}_{j,1} \]
  \[ ID_j := ID_j \cdot 1000 + 1 \text{ Counter for number of bolts in pattern} \]

- **Load Case Number**
  \[ LC_j := \text{data}_{j,2} \]

- **Applied Bending Moment at Bolts**
  \[ M_j := 0 \text{in-lbf} \]

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

```plaintext
ID := stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5, ID + 6, ID + 7)

LC := stack(LC, LC, LC, LC, LC, LC, LC, LC)
```
**Moment Distribution**

\[
M_{tot}^{(j)} := \begin{pmatrix}
M_{x_j} \\
M_{y_j} \\
M_{z_j}
\end{pmatrix} + r_{load} \times \begin{pmatrix}
F_{x_j} \\
F_{y_j} \\
F_{z_j}
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x_{boltcg}} := M_{tot1,j} \\
M_{y_{boltcg}} := M_{tot2,j} \\
M_{z_{boltcg}} := M_{tot3,j}
\]

**Tension on bolts**

\[
F_{tdirect, i,j} := \begin{cases} 
0\text{-lbf} & \text{if } F_{x,j} \leq 0\text{lbf} \\
\frac{F_{x,j}}{\text{num_bolts}} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz, i,j} := 0\text{-lbf} \quad \text{if } (y_i - yc) = 0\text{-in}
\]

\[
\frac{\sum_i \left[(y_i - yc)^2 \cdot A_{t_i}\right]}{M_{z_{boltcg}, j} \cdot (y_i - yc) \cdot A_{t_i}}
\]

\[
F_{mz, i,j} := 0\text{-lbf} \quad \text{if } (z_i - zc) = 0\text{-in}
\]

\[
\frac{\sum_i \left[(z_i - zc)^2 \cdot A_{t_i}\right]}{M_{z_{boltcg}, j} \cdot (z_i - zc) \cdot A_{t_i}}
\]

\[
F_{t, i,j} := F_{tdirect, i,j} + F_{mz, i,j} + F_{my, i,j}
\]

Total Tensile load

**Shear on bolts**

Direct shear Loads

\[
F_{sd, i,j} := \sqrt{\left(\frac{F_{y,j}}{\text{num_bolts}}\right)^2 + \left(\frac{F_{z,j}}{\text{num_bolts}}\right)^2}
\]

Secondary shear on bolts

\[
F_{s, i,j} := \frac{M_{x_{boltcg}, j} \cdot r_{j} \cdot A_{s_{i,j}}}{\sum_i \left[r_{i,j}^2 \cdot A_{s_{i,j}}\right]}
\]

Total shear load

\[
F_{stot, i,j} := F_{s, i,j} + F_{sd, i,j}
\]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P := \text{stack} \left[ \left( Ft \right)^{(1)}, \left( Ft \right)^{(2)}, \left( Ft \right)^{(3)}, \left( Ft \right)^{(4)}, \left( Ft \right)^{(5)}, \left( Ft \right)^{(6)}, \left( Ft \right)^{(7)}, \left( Ft \right)^{(8)} \right]
\]

\[
V := \text{stack} \left[ \left( F_{\text{stot}} \right)^{(1)}, \left( F_{\text{stot}} \right)^{(2)}, \left( F_{\text{stot}} \right)^{(3)}, \left( F_{\text{stot}} \right)^{(4)}, \left( F_{\text{stot}} \right)^{(5)}, \left( F_{\text{stot}} \right)^{(6)}, \left( F_{\text{stot}} \right)^{(7)}, \left( F_{\text{stot}} \right)^{(8)} \right]
\]

\[
\]

The "Output" file outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

\[
\text{Output} := \text{augment} \left( \text{ID, LC, } \frac{P}{\text{lb}}, \frac{V}{\text{lb}}, \frac{M}{\text{in-lbf}} \right)
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \( \text{rows} \left( \text{Output} \right) = 192 \)

\[
\text{WRITEPRN} \left( \text{"VC\_Cover-v2.txt"} \right) := \text{Output}
\]
CHECK BOLTS (Bolts NAS1351N3H16,0.19x1L, Material-A-286, Insert MS51830CA201L, Washer NAS1149E0363R)

The array from the text file above is read:

data := READPRN("VC_Cover-v2.txt")

s := 1 .. rows(data)

Flange 1: Cover Plate Feed-thru-port
Part number: SDG39135791
Material: Al Alloy 6061-T651

Flange 2: Upper VC Support Ring
Part number: SEG39135786/87
Material: Al Alloy 7050-T7451

Loads from Abort Landing Load Cases

Applied tensile load
\[ P_s := \text{data}_s,3 \text{lbf} \]

Applied shear load
\[ V_s := \text{data}_s,4 \text{lbf} \]

Applied bending moment
\[ M_s := \text{data}_s,5 \text{in-lbf} \]

Factors of Safety

Ultimate
\[ SF_u := 2.0 \]

Yield
\[ SF_y := 1.25 \]

Joint Separation
\[ SF_{sep} := 1.2 \]

Fitting factor
\[ FF := 1.15 \]

Temperature Data

Assembly
\[ \text{Temp}_{initial} := 70\text{-deg} \]

Maximum
\[ \text{Temp}_{max} := 150\text{-deg} \]

Minimum
\[ \text{Temp}_{min} := 40\text{-deg} \]

Bolt and Insert Data

Nominal diameter of bolt
\[ D := 0.19\text{-in} \]

Number of threads/inch
\[ \text{Nt} := 32\frac{1}{\text{in}} \]

Total length of bolt
\[ L := 1.0\text{-in} \]

Length of insert
\[ \text{Lins} := 0.312\text{-in} \]

Threaded length
\[ Lt := 0.875\text{-in} \]

Min. external diameter of insert
\[ F_{min} := 0.249\text{-in} \]

Depth of recess for insert
\[ lr := 0.02\text{-in} \]

(If bolt is fully threaded, input \( Lt = L \))

This file uses the calculations shown in \escfile02\2i11_mathcad\8307_bolts\thread_data.mcd

Thread Data File
Washer Data

Thickness of washer \( t_w := 0.063 \text{ in} \)

Outer Diameter of washer \( D_w := 0.438 \text{ in} \)

Inner Diameter of washer \( D_{wi} := 0.203 \text{ in} \)

Bolt head dia. across flats \( d_w := 0.0 \text{ in} \)

(Taken only if there is no washer)

Flange data

Thickness of flange 1 \( t_f 1 := 0.5 \text{ in} \)

Thickness of flange 2 \( t_f 2 := 0.312 \text{ in} \) (insert length)

Diameter of hole \( D_{\text{hole}} := 0.212 \text{ in} \)

Note: If there is no washer, \( t_w, D_w, \) and \( D_{wi} \) should be zero.

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5H, fig. 6.2.1.1.1)

\( T_{Su_{\text{bolt}}} := 0.97 \) yield \( T_{Sy_{\text{bolt}}} := 0.97 \)

Bolt ultimate tensile allowable stress \( F_{tu_{\text{bolt}}} := 160000 \text{ psi} \) (Ref. NAS1958)

Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 F_{tu_{\text{bolt}}} \)

Bolt yield tensile allowable \( F_{ty_{\text{bolt}}} := 120000 \text{ psi} \)

Temperature correction factor for bolt modulus \( T_{E_{\text{bolt}}} := 0.97 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \cdot 10^6 \text{ psi}\right) \) (Ref. MIL-HDBK-5H, table 6.2.1.0(b))

Thermal coefficient for bolt:

\( u_{\text{bolt\_hot}} := 9.1 \cdot 10^{-6} \text{ in} \text{ deg}^{-1} \)

\( u_{\text{bolt\_cold}} := 8.65 \cdot 10^{-6} \text{ in} \text{ deg}^{-1} \)

Insert

Temperature correction factor for insert strength \( T_{S_{\text{ins}}} := 0.97 \)

Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} := 140000 \text{ psi} \)

Ultimate shear allowable stress \( F_{su_{\text{ins}}} := 0.6 F_{tu_{\text{ins}}} \)

Washer

Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} := 1.0 \)

Modulus of elasticity of washer \( E_{\text{washer}} := \left(29.1 \cdot 10^6 \text{ psi}\right) \)
Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1  
Temperature correction factor for flange 2

Temperature correction factor for flange 1  
Temperature correction factor for flange 2

Shear Strength Allowable for flanges

Modulus of elasticity for the parts in the joint  
(Ref. MIL-HDBK-5H, table 3.6.2.0(b2))

Coefficient of thermal expansion for flanges  
(Ref. MIL-HDBK-5H, fig. 3.6.2.0)

Torque/Preload data

Maximum torque (60% of yield)

Minimum torque (85% of max. torque)

Torque coefficient:

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Preload due to temperature

Pthr_pos = 157.4 lbf
Pthr_neg = -56 lbf

Bolt/joint stiffness factor
= = 0.184

Max. preload
PLDmax = 1955.7 lbf

Min. preload
PLDmin = 771.2 lbf

Joint separation load
max(Psep) = 232.454 lbf

Max. load on the bolt (ultimate)
max(Pb) = 1996.7 lbf

Max. load on the bolt (yield)
max(Pby) = 1981.4 lbf

Bolt ultimate tensile strength
PA_t = 2987.4 lbf

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation
MS_min_1,1 = 2.178
Direct Thread shear Ultimate
MS_min_6,1 = 10.000

Direct Tension Ultimate
MS_min_2,1 = 5.705
Total Thread shear Ultimate
MS_min_7,1 = 1.567

Direct Tension Yield
MS_min_3,1 = 7.046
Shear Ultimate
MS_min_8,1 = 4.23

Total Tension Ultimate
MS_min_4,1 = 0.496
Bending Ultimate
MS_min_9,1 = 10

Total Tension Yield
MS_min_5,1 = 0.131
Combined shear, tension and bending ultimate
MS_min_10,1 = 0.492

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

MSbolt = 0.131
Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

MS_min_ID = 1007
Bolt Number 7 for Minimum Margin

MS_min_LC = 2
Load Case Number 2 for Minimum Margin

MS_min_P = 193.7
Applied Tensile Load for Minimum Margin

MS_min_V = 46.6
Applied Shear Load for Minimum Margin

MS_min_M = 0
Applied Bending Moment for Minimum Margin
Vacuum Case Feed-thru-port Cover Bolts

Fail-safe Analysis

There are a total of 8 fasteners attaching the vacuum case feed-thru-port cover to the vacuum case ring. The fasteners are NAS1351N3H16 (160 ksi).

In the baseline analysis, bolt 7 had the lowest margin. For the fail-safe analysis, this bolt is assumed to fail first and has been removed from the pattern. The fail-safe analysis was performed with SFult = 1.0 and SFsep 1.0.

Bolt Geometry

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0.19 32)</td>
</tr>
<tr>
<td>2</td>
<td>(0.19 32)</td>
</tr>
<tr>
<td>3</td>
<td>(0.19 32)</td>
</tr>
<tr>
<td>4</td>
<td>(0.19 32)</td>
</tr>
<tr>
<td>5</td>
<td>(0.19 32)</td>
</tr>
<tr>
<td>6</td>
<td>(0.19 32)</td>
</tr>
<tr>
<td>8</td>
<td>(0.19 32)</td>
</tr>
</tbody>
</table>

s := 1..rows(bolt2)

\[ N_{2s} := \text{bolt2}_{s,2} \times \frac{1}{\text{pitch of bolt}} \]

\[ D_{2s} := \text{bolt2}_{s,1} \times \text{in} \quad \text{bolt diameter} \]

\[ A_{t2s} := \beta \cdot \left( \frac{D_{2s} - 0.9743 \times \frac{1}{N_{2s}}}{2} \right)^2 \quad \text{Tensile Area of bolt} \]

\[ A_{s2s} := \beta \cdot \left( \frac{D_{2s} - 1.299038 \times \frac{1}{N_{2s}}}{2} \right)^2 \quad \text{Shear Area of bolt} \]
## Title
Bolts connecting Vacuum Case Feed-thru-Port Cover Plate to Vacuum Case Ring

### Diagram

**Bolt Pattern with Bolt 7 Removed**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.25</td>
<td>-1.0524</td>
<td>2.5407</td>
</tr>
<tr>
<td>2</td>
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<td>1.0524</td>
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<td>6</td>
<td>0.25</td>
<td>2.5407</td>
<td>-1.0524</td>
</tr>
<tr>
<td>8</td>
<td>0.25</td>
<td>1.0524</td>
<td>2.5407</td>
</tr>
</tbody>
</table>
Location of applied forces and moments

\[ \text{xforce}2 := 0.0 \text{in} \quad \text{yforce}2 := 0.0 \text{in} \quad \text{zforce}2 := 0.0 \text{in} \]

\[
\text{cgload}2 := \begin{pmatrix} \text{xforce}2 \\ \text{yforce}2 \\ \text{zforce}2 \end{pmatrix} 
\]

\[ \text{cgload}2 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \]

Center of gravity of bolt group

\[
\text{xcg}2 := \frac{s}{\text{rows(x2)}} \quad \text{ycg}2 := \frac{s}{\text{rows(y2)}} \quad \text{zcg}2 := \frac{s}{\text{rows(z2)}}
\]

\[ \text{xcg}2 = 0.25 \text{ in} \quad \text{ycg}2 = -0.363 \text{ in} \quad \text{zcg}2 = -0.15 \text{ in} \]

\[
\text{cgbolt}2 := \begin{pmatrix} \text{xcg}2 \\ \text{ycg}2 \\ \text{zcg}2 \end{pmatrix} 
\]

\[ \text{cgbolt}2 = \begin{pmatrix} 0.25 \\ -0.363 \\ -0.15 \end{pmatrix} \text{ in} \]

Load Vector

\[
\text{r}_\text{load}2 := \text{cgload}2 - \text{cgbolt}2
\]

\[ \text{r}_\text{load}2 = \begin{pmatrix} -0.25 \\ 0.363 \\ 0.15 \end{pmatrix} \text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ \text{r}_s := \sqrt{(\text{z}_s - \text{zcg}2)^2 + (\text{y}_s - \text{ycg}2)^2} \]

\[ \text{r}_s = \begin{pmatrix} 2.778 \\ 2.488 \\ 2.357 \end{pmatrix} \text{ in} \]
Reading database file

The following file reads in all loads:

```plaintext
data := READPRN("VC-port-cover-bolt-loads-v2.txt")
num_bolts2 := rows(bolt2) q := 1..rows(data)
num_bolts2 = 7 rows(data) = 24
```

Loads from PSS loads model

- **Axial Load**
  \[ F_{x2} := \text{data}_{q,3} \text{in-lbf} \]

- **Shear in Y axis**
  \[ F_{y2} := \text{data}_{q,4} \text{in-lbf} \]

- **Shear in Z axis**
  \[ F_{z2} := \text{data}_{q,5} \text{in-lbf} \]

- **Element Identification**
  \[ ID_{2q} := \text{data}_{q,1} \]

- **Load Case Number**
  \[ LC_{2q} := \text{data}_{q,2} \]

- **Applied Bending Moment at Bolts**
  \[ M_{2q} := 0\text{-in-lbf} \]

- **Torsion**
  \[ M_{x2} := \text{data}_{q,6} \text{in-lbf} \]

- **Moment about Y axis**
  \[ M_{y2} := \text{data}_{q,8} \text{in-lbf} \]

- **Moment about Z axis**
  \[ M_{z2} := \text{data}_{q,7} \text{in-lbf} \]

Element ID number is located in the first column and the LC numbers in the second column.

Counter for number of bolts in pattern

\[ ID_{2q} := \text{ID}_{2q} \cdot 1000 + 1 \]

Format of Output File

The stack commands below are used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\[ ID_{2} := \text{stack}(ID_{2}, ID_{2} + 1, ID_{2} + 2, ID_{2} + 3, ID_{2} + 4, ID_{2} + 5, ID_{2} + 7) \]

\[ LC_{2} := \text{stack}(LC_{2}, LC_{2}, LC_{2}, LC_{2}, LC_{2}, LC_{2}, LC_{2}) \]
Moment Distribution

\[ M_{\text{tot}}^{(q)} := \begin{pmatrix} Mx_2^{(q)} \\ My_2^{(q)} \\ Mz_2^{(q)} \end{pmatrix} + f_{\text{load2}} \times \begin{pmatrix} Fx_2^{(q)} \\ Fy_2^{(q)} \\ Fz_2^{(q)} \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{\text{bolteg}_2}^{(q)} := M_{\text{tot1},q} \quad \text{My}_2^{(q)} := M_{\text{tot2},q} \quad M_{\text{bolteg}_2}^{(q)} := M_{\text{tot3},q} \]

Tension on bolts

\[ F_{\text{direct2}}^{(s,q)} := \begin{cases} 0 \text{-lbf} & \text{if } Fx_2^{(q)} \leq 0 \text{lbf} \\ \frac{Fx_2^{(q)}}{\text{num_bolts2}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ F_{\text{mz2}}^{(s,q)} := \begin{cases} 0 \text{-lbf} & \text{if } (y_2^{(s)} - y_{\text{cg2}}) = 0 \text{-in} \\ \frac{M_{\text{bolteg2}}^{(q)}(y_2^{(s)} - y_{\text{cg2}})}{\sum_s (y_2^{(s)} - y_{\text{cg2}})^2 \cdot At_2^{(s)}} & \text{otherwise} \end{cases} \]

\[ F_{\text{y2}}^{(s,q)} := \frac{\left( z_2^{(s)} - z_{\text{cg2}} \right)}{\sum_s (z_2^{(s)} - z_{\text{cg2}})^2 \cdot At_2^{(s)}} \]

\[ F_{\text{t2}}^{(s,q)} := F_{\text{direct2}}^{(s,q)} + F_{\text{mz2}}^{(s,q)} + F_{\text{y2}}^{(s,q)} \quad \text{Total Tensile load} \]

Shear on bolts

Direct shear Loads

\[ F_{\text{sd2}}^{(s,q)} := \sqrt{\frac{(Fy_2^{(q)})^2 + (Fz_2^{(q)})^2}{\text{num_bolts2}}} \]

Secondary shear on bolts

\[ F_{\text{s2}}^{(s,q)} := \frac{\left| M_{\text{bolteg2}}^{(q)} \cdot r_2^{(s)} \cdot As_2^{(s)} \right|}{\sum_s (r_2^{(s)})^2 \cdot (As_2^{(s)})} \quad \text{Total shear load} \]

\[ F_{\text{stot2}}^{(s,q)} := F_{\text{s2}}^{(s,q)} + F_{\text{sd2}}^{(s,q)} \]

3.9-19
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P_2 := \text{stack}\left[\begin{array}{l}
(Ft^2)^{(1)}, (Ft^2)^{(2)}, (Ft^2)^{(3)}, (Ft^2)^{(4)}, (Ft^2)^{(5)}, (Ft^2)^{(6)}, (Ft^2)^{(7)}\end{array}\right]
\]

\[
V_2 := \text{stack}\left[\begin{array}{l}
(Fstot^2)^{(1)}, (Fstot^2)^{(2)}, (Fstot^2)^{(3)}, (Fstot^2)^{(4)}, (Fstot^2)^{(5)}, (Fstot^2)^{(6)}, (Fstot^2)^{(7)}\end{array}\right]
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). The array is then written to a text file.

\[
\text{Output2} := \text{augment}\left(\begin{array}{l}
\text{ID2, LC2, }\frac{P_2}{\text{lbf}}, \frac{V_2}{\text{lbf}}, \frac{M_2}{\text{in-lbf}}\end{array}\right)
\]

(Note: Since the ID and LC numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \(\text{rows(Output2)} = 168\)

(The output size corresponds to 24 loads cases times 7 bolts which equals 168 total items.)

\[
\text{WRITEPRN("VC_Cover_FS-v2.txt"); := Output2}
\]

**Fail-Safe Analysis**

**Loads from 24 combinations of pressure and inertia load cases**

The array from the text file above is read:

\[
data_fs := \text{READPRN("VC_Cover_FS-v2.txt")}
\]

\[
s := 1..\text{rows(data_fs)}
\]

Applied tensile load \( P_{FS_s} := \text{data_fs}_{s,3}\text{lbf} \)

Applied shear load \( V_{FS_s} := \text{data_fs}_{s,4}\text{lbf} \)

Applied bending moment \( M_{FS_s} := \text{data_fs}_{s,5}\text{in-lbf} \)

Rows(data_fs) = 168
Title: Bolts connecting Vacuum Case Feed-thru-Port Cover Plate to Vacuum Case Ring

Factors of Safety

Ultimate  \( SF_{u\_FS} = 1.0 \)

Joint Separation  \( SF_{sep\_FS} = 1.0 \)  Fitting factor  \( FF := 1.15 \)

Temperature Data

Assembly  \( \text{Temp\_initial} = 70\text{-deg} \)
Maximum  \( \text{Temp\_max} = 150\text{-deg} \)
Minimum  \( \text{Temp\_min} = 40\text{-deg} \)

This file uses the calculations shown in \escrio\211\_mathcad\8307\_bolts\multi\_bolt\_stiffness\_insert\_FS\_RevA

Bolt Fail-safe Load data

Joint separation load  \( \text{max(Psep\_FS)} = 222.855 \text{lbf} \)  \( \text{max(P\_FS)} = 222.855 \text{lbf} \)
Max. load on the bolt(ultimate)  \( \text{max(Pb\_FS)} = 1979.3 \text{lbf} \)  \( \text{max(V\_FS)} = 155.205 \text{lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS_{min_FS}</th>
<th>Ultimate Type</th>
<th>MS_{min_FS}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>2.314</td>
<td>Total Thread shear</td>
<td>1.589</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>10.000</td>
<td>Shear</td>
<td>8.15</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.509</td>
<td>Bending</td>
<td>10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>10</td>
<td>Combined shear, tension and bending ultimate</td>
<td>0.509</td>
</tr>
</tbody>
</table>
Bolts connecting Vacuum Case Feed-thru-Port Cover Plate to Vacuum Case Ring

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MS}_{\text{bolt,FS}} := \min(\text{MS}_{\text{FS}})
\]

\[
\text{MS}_{\text{bolt,FS}} = 0.509 \quad \text{Failure Mode}_{\text{FS}} = "\text{Combined Shear Tension Bending Ultimate}" 
\]

\[
\text{MS}_{\text{min,ID}} = 1006 \quad \text{Bolt Number 6 for Minimum Margin}
\]

\[
\text{MS}_{\text{min,LC}} = 4 \quad \text{Load Case Number 4 for Minimum Margin}
\]

\[
\text{MS}_{\text{min,P}} = 222.9 \quad \text{Applied Tensile Load for Minimum Margin}
\]

\[
\text{MS}_{\text{min,V}} = 53.2 \quad \text{Applied Shear Load for Minimum Margin}
\]

\[
\text{MS}_{\text{min,M}} = 0 \quad \text{Applied Bending Moment for Minimum Margin}
\]
Loads on the Covers for the Vacuum Case Feed-thru Ports

During flight operation, the vacuum case port covers serve as a closure for unused ports. All of the ports are located on either the upper or lower support ring of the vacuum case.

Port Cover Characteristics

1. Circular plate with outer diameter of 6.125 inches and thickness of 0.50 inches.
2. Material: 6061 T651 Aluminum plate
Compute port cover weight:

\[ E := 9.910^6 \text{ psi } \quad \beta := 0.33 \quad \frac{u}{\text{pci}} := 0.098 \text{pci} \]

\[ d := 6.125 \text{in} \quad t := 0.5 \text{in} \]

\[ \text{weight} := \left( \frac{d}{2} \right)^2 t \cdot u \quad \text{weight} = 1.444 \text{lbf} \]

Compute force on the port cover:

\[ \text{g\_load} := 40 \]

\[ \text{Force} := \text{weight} \cdot \text{g\_load} \quad \text{Force} = 57.751 \text{lbf} \]

Represent inertia load as a distributed force:

\[ \text{Area} := \left( \frac{d}{2} \right)^2 \quad \text{Area} = 29.465 \text{in}^2 \]

\[ \text{dist\_force} := \frac{\text{Force}}{\text{Area}} \quad \text{dist\_force} = 1.96 \text{ psi} \]

Compute pressure differential across port:

\[ \text{p\_outside} := 14.7 \text{psi} \quad \text{p\_inside} := 0 \text{psi} \]

\[ \text{delta\_p} := \text{p\_outside} - \text{p\_inside} \]

\[ \text{delta\_p} = 14.7 \text{psi} \]

Compute total load acting on cover plate:

\[ \text{Total\_load} := \text{dist\_force} + \text{delta\_p} \]

\[ \text{Total\_load} = 16.66 \text{psi} \]
Stresses for the Vacuum Case Feed-thru Port Covers

The formulas for stress of a flat circular plate of constant thickness are given in Table 24 of "Roark's Formulas for Stress and Strain". Case 10a provides the formulas for a solid circular plate that is simply supported at the edge and has a uniformly distributed pressure across the face. These formulas were implemented as an electronic book for MathCAD by MathSoft Inc. and have been included on the following pages to compute the stresses in the cover plate.

The material allowable for Al 6061 T651 plate are 35 ksi for yield and 41 ksi for ultimate. (Reference: Table 3.6.2.0 from MIL-HDBK-5J)

The factors of safety are 1.4 for yield and 2.0 for ultimate.

\[ \text{MAu} := 42000 \text{psi} \quad \text{MAy} := 35000 \text{psi} \]

\[ \text{FSu} := 2.0 \quad \text{FSy} := 1.25 \]
NOTE --- this begins the section that was extracted from the MathSoft electronic book of Roark equations.

Table 24 Formulas for shear, moment and deflection of flat circular plates of constant thickness

Case 10a Solid Circular Plate Simply Supported; Uniformly Distributed Pressure from \( r_o \) to \( a \)

Solid circular plate

Uniformly distributed pressure from \( r_o \) to \( a \)
Notation file

Provides a description of Table 24 and the notation used.

Enter dimensions, properties and loading

Plate dimensions:
- thickness: $t = 0.5\text{in}$
- radius: $a = \frac{6.125}{2}\text{in}$

Applied uniform pressure: $q = 16.66\text{psi}$

Modulus of elasticity: $E = 9.9 \times 10^6\frac{\text{lbf}}{\text{in}^2}$

Poisson's ratio: $\beta = 0.33$

Radial location of applied load: $r_o = 0.0001\text{in}$

Constants

Shear modulus: $G = \frac{E}{2(1 + \beta)}$

$D$ is a plate constant used in determining boundary values; it is also used in the general equations for deflection, slope, moment and shear. $K_{sro}$ is the tangential shear constant used in determining the deflection due to shear.

$$D = \frac{E \cdot t^3}{12 \left(1 - \beta^2\right)}$$

$$D = 1.157 \times 10^5\frac{\text{lbf}}{\text{in}}$$

$$K_{sro} = \begin{cases} r_o > 0, & -0.30 \left[1 - \left(\frac{r_o}{a}\right)^2 \left(1 + 2 \ln\left(\frac{a}{r_o}\right)\right)\right] - 0.30 \quad \text{if } r_o > 0, -0.30 \left[1 - \left(\frac{r_o}{a}\right)^2 \left(1 + 2 \ln\left(\frac{a}{r_o}\right)\right)\right] - 0.30 \quad \text{if } r_o < 0 \end{cases}$$

$K_{sro} = -0.3$
Boundary values

The $G_n$ and $L_n$ functions used in the equations below are defined at the end of this document.

$M_r$ is radial moment, $Q$ is shear, $y$ is deflection and $\theta$ is slope.

Due to bending:

At the edge of the plate (a):

\[
M_{ra} := 0 \text{ lbf}\cdot\text{in} \quad M_{ra} = 0 \text{ lbf}\cdot\text{in}
\]

\[
Q_a := \frac{-q}{2a} \left(a^2 - r_o^2\right) \quad Q_a = -25.511 \frac{\text{lbf}}{\text{in}}
\]

\[
y_a := 0 \text{ in} \quad y_a = 0 \text{ in}
\]

\[
\gamma_a := \frac{q}{8D\cdot a(1 + \beta)} \left(a^2 - r_o^2\right)^2 \quad \gamma_a = 0.022 \text{ deg}
\]

At the center of the plate (c):

\[
M_c := q\cdot a^2 \cdot L_{17} \quad M_c = 32.52 \frac{\text{lbf}\cdot\text{in}}{\text{in}}
\]

\[
y_c := -\frac{q}{2D} \cdot \left(\frac{L_{17}}{1 + \beta} - 2\cdot L_{11}\right) \quad y_c = -7.929 \times 10^{-4} \text{ in}
\]

Due to tangential shear stresses:

\[
y_{sro} := \frac{K_{sro} \cdot q \cdot a^2}{t \cdot G} \quad y_{sro} = -2.519 \times 10^{-5} \text{ in}
\]
General formulas and graphs for deflection, slope, moment, shear and stress as a function of $r$

Define $r$, the range of the radius:

$$ r = \frac{a}{100} \cdot \frac{a}{50} $$

**Deflection**

$$ y(r) := y_c + \frac{M_c \cdot r^2}{2 \cdot D \cdot (1 + \beta)} + LT_y(r) $$

Deflections at the center and outer radius:

$$ y(0\text{-in}) = -7.929 \times 10^{-4} \text{ in} \quad y(a) = 0 \text{ in} $$

Maximum deflection (magnitude):

$$ Y \frac{r}{a} := y(r) \quad A := \max(Y) \quad B := \min(Y) $$

$$ y_{\max} := (A > -B) \cdot A + (A \leq -B) \cdot B \quad y_{\max} = -7.928 \times 10^{-4} \text{ in} $$
Large deflection condition check

Check to verify that the absolute value of the maximum deflection is less than one-half the plate thickness (an assumption stated in the Notation file which must hold true). If |y_{\text{max}}| is greater than t/2 (large deflection), the equations in this table used for plates with small deflections are subject to large errors.

\[
\text{check} := \begin{cases} 1 & \text{if } |y_{\text{max}}| > \frac{t}{2}, 0, 1 \\ 0 & \text{otherwise} \end{cases}
\]

If |y_{\text{max}}| is greater than t/2 (i.e., check = 0), only max y and \(\sigma\) can be found. They are found using the equations on this page and the next.

If |y_{\text{max}}| is not greater than t/2 (i.e., check = 1), hit \text{Shift-PageDown} twice to continue with the Table 24 solution of plates without large deflections.

The large deflection equations are

\[
\frac{q \cdot a^4}{E \cdot t^4} = K_1 \cdot \frac{y_{\text{large}}}{t} + K_2 \left( \frac{y_{\text{large}}}{t} \right)^3
\]

\[
\frac{y \cdot a^2}{E \cdot t^2} = K_3 \cdot \frac{y_{\text{large}}}{t} + K_4 \left( \frac{y_{\text{large}}}{t} \right)^2
\]

where

\[
K_1 := \frac{1.016}{1 - \beta} \quad K_2 := 0.376
\]

\[
K_3 := \frac{1.238}{1 - \beta} \quad K_4 := 0.294
\]
Make guesses for max $y$ and $\sigma$ and solve for them using the \textbf{Find} function:

\[ y_{\text{large}} := 0.25\text{ in} \quad y := 10\text{ psi} \]

Solution for $y$:

Given

\[
\frac{q\cdot a^4}{E\cdot t^4} = K_1 \cdot \frac{y_{\text{large}}}{t} + K_2 \left( \frac{y_{\text{large}}}{t} \right)^3
\]

\[ y_{\text{large}} := \text{Find}(y_{\text{large}}) \quad y_{\text{large}} = 7.809 \times 10^{-4}\text{ in} \]

Solution for $\sigma$:

Given

\[
\frac{y\cdot a^2}{E\cdot t^2} = K_3 \cdot \frac{y_{\text{large}}}{t} + K_4 \left( \frac{y_{\text{large}}}{t} \right)^2
\]

\[ y := \text{Find}(y) \quad y = 761.766\text{ psi} \]

If your deflection was a large deflection, stop here. The remainder of the document only calculates values for plates without large deflections.
Slope

\[ \gamma(r) := \frac{M_c \cdot r}{D(1 + \beta)} + L T \cdot (r) \]

Slope at center and outer radius:

\[ \gamma(0 \text{ in}) = 0 \text{ deg} \]

\[ \gamma(a) = 0.022 \text{ deg} \]

Maximum slope (magnitude):

\[ S = \frac{100}{a} \gamma(r) \quad A := \max(S) \quad B := \min(S) \]

\[ \gamma_{\max} := (A > -B) \cdot A + (A \leq -B) \cdot B \quad \gamma_{\max} = 0.023 \text{ deg} \]
Moment; radial and tangential

\[ M_r(r) := M_c + LT M(r) \]
\[ M_r(r) := \frac{\gamma(r) \cdot D \left(1 - \beta^2\right)}{r} + \beta M_r(r) \]

Radial and tangential moment at center and outer radius:

\[ M_r(0\text{-in}) = 32.52 \text{ lbf} \cdot \text{in} \]
\[ M_r(a\text{-in}) = 0 \text{ lbf} \cdot \text{in} \]
\[ M_r(0.01\text{-in}) = 32.52 \text{ lbf} \cdot \text{in} \]
\[ M_r(a\text{-in}) = 13.086 \text{ lbf} \cdot \text{in} \]

Maximum radial and tangential moment (magnitude):

\[ M_{r_{\text{max}}} := (Ar > -B) \cdot Ar + (Ar \leq -B) \cdot B \]
\[ M_{r_{\text{max}}} = 32.517 \text{ lbf} \cdot \text{in} \]

\[ M_{t_{\text{max}}} := (At > -Bt) \cdot At + (At \leq -Bt) \cdot Bt \]
\[ M_{t_{\text{max}}} = 32.518 \text{ lbf} \cdot \text{in} \]
Shear

\[ Q(r) := LTQ(r) \]

Shear at center and outer radius:

\[ Q(0.01\text{-in}) = -0.083 \frac{\text{lbf}}{\text{in}} \quad Q(a) = -25.511 \frac{\text{lbf}}{\text{in}} \]

Maximum shear (magnitude):

\[ V_{(r)\frac{100}{a}} := Q(r) \quad A := \max(V) \quad B := \min(V) \]

\[ Q_{\text{max}} := (A > -B) \cdot A + (A \leq -B) \cdot B \quad Q_{\text{max}} = -25.511 \frac{\text{lbf}}{\text{in}} \]
Bending stresses; radial and tangential

\[ y_r(r) := \frac{6 \cdot M_t(r)}{t^2} \]

\[ y_t(r) := \frac{6 \cdot M_t(r)}{2t} \]

\[ r \quad \text{in} \]

\[ y_r(r) \quad \text{psi} \]

\[ y_t(r) \quad \text{psi} \]

\[ 0 \quad 0.0306 \quad 0.7886 \quad 1.5466 \quad 2.3045 \quad 3.0625 \]

\[ 114.286 \quad 145.714 \quad 185.714 \quad 228.571 \quad 272.857 \quad 342.857 \quad 457.143 \quad 685.714 \quad 800 \]
Radial and tangential stress at center and outer radius:

\[ \begin{align*}
  y_r(0.01\text{-in}) &= 780.473 \text{ psi} & y_t(a) &= 0 \text{ psi} \\
  y_t(0.01\text{-in}) &= 780.477 \text{ psi} & y_t(a) &= 314.068 \text{ psi}
\end{align*} \]

Maximum radial and tangential stresses:

\[ \begin{align*}
  y_r^r &:= y_r(r) & A_r := \max(y_r) & B_r := \min(y_r) \\
  y_t^r &:= y_t(r) & A_t := \max(y_t) & B_t := \min(y_t) \\
  y_r^\max &:= (A_r > -B_r) \cdot A_r + (A_r \leq -B_r) \cdot B_r & y_r^\max &= 780.404 \text{ psi} \\
  y_t^\max &:= (A_t > -B_t) \cdot A_t + (A_t \leq -B_t) \cdot B_t & y_t^\max &= 780.435 \text{ psi}
\end{align*} \]
Review the maximum values for deflection, slope, moment, stress and shear

\[ y_{\text{max}} = -7.928 \times 10^{-4} \text{ in} \]
\[ \theta_{\text{max}} = 0.023 \text{ deg} \]
\[ M_r_{\text{max}} = 32.517 \frac{\text{lbf} \cdot \text{in}}{\text{in}} \]
\[ M_t_{\text{max}} = 32.518 \frac{\text{lbf} \cdot \text{in}}{\text{in}} \]
\[ y_{\text{rmax}} = 780.404 \text{ psi} \]
\[ y_{\text{tmax}} = 780.435 \text{ psi} \]
\[ Q_{\text{max}} = -25.511 \frac{\text{lbf}}{\text{in}} \]

Total deflection of plate (bending induced plus shear induced):

\[ y_{\text{ro.total}} := y(0 \cdot \text{in}) + y_{\text{sro}} \]
\[ y_{\text{ro.total}} = -8.181 \times 10^{-4} \text{ in} \]
The remainder of the document displays the general plate functions and constants used in the equations above.

\[
L_{11} = \frac{1}{64} \left[ \frac{1}{64} \left( \frac{r_0}{a} \right)^2 - 5 \left( \frac{r_0}{a} \right)^4 \right] \ln \left( \frac{a}{r_0} \right)
\]

\[
L_{17} = \frac{1}{4} \left[ 1 - \left( \frac{1 - \beta}{4} \right) \right] \left[ 1 - \left( \frac{r_0}{r} \right)^2 \right] + 4 \left( \frac{r_0}{r} \right)^2 \ln \left( \frac{r_0}{r} \right)
\]

\[
G_{11}(r) = \frac{1}{64} \left[ 1 + 4 \left( \frac{r_0}{r} \right)^2 - 5 \left( \frac{r_0}{r} \right)^4 \right] \ln \left( \frac{r_0}{r} \right)
\]

\[
G_{14}(r) = \frac{1}{16} \left[ 1 - \left( \frac{r_0}{r} \right)^4 \right] - 4 \left( \frac{r_0}{r} \right)^2 \ln \left( \frac{r_0}{r} \right)
\]

\[
G_{17}(r) = \frac{1}{4} \left[ 1 - \left( \frac{1 - \beta}{4} \right) \right] \left[ 1 - \left( \frac{r_0}{r} \right)^4 \right] - \left( \frac{r_0}{r} \right)^2 \ln \left( \frac{r_0}{r} \right)
\]

\[
LT_y(r) = -\frac{q \cdot r}{D} \cdot G_{11}(r)
\]

\[
LT_M(r) = -q \cdot r^2 \cdot G_{17}(r)
\]

\[
LT_z(r) = -\frac{q \cdot r}{D} \cdot G_{14}(r)
\]

\[
LT_Q(r) = \begin{cases} 
q \cdot r^2 - \frac{q}{2} \left( r^2 - r_0^2 \right) & r > r_0 \\
0 & \text{otherwise}
\end{cases}
\]

NOTE --- this ends the section that was extracted from the MathSoft electronic book of Roark equations.
Margins of Safety for the Vacuum Case Feed-thru Port Covers

The maximum stress is the largest of the radial and tangential stresses:

\[ y_{\text{max}} := \max \left( r_{\text{max}} \cdot y_{r\text{max}}, t_{\text{max}} \right) \]

The margins of safety are calculated as follows for ultimate (MSu) and yield (MSy):

\[ \text{MSu} := \left( \frac{MA_u}{FS_u \cdot y_{\text{max}}} \right) - 1 \quad \text{MSu} = 25.908 \]

\[ \text{MSy} := \left( \frac{MA_y}{FS_y \cdot y_{\text{max}}} \right) - 1 \quad \text{MSy} = 34.877 \]
3.10 Vacuum Case Bolted Interfaces
Vacuum Case Bolted Interfaces

The Vacuum Case Bolt Analysis is performed in the following report sections.

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<td>3.10.7.1</td>
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<td>3.10.7.1</td>
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<td>3.10.7.2</td>
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<tr>
<td>3.10.7.2</td>
<td>Lower Interface Plate to Vacuum Case Fail-Safe - .500&quot; (Shear Pin Failure)</td>
</tr>
</tbody>
</table>
3.10.1 Upper Support Ring to Conical Flange
## Upper Support Ring to Conical Flange Bolt Analysis

In the Vacuum Case Assembly, the Upper Conical Flange is installed on the Upper Support Ring. A total of 232 fasteners are used to attach the Upper Conical Flange to the Upper Support Ring. The fasteners are EWB0420-4H-9 (200 ksi), 0.25-28 UNJF. The drawing number illustrating the Upper Conical Flange to the Upper Support Ring is SEG39135776.

![Top View of Vacuum Case Assembly](image1.png)

![Side View of Vacuum Case Assembly](image2.png)

Load model 2-05 was used to retrieve loads at the bolted interfaces. The CBUSH elements were post processed in NASPOST for forces and moments. The CBUSH element identification numbers are 920001-920232. A total of 64 load cases are included in the NASPOST run. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.
CHECK BOLTS (EWB 0420-4H-9 bolts 0.250-28UNJF-3A, Material-A-286), Insert MS51830CA-202L, Washer NAS1587-4C

Reading database file for bolted interface, abort landing case

Note that "*.dat" is generated from NASPOST result (.LIS file) by just removing all words and comments.

data := READPRN("uppervc_abort.dat")

s := 1..rows(data)

Flange 1: Conical Flange
Part number: SEG39135801-301

Flange 2: Upper Support Ring
Part number: SEG39135786-301
Material: 7050-T7451, AMS 4108

Loads
Applied tensile load
\[ P_s := (\text{data}_{s,3}) \text{lb} \]
\[ \text{ID}_{s} := \text{data}_{s,1} \]

Applied shear load
\[ V_s := (\text{data}_{s,4}) \text{lb} \]
\[ \text{LC}_{s} := \text{data}_{s,2} \]

Applied bending moment
\[ M_s := (\text{data}_{s,5}) \text{in-lb} \]

Factors of Safety

Temperature data (Ref Appendix C2), Abort Landing Case

Ultimate
SFu := 1.4
Yield
SFy := 1.1
Assembly
Temp_initial := 70 deg

Joint Separation
SFsep := 1.2
Fitting factor
FF := 1.15
Maximum
Temp_max := 150 deg

Minimum
Temp_min := 40 deg

Bolt and Insert Data

Nominal diameter of bolt
\[ D := 0.250 \text{in} \]
Number of threads/inch
\[ Nt := 28 \frac{1}{\text{in}} \]

Total length of bolt
\[ L := 1.050 \text{in} \]
Length of insert
\[ \text{Lins} := 0.375 \text{in} \]

Threaded length
\[ Lt := 0.487 \text{in} \]
Min. external diameter of insert
\[ Fmin := 0.312 \text{in} \]
(If bolt is fully threaded, input \( Lt = L \))
Depth of recess for insert
\[ lr := 0.02 \text{in} \]

This file uses the calculations shown in \\escfl02\2i11_mathcad\8307_bolts\thread_data.mcd

3.10.1-3 ESCG-4005-05-AMS-0039
Bolts from Upper Support Ring to Conical Flange

**Washer Data**

- **Thickness of washer**  \( tw := 0.078 \text{ in} \)
- **Outer Diameter of washer**  \( Dw := 0.531 \text{ in} \)
- **Inner Diameter of washer**  \( Dwi := 0.252 \text{ in} \)
- **Bolt head dia. across flats**  \( dw := 0.433 \text{ in} \)

**Flange data**

- **Thickness of flange 1**  \( tf1 := 0.510 \text{ in} \)
- **Thickness of flange 2**  \( tf2 := 0.375 \text{ in} \)
- **Diameter of hole**  \( D_{hole} := 0.296 \text{ in} \)

*Note: If there is no washer, \( tw, Dw, \) and \( Dwi \) should be zero.*

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate  \( \text{TS}_{\text{bolt}} := .97 \)  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Bolt ultimate tensile allowable stress  \( \text{F}_{\text{tu}} := 200000 \text{ psi} \)  
  (EWB 0420)
- Bolt ultimate shear allowable stress  \( \text{F}_{\text{su}} := 0.6 \cdot \text{F}_{\text{tu}} \)
- Bolt yield tensile allowable  \( \text{F}_{\text{ty}} := 180000 \text{ psi} \)  
  (AMS 5726C)
- Temperature correction factor for bolt modulus  \( \text{TE}_{\text{bolt}} := .98 \)  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.4(a))

- **Modulus of elasticity of bolt**  \( E_{\text{bolt}} := \left( 29.1 \cdot 10^6 \text{ psi} \right) \)  
  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- **Thermal coefficient for bolt:**  
  \[ \beta_{\text{bolt\_hot}} := 9.1 \cdot 10^{-6} \text{ in}^2/\text{deg} \]  
  \[ \beta_{\text{bolt\_cold}} := 8.9 \cdot 10^{-6} \text{ in}^2/\text{deg} \]  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

**Insert**

- Temperature correction factor for insert strength  \( \text{TS}_{\text{ins}} := .97 \)  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress  \( \text{F}_{\text{tu}} := 140000 \text{ psi} \)  
  (Ref. MS51830)
- Ultimate shear allowable stress  \( \text{F}_{\text{su}} := 0.6 \cdot \text{F}_{\text{tu}} \)

**Washer**

- Temperature correction factor for washer modulus  \( \text{TE}_{\text{washer}} := .97 \)  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- **Modulus of elasticity of washer**  \( E_{\text{washer}} := \left( 29.1 \cdot 10^6 \text{ psi} \right) \)  
  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1E} := 0.98 \text{ (modulus)} \] (Ref. MIL-HDBK-5J, fig. 3.2.8.1.1(a))

Temperature correction factor for flange 2
\[ T_{f2E} := 0.97 \text{ (modulus)} \] (Ref. MIL-HDBK-5J, fig. 3.2.8.1.1(a) and Appendix C9)

\[ T_{f2s} := 0.98 \text{ (strength)} \] (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear strength allowable for flanges
\[ F_{su\_f2} := 42000 \text{-psi} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := \left( 10.5 \times 10^{-6} \right) \text{-psi} \] (Ref. MIL-HDBK-5J, table 3.2.8.0(b1))

\[ E_{\text{flange2}} := \left( 10.2 \times 10^{-6} \right) \text{-psi} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Coefficient of thermal expansion for flanges
\[ \beta_{\text{flange1\_hot}} := 12.45 \times 10^{-6} \text{ in in deg} \] (Ref. MIL-HDBK-5J, fig. 3.2.8.0)

\[ \beta_{\text{flange1\_cold}} := 11.8 \times 10^{-6} \text{ in in deg} \]

\[ \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \text{ in in deg} \] (Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)

\[ \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ in in deg} \]

Torque/Preload data

Maximum torque (65% of yield)
\[ T_{\text{max}} := 160 \text{-in-lbf} \]

Minimum torque (95% of max. torque)
\[ T_{\text{min}} := 152 \text{-in-lbf} \]

Torque coefficient:
\[ k := 0.15 \]

Loading plane factor:
\[ n := 0.5 \]

Preload Uncertainty:
\[ u := 0.25 \]
Bolt Load data

Bolt/joint stiffness factor \( = 0.272 \)  
Preload due to temperature \( P_{thr\_pos} = 291.4 \text{ lbf} \)

Max. preload \( PLD_{\text{max}} = 5624.8 \text{ lbf} \)  
Uncertainty factor \( u = 0.25 \)

Min. preload \( PLD_{\text{min}} = 2678.8 \text{ lbf} \)  
Torque coefficient \( k = 0.15 \)

Joint separation load \( \max(P_{\text{sep}}) = 591.6 \text{ lbf} \)  
Loading plane factor \( P_{\text{ths}} = 12830.3 \text{ lbf} \)

Max. load on the bolt(ultimate) \( \max(P_B) = 5732.8 \text{ lbf} \)  
Thread shear pullout load of bolt or insert \( P_{\text{pths}} = 7564.5 \text{ lbf} \)

Max. load on the bolt(yield) \( \max(P_{by}) = 5709.7 \text{ lbf} \)  
Thread shear pullout load in parent metal

Bolt ultimate tensile strength \( P_{At} = 6844.9 \text{ lbf} \)  
Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation MS\(_{\text{min},1}\) = 3.558 Direct Thread shear Ultimate MS\(_{\text{min},6}\) = 8.530

Direct Tension Ultimate MS\(_{\text{min},2}\) = 7.624 Total Thread shear Ultimate MS\(_{\text{min},7}\) = 0.320

Direct Tension Yield MS\(_{\text{min},3}\) = 8.878 Shear Ultimate MS\(_{\text{min},8}\) = 2.56

Total Tension Ultimate MS\(_{\text{min},4}\) = 0.194 Bending Ultimate MS\(_{\text{min},9}\) = 10

Total Tension Yield MS\(_{\text{min},5}\) = 0.079 Combined shear, tension and bending ultimate MS\(_{\text{min},10}\) = 0.177

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt}} := \min(\text{MS}) \]

\[ MS_{\text{bolt}} = 0.079 \]

Failure_Mode = "Total Tension Yield"

Element Identification and Bolt Number (920027) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin

3.10.1-6 ESCG-4005-05-AMS-0039
Bolt Fail-Safe Analysis for Upper Support Ring to Conical Flange Bolts

It will be assumed that one bolt will fail. Bolt number 920027 has been removed and only load case 2003 is included in the following fail-safe analysis. There are now 231, EWB0420-4H-9 (200 ksi), 0.25-28 UNJF fasteners, holding the Upper Conical Flange to the Upper Support Ring. The drawing number illustrating the Upper Conical Flange to the Upper Support Ring is SEG39135776.

![Side View of Vacuum Case Assembly](image)

**Reading database file for bolted interface, abort landing case**

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```plaintext
data_fs := READPRN("usr_cf_fs.txt")
s := 1..rows(data_fs)

**Fail-safe Loads - loads model 2-05**

<table>
<thead>
<tr>
<th>Load Case 2003</th>
<th>( P_{FS_s} := data_{fs_s,3} \text{lbf} )</th>
<th>( ID_{FS_s} := data_{fs_s,1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>( V_{FS_s} := data_{fs_s,4} \text{lbf} )</td>
<td>( LC_{FS_s} := data_{fs_s,2} )</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>( M_{FS_s} := data_{fs_s,5} \text{in-lbf} )</td>
<td></td>
</tr>
<tr>
<td>Applied bending moment</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

- Ultimate \( SF_{U,FS} := 1.0 \)
- Joint Separation \( SF_{sep,FS} := 1.0 \)

This file uses the calculations shown in `\\escfil02\\2111_mathcad\\8307_bolts\\multi_bolt_stiffness_insert_FS_RevC`
**Bolt Fail-safe Load data**

Joint separation load \[ \text{max(Psep FS)} = 715.451 \text{ lbf} \]

Max. load on the bolt (ultimate) \[ \text{max(Pb FS)} = 5736.8 \text{ lbf} \]

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>MS\text{minFS}_{1,1} = 2.769</th>
<th>Total Thread shear Ultimate</th>
<th>MS\text{minFS}_{5,1} = 0.319</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS\text{minFS}_{2,1} = 7.319</td>
<td>Shear Ultimate</td>
<td>MS\text{minFS}_{6,1} = 4.13</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS\text{minFS}_{3,1} = 0.193</td>
<td>Bending Ultimate</td>
<td>MS\text{minFS}_{7,1} = 10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS\text{minFS}_{4,1} = 8.19</td>
<td>Combined shear, tension and</td>
<td>MS\text{minFS}_{8,1} = 0.1858</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bending ultimate</td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ \text{MSbolt FS} := \min(\text{MS FS}) \]

<table>
<thead>
<tr>
<th>MSbolt\text{FS} = 0.186</th>
<th>Failure\text{Mode FS} = &quot;Combined Shear Tension Bending Ultimate&quot;</th>
</tr>
</thead>
</table>

MS\text{min ID} = 920026  
MS\text{min LC} = 2003  
MS\text{min P} = 715.5  
MS\text{min V} = 642.4  
MS\text{min M} = 0  
Element Identification and Bolt Number (920026) for Minimum Margin  
Load Case Number for Minimum Margin  
Applied Tensile Load for Minimum Margin  
Applied Shear Load for Minimum Margin  
Applied Bending Moment for Minimum Margin
3.10.2  Lower Support Ring to Conical Flange
Lower Support Ring to Conical Flange Bolt Analysis

In the Vacuum Case Assembly, the Lower Conical Flange is installed on the Lower Support Ring. A total of 192 fasteners are used to attach the Lower Conical Flange to the Lower Support Ring. The fasteners are EWB0420-4H-9 (200 ksi), 0.25-28 UNJF. The drawing number illustrating the Lower Conical Flange to the Lower Support Ring is SEG39135776.

![Section View of Vacuum Case Assembly](image1)

![Exploded View of Vacuum Case Assembly (Lower Section Shown Only)](image2)

Loads model 2-05 was used to retrieve loads at the bolted interfaces. The CBUSH elements were post processed in NASPOST for forces and moments. The CBUSH element identification numbers are 940001-940192. A total of 64 load cases are included in the NASPOST run. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.
CHECK BOLTS (EWB 0420-4H-9 bolts 0.250-28UNJF-3A, Material-A-286), Insert MS51830CA-202L, Washer NAS1587-4C

**Reading database file for bolted interface, abort landing case**

Note that ".dat" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```plaintext
data := READPRN("lowervc_abort.dat")
s := 1..rows(data)
```

**Flange 1: Conical Flange**
Part number: SEG39135780-301
Material: 2219-T62

**Flange 2: Lower Support Ring**
Part number: SEG39135787-301
Material: 7050-T7451, AMS 4108

**Loads**

Applied tensile load
\[ P_s := \left(\text{data}_{s,3}\right) \text{lbf} \]

ID\( s := \text{data}_{s,1} \)

Applied shear load
\[ V_s := \left(\text{data}_{s,4}\right) \text{lbf} \]

LC\( s := \text{data}_{s,2} \)

Applied bending moment
\[ M_s := \left(\text{data}_{s,5}\right) \text{in} \times \text{lbf} \]

**Factors of Safety**

Ultimate
\[ SF_u := 1.4 \]

Yield
\[ SF_y := 1.1 \]

Assembly
\[ Temp_{\text{initial}} := 70-\text{deg} \]

Joint Separation
\[ SF_{\text{sep}} := 1.2 \]

Fitting factor
\[ FF := 1.15 \]

Maximum
\[ Temp_{\text{max}} := 150-\text{deg} \]

Minimum
\[ Temp_{\text{min}} := 40-\text{deg} \]

**Bolt and Insert Data**

Nominal diameter of bolt
\[ D := 0.250-\text{in} \]

Number of threads/inch
\[ N_t := 28 \times \frac{1}{\text{in}} \]

Total length of bolt
\[ L := 1.050-\text{in} \]

Length of insert
\[ \text{Lins} := 0.375-\text{in} \]

Threaded length
\[ L_t := 0.487-\text{in} \]

Min. external diameter of insert
\[ F_{\text{min}} := 0.312-\text{in} \]

(If bolt is fully threaded, input \( L_t = L \))

Depth of recess for insert
\[ l_r := 0.02-\text{in} \]

**This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd**
**Washer Data**

- Thickness of washer: $t_w := 0.078\text{-in}$
- Outer Diameter of washer: $D_w := 0.531\text{-in}$
- Inner Diameter of washer: $D_{wi} := 0.252\text{-in}$
- Bolt head dia. across flats: $d_w := 0.433\text{-in}$ (used only if there is no washer)

**Flange Data**

- Thickness of flange 1: $t_{f1} := .510\text{-in}$
- Thickness of flange 2: $t_{f2} := .375\text{-in}$
- Diameter of hole: $D_{hole} := 0.296\text{-in}$

Note: If there is no washer, $t_w$, $D_w$, and $D_{wi}$ should be zero.

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate: $T_{Su\_bolt} := .97$ yield $T_{Sy\_bolt} := .97$

  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Bolt ultimate tensile allowable stress: $F_{tu\_bolt} := 200000\text{-psi}$ (EWB 0420)

- Bolt ultimate shear allowable stress: $F_{su\_bolt} := 0.6F_{tu\_bolt}$

- Bolt yield tensile allowable: $F_{ty\_bolt} := 180000\text{-psi}$ (AMS 5726C)

- Temperature correction factor for bolt modulus: $T_{E\_bolt} := .98$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

- Modulus of elasticity of bolt: $E_{\_bolt} := \left(29.1\cdot10^6\text{-psi}\right)$

  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt: $\beta_{\_bolt\_hot} := 9.1\cdot10^{-6}\text{-in}\text{-deg}^{-1}$ $\beta_{\_bolt\_cold} := 8.9\cdot10^{-6}\text{-in}\text{-deg}^{-1}$

  (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

**Insert**

- Temperature correction factor for insert strength: $T_{S\_ins} := .97$

  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Ultimate tensile allowable stress: $F_{tu\_ins} := 140000\text{-psi}$ (Ref. MS51830)

- Ultimate shear allowable stress: $F_{su\_ins} := 0.6F_{tu\_ins}$

**Washer**

- Temperature correction factor for washer modulus: $T_{E\_washer} := .97$

  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Modulus of elasticity of washer: $E_{\_washer} := \left(29.1\cdot10^6\text{-psi}\right)$

  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1} := 0.98 \quad \text{(modulus)} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.2.8.1.1(a))} \]

Temperature correction factor for flange 2
\[ T_{f2} := 0.97 \quad \text{(modulus)} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)} \]

Shear strength allowable for flanges
\[ F_{su_f2} := 42000 \text{ psi} \quad \text{(Ref. MIL-HDBK-5J, table 3.7.4.0(d))} \]

Modulus of elasticity for the parts in the joint
\[ E_{flange1} := \left( 10.5 \times 10^6 \text{ psi} \right) \quad \text{(Ref. MIL-HDBK-5J, table 3.2.8.0(b1))} \]
\[ E_{flange2} := \left( 10.2 \times 10^6 \text{ psi} \right) \quad \text{(Ref. MIL-HDBK-5J, table 3.7.4.0(d))} \]

Coefficient of thermal expansion for flanges
\[ \beta_{flange1\_hot} := 12.45 \times 10^{-6} \quad \text{in} \quad \text{in} \quad \text{deg} \quad \text{(Ref. MIL-HDBK-5J, table 3.2.8.0)} \]
\[ \beta_{flange1\_cold} := 11.8 \times 10^{-6} \quad \text{in} \quad \text{in} \quad \text{deg} \]
\[ \beta_{flange2\_hot} := 12.8 \times 10^{-6} \quad \text{in} \quad \text{in} \quad \text{deg} \quad \text{(Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)} \]
\[ \beta_{flange2\_cold} := 12.1 \times 10^{-6} \quad \text{in} \quad \text{in} \quad \text{deg} \]

Torque/Preload data

Maximum torque (65% of yield)
\[ T_{max} := 160 \text{ in-lbf} \]

Minimum torque (95% of max. torque)
\[ T_{min} := 152 \text{ in-lbf} \]

Torque coefficient:
\[ k := 0.15 \]

Loading plane factor:
\[ n := 0.5 \]

Preload Uncertainty:
\[ u := 0.25 \]

This file uses the calculations shown in \escfim02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Bolt/joint stiffness factor \( = 0.272 \)

Preload due to temperature

Max. preload \( \text{PLD}_{\text{max}} = 5624.8 \text{lbf} \)

Uncertainty factor \( u = 0.25 \)

Min. preload \( \text{PLD}_{\text{min}} = 2678.8 \text{lbf} \)

Torque coefficient \( k = 0.15 \)

Joint separation load \( \text{max}(P_{\text{sep}}) = 672 \text{lbf} \)

Loading plane factor \( n = 0.5 \)

Max. load on the bolt(ultimate) \( \text{max}(P_b) = 5747.5 \text{lbf} \)

Thread shear pullout load of bolt or insert \( \text{Pths} = 12830.3 \text{lbf} \)

Max. load on the bolt(yield) \( \text{max}(P_{by}) = 5721.2 \text{lbf} \)

Thread shear pullout load in parent metal \( \text{Ppths} = 7564.5 \text{lbf} \)

Bolt ultimate tensile strength \( P_{At} = 6844.9 \text{lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation \( \text{MS}_{\text{min}}_{1,1} = 3.012 \)

Direct Thread shear Ultimate \( \text{MS}_{\text{min}}_{6,1} = 7.390 \)

Direct Tension Ultimate \( \text{MS}_{\text{min}}_{2,1} = 6.592 \)

Total Thread shear Ultimate \( \text{MS}_{\text{min}}_{7,1} = 0.316 \)

Direct Tension Yield \( \text{MS}_{\text{min}}_{3,1} = 7.696 \)

Shear Ultimate \( \text{MS}_{\text{min}}_{8,1} = 1.63 \)

Total Tension Ultimate \( \text{MS}_{\text{min}}_{4,1} = 0.191 \)

Bending Ultimate \( \text{MS}_{\text{min}}_{9,1} = 10 \)

Total Tension Yield \( \text{MS}_{\text{min}}_{5,1} = 0.077 \)

Combined shear, tension and bending ultimate \( \text{MS}_{\text{min}}_{10,1} = 0.142 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{\text{bolt}} := \min(\text{MS}) \]

\[ \text{MS}_{\text{bolt}} = 0.077 \]

Failure Mode = "Total Tension Yield"

- \( \text{MS}_{\text{min}}_{\text{ID}} = 940071 \)
- Element Identification and Bolt Number (940071) for Minimum Margin
- \( \text{MS}_{\text{min}}_{\text{LC}} = 2027 \)
- Load Case Number for Minimum Margin
- \( \text{MS}_{\text{min}}_{\text{P}} = 560 \)
- Applied Tensile Load for Minimum Margin
- \( \text{MS}_{\text{min}}_{\text{V}} = 815 \)
- Applied Shear Load for Minimum Margin
- \( \text{MS}_{\text{min}}_{\text{M}} = 0 \)
- Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Lower Support Ring to Conical Flange Bolts

It will be assumed that one bolt will fail. Bolt number 940071 has been removed and only load case 2027 is included in the following fail-safe analysis. There are now 191, EWB0420-4H-9 (200 ksi), 0.25-28 UNJF fasteners, holding the Lower Conical Flange to the Lower Support Ring. The drawing number illustrating the Lower Conical Flange to the Lower Support Ring is SEG39135776.

![Exploded View of Vacuum Case Assembly (Lower Section Shown Only)](image)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```plaintext
data_fs := READPRN("lsr Cf_fs.txt")
s := 1..rows(data_fs)
```

### Fail-safe Loads from Loads Model 2-05

#### Load Case 2027

- **Applied tensile load**
  
  \[ P_{FS_s} := \text{data}_{fs,s,3} \text{ lbf} \]

- **Applied shear load**
  
  \[ V_{FS_s} := \text{data}_{fs,s,4} \text{ lbf} \]

- **Applied bending moment**
  
  \[ M_{FS_s} := \text{data}_{fs,s,5} \text{ in lbf} \]

### Fail-safe Factors of Safety

- **Ultimate**
  
  \[ SFu_{FS} := 1.0 \]

- **Joint Separation**
  
  \[ SFsep_{FS} := 1.0 \]

This file uses the calculations shown in `\escfii02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_Fs_RevC`

Fail-Safe Stiffness File
Bolt Fail-safe Load data

Joint separation load \( \max(P_{sep\_FS}) = 799.317 \text{ lbf} \)

Max. load on the bolt (ultimate) \( \max(P_{b\_FS}) = 5749.9 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

- **Joint separation**
  - \( MS_{min}\_FS_{1,1} = 2.373 \)
  - Total Thread shear Ultimate
  - \( MS_{min}\_FS_{5,1} = 0.316 \)

- **Direct Tension Ultimate**
  - \( MS_{min}\_FS_{2,1} = 6.446 \)
  - Shear Ultimate
  - \( MS_{min}\_FS_{6,1} = 2.42 \)

- **Total Tension Ultimate**
  - \( MS_{min}\_FS_{3,1} = 0.19 \)
  - Bending Ultimate
  - \( MS_{min}\_FS_{7,1} = 10 \)

- **Direct Thread shear Ultimate**
  - \( MS_{min}\_FS_{4,1} = 7.23 \)
  - Combined shear, tension and bending ultimate
  - \( MS_{min}\_FS_{8,1} = 0.1692 \)

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
MS_{bolt\_FS} := \min(\text{MS}_{FS})
\]

\( MS_{bolt\_FS} = 0.169 \)

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

Element Identification and Bolt Number (940072) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
3.10.3 Upper Support Ring to Outer Cylinder
Upper Support Ring to Outer Cylinder Bolt Analysis

In the Vacuum Case Assembly, the Upper Support Ring is installed on the Outer Cylinder. Two separate sets of fasteners are used to attach the Upper Support Ring to the Outer Cylinder. The fasteners are EWB0420-4H-7 (200 ksi), 0.25-28 UNJF and EWB 0420-4H-13 (200 ksi), 0.25-28 UNJF. A total of 192 fasteners are used to attach the Upper Support Ring to the Outer Cylinder. Both sets of fasteners will be analyzed separately. The drawing number illustrating the Upper Support Ring to the Outer Cylinder is SEG39135776.
Loads model 2-05 was used to retrieve loads at the bolted interfaces. The CBUSH elements were post processed in NASPOST for forces and moments. The CBUSH element identification numbers are 940001-940192. The following table shows the CBUSH element identification numbers corresponding to the appropriate fasteners. A total of 64 load cases are included in the NASPOST run for the EWB0420-4H-13 fasteners and a total of 20 load cases are included in the NASPOST run for the EWB0420-4H-7 fasteners. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.

<table>
<thead>
<tr>
<th>CBUSH Element ID's for EWB0420-4H-7</th>
<th>CBUSH Element ID's for EWB0420-4H-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>940009 THRU 940011</td>
<td>940001 THRU 940008</td>
</tr>
<tr>
<td>940022 THRU 940027</td>
<td>940012 THRU 940021</td>
</tr>
<tr>
<td>940030 THRU 940032</td>
<td>940028 THRU 940029</td>
</tr>
<tr>
<td>940038 THRU 940042</td>
<td>940033 THRU 940037</td>
</tr>
<tr>
<td>940048 THRU 940050</td>
<td>940043 THRU 940047</td>
</tr>
<tr>
<td>940053 THRU 940055</td>
<td>940051 THRU 940052</td>
</tr>
<tr>
<td>940066 THRU 940068</td>
<td>940056 THRU 940065</td>
</tr>
<tr>
<td>940070 THRU 940078</td>
<td>940069</td>
</tr>
<tr>
<td>940085 THRU 940093</td>
<td>940079 THRU 940084</td>
</tr>
<tr>
<td>940105 THRU 940107</td>
<td>940094 THRU 940104</td>
</tr>
<tr>
<td>940113 THRU 940123</td>
<td>940108 THRU 940112</td>
</tr>
<tr>
<td>940138 THRU 940140</td>
<td>940124 THRU 940137</td>
</tr>
<tr>
<td>940151 THRU 940155</td>
<td>940141 THRU 940150</td>
</tr>
<tr>
<td>940166 THRU 940171</td>
<td>940156 THRU 940165</td>
</tr>
<tr>
<td>940173 THRU 940174</td>
<td>940172</td>
</tr>
<tr>
<td>940181 THRU 940189</td>
<td>940175 THRU 940180</td>
</tr>
<tr>
<td>940190 THRU 940192</td>
<td></td>
</tr>
</tbody>
</table>

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. The following bolt analysis will analyze the EWB0420-4H-13 (200 ksi), 0.25-28 UNJF fasteners. There is a total of 109, EWB0420-4H-13, fasteners used to attach the Upper Support Ring to the Outer Cylinder.

```
data := READPRN("USROC_250nut_abortland.txt")
```

Flange 1: Outer Cylinder
Part number: SDG39135779-001
Material: 7050-T7451, AMS 4108

Flange 2: Upper Support Ring
Part number: SEG39135786-301
Material: 7050-T7451, AMS 4108

**Loads**

Applied tensile load

\[ P_s := \text{data}_{s,3}, \text{lbf} \]

ID \( s \) := data \( s,1 \)

Applied shear load

\[ V_s := \text{data}_{s,4}, \text{lbf} \]

LC \( s \) := data \( s,2 \)

Applied bending moment

\[ M_s := \text{data}_{s,5}, \text{in-lbf} \]

**Factors of Safety**

Ultimate \( \text{SFu} := 1.4 \)

Yield \( \text{SFy} := 1.1 \)

Assembly

\( \text{SF} := 1.15 \)

Maximum

\( \text{Temperature data (Ref Appendix C2), Abort Landing Case} \)

\( \text{Temp}_\text{initial} := 70\text{-deg} \)

\( \text{Temp}_\text{max} := 150\text{-deg} \)

\( \text{Temp}_\text{min} := 40\text{-deg} \)

**Joint Separation**

\( \text{SFsep} := 1.2 \)

Fitting factor \( \text{FF} := 1.15 \)

**Bolt and Nut Data**

Nominal diameter of bolt

\( D := 0.250\text{-in} \)

Number of threads/\( \text{inch} \)

\( N_t := 28\frac{1}{\text{in}} \)

Total length of bolt

\( L := 1.2995\text{-in} \)

Height of nut

\( H := 0.280\text{-in} \)

Threaded length

\( \text{Lt} := 0.487\text{-in} \)

(If bolt is fully threaded, input \( \text{Lt} = L \))

This file uses the calculations shown in \escfil02\11_mathcad\8307_bolts\thread_data.mcd

---

G. Reyes
03/30/06

Title
Bolts from Upper Support Ring to Outer Cylinder

C. Bala

File Name
USROC_250_r3.mcd

Prepared By

Checked By

Drawing No.
SEG39135776

USROC 250_r3.mcd

3.10.3 - 4

ESCG-4005-05-AMS-0039
Washer Data

<table>
<thead>
<tr>
<th>Thickness of washers</th>
<th>tfw := 0.141-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Includes thickness of NAS1587-4C and NAS1149E0463R)</td>
<td></td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := 0.531in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.252-in</td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>dw := 0.433-in</td>
</tr>
</tbody>
</table>

Note: If there is no washer tw, Dw and Dwi should be zero

Flange data

<table>
<thead>
<tr>
<th>Thickness of flange 1</th>
<th>tf1 := .375-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 2</td>
<td>tf2 := .375-in</td>
</tr>
<tr>
<td>Diameter of hole</td>
<td>D_hole := 0.289-in</td>
</tr>
</tbody>
</table>

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

<table>
<thead>
<tr>
<th>TSu_bolt := 0.97</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
</tr>
<tr>
<td>TSy_bolt := 0.97</td>
</tr>
</tbody>
</table>

Bolt ultimate tensile allowable stress Ftu_bolt := 200000-psi (EWB 0420)

Bolt ultimate shear allowable stress Fsu_bolt := 0.6*Ftu_bolt

Bolt yield Tensile allowable stress Fty_bolt := 180000-psi (AMS 5726C)

Temperature correction factor for bolt modulus TE_bolt := 0.98 (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

Modulus of elasticity of bolt E_bolt := \((29.1\cdot10^6\text{ psi})\) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Thermal coefficient for bolt \(\beta_{\text{bolt_hot}} := 9.1\cdot10^{-6}\dfrac{\text{in}}{\text{in}}\dfrac{\text{deg}}{}\)

\(\beta_{\text{bolt_cold}} := 8.9\cdot10^{-6}\dfrac{\text{in}}{\text{in}}\dfrac{\text{deg}}{}\) (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

Nut

Temperature correction factor for nut strength TS_nut := 0.97

Ultimate tensile allowable stress Ftu_nut := 220000-psi (Ref. BACN10HR)

Ultimate shear allowable stress: Fsu_nut := 0.6*Ftu_nut

Ultimate axial strength of nut Ptu_nut := 7973-lbf (220/125=1.76, 4530*1.76=7973, Ref. NAS1291)

Washer

Temperature correction factor for washer modulus TE_washer := .97 (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer: E_washer := \((29.1\cdot10^6\text{ psi})\) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1} = 0.98 \text{ (modulus)} \]  
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2

\[ T_{f2} = 0.98 \]

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange1}} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{\text{flange2}} := \left(10.3 \times 10^6 \text{ psi}\right) \]
(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \text{ \(\frac{\text{in}}{\text{deg}}\)} \quad \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \text{ \(\frac{\text{in}}{\text{deg}}\)} \]
(Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)

\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \text{ \(\frac{\text{in}}{\text{deg}}\)} \quad \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ \(\frac{\text{in}}{\text{deg}}\)} \]

Torque/Preload data

Maximum torque (65% of yield)

\[ T_{\text{max}} := 160 \text{ in-lbf} \]

Minimum torque (95% of max. torque)

\[ T_{\text{min}} := 152 \text{ in-lbf} \]

Loading plane factor

\[ n := 0.5 \]

Preload Uncertainty

\[ u := 0.25 \]

Torque coefficient

\[ k := 0.15 \]

This file uses the calculations shown in \\mathcal{ESC}G\mathcal{ESC}l02\mathcal{ESC}f\mathcal{ESC}i\mathcal{ESC}l02\mathcal{ESC}r\mathcal{ESC}i\mathcal{ESC}l02\mathcal{ESC}\text{\textasciitilde} Mathcad8307_bolts\mathcal{ESC}multi_bolt_stiffness_nut RevC
Bolt Load data

Bolt/joint stiffness factor \( = 0.28 \)

Preload due to temperature \( \text{Pth}_\text{pos} = 242.6 \text{lbf} \)

Max. preload \( \text{PLDmax} = 5576 \text{lbf} \)

Uncertainty factor \( \text{u} = 0.25 \)

Min. preload \( \text{PLDmin} = 2694.6 \text{lbf} \)

Torque coefficient \( \text{k} = 0.15 \)

Joint separation load \( \text{max}(P_{\text{sep}}) = 924 \text{lbf} \)

Loading plane factor \( \text{n} = 0.5 \)

Max. load on the bolt(ultimate) \( \text{max}(P_b) = 5749.8 \text{lbf} \)

Thread pullout strength required to develop full strength of bolt \( \text{PAs} = 8213.8 \text{lbf} \)

Max. load on the bolt(yield) \( \text{max}(P_{by}) = 5712.5 \text{lbf} \)

Nut ultimate tensile strength \( \text{Ptu}_{\text{nut}} = 7733.8 \text{lbf} \)

Bolt ultimate tensile strength \( \text{PA}_t = 6844.9 \text{lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation \( \text{MS}_{\text{min}}_{1,1} = 1.949 \)

Direct Thread shear Ultimate \( \text{MS}_{\text{min}}_{6,1} = 5.626 \)

Direct Tension Ultimate \( \text{MS}_{\text{min}}_{2,1} = 4.521 \)

Total Thread shear Ultimate \( \text{MS}_{\text{min}}_{7,1} = 0.429 \)

Direct Tension Yield \( \text{MS}_{\text{min}}_{3,1} = 5.324 \)

Shear Ultimate \( \text{MS}_{\text{min}}_{8,1} = 5.43 \)

Total Tension Ultimate \( \text{MS}_{\text{min}}_{4,1} = 0.190 \)

Bending Ultimate \( \text{MS}_{\text{min}}_{9,1} = 10 \)

Total Tension Yield \( \text{MS}_{\text{min}}_{5,1} = 0.078 \)

Combined shear, tension and bending ultimate \( \text{MS}_{\text{min}}_{10,1} = 0.189 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\( \text{MS}_{\text{bolt}} = \text{min}(\text{MS}) \)

\( \text{MS}_{\text{bolt}} = 0.078 \) Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

Element Identification and Bolt Number (940131) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Upper Support Ring to Outer Cylinder  EWB0420-4H-13 Bolts

It will be assumed that one bolt will fail. Bolt number 940131 has been removed and only load case 2038 is included in the following fail-safe analysis. There are now 108, EWB0420-4H-13 (200 ksi), 0.25-28 UNJF fasteners, holding the Upper Support Ring to the Outer Cylinder. The drawing number illustrating the Outer Cylinder to the Upper Support Ring is SEG39135776.

Close View of Vacuum Case Assembly  
(Location of fasteners is shown)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

data_fs := READPRN("fs_USROC_250nut_lc2038.txt")

s := 1..rows(data_fs)

Fail-safe Loads from Loads Model 2-05
Load Case 2038

<table>
<thead>
<tr>
<th>Applied</th>
<th>tensile load</th>
<th>P_FS_s := data_fs_s, 3 lbf</th>
<th>ID_FS_s := data_fs_s, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>shear load</td>
<td>V_FS_s := data_fs_s, 4 lbf</td>
<td>LC_FS_s := data_fs_s, 2</td>
<td></td>
</tr>
<tr>
<td>bending moment</td>
<td>M_FS_s := data_fs_s, 5 in.lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fail-safe Factors of Safety

| Ultimate  | SFu_FS := 1.0 |
| Joint Separation | SFsep_FS := 1.0 |

This file uses the calculations shown in \escf\il02\2i11\mathcad\8307\bolts\multi_bolt_stiffness_nut_FS_RevC
Bolt Fail-safe Load data

Joint separation load \( \max(P_{\text{sep\_FS}}) = 1023.829 \text{ lbf} \)

Max. load on the bolt (ultimate) \( \max(P_{\text{b\_FS}}) = 5741 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

Joint separation \( MS_{\text{min\_FS}}_{1,1} = 1.662 \) \( MS_{\text{min\_FS}}_{5,1} = 0.431 \)

Direct Tension Ultimate \( MS_{\text{min\_FS}}_{2,1} = 4.814 \) \( MS_{\text{min\_FS}}_{6,1} = 10.15 \)

Total Tension Ultimate \( MS_{\text{min\_FS}}_{3,1} = 0.192 \) \( MS_{\text{min\_FS}}_{7,1} = 10 \)

Direct Thread shear Ultimate \( MS_{\text{min\_FS}}_{4,1} = 5.98 \) \( MS_{\text{min\_FS}}_{8,1} = 0.1918 \)

Bending Ultimate \( MS_{\text{min\_FS}}_{8,1} = 0.1918 \)

Combining shear, tension and bending ultimate

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{\text{bolt\_FS}} := \min(MS_{\text{FS}}) \)

\( MS_{\text{bolt\_FS}} = 0.192 \) Failure Mode FS = “Combined Shear Tension Bending Ultimate”

Joint and Load Case Identification:

\( MS_{\text{min\_ID}} = 940132 \) Element Identification and Bolt Number (940132) for Minimum Margin

\( MS_{\text{min\_LC}} = 2038 \) Load Case Number for Minimum Margin

\( MS_{\text{min\_P}} = 1023.8 \) Applied Tensile Load for Minimum Margin

\( MS_{\text{min\_V}} = 391.2 \) Applied Shear Load for Minimum Margin

\( MS_{\text{min\_M}} = 0 \) Applied Bending Moment for Minimum Margin
Cont: Bolt Fail-Safe Analysis for Upper Support Ring to Outer Cylinder EWB0420-4H-13 Bolts

An additional fail-safe check will be performed on the EWB0420-4H-13 fasteners. On page 3.10.3-11, analysis will be performed on the EWB0420-4H-7 fasteners with the MS51830CA-202L insert. For this case, the minimum margin of safety was determined to be at Bolt Number 940009, with Load Case 2057. Therefore, this check will apply the new loads from Load Case 2057 without Bolt Number 940009 and will show how the Load Case 2057 will affect the EWB0420-4H-13 fasteners when removing a EWB0420-4H-7 fastener.

Close View of Vacuum Case Assembly
(Location of fasteners is shown)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

data_fs := READPRN("fs_250int_lc2057_check.txt")

s := 1..rows(data_fs)

 Fail-safe Loads from Loads Model 2-05
 Load Case 2057

- Applied tensile load  \( P_{FS} := data_{fs} \times \text{lbf} \)
- Applied shear load  \( V_{FS} := data_{fs} \times \text{lbf} \)
- Applied bending moment  \( M_{FS} := data_{fs} \times \text{in-lbf} \)

 Fail-safe Factors of Safety

- Ultimate  \( SFu_{FS} := 1.0 \)
- Joint Separation  \( SFsep_{FS} := 1.0 \)

This file uses the calculations shown in \escg\multi_bolt_stiffness_nut_FS_RevC
Bolt Fail-safe Load data

Joint separation load \[ \text{max}(P_{\text{sep FS}}) = 695.345 \text{ lbf} \]

Max. load on the bolt(ultimate) \[ \text{max}(P_{b FS}) = 5688.1 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>MS_minFS_1,1 = 2.919</th>
<th>Total Thread shear Ultimate</th>
<th>MS_minFS_5,1 = 0.444</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_minFS_2,1 = 7.560</td>
<td>Shear Ultimate</td>
<td>MS_minFS_6,1 = 9.04</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_minFS_3,1 = 0.203</td>
<td>Bending Ultimate</td>
<td>MS_minFS_7,1 = 10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_minFS_4,1 = 9.27</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_minFS_8,1 = 0.2032</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ \text{MSb Bolt}_FS := \min(\text{MS}_FS) \]

\[ \text{MSb Bolt}_FS = 0.203 \]

Failure Mode \_\_FS = “Combined Shear Tension Bending Ultimate”

Joint and Load Case Identification:

- MS\_min\_ID = 940131: Element Identification and Bolt Number (940131) for Minimum Margin
- MS\_min\_LC = 2057: Load Case Number for Minimum Margin
- MS\_min\_P = 695.3: Applied Tensile Load for Minimum Margin
- MS\_min\_V = 289.8: Applied Shear Load for Minimum Margin
- MS\_min\_M = 0: Applied Bending Moment for Minimum Margin
CHECK BOLTS (EBW 0420-4H-7 bolts 0.250-28UNJF-3A, Material-A-286), Insert MS51830CA-202L, Washer NAS1587-4C

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. The following bolt analysis will analyze the EWB0420-4H-7 (200 ksi), 0.25-28 UNJF fasteners. There is a total of 83, EWB 0420-4H-7, fasteners used to attach the Upper Support Ring to the Outer Cylinder. A total of 20 load cases are included in the NASPOST run. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.

```
data := READPRN("USROC_250int_abortland.txt")
s := 1..rows(data)
```

**Flange 1: Outer Cylinder**
Part number: SEG39135779-001
Material: 7050-T7451, AMS 4108

**Flange 2: Upper Support Ring**
Part number: SEG39135786-301
Material: 7050-T7451, AMS 4108

**Loads**
- Applied tensile load
  \( P_s := data_{3,s} \times \text{lbf} \)
  \( ID_s := data_{1,s} \)
- Applied shear load
  \( V_s := data_{4,s} \times \text{lbf} \)
  \( LC_s := data_{2,s} \)
- Applied bending moment
  \( M_s := data_{5,s} \times \text{in-lbf} \)

**Factors of Safety**

<table>
<thead>
<tr>
<th>Safety Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate SFu</td>
<td>1.4</td>
</tr>
<tr>
<td>Yield SFy</td>
<td>1.1</td>
</tr>
<tr>
<td>Assembly</td>
<td></td>
</tr>
<tr>
<td>Joint Separation SFsep</td>
<td>1.2</td>
</tr>
<tr>
<td>Fitting factor FF</td>
<td>1.15</td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td></td>
</tr>
</tbody>
</table>

**Temperature data**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp_initial</td>
<td>70-deg</td>
</tr>
<tr>
<td>Temp_max</td>
<td>150-deg</td>
</tr>
<tr>
<td>Temp_min</td>
<td>40-deg</td>
</tr>
</tbody>
</table>

**Bolt and Insert Data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter of bolt D</td>
<td>0.250-in</td>
</tr>
<tr>
<td>Number of threads/inch Nt</td>
<td>28 (\frac{1}{\text{in}})</td>
</tr>
<tr>
<td>Total length of bolt L</td>
<td>0.9245-in</td>
</tr>
<tr>
<td>Length of insert Lins</td>
<td>0.375-in</td>
</tr>
<tr>
<td>Threaded length Lt</td>
<td>0.487-in</td>
</tr>
<tr>
<td>Min. external diameter of insert Fmin</td>
<td>0.312-in</td>
</tr>
<tr>
<td>Depth of recess for insert lr</td>
<td>0.02-in</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfil02\2111_mathcad\8307_bolts\thread_data.mcd`
Washer Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of washer</td>
<td>tw := 0.078-in</td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := .531in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.252-in</td>
</tr>
</tbody>
</table>

Flange data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 1</td>
<td>tf1 := .375-in</td>
</tr>
<tr>
<td>Thickness of flange 2</td>
<td>tf2 := .375-in</td>
</tr>
<tr>
<td>Diameter of hole</td>
<td>D Hole := 0.289-in</td>
</tr>
</tbody>
</table>

Bolt head dia. across flats      | dw := 0.433-in

Note: If there is no washer, tw, Dw, and Dwi should be zero.

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsu_bolt : yield</td>
<td>.97</td>
</tr>
<tr>
<td>Tsy_bolt : yield</td>
<td>.97</td>
</tr>
<tr>
<td>Ftu_bolt</td>
<td>200000 psi</td>
</tr>
<tr>
<td>Fsu_bolt : 0.6 Ftu_bolt</td>
<td></td>
</tr>
<tr>
<td>Fty_bolt</td>
<td>180000 psi</td>
</tr>
<tr>
<td>Te_bolt : .98</td>
<td>(Ref. MIL-HDBK-5J, fig. 6.2.1.4(a))</td>
</tr>
</tbody>
</table>

Modulus of elasticity of bolt    | E_bolt := (29.1 × 10^6 psi) |

Thermal coefficient for bolt:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta_bolt_hot :=</td>
<td>9.1 × 10^-6 in/in/deg</td>
</tr>
<tr>
<td>Beta_bolt_cold :=</td>
<td>8.9 × 10^-6 in/in/deg</td>
</tr>
</tbody>
</table>

Insert

Temperature correction factor for insert strength (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS_ins : .97</td>
<td>(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)</td>
</tr>
<tr>
<td>Ftu_ins : 140000 psi</td>
<td>(Ref. MS51830)</td>
</tr>
<tr>
<td>Fsu_ins : 0.6 Ftu_ins</td>
<td></td>
</tr>
</tbody>
</table>

Washer

Temperature correction factor for washer modulus (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te_washer := .97</td>
<td>(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)</td>
</tr>
</tbody>
</table>

Modulus of elasticity of washer  | E_washer := (29.1 × 10^6 psi) |

(Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1}E := 0.98 \quad \text{(modulus)} \]

(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2

\[ T_{f2}E := 0.98 \quad \text{(modulus)} \]

\[ T_{f2}s := 0.97 \quad \text{(strength)} \]

(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear strength allowable for flanges

\[ F_{su\_f2} := 42000 \text{psi} \]

(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange}1} := \left(10.3 \cdot 10^6 \text{ psi}\right) \quad E_{\text{flange}2} := \left(10.3 \cdot 10^6 \text{ psi}\right) \]

(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange}1\_hot} := 12.8 \cdot 10^{-6} \quad \text{in}^{-1} \quad \text{deg}^{-1} \quad \beta_{\text{flange}2\_hot} := 12.8 \cdot 10^{-6} \quad \text{in}^{-1} \quad \text{deg}^{-1} \]

(Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)

\[ \beta_{\text{flange}1\_cold} := 12.1 \cdot 10^{-6} \quad \text{in}^{-1} \quad \text{deg}^{-1} \quad \beta_{\text{flange}2\_cold} := 12.1 \cdot 10^{-6} \quad \text{in}^{-1} \quad \text{deg}^{-1} \]

Torque/Preload data

Maximum torque (65% of yield)

\[ T_{\text{max}} := 160 \text{ in-lbf} \]

Loading plane factor:

\[ n := 0.5 \]

Minimum torque (95% of max. torque)

\[ T_{\text{min}} := 152 \text{ in-lbf} \]

Preload Uncertainty:

\[ u := 0.25 \]

Torque coefficient:

\[ k := 0.15 \]

This file uses the calculations shown in \escgil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC

[Insert Stiffness File]
Bolt Load data

Bolt/joint stiffness factor = 0.284
Preload due to temperature
Pth_r_pos = 305.6 lbf
Pth_r_neg = -99.1 lbf

Max. preload
PLD_max = 5639 lbf

Min. preload
PLD_min = 2674.2 lbf
Uncertainty factor
u = 0.25

Joint separation load
max(Psep) = 924 lbf
Torque coefficient
k = 0.15

Max. load on the bolt(ultimate)
max(Pb) = 5814.8 lbf
Loading plane factor
n = 0.5

Max. load on the bolt(yield)
max(Pby) = 5777.1 lbf
Thread shear pullout load of bolt or insert
Pths = 13106 lbf

Bolt ultimate tensile strength
PA_t = 6844.9 lbf
Thread shear pullout load in parent metal
Ppth_s = 7487.3 lbf

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation
MS_min^1,1 = 1.949
Direct Thread shear Ultimate
MS_min^6,1 = 5.284

Direct Tension Ultimate
MS_min^2,1 = 4.521
Total Thread shear Ultimate
MS_min^7,1 = 0.289

Direct Tension Yield
MS_min^3,1 = 5.324
Shear Ultimate
MS_min^8,1 = 5.28

Total Tension Ultimate
MS_min^4,1 = 0.179
Bending Ultimate
MS_min^9,1 = 10

Total Tension Yield
MS_min^5,1 = 0.067
Combined shear, tension and bending ultimate
MS_min^10,1 = 0.178

Determination of the smallest margin of safety for the bolt, and the failure mode:

MS_bolt := min(MS)

MS_bolt = 0.067
Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

MS_min_ID = 940009
Element Identification and Bolt Number (940009) for Minimum Margin

MS_min_HC = 2057
Load Case Number for Minimum Margin

MS_min_P = 740
Applied Tensile Load for Minimum Margin

MS_min_V = 165
Applied Shear Load for Minimum Margin

MS_min_M = 0
Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Upper Support Ring to Outer Cylinder  EWB0420-4H-7 Bolts

It will be assumed that one bolt will fail. Bolt number 940009 has been removed and only load case 2057 is included in the following fail-safe analysis. There are now 82, EWB0420-4H-7 (200 ksi), 0.25-28 UNJF fasteners, holding the Upper Support Ring to the Outer Cylinder. The drawing number illustrating the Outer Cylinder to the Upper Support Ring is SEG39135776.

Close View of Vacuum Case Assembly
(Location of fasteners is shown)

Reading database file for bolted interface, abort landing case
Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```
data_fs := READPRN("fs_USROC_250int_lc2057.txt")
s := 1..rows(data_fs)
```

Fail-safe Loads from Loads Model 2-05
Load Case 2057

<table>
<thead>
<tr>
<th>Applied</th>
<th>tensile load</th>
<th>shear load</th>
<th>bending moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{FS} s := data_fs s,3 , lbf</td>
<td>ID_{FS} s := data_fs s,1</td>
<td>LC_{FS} s := data_fs s,2</td>
<td></td>
</tr>
<tr>
<td>V_{FS} s := data_fs s,4 , lbf</td>
<td>M_{FS} s := data_fs s,5 , in\cdot lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fail-safe Factors of Safety

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu_{FS} := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep_{FS} := 1.0</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escfil02\2i11_mathcad8307_bolts\multi_bolt_stiffness_insert_FS_RevC
Bolt Fail-safe Load data

Joint separation load \( \text{max}(P_{\text{sep,Fs}}) = 813.652 \text{ lbf} \)

Max. load on the bolt(ultimate) \( \text{max}(P_{b,Fs}) = 5771.7 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

| Joint separation | \( MS_{\text{min,Fs}}^{1,1} \) | 2.330 | Total Thread shear Ultimate | \( MS_{\text{min,Fs}}^{5,1} \) | 0.297 |
| Direct Tension Ultimate | \( MS_{\text{min,Fs}}^{2,1} \) | 6.315 | Shear Ultimate | \( MS_{\text{min,Fs}}^{6,1} \) | 8.28 |
| Total Tension Ultimate | \( MS_{\text{min,Fs}}^{3,1} \) | 0.186 | Bending Ultimate | \( MS_{\text{min,Fs}}^{7,1} \) | 10 |
| Direct Thread shear Ultimate | \( MS_{\text{min,Fs}}^{4,1} \) | 7 | Combined shear, tension and bending ultimate | \( MS_{\text{min,Fs}}^{8,1} \) | 0.1857 |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( \text{MSbolt}_{\text{FS}} := \text{min}(MS_{\text{FS}}) \)

\( MS_{\text{bolt,Fs}} = 0.186 \)  
Failure Mode _FS = "Combined Shear Tension Bending Ultimate"

Joint and Load Case Identification:

| \( MS_{\text{min,ID}} \) | 940010 | Element Identification and Bolt Number (940010) for Minimum Margin |
| \( MS_{\text{min,LC}} \) | 2057 | Load Case Number for Minimum Margin |
| \( MS_{\text{min,P}} \) | 813.7 | Applied Tensile Load for Minimum Margin |
| \( MS_{\text{min,V}} \) | 192 | Applied Shear Load for Minimum Margin |
| \( MS_{\text{min,M}} \) | 0 | Applied Bending Moment for Minimum Margin |
Cont: Bolt Fail-Safe Analysis for Upper Support Ring to Outer Cylinder EWB0420-4H-7 Bolts

An additional fail-safe check will be performed on the EWB0420-4H-7 fasteners. On page 3.10.3-3, analysis was performed on the EWB0420-4H-13 fasteners with the BACN10HR4CS nut. For this case, the minimum margin of safety was determined to be at Bolt Number 940131, with Load Case 2038. Therefore, this check will apply the new loads from Load Case 2038 without Bolt Number 940131 and will show how the Load Case 2038 will affect the EWB0420-4H-7 fasteners when removing a EWB0420-4H-13 fastener.

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```
data_fs := READPRN("fs_250nut_lc2038_check.txt")
s := 1..rows(data_fs)
```

**Fail-safe Loads - loads model 2-05**

**Load Case 2038**

<table>
<thead>
<tr>
<th>Applied</th>
<th>tensile load</th>
<th>shear load</th>
<th>bending moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;Fs&lt;/sub&gt; := data&lt;sub&gt;fs&lt;/sub&gt;_s,3 lbf</td>
<td>V&lt;sub&gt;Fs&lt;/sub&gt; := data&lt;sub&gt;fs&lt;/sub&gt;_s,4 lbf</td>
<td>M&lt;sub&gt;Fs&lt;/sub&gt; := data&lt;sub&gt;fs&lt;/sub&gt;_s,5 in-lbf</td>
<td></td>
</tr>
<tr>
<td>(ID_FS := data_fs_s,1)</td>
<td>(LC_FS := data_fs_s,2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

- Ultimate \(SFu\_FS := 1.0\)
- Joint Separation \(SFsep\_FS := 1.0\)

This file uses the calculations shown in \escg\_02\_ii11\_mathcad\_8307\_bolts\multi\_bolt\_stiffness\_insert\_FS\_RevC
**Bolt Fail-safe Load data**

Joint separation load \[ \text{max}(P_{\text{sep,FS}}) = 608.803 \text{ lbf} \]

Max. load on the bolt (ultimate) \[ \text{max}(P_{\text{b,FS}}) = 5738.3 \text{ lbf} \]

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Case</th>
<th>MS(<em>{\text{min}})FS(</em>{i,j})</th>
<th>Unit</th>
<th>MS(<em>{\text{min}})FS(</em>{k,l})</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>3.451</td>
<td></td>
<td>0.305</td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>8.777</td>
<td>Shear Ultimate</td>
<td>9.04</td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.193</td>
<td>Bending Ultimate</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>9.69</td>
<td>Combined shear, tension and bending ultimate</td>
<td>0.1928</td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ M_{\text{Sbolt,FS}} = \text{min}(M_{\text{S,FS}}) \]

**Failure_MODE_FS = "Combined Shear Tension Bending Ultimate"**

**Joint and Load Case Identification:**

1. Element Identification and Bolt Number (940009) for Minimum Margin
2. Load Case Number for Minimum Margin (2038)
3. Applied Tensile Load for Minimum Margin (608.8)
4. Applied Shear Load for Minimum Margin (80.8)
5. Applied Bending Moment for Minimum Margin (0)
3.10.4 Lower Support Ring to Outer Cylinder Bolted Interface
Lower Support Ring to Outer Cylinder Bolted Interface

The Lower Support Ring to Outer Cylinder Bolt Analysis is performed in the following report sections:

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.10.4.1</td>
<td>Lower Support Ring to Outer Cylinder</td>
</tr>
<tr>
<td>3.10.4.1</td>
<td>Lower Support Ring to Outer Cylinder Fail-Safe</td>
</tr>
<tr>
<td>3.10.4.2</td>
<td>Lower Support Ring to Outer Cylinder - .3125&quot;</td>
</tr>
<tr>
<td>3.10.4.2</td>
<td>Lower Support Ring to Outer Cylinder Fail-Safe - .3125&quot;</td>
</tr>
</tbody>
</table>
3.10.4.1 Lower Support Ring to Outer Cylinder
Lower Support Ring to Outer Cylinder Bolt Analysis

In the Vacuum Case Assembly, the Lower Support Ring is installed on the Outer Cylinder. Three separate sets of fasteners are used to attach the Lower Support Ring to the Outer Cylinder. The fasteners are EWB0420-5H-7 (200 ksi, 0.3125-24 UNJF), EWB 0420-4H-7 (200 ksi, 0.25-28 UNJF), and EWB 0420-4H-13 (200 ksi, 0.25-28 UNJF). A total of 200 fasteners are used to attach the Lower Support Ring to the Outer Cylinder. The three sets of fasteners will be analyzed separately. This section will analyze the EWB 0420-4H-7 and EWB 0420-4H-13 fasteners. Refer to Section 3.10.4.2 for bolt analysis of fasteners EWB0420-5H-7. The drawing number illustrating the Lower Support Ring to the Outer Cylinder is SEG39135776.

**Figure of Vacuum Case Assembly**

Fasteners (EWB0420-4H-7, EWB0420-4H-13 and EWB0420-5H-7) are located between Outer Cylinder and Lower Support Ring.

**Close View of Vacuum Case Assembly**

(Location of fasteners is shown)
Loads model 2-05 was used to retrieve loads at the bolted interfaces. The CBUSH elements were post processed in NASPOST for forces and moments. The CBUSH element identification numbers are 940001-940200. The following table shows the CBUSH element identification numbers corresponding to the appropriate fasteners. A linear gap model was ran for a total of 6 load cases. The load cases include 2019-2020, 2031-2032, 2053-2054 and are all included in the NASPOST run. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.

<table>
<thead>
<tr>
<th>CBUSH Element ID's for EWB0420-5H-7</th>
<th>CBUSH Element ID's for EWB0420-4H-7</th>
<th>CBUSH Element ID's for EWB0420-4H-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>940022 THRU 940027</td>
<td>940009 THRU 940011</td>
<td>940001 THRU 940008</td>
</tr>
<tr>
<td>940070 THRU 940075</td>
<td>940019 THRU 940020</td>
<td>940012 THRU 940018</td>
</tr>
<tr>
<td>940118 THRU 940123</td>
<td>940042 THRU 940044</td>
<td>940021</td>
</tr>
<tr>
<td>940166 THRU 940170</td>
<td>940047 THRU 940049</td>
<td>940028 THRU 940041</td>
</tr>
<tr>
<td>940193 THRU 940200</td>
<td>940051 THRU 940059</td>
<td>940045 THRU 940046</td>
</tr>
<tr>
<td>940065 THRU 940067</td>
<td>940065 THRU 940065</td>
<td>940050</td>
</tr>
<tr>
<td>940100 THRU 940108</td>
<td>940010 THRU 940108</td>
<td>940060 THRU 940064</td>
</tr>
<tr>
<td>940115 THRU 940116</td>
<td>940015 THRU 940115</td>
<td>940068 THRU 940069</td>
</tr>
<tr>
<td>940147 THRU 940155</td>
<td>940076 THRU 940099</td>
<td>940076 THRU 940099</td>
</tr>
<tr>
<td>940161 THRU 940163</td>
<td>940109 THRU 940114</td>
<td>940109 THRU 940114</td>
</tr>
<tr>
<td>940173 THRU 940175</td>
<td>940117</td>
<td>940117</td>
</tr>
<tr>
<td>940182 THRU 940184</td>
<td>940124 THRU 940146</td>
<td>940124 THRU 940146</td>
</tr>
<tr>
<td></td>
<td>940166 THRU 940165</td>
<td>940166 THRU 940165</td>
</tr>
<tr>
<td></td>
<td>940171 THRU 940172</td>
<td>940171 THRU 940172</td>
</tr>
<tr>
<td></td>
<td>940176 THRU 940181</td>
<td>940176 THRU 940181</td>
</tr>
<tr>
<td></td>
<td>940185 THRU 940192</td>
<td>940185 THRU 940192</td>
</tr>
</tbody>
</table>
CHECK BOLTS (EWB0420-4H-7  0.250-28UNJF-3A, Material-A-286), Insert MS51830CA202L, Washer NAS1587-4C

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. The following bolt analysis will analyze the EWB0420-4H-7 (200 ksi), 0.25-28 UNJF fasteners. There is a total of 52, EWB0420-4H-7, fasteners used to attach the Lower Support Ring to the Outer Cylinder.

data := READPRN("LSR_OC_250int_abortland.txt")

\s := 1..rows(data)

Flange 1: Outer Cylinder
Part number: SDG39135779-001
Material: 7050-T7451, AMS4108

Flange 2: Lower Support Ring
Part number: SEG39135787-301
Material: 7050-T7451, AMS4108

Loads

Applied tensile load \( P_s := data\_s, 3\) lbf

Applied shear load \( V_s := data\_s, 4\) lbf

Applied bending moment \( M_s := data\_s, 5\) in-lbf

Factors of Safety

Ultimate SFu := 1.4

Yield SFy := 1.1

Joint Separation SFsep := 1.2

Fitting factor FF := 1.15

Temperature data (Ref Appendix C2), Abort Landing Case

Assembly Temp\_initial := 70-deg

Maximum Temp\_max := 150-deg

Minimum Temp\_min := 40-deg

Bolt and Insert Data

Nominal diameter of bolt \( D := 0.250\)-in

Number of threads/inch \( Nt := 28\frac{1}{\text{in}}\)

Total length of bolt \( L := .9245\)-in

Length of insert \( \text{Lins} := 0.375\)-in

Threaded length \( \text{Lt} := 0.487\)-in

Min. external diameter of insert \( \text{Fmin} := 0.310\)-in

Depth of recess for insert \( \text{lr} := 0.02\)-in

This file uses the calculations shown in \escfil02\2111_mathcad\8307_bolts\thread_data.mcd
**Washer Data**

Thickness of washer \( t_w := 0.078 \text{ in} \)

Outer Diameter of washer \( D_w := 0.531 \text{ in} \)

Inner Diameter of washer \( D_{wi} := 0.252 \text{ in} \)

Bolt head dia. across flats \( d_w := 0.433 \text{ in} \) (used only if there is no washer)

Note: If there is no washer, \( t_w, D_w, \) and \( D_{wi} \) should be zero.

**Flange data**

Thickness of flange 1 \( t_{f1} := 0.375 \text{ in} \) (Ref. SDG39135779-001)

Thickness of flange 2 \( t_{f2} := 0.375 \text{ in} \) (Length of insert)

Diameter of hole \( D_{hole} := 0.289 \text{ in} \) (Ref. SDG39135779-001)

**Material Property Data**

**Bolt**

Temperature correction factor for bolt strength ultimate
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Temperature correction factor for bolt modulus
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \times 10^6 \text{ psi}\right) \)

Ultimate tensile allowable stress \( F_{tu_{\text{bolt}}} := 200000 \text{ psi} \) (EWB 0420)

Ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 F_{tu_{\text{bolt}}} \)

Bolt yield tensile allowable \( F_{ty_{\text{bolt}}} := 180000 \text{ psi} \) (AMS 5726C)

Ultimate tensile allowable stress
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Ultimate shear allowable stress
(Ref. MS51830)

**Insert**

Temperature correction factor for insert strength \( T_{S_{\text{ins}}} := .97 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} := 140000 \text{ psi} \) (Ref. MS51830)

Ultimate shear allowable stress \( F_{su_{\text{ins}}} := 0.6 F_{tu_{\text{ins}}} \)

**Washer**

Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} := .97 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer \( E_{\text{washer}} := \left(29.1 \times 10^6 \text{ psi}\right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{f1E} := 0.98 \) (modulus) (Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2 \( T_{f2E} := 0.98 \) (modulus)

\( T_{f2s} := 0.97 \) (strength) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear strength allowable for flanges \( F_{su\_f2} := 42000\text{ psi} \) (Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Modulus of elasticity for the parts in the joint \( E_{\text{flange}1} := \left(10.3 \times 10^6\text{ psi}\right) \) \( E_{\text{flange}2} := \left(10.3 \times 10^6\text{ psi}\right) \) (Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Coefficient of thermal expansion for flanges \( \beta_{\text{flange}1\_hot} := 12.8 \times 10^{-6}\text{ in }\text{ in}^{-1} \text{ deg}^{-1} \) \( \beta_{\text{flange}2\_hot} := 12.8 \times 10^{-6}\text{ in }\text{ in}^{-1} \text{ deg}^{-1} \) (Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)

\( \beta_{\text{flange}1\_cold} := 12.1 \times 10^{-6}\text{ in }\text{ in}^{-1} \text{ deg}^{-1} \) \( \beta_{\text{flange}2\_cold} := 12.1 \times 10^{-6}\text{ in }\text{ in}^{-1} \text{ deg}^{-1} \)

Torque/Preload data

Maximum torque (65% of yield) \( T_{\text{max}} := 160\text{ in-lbf} \) Loading plane factor: \( n := 0.5 \)

Minimum torque (95% of max. torque) \( T_{\text{min}} := 152\text{ in-lbf} \) Preload Uncertainty: \( u := 0.25 \)

Torque coefficient: \( k := 0.15 \)

This file uses the calculations shown in \texttt{\textbackslash escfil02\textbackslash 2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC}
Bolt Load data

- Bolt/joint stiffness factor = 0.284
- Max. preload PLDmax = 5639 lbf
- Min. preload PLDmin = 2674.2 lbf
- Joint separation load max(Psep) = 765.6 lbf
- Max. load on the bolt(ultimate) max(Pb) = 5784.7 lbf
- Max. load on the bolt(yield) max(Pby) = 5753.5 lbf
- Bolt ultimate tensile strength PAt = 6844.9 lbf

Length_check = "Bolt length is sufficient"

Preload due to temperature
Pthr_pos = 305.6 lbf
Pthr_neg = -99.1 lbf

Uncertainty factor
u = 0.25

Torque coefficient
k = 0.15

n = 0.5

Loading plane factor
Pths = 13106 lbf
Ppths = 7439.3 lbf

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Component</th>
<th>MS_min,</th>
<th>Description</th>
<th>MS_min,</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1, 1</td>
<td>Direct Thread shear Ultimate</td>
<td>6, 1</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>2, 1</td>
<td>Total Thread shear Ultimate</td>
<td>7, 1</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>3, 1</td>
<td>Shear Ultimate</td>
<td>8, 1</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>4, 1</td>
<td>Bending Ultimate</td>
<td>9, 1</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>5, 1</td>
<td>Combined shear, tension and bending ultimate</td>
<td>10, 1</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

**Minimum Margin of Safety**

Failure_Mode = "Total Tension Yield"

Element Identification and Bolt Number (940147) for Minimum Margin
MS_min_ID = 940147

Load Case Number for Minimum Margin
MS_min_LC = 2053

Applied Tensile Load for Minimum Margin
MS_min_P = 638

Applied Shear Load for Minimum Margin
MS_min_V = 326

Applied Bending Moment for Minimum Margin
MS_min_M = 0
Bolt Fail-Safe Analysis for Lower Support Ring to Outer Cylinder - EWB0420-4H-7 Bolts

It will be assumed that one bolt will fail. Bolt number 940147 has been removed and only load case 2053 is included in the following fail-safe analysis. There are now 51, EWB0420-4H-7 (200 ksi), 0.25-28 UNJF fasteners, holding the Lower Support Ring to the Outer Cylinder. The drawing number illustrating the Outer Cylinder to the Lower Support Ring is SEG39135776.

Close View of Vacuum Case Assembly (Location of fasteners is shown)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```
data_fs := READPRN("LSR_OC_LC2053_fs.txt")

s := 1..rows(data_fs)
```

Fail-safe Loads from Loads Model 2-05

<table>
<thead>
<tr>
<th>Load Case 2053</th>
<th>Applied tensile load</th>
<th>Applied shear load</th>
<th>Applied bending moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_FS_s := data_fs_{s,3} lbf</td>
<td>V_FS_s := data_fs_{s,4} lbf</td>
<td>M_FS_s := data_fs_{s,5} in-lbf</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fail-safe Factors of Safety</th>
<th>Ultimate</th>
<th>SFSu_FS := 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>SFSep_FS := 1.0</td>
<td></td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escg\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC
Bolt Fail-safe Load data

Joint separation load \( \max(P_{\text{sep FS}}) = 824.423 \text{ lbf} \)

Max. load on the bolt (ultimate) \( \max(P_{\text{b FS}}) = 5773.5 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Component</th>
<th>MS_minFS_{1,1}</th>
<th>MS_minFS_{5,1}</th>
<th>Component</th>
<th>MS_minFS_{6,1}</th>
<th>MS_minFS_{7,1}</th>
<th>MS_minFS_{8,1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>2.287</td>
<td>0.289</td>
<td>Total Thread shear Ultimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>6.220</td>
<td>5.13</td>
<td>Shear Ultimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.186</td>
<td>10</td>
<td>Bending Ultimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>6.85</td>
<td>0.1839</td>
<td>Combined shear, tension and bending ultimate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( \text{MS}_{\text{bolt FS}} := \min(\text{MS}_{\text{FS}}) \)

\( \text{MS}_{\text{bolt FS}} = 0.184 \) Failure Mode FS = “Combined Shear Tension Bending Ultimate”

Joint and Load Case Identification:

\( \text{MS}_{\text{min ID}} = 940131 \) Element Identification and Bolt Number (940131) for Minimum Margin

\( \text{MS}_{\text{min LC}} = 2053 \) Load Case Number for Minimum Margin

\( \text{MS}_{\text{min P}} = 824.4 \) Applied Tensile Load for Minimum Margin

\( \text{MS}_{\text{min V}} = 394.8 \) Applied Shear Load for Minimum Margin

\( \text{MS}_{\text{min M}} = 0 \) Applied Bending Moment for Minimum Margin
Cont: Bolt Fail-Safe Analysis for Lower Support Ring to Outer Cylinder EWB0420-4H-7 Bolts

An additional fail-safe check will be performed on the EWB0420-4H-7 fasteners. On page 3.10.4.1-12, analysis will be performed on the EWB0420-4H-13 fasteners with the BACN10HR4CS nut. For this case, the minimum margin of safety was determined to be at Bolt Number 940131, with Load Case 2054. Therefore, this check will apply the new loads from Load Case 2054 without Bolt Number 940131 and will show how the Load Case 2054 will affect the EWB0420-4H-7 fasteners when removing a EWB0420-4H-13 fastener.

![Diagram of Vacuum Case Assembly](image)

Close View of Vacuum Case Assembly
(Location of fasteners is shown)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```plaintext
data_fs1 := READPRN("fs_LSR_OC_LC2054_check.txt")
```

z := 1..rows(data_fs1)

**Fail-safe Loads from Loads Model 2-05**

**Load Case 2054**

- **Applied tensile load**
  \[ P_{FS1} := \text{data}_{fs1}_{z,3} \text{ lbf} \]
  \[ ID_{FS1} := \text{data}_{fs1}_{z,1} \]

- **Applied shear load**
  \[ V_{FS1} := \text{data}_{fs1}_{z,4} \text{ lbf} \]
  \[ LC_{FS1} := \text{data}_{fs1}_{z,2} \]

- **Applied bending moment**
  \[ M_{FS1} := \text{data}_{fs1}_{z,5} \text{ in lbf} \]

**Fail-safe Factors of Safety**

- **Ultimate**
  \[ SFu_{FS} := 1.0 \]

- **Joint Separation**
  \[ SFsep_{FS} := 1.0 \]

This file uses the calculations shown in `\escfil02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`
Bolt Fail-safe Load data

Joint separation load \[ \text{max}(P_{\text{sep}_{\text{FS}}}) = 636.874 \text{lbf} \]

Max. load on the bolt(ultimate) \[ \text{max}(P_{\text{b}_{\text{FS}}}) = 5742.9 \text{lbf} \]

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Description</th>
<th>Minimum Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{\text{min}_{1,1}} = 3.255 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{\text{min}_{2,1}} = 8.346 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{\text{min}_{3,1}} = 0.192 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{\text{min}_{4,1}} = 9.16 )</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt}_{\text{FS}}} := \text{min}(MS_{\text{FS}}) \]

\[ MS_{\text{bolt}_{\text{FS}}} = 0.191 \quad \text{Failure Mode}_{\text{FS}} = \text{"Combined Shear Tension Bending Ultimate"} \]

Joint and Load Case Identification:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Identification and Bolt Number</td>
<td>940147</td>
</tr>
<tr>
<td>Load Case Number</td>
<td>2054</td>
</tr>
<tr>
<td>Applied Tensile Load</td>
<td>636.9</td>
</tr>
<tr>
<td>Applied Shear Load</td>
<td>345.1</td>
</tr>
<tr>
<td>Applied Bending Moment</td>
<td>0</td>
</tr>
</tbody>
</table>

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. The following bolt analysis will analyze the EWB0420-4H-13 (200 ksi), 0.25-28 UNJF fasteners. There is a total of 116, EWB 0420-4H-13, fasteners used to attach the Lower Support Ring to the Outer Cylinder. A total of 6 load cases (2019, 2020, 2031, 2032, 2053, 2054) are included in the NASPOST run. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.

data := READPRN("LSR_OC_250nut_abortland.txt")

Flange 1: Outer Cylinder
Part number: SDG39135779-001
Material: 7050-T7451, AMS 4108

Flange 2: Lower Support Ring
Part number: SEG39135787-301
Material: 7050-T7451, AMS 4108

Loads

Applied tensile load \( P_s := \text{data}_s,3 \text{lbf} \) \( ID_s := \text{data}_s,1 \)

Applied shear load \( V_s := \text{data}_s,4 \text{lbf} \) \( LC_s := \text{data}_s,2 \)

Applied bending moment \( M_s := \text{data}_s,5 \text{in-lbf} \)

Factors of Safety

Ultimate \( SF_u := 1.4 \) Yield \( SF_y := 1.1 \) Assembly \( Temp_{initial} := 70\text{-deg} \)

Joint Separation \( SF_{sep} := 1.2 \) Fitting factor \( FF := 1.15 \) Maximum \( Temp_{max} := 150\text{-deg} \)

Minimum \( Temp_{min} := 40\text{-deg} \)

Bolt and Nut Data

Nominal diameter of bolt \( D := 0.250\text{-in} \) Number of threads/inch \( Nt := 28\cdot\frac{1}{\text{in}} \)

Total length of bolt \( L := 1.2995\text{-in} \) Height of nut \( H := 0.280\text{-in} \)

Threaded length \( Lt := 0.487\text{-in} \) (If bolt is fully threaded, input \( Lt = L \))

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
Bolts from Lower Support Ring to Outer Cylinder

Washer Data
Thickness of washers \( t_w := 0.141 \text{-in} \)
(Includes thickness of NAS1587-4C and NAS1149E0463R)
Outer Diameter of washer \( D_w := 0.531 \text{-in} \)
Inner Diameter of washer \( D_{wi} := 0.252 \text{-in} \)

Flange data
Thickness of flange 1 \( t_1 := .375 \text{-in} \)
Thickness of flange 2 \( t_2 := .375 \text{in} \)
Diameter of hole \( D_{hole} := 0.289 \text{-in} \)

Bolt head dia. across flats \( d_w := 0.433 \text{-in} \)
Note: If there is no washer \( t_w \), \( D_w \) and \( D_{wi} \) should be zero

Material Property Data
Bolt
Temperature correction factor for bolt strength ultimate
\( T_S_{bolt} := 0.97 \)
Yield \( T_S_{y_{bolt}} := 0.97 \)

Bolt ultimate tensile allowable stress
\( F_{tu_{bolt}} := 200000 \text{-psi} \)
(EWB 0420)

Bolt ultimate shear allowable stress
\( F_{su_{bolt}} := 0.6 \times F_{tu_{bolt}} \)

Bolt yield Tensile allowable stress
\( F_{ty_{bolt}} := 180000 \text{-psi} \)
(AMS 5726C)

Temperature correction factor for bolt modulus
\( T_E_{bolt} := 0.98 \)
(Ref. MIL-HDBK-5J, fig. 6.2.1.4(a))

Modulus of elasticity of bolt
\( E_{bolt} := \left( 29.1 \times 10^6 \text{-psi} \right) \)
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Thermal coefficient for bolt
\( \beta_{bolt_{hot}} := 9.1 \times 10^{-6} \text{-in/in/deg} \)
\( \beta_{bolt_{cold}} := 8.9 \times 10^{-6} \text{-in/in/deg} \)

Nut
Temperature correction factor for nut strength
\( T_S_{nut} := 0.97 \)

Ultimate tensile allowable stress
\( F_{tu_{nut}} := 220000 \text{-psi} \)
(Ref. BACN10HR)

Ultimate Shear allowable stress:
\( F_{su_{nut}} := 0.6 \times F_{tu_{nut}} \)

Ultimate axial strength of nut
\( P_{tu_{nut}} := 7973 \text{-lbf} \)
\( 220/125=1.76, 4530*1.76=7973, \)
(AMS 5726C)

Washer
Temperature correction factor for washer modulus
\( T_E_{washer} := .97 \)

Modulus of elasticity of washer:
\( E_{washer} := \left( 29.1 \times 10^6 \text{-psi} \right) \)
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1}E := 0.98 \text{ (modulus)} \]  
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2

\[ T_{f2}E := 0.98 \]

Modulus of elasticity for the parts in the joint

\[ E_{flange1} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{flange2} := \left(10.3 \times 10^6 \text{ psi}\right) \]
(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Coefficient of thermal expansion for flanges

\[ \beta_{flange1\_hot} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{flange2\_hot} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
(Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)

\[ \beta_{flange1\_cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{flange2\_cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data

Maximum torque (65% of yield) \[ T_{max} := 160\text{-in-lbf} \]
Loading plane factor \[ n := 0.5 \]
Minimum torque (95% of max. torque) \[ T_{min} := 152\text{-in-lbf} \]
Preload Uncertainty \[ u := 0.25 \]
Torque coefficient \[ k := 0.15 \]

This file uses the calculations shown in \textbackslash escfili02\textbackslash 2i11_matcad\8307_bolts\multi\_bolt\_stiffness\_nut\_RevC
Bolt Load data

Bolt/joint stiffness factor \( = 0.28 \)
Preload due to temperature \( P_{\text{thrd pos}} = 242.6 \text{lbf} \)
Max. preload \( P_{\text{LD max}} = 5576 \text{lbf} \)
Min. preload \( P_{\text{LD min}} = 2694.6 \text{lbf} \)
Joint separation load \( \max(P_{\text{sep}}) = 1057.2 \text{lbf} \)
Torque coefficient \( k = 0.15 \)
Max. load on the bolt(ultimate) \( \max(P_{\text{b}}) = 5774.8 \text{lbf} \)
Loading plane factor \( n = 0.5 \)
Max. load on the bolt(yield) \( \max(P_{\text{by}}) = 5732.2 \text{lbf} \)
Thread pullout strength required to develop full strength of bolt \( P_{\text{As}} = 8213.8 \text{lbf} \)
Bolt ultimate tensile strength \( P_{\text{At}} = 6844.9 \text{lbf} \)
Nut ultimate tensile strength \( P_{\text{tu nut}} = 7733.8 \text{lbf} \)

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MS_min (_{i,j} )</th>
<th>Description</th>
<th>MS_min (_{k,l} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1.578</td>
<td>Direct Thread shear Ultimate</td>
<td>4.791</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>3.826</td>
<td>Total Thread shear Ultimate</td>
<td>0.422</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>4.528</td>
<td>Shear Ultimate</td>
<td>6.29</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.185</td>
<td>Bending Ultimate</td>
<td>10</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.075</td>
<td>Combined shear, tension and bending ultimate</td>
<td>0.184</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MSbolt} := \min(\text{MS}) \]

\[ \text{MSbolt} = 0.075 \]

Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

Element Identification and Bolt Number (940131) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Lower Support Ring to Outer Cylinder - EWB0420-4H-13 Bolts

It will be assumed that one bolt will fail. Bolt number 940131 has been removed and only load case 2054 is included in the following fail-safe analysis. There are now 115, EWB0420-4H-13 (200 ksi), 0.25-28 UNJF fasteners, holding the Lower Support Ring to the Outer Cylinder. The drawing number illustrating the Outer Cylinder to the Lower Support Ring is SEG39135776.

Close View of Vacuum Case Assembly
(Location of fasteners is shown)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```
data_fs := READPRN("LSR_OC_LC2054_fs.txt")
s := 1..rows(data_fs)
```

**Fail-safe Loads from Loads Model 2-05**

**Load Case 2054**

<table>
<thead>
<tr>
<th>Applied load</th>
<th>P_{FS} := data_fs_{s,3}, lbf</th>
<th>ID_{FS} := data_fs_{s,1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear load</td>
<td>V_{FS} := data_fs_{s,4}, lbf</td>
<td>LC_{FS} := data_fs_{s,2}</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_{FS} := data_fs_{s,5}, in-lbf</td>
<td></td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>SFu_{FS} := 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>SFsep_{FS} := 1.0</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escf\iil02\2\11_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC
Bolt Fail-safe Load data

Joint separation load  \[ \text{max}(P_{\text{sep FS}}) = 1137.236 \text{lbf} \]

Max. load on the bolt(ultimate)  \[ \text{max}(P_{b FS}) = 5759.3 \text{lbf} \]

Summary of fail-safe Margins for bolt:

- Joint separation  \[ MS_{\text{min FS}}_{1,1} = 1.396 \]
- Direct Tension Ultimate  \[ MS_{\text{min FS}}_{2,1} = 4.234 \]
- Total Tension Ultimate  \[ MS_{\text{min FS}}_{3,1} = 0.188 \]
- Direct Thread shear Ultimate  \[ MS_{\text{min FS}}_{4,1} = 5.28 \]

Total Thread shear Ultimate  \[ MS_{\text{min FS}}_{5,1} = 0.426 \]
Shear Ultimate  \[ MS_{\text{min FS}}_{6,1} = 7.43 \]
Bending Ultimate  \[ MS_{\text{min FS}}_{7,1} = 10 \]
Combined shear, tension and bending ultimate  \[ MS_{\text{min FS}}_{8,1} = 0.1880 \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt FS}} := \text{min}(MS_{FS}) \]

\[ MS_{\text{bolt FS}} = 0.188 \]

Failure Mode FS = “Combined Shear Tension Bending Ultimate”

Joint and Load Case Identification:

Element Identification and Bolt Number (940132) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
Cont: Bolt Fail-Safe Analysis for Lower Support Ring to Outer Cylinder EWB0420-4H-13 Bolts

An additional fail-safe check will be performed on the EWB0420-4H-13 fasteners. On page 3.10.4.1-4, analysis was performed on the EWB0420-4H-7 fasteners with the MS51830CA202L insert. For this case, the minimum margin of safety was determined to be at Bolt Number 940147, with Load Case 2053. Therefore, this check will apply the new loads from Load Case 2053 without Bolt Number 940147 and will show how the Load Case 2053 will affect the EWB0420-4H-13 fasteners when removing a EWB0420-4H-7 fastener.

![Diagram of Upper Support Ring and Outer Cylinder with EWB0430-4H-13 and EWB0430-4H-7 notations]

Close View of Vacuum Case Assembly  
(Location of fasteners is shown)

**Reading database file for bolted interface, abort landing case**

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```plaintext
data_fs2 := READPRN("fs_LSR_OC_LC2053_check.txt")
x := 1..rows(data_fs2)
```

**Fail-safe Loads from Loads Model 2-05**

**Load Case 2053**

<table>
<thead>
<tr>
<th>Applied load</th>
<th>Load expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load</td>
<td>(P_{FS2} = data_{fs2,x,3}, \text{lbf})</td>
</tr>
<tr>
<td>Shear load</td>
<td>(V_{FS2} = data_{fs2,x,4}, \text{lbf})</td>
</tr>
<tr>
<td>Bending moment</td>
<td>(M_{FS2} = data_{fs2,x,5}, \text{in-lbf})</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>(SF_{U,F,S} := 1.0)</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>(SF_{Sep,F,S} := 1.0)</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfl02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC`
Bolt Fail-safe Load data

Joint separation load \[ \text{max}(P_{\text{sep FS}}) = 824.423 \text{ lbf} \]

Max. load on the bolt(ultimate) \[ \text{max}(P_{b \text{ FS}}) = 5708.9 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

| Joint separation | MS\_minFS\_1,1 = 2.306 | Total Thread shear Ultimate | MS\_minFS\_5,1 = 0.439 |
| Direct Tension Ultimate | MS\_minFS\_2,1 = 6.220 | Shear Ultimate | MS\_minFS\_6,1 = 8.76 |
| Total Tension Ultimate | MS\_minFS\_3,1 = 0.199 | Bending Ultimate | MS\_minFS\_7,1 = 10 |
| Direct Thread shear Ultimate | MS\_minFS\_4,1 = 7.66 | Combined shear, tension and bending ultimate | MS\_minFS\_8,1 = 0.1985 |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{\text{bolt FS}} := \min(\text{MS}_{\text{FS}}) \]

\[ \text{MS}_{\text{bolt FS}} = 0.198 \]

Failure Mode\_FS = “Combined Shear Tension Bending Ultimate”

Joint and Load Case Identification:

| MS\_min_ID = 940131 | Element Identification and Bolt Number (940131) for Minimum Margin |
| MS\_min_LC = 2053 | Load Case Number for Minimum Margin |
| MS\_min_P = 824.4 | Applied Tensile Load for Minimum Margin |
| MS\_min_V = 394.8 | Applied Shear Load for Minimum Margin |
| MS\_min_M = 0 | Applied Bending Moment for Minimum Margin |
3.10.4.2 Lower Support Ring to Outer Cylinder - .3125"
Lower Support Ring to Outer Cylinder Bolt Analysis

In the Vacuum Case Assembly, the Lower Support Ring is installed on the Outer Cylinder. Three separate sets of fasteners are used to attach the Lower Support Ring to the Outer Cylinder. The fasteners are EWB0420-5H-7 (200 ksi, 0.3125-24 UNJF), EWB0420-4H-7 (200 ksi, 0.25-28 UNJF), and EWB0420-4H-13 (200 ksi, 0.25-28 UNJF). A total of 200 fasteners are used to attach the Lower Support Ring to the Outer Cylinder. The three sets of fasteners will be analyzed separately. This section will only analyze the EWB0420-5H-7 fasteners. Refer to Section 3.10.4.1 for bolt analysis of fasteners EWB 0420-4H-7 and EWB 0420-4H-13. The drawing number illustrating the Lower Support Ring to the Outer Cylinder is SEG39135776.
Loads model 2-05 was used to retrieve loads at the bolted interfaces. The CBUSH elements were post processed in NASPOST for forces and moments. The CBUSH element identification numbers are 940001-940200. The following table shows the CBUSH element identification numbers corresponding to the appropriate fasteners. A linear gap model was ran for a total of 6 load cases. The load cases include 2019-2020, 2031-2032, 2053-2054 and are all included in the NASPOST run. Note that this bolted interface was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing case combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing case is used in this analysis.

<table>
<thead>
<tr>
<th>CBUSH Element ID's for EWB0420-5H-7</th>
<th>CBUSH Element ID's for EWB0420-4H-7</th>
<th>CBUSH Element ID's for EWB0420-4H-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>940022 THRU 940027</td>
<td>940009 THRU 940011</td>
<td>940001 THRU 940008</td>
</tr>
<tr>
<td>940070 THRU 940075</td>
<td>940019 THRU 940020</td>
<td>940012 THRU 940018</td>
</tr>
<tr>
<td>940118 THRU 940123</td>
<td>940042 THRU 940044</td>
<td>940021</td>
</tr>
<tr>
<td>940166 THRU 940170</td>
<td>940047 THRU 940049</td>
<td>940028 THRU 940041</td>
</tr>
<tr>
<td>940193 THRU 940200</td>
<td>940051 THRU 940059</td>
<td>940045 THRU 940046</td>
</tr>
<tr>
<td>940065 THRU 940067</td>
<td>940060 THRU 940064</td>
<td>940068 THRU 940069</td>
</tr>
<tr>
<td>940100 THRU 940108</td>
<td>940065 THRU 940069</td>
<td>940076 THRU 940099</td>
</tr>
<tr>
<td>940115 THRU 940116</td>
<td>940013 THRU 940014</td>
<td>940009 THRU 940011</td>
</tr>
<tr>
<td>940147 THRU 940155</td>
<td>940014 THRU 940015</td>
<td>940007 THRU 940076</td>
</tr>
<tr>
<td>940161 THRU 940163</td>
<td>940018 THRU 940019</td>
<td>940012 THRU 940018</td>
</tr>
<tr>
<td>940173 THRU 940175</td>
<td>940022 THRU 940023</td>
<td>940001 THRU 940008</td>
</tr>
<tr>
<td>940182 THRU 940184</td>
<td>940024 THRU 940025</td>
<td>940000 THRU 940001</td>
</tr>
<tr>
<td>940156 THRU 940160</td>
<td>940168 THRU 940169</td>
<td>940109 THRU 940114</td>
</tr>
<tr>
<td>940164 THRU 940165</td>
<td>940101 THRU 940112</td>
<td>940017 THRU 940018</td>
</tr>
<tr>
<td>940171 THRU 940172</td>
<td>940176 THRU 940181</td>
<td>940019 THRU 940192</td>
</tr>
<tr>
<td>940179 THRU 940189</td>
<td>940185 THRU 940192</td>
<td>940000 THRU 940001</td>
</tr>
</tbody>
</table>
CHECK BOLTS (EWB0420-5H-7 0.3125"-24 UNJF-3A, Material-A-286), Insert NASM21209F5-20L, Washer NAS1587-5C

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. The following bolt analysis will analyze the EWB0420-5H-7 (200 ksi ), 0.3125-24 UNJF fasteners. There is a total of 32, EWB0420-5H-7, fasteners used to attach the Lower Support Ring to the Outer Cylinder.

```
data := READPRN("LSR_OC_3125int_abortland.txt")
```

Flange 1: Outer Cylinder
Part number: SDG39135779-001
Material: 7050-T7451, AMS 4108

Flange 2: Lower Support Ring
Part number: SEG39135787-301
Material: 7050-T7451, AMS 4108

Loads

<table>
<thead>
<tr>
<th>Applied tensile load</th>
<th>ps := data_s,3,lbf</th>
<th>ID_s := data_s,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear load</td>
<td>vs := data_s,4,lbf</td>
<td>LC_s := data_s,2</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>Ms := data_s,5-in-lbf</td>
<td></td>
</tr>
</tbody>
</table>

Factors of Safety

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>SFu := 1.4</th>
<th>Yield</th>
<th>SFy := 1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>SFsep := 1.2</td>
<td>Fitting factor</td>
<td>FF := 1.15</td>
</tr>
<tr>
<td>Assembly</td>
<td>Temp_initial := 70-deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>Temp_max := 150-deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>Temp_min := 40-deg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bolt and Insert Data

| Nominal diameter of bolt | D := 0.3125-in   | Number of threads/inch | Nt := 24·\(\frac{1}{\text{in}}\) |
| Total length of bolt    | L := 1.0245-in   | Length of insert        | Lins := 0.625-in |
| Threaded length         | Lt := 0.587-in   | Min. external diameter of insert | Fmin := 0.380-in |
|                        |                 | Depth of recess for insert | lr := 0.02-in |

(If bolt is fully threaded, input Lt = L)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

3.10.4.2 - 4
ESC-4005-05-AMS-0039
Washer Data

Thickness of washer \( t_w := 0.078\text{ in} \)
Outer Diameter of washer \( D_w := 0.593\text{ in} \)
Inner Diameter of washer \( D_{wi} := 0.315\text{ in} \)

Bolt head dia. across flats \( d_w := 0.526\text{ in} \) (used only if there is no washer)

Note: If there is no washer, \( t_w, D_w, \text{ and } D_{wi} \) should be zero.

Flange data

Thickness of flange 1 \( t_{f1} := 0.375\text{ in} \)
(Ref. SDG39135779-001)
Thickness of flange 2 \( t_{f2} := 0.625\text{ in} \) (Length of insert)
Diameter of hole \( D_{hole} := 0.357\text{ in} \)
(Ref. SDG39135779-001)

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate \( T_{Su\_bolt} := 0.97 \)
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Bolt ultimate tensile allowable stress \( F_{tu\_bolt} := 200000\text{ psi} \) (EWB 0420)
Bolt ultimate shear allowable stress \( F_{su\_bolt} := 0.6 F_{tu\_bolt} \)
Bolt yield tensile allowable \( F_{ty\_bolt} := 180000\text{ psi} \) (AMS 5726C)
Temperature correction factor for bolt modulus \( T_{E\_bolt} := 0.98 \)
(Ref. MIL-HDBK-5J, fig. 6.2.1.4(a))
Modulus of elasticity of bolt \( E_{\_bolt} := \left(29.1 \times 10^6\text{ psi}\right) \)
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

\[ \beta_{\_bolt\_hot} := 9.1 \times 10^{-6}\frac{\text{in}}{\text{deg}} \quad \beta_{\_bolt\_cold} := 8.9 \times 10^{-6}\frac{\text{in}}{\text{deg}} \]
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

Insert

Temperature correction factor for insert strength \( T_{S\_ins} := 0.97 \)
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Ultimate tensile allowable stress \( F_{tu\_ins} := 140000\text{ psi} \)
(Ref. NASM21209)
Ultimate shear allowable stress \( F_{su\_ins} := 0.6 F_{tu\_ins} \)

Washer

Temperature correction factor for washer modulus \( T_{E\_washer} := 0.97 \)
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Modulus of elasticity of washer \( E_{\_washer} := \left(29.1 \times 10^6\text{ psi}\right) \)
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1} := .98 \quad \text{modulus} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)} \]

Temperature correction factor for flange 2

\[ T_{f2} := .98 \quad \text{modulus} \quad T_{f2s} := .97 \quad \text{strength} \quad \text{(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)} \]

Shear strength allowable for flanges

\[ F_{su_{f2}} := 42000 \; \text{psi} \quad \text{(Ref. MIL-HDBK-5J, table 3.7.4.0(d))} \]

Modulus of elasticity for the parts in the joint

\[ E_{flange1} := \left( 10.3 \times 10^6 \; \text{psi} \right) \quad E_{flange2} := \left( 10.3 \times 10^6 \; \text{psi} \right) \]

Coefficient of thermal expansion for flanges

\[ \beta_{flange1_{hot}} := 12.8 \times 10^{-6} \quad \text{in} \; \text{deg} \quad \beta_{flange2_{hot}} := 12.8 \times 10^{-6} \quad \text{in} \; \text{deg} \]

\[ \beta_{flange1_{cold}} := 12.1 \times 10^{-6} \quad \text{in} \; \text{deg} \quad \beta_{flange2_{cold}} := 12.1 \times 10^{-6} \quad \text{in} \; \text{deg} \]

Torque/Preload data

Maximum torque (65% of yield)

\[ T_{max} := 318.09 \; \text{in-lbf} \]

Minimum torque (95% of max. torque)

\[ T_{min} := 302.2 \; \text{in-lbf} \]

Torque coefficient:

\[ k := 0.15 \]

Loading plane factor:

\[ n := 0.5 \]

Preload Uncertainty:

\[ u := 0.25 \]

This file uses the calculations shown in \escfile{2i11_mathcad\8307\bolts\multi_bolt_stiffness_insert_RevC}
Bolt Load data

Bolt/joint stiffness factor: \( = 0.341 \)

Preload due to temperature: \( P_{\text{thr\_pos}} = 469.7 \text{ lbf} \)

Max. preload: \( PLD_{\text{max}} = 8952.1 \text{ lbf} \)

Uncertainty factor: \( u = 0.25 \)

Min. preload: \( PLD_{\text{min}} = 4258.7 \text{ lbf} \)

Torque coefficient: \( k = 0.15 \)

Joint separation load: \( \max(P_{\text{sep}}) = 585.6 \text{ lbf} \)

Loading plane factor: \( n = 0.5 \)

Max. load on the bolt(ultimate): \( \max(P_b) = 9086 \text{ lbf} \)

Thread shear pullout load of bolt or insert: \( P_{\text{thrs}} = 20145.1 \text{ lbf} \)

Max. load on the bolt(yield): \( \max(P_{by}) = 9057.3 \text{ lbf} \)

Thread shear pullout load in parent metal: \( P_{\text{pthrs}} = 15198.6 \text{ lbf} \)

Bolt ultimate tensile strength: \( PA_T = 10965.6 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

| Joint separation | \( MS_{\text{min\_1,1}} = 6.623 \) | Direct Thread shear Ultimate | \( MS_{\text{min\_6,1}} = 18.345 \) |
| Direct Tension Ultimate | \( MS_{\text{min\_2,1}} = 12.957 \) | Total Thread shear Ultimate | \( MS_{\text{min\_7,1}} = 0.673 \) |
| Direct Tension Yield | \( MS_{\text{min\_3,1}} = 14.987 \) | Shear Ultimate | \( MS_{\text{min\_8,1}} = 3.15 \) |
| Total Tension Ultimate | \( MS_{\text{min\_4,1}} = 0.207 \) | Bending Ultimate | \( MS_{\text{min\_9,1}} = 10 \) |
| Total Tension Yield | \( MS_{\text{min\_5,1}} = 0.090 \) | Combined shear, tension and bending ultimate | \( MS_{\text{min\_10,1}} = 0.202 \) |

Determination of the smallest margin of safety for the bolt, and the failure mode:

\( MS_{\text{bolt}} = \min(\text{MS}) \)

\( MS_{\text{bolt}} = 0.09 \)

Minimum Margin of Safety

Failure_Mode = "Total Tension Yield"

| \( MS_{\text{min\_ID}} = 940025 \) | Element Identification and Bolt Number (940025) for Minimum Margin |
| \( MS_{\text{min\_LC}} = 2031 \) | Load Case Number for Minimum Margin |
| \( MS_{\text{min\_P}} = 488 \) | Applied Tensile Load for Minimum Margin |
| \( MS_{\text{min\_V}} = 291 \) | Applied Shear Load for Minimum Margin |
| \( MS_{\text{min\_M}} = 0 \) | Applied Bending Moment for Minimum Margin |
Bolt Fail-Safe Analysis for Lower Support Ring to Outer Cylinder - EWB0420-5H-7 Bolts

It will be assumed that one bolt will fail. Bolt number 940025 has been removed and only load case 2031 is included in the following fail-safe analysis. There are now 31, EWB0420-5H-7 (200 ksi), 0.3125-24 UNJF fasteners, holding the Lower Support Ring to the Outer Cylinder. The drawing number illustrating the Outer Cylinder to the Lower Support Ring is SEG39135776.

![Diagram of bolt assembly](image)

Close View of Vacuum Case Assembly (Location of fasteners is shown)

Reading database file for bolted interface, abort landing case

Note that ".txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```
data_fs := READPRN("LSR_OC_LC2031_fs.txt")
s := 1., rows(data_fs)
```

### Fail-safe Loads from Loads Model 2-05

#### Load Case 2031

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Applied Load</th>
<th>Load Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load</td>
<td>P&lt;sub&gt;FS&lt;/sub&gt; := data&lt;sub&gt;fs&lt;/sub&gt; s,3 lbf</td>
<td>ID&lt;sub&gt;FS&lt;/sub&gt; s := data&lt;sub&gt;fs&lt;/sub&gt; s,1</td>
</tr>
<tr>
<td>Shear load</td>
<td>V&lt;sub&gt;FS&lt;/sub&gt; := data&lt;sub&gt;fs&lt;/sub&gt; s,4 lbf</td>
<td>LC&lt;sub&gt;FS&lt;/sub&gt; s := data&lt;sub&gt;fs&lt;/sub&gt; s,2</td>
</tr>
<tr>
<td>Bending moment</td>
<td>M&lt;sub&gt;FS&lt;/sub&gt; := data&lt;sub&gt;fs&lt;/sub&gt; s,5 in-lbf</td>
<td></td>
</tr>
</tbody>
</table>

### Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Condition</th>
<th>SF&lt;sub&gt;FS&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>1.0</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`
Bolt Fail-safe Load data

Joint separation load \( \max(P_{\text{sep\_FS}}) = 792.577 \text{lbf} \)

Max. load on the bolt(ultimate) \( \max(P_{\text{b\_FS}}) = 9107.5 \text{lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th></th>
<th>( \text{MS}_{\text{min_FS}} )</th>
<th>( \text{MS}_{\text{min_FS}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>4.633</td>
<td>0.669</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>10.000</td>
<td>5.11</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.204</td>
<td>10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>10</td>
<td>0.2033</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MS}_{\text{bolt\_FS}} := \min(\text{MS}_{\text{FS}})
\]

\[
\text{MS}_{\text{bolt\_FS}} = 0.203 \\
\text{Failure\_Mode}_{\text{FS}} = "\text{Combined Shear Tension Bending Ultimate}" \\
\]

Joint and Load Case Identification:

- **Element Identification and Bolt Number (940035) for Minimum Margin**
- **Load Case Number for Minimum Margin**
- **Applied Tensile Load for Minimum Margin**
- **Applied Shear Load for Minimum Margin**
- **Applied Bending Moment for Minimum Margin**
3.10.5 Clevis Plate to Upper Support Ring
Clevis Plate to Upper Support Ring Bolt Analysis

Two clevis plates will be installed in the Vacuum Case assembly. There are a total of 6 fasteners attaching the Clevis Plate to the Upper Support Ring. The fasteners are NAS1958C9 (180 ksi), 0.50-20 UNJF. The drawing number illustrating the Clevis Plate to the Upper Support Ring is SEG39135776.

Loads model 2-04 was used to retrieve loads at the two bolted interfaces. Refer to Appendix A12 for NASPOST results. Note that this joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The launch case combined with launch temperature data resulted in the lowest minimum margins of safety. Therefore, the launch case is used in this analysis.
Lug analysis was performed to calculate the axial and transverse loads. The complete lug analysis analysis can be found in Section 3.8. Note that the load obtained from loads model 2-04 is a compressive load.

Angle of applied force: \( \beta := [90 - (110.3078 - 90)] \)·deg \( \beta = 69.692 \)·deg

Applied force: \( f := 34052.77 \)·lbf (Obtained from loads model 2-04, Launch Case)

Axial load is:
\[
Py_{\text{lug}} := \frac{f}{2} \cdot \cos(\beta)
\]
\[
Py_{\text{lug}} = 5909 \text{-lbf}
\]

Transverse load is:
\[
Pz_{\text{lug}} := \frac{f}{2} \cdot \sin(\beta)
\]
\[
Pz_{\text{lug}} = 15968 \text{-lbf}
\]

The following are the loads on the clevis pin. Section 2.1.14.2 includes a complete analysis of the clevis pin for the Clevis Plate.

Axial load on section \( Py_{\text{pin}} := 2 \cdot Py_{\text{lug}} \) \( Py_{\text{pin}} = 11818 \)·lbf

Transverse load on section \( Pz_{\text{pin}} := 2 \cdot Pz_{\text{lug}} \) \( Pz_{\text{pin}} = 31936 \)·lbf
Bolts from Clevis Plate to Upper Support Ring

**Forces at the Bolts:**

Distance from pin to base
\[ \text{dy1} := 1.745 \text{-in} \]

Distance between bolts:
\[ \text{dz1} := 4.625 \text{-in} \]

Resultant moment at end of base
\[ \text{Mbase} := \text{Pz-pin-dy1} \]
\[ \text{Mbase} = 55729 \text{-in-lbf} \]

Bolt tensile force
\[ \text{P} := \frac{\text{Mbase}}{3 \cdot \text{dz1}} + \frac{\text{Py-pin}}{6} \]
\[ \text{P} = 5986 \text{-lbf} \]

Bolt shear force
\[ \text{V} := \frac{\text{Pz-pin}}{6} \]
\[ \text{V} = 5323 \text{-lbf} \]
CHECK BOLTS (NAS1958C9 bolts 0.500-20UNJF-3A, Material-A-286), Insert MS51831CA-206L, Washer NAS1587-8C

Flange 1: Clevis Plate
Part number: SDG39135790
Material: CRES A-286, AMS 5737

Flange 2: Upper Support Ring
Part number: SEG39135786
Material: 7050-T7451, AMS 4108

Loads - loads model 2-04 (f=34052.77) LC=1032

Applied tensile load $P := 5986$-lbf
Applied shear load $V := 5323$-lbf
Applied bending moment $M := 0$-in-lbf

Factors of Safety

Ultimate $SF_u := 1.4$ Yield $SF_y := 1.1$
Joint Separation $SF_{sep} := 1.2$ Fitting factor $FF := 1.15$

Temperature Data (Ref Appendix C2), Launch Case

Assembly
Temp_initial := 70-deg

Maximum
Temp_max := 120-deg

Minimum
Temp_min := 40-deg

Bolt and Insert Data

Nominal diameter of bolt $D := 0.500$-in
Total length of bolt $L := 1.297$-in
Threaded length $L_t := 0.735$-in
(If bolt is fully threaded, input $L_t = L$)

Number of threads/inch $N_t := 20 \cdot \frac{1}{\text{in}}$
Length of insert $L_{ins} := 0.688$-in
Min. external diameter of insert $F_{min} := 0.615$-in
Depth of recess for insert $l_r := 0.02$-in

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Washer Data

Thickness of washer $tw := 0.078$-in
Outer Diameter of washer $D_w := 0.875$-in
Inner Diameter of washer $D_{wi} := 0.504$-in
Bolt head dia. across flats $d_w := 0.710$-in

Flange data

Thickness of flange 1 (SDG39135790) $tf_1 := 0.500$-in
Thickness of flange 2 (Length of insert) $tf_2 := 0.688$-in
Diameter of hole (SDG39135790) $D_{hole} := 0.508$-in

Note: If there is no washer, $tw$, $D_w$, and $D_{wi}$ should be zero.
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate
\( TS_{u \_ bolt} := .97 \) yield \( TS_{y \_ bolt} := .97 \)

Bolt ultimate tensile allowable stress
\( Fu_{\_ bolt} := 180000 \text{ psi} \) (NAS1958)

Bolt ultimate shear allowable stress
\( Fs_{\_ bolt} := 0.6 \times Fu_{\_ bolt} \)

Bolt yield tensile allowable
\( Fy_{\_ bolt} := 132353 \text{ psi} \) (Ref. Appendix C10)

Temperature correction factor for bolt modulus
\( TE_{\_ bolt} := .98 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4 (a))

Modulus of elasticity of bolt
\( E_{\_ bolt} := \left( 29.1 \times 10^6 \text{ psi} \right) \)
(Ref. MIL-HDBK-5J, table 6.2.1.0 (b))

Thermal coefficient for bolt:
\( \beta_{\_ bolt \_ hot} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
\( \beta_{\_ bolt \_ cold} := 8.9 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

Insert

Temperature correction factor for insert strength
\( TS_{\_ ins} := .97 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Ultimate tensile allowable stress
\( Fu_{\_ ins} := 140000 \text{ psi} \) (Ref. MS51831)

Ultimate shear allowable stress
\( Fs_{\_ ins} := 0.6 \times Fu_{\_ ins} \)

Washer

Temperature correction factor for washer modulus
\( TE_{\_ washer} := .97 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer
\( E_{\_ washer} := \left( 29.1 \times 10^6 \text{ psi} \right) \)
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1E} := .97 \quad \text{(modulus)} \]

(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Temperature correction factor for flange 2

\[ T_{f2E} := .99 \quad \text{(modulus)} \]

(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

\[ T_{f2s} := .98 \quad \text{(strength)} \]

(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear strength allowable for flanges

\[ F_{s_u2} := 44000\,\text{psi} \]

(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange}1} := \left(29.1 \times 10^6\,\text{psi} \right) \]

(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

\[ E_{\text{flange}2} := \left(10.3 \times 10^6\,\text{psi} \right) \]

(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange}1\_\text{hot}} := 9.1 \times 10^{-6}\,\frac{\text{in}}{\text{in}}\,\text{deg} \]

(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

\[ \beta_{\text{flange}1\_\text{cold}} := 9.0 \times 10^{-6}\,\frac{\text{in}}{\text{in}}\,\text{deg} \]

\[ \beta_{\text{flange}2\_\text{hot}} := 12.8 \times 10^{-6}\,\frac{\text{in}}{\text{in}}\,\text{deg} \]

(Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)

\[ \beta_{\text{flange}2\_\text{cold}} := 12.3 \times 10^{-6}\,\frac{\text{in}}{\text{in}}\,\text{deg} \]

Torque/Preload data

Maximum torque (65% of Yield)

\[ T_{\text{max}} := 1032\,\text{in-lbf} \]

Loading plane factor: \[ n := .5 \]

Minimum torque (95% of max. torque)

\[ T_{\text{min}} := 980\,\text{in-lbf} \]

Preload Uncertainty: \[ u := 0.25 \]

Torque coefficient: \[ k := 0.15 \]

This file uses the calculations shown in \esceil02\2i11_mathcad\8307_bolts\bolt_stiffness_insert_RevC
**Bolt Load data**

Bolt/joint stiffness factor  \( = 0.305 \)

Preload due to temperature \( P_{\text{thrm}} = 491.4 \text{ lbf} \)

Max. preload \( P_{\text{LDMax}} = 17691.4 \text{ lbf} \)

Min. preload \( P_{\text{LDMin}} = 8663.4 \text{ lbf} \)

Joint separation load \( P_{\text{Sep}} = 7183.2 \text{ lbf} \)

Uncertainty factor \( u = 0.25 \)

Torque coefficient \( k = 0.15 \)

Max. load on the bolt(ultimate) \( P_b = 19161.9 \text{ lbf} \)

Max. load on the bolt(yield) \( P_{by} = 18846.8 \text{ lbf} \)

Bolt ultimate tensile strength \( P_{At} = 27425.9 \text{ lbf} \)

Length check = "Bolt length is sufficient"

**Summary of Margins for bolt:**

- Joint separation \( MS_1 = 0.238 \)
  Direct Thread shear Ultimate \( MS_6 = 1.97 \)

- Direct Tension Ultimate \( MS_2 = 1.85 \)
  Total Thread shear Ultimate \( MS_7 = 0.5 \)

- Direct Tension Yield \( MS_3 = 1.66 \)
  Shear Ultimate \( MS_8 = 0.82 \)

- Total Tension Ultimate \( MS_4 = 0.43 \)
  Bending Ultimate \( MS_9 = 10 \)

- Total Tension Yield \( MS_5 = 0.07 \)
  Combined shear, tension and bending ultimate \( MS_{10} = 0.205 \)

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

\[
MS_{\text{bolt}} := \min(\text{MS}) \\
MS_{\text{bolt}} = 0.070 \\
\text{Failure Mode = "Total Tension Yield"}
\]
Bolt Fail-Safe Analysis for Clevis Plate to Upper Support Ring

It will be assumed that one bolt will fail. There are now five, NAS1958C9 0.50-20 UNJF fasteners, holding the Clevis Plate to the Upper Support Ring. The drawing number illustrating the Clevis Plate to the Upper Support Ring is SEG39135776.

Determining Fail Safe Loads:

\[
ftfs := \frac{M_{\text{base}}}{3 \cdot d_z 1} + \frac{P_y_{\text{pin}}}{5} \quad ftfs = 6380.163\text{lbf}
\]

\[
fsfs := \frac{P_z_{\text{pin}}}{5} \quad fsfs = 6387.222\text{lbf}
\]

**Fail-safe Loads. Launch case**

**Fail-safe Factors of Safety**

- Applied tensile load: \( P_{\text{FS}} := 6380\text{lbf} \)
  - Ultimate: \( SFu_{\text{FS}} := 1.0 \)
- Applied shear load: \( V_{\text{FS}} := 6387\text{lbf} \)
  - Joint Separation: \( SFsep_{\text{FS}} := 1.0 \)
- Applied bending moment: \( M_{\text{FS}} := 0\text{in-lbf} \)

This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\bolt_stiffness_insert_FS_RevC

---

**Bolt Fail-safe Load data**

- Joint separation load: \( P_{\text{sepFS}} = 6380\text{lbf} \)
- Max. load on the bolt(ultimate): \( P_{b_{\text{FS}}} = 18810.9\text{lbf} \)

**Summary of fail-safe Margins for bolt:**

- Joint separation: \( MS_{\text{FS}}_1 = 0.393 \)
- Direct Tension Ultimate: \( MS_{\text{FS}}_2 = 2.74 \)
- Total Tension Ultimate: \( MS_{\text{FS}}_3 = 0.458 \)
- Direct Thread shear Ultimate: \( MS_{\text{FS}}_4 = 2.91 \)
- Total Thread shear Ultimate: \( MS_{\text{FS}}_5 = 0.52 \)
- Shear Ultimate: \( MS_{\text{FS}}_6 = 1.12 \)
- Bending Ultimate: \( MS_{\text{FS}}_7 = 10 \)
- Combined shear, tension and bending ultimate: \( MS_{\text{FS}}_8 = 0.285 \)

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ MS_{\text{boltFS}} := \min(MS_{\text{FS}}) \]

\[ MS_{\text{boltFS}} = 0.285 \quad \text{Failure Mode}_{\text{FS}} = "\text{Combined Shear Tension Bending Ultimate}" \]
3.10.6 Upper Interface Plate to Vacuum Case
**Upper Interface Plate to Vacuum Case Bolt Analysis**

The Vacuum Case Assembly consists of four upper interface plates. There are a total of 12 fasteners attaching the upper interface plate to the vacuum case. The fasteners are NAS1956C10 (4 bolts), NAS1956C8 (6 bolts), and NAS1956C7 (2 bolts), 180 ksi, 0.375-24 UNJF. Fastener NAS1956C10 will experience a higher load and therefore the following bolt analysis will assume that all bolts are NAS1956C10. There is also one shear pin 0.875" in diameter. The drawing number for the Vacuum Case Assembly is SEG39135776.

**Bolt Geometry**

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
</tbody>
</table>

\[\text{bolt} := \begin{pmatrix}
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375
\end{pmatrix} \quad 24\]

\[\text{i} := 1 \ldots \text{rows(bolt)}\]

\[\text{N}_i := \text{bolt}, \quad \frac{1}{\text{in}} \quad \text{pitch of bolt}\]

\[\text{D}_i := \text{bolt}, \quad \frac{1}{\text{in}} \quad \text{bolt diameter}\]

\[\text{At}_i = \beta \left( \frac{\text{D}_i - 0.9743}{\text{N}_i^2} \right)^2 \quad \text{Tensile Area of bolt}\]

\[\text{As}_i = \beta \left( \frac{\text{D}_i - 1.299038}{\text{N}_i^2} \right)^2 \quad \text{Shear Area of bolt}\]
Title: Bolts from Upper Interface Plate to Vacuum Case

Upper Interface Plate to Vacuum Case Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.0</td>
<td>1.362</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>1.362</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.0</td>
<td>1.362</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.0</td>
<td>-1.563</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.563</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>3.0</td>
<td>-1.563</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>-1.75</td>
<td>-2.838</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>1.75</td>
<td>-2.838</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-4.5</td>
<td>1.362</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>4.5</td>
<td>1.362</td>
</tr>
<tr>
<td>11</td>
<td>0.0</td>
<td>-4.5</td>
<td>-1.563</td>
</tr>
<tr>
<td>12</td>
<td>0.0</td>
<td>4.5</td>
<td>-1.563</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
\text{cgload} := \begin{pmatrix} xforce \\ yforce \\ zforce \end{pmatrix} \quad \text{cgload} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

xforce := 0.0in  \quad yforce := 0.0in  \quad zforce := 0.0in
Center of gravity of bolt group

\[
\begin{align*}
\text{xcg} := & \frac{\sum x_i}{\text{rows}(x)} & \text{ycg} := & \frac{\sum y_i}{\text{rows}(y)} & \text{zcg} := & \frac{\sum z_i}{\text{rows}(z)} \\
x_{cg} = & 0 \text{ in} & y_{cg} = & 0 \text{ in} & z_{cg} = & 0.557 \text{ in}
\end{align*}
\]

\[
\begin{bmatrix}
\text{xcg} \\ \text{ycg} \\ \text{zcg}
\end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -0.557 \end{bmatrix} \text{ in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. In the z direction the bolt pattern is unsymmetric and has a -0.557" offset from the center of gravity.

Load Vector

\[
\mathbf{r}_{\text{load}} := \mathbf{c}_{g\text{load}} - \mathbf{c}_{gbolt}
\]

\[
\mathbf{r}_{\text{load}} = \begin{bmatrix} 0 \\ 0 \\ 0.557 \end{bmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(x_i - x_{cg})^2 + (y_i - y_{cg})^2}
\]

\[
r = \begin{bmatrix} 3.561 \\ 1.919 \\ 3.561 \\ 3.164 \\ 1.006 \\ 3.164 \\ 2.875 \\ 2.875 \\ 4.892 \\ 4.892 \\ 4.611 \\ 4.611 \end{bmatrix} \text{ in}
\]

Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 64001, 64002, 64003, and 64004. These loads are read into an array and distributed out to the 12 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis.)
**Reading database file for bolted joint, abort landing case**

data := READPRN("upperipvcf_r2_abortland.txt")
num_bolts := rows(bolt)
j := 1..rows(data)

**Loads from 2-04 loads model, abort landing case**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Expression</th>
<th>Load Case</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Load</td>
<td>$F_{x_{j}} := \text{data}_{j,3}\text{-lbf}$</td>
<td>Torsion</td>
<td>$M_{x_{j}} := \text{data}_{j,6}\text{-in-lbf}$</td>
</tr>
<tr>
<td>Shear in Y axis</td>
<td>$F_{y_{j}} := \text{data}_{j,4}\text{-lbf}$</td>
<td>Moment about Y axis</td>
<td>$M_{y_{j}} := \text{data}_{j,7}\text{-in-lbf}$</td>
</tr>
<tr>
<td>Shear in Z axis</td>
<td>$F_{z_{j}} := \text{data}_{j,5}\text{-lbf}$</td>
<td>Moment about Z axis</td>
<td>$M_{z_{j}} := \text{data}_{j,8}\text{-in-lbf}$</td>
</tr>
<tr>
<td>Element Identification</td>
<td>$\text{ID}<em>{j} := \text{data}</em>{j,1}$</td>
<td>Counter for number of bolts in pattern</td>
<td>$\text{ID}<em>{j} := \text{ID}</em>{j,100} + 1$</td>
</tr>
<tr>
<td>Load Case Number</td>
<td>$\text{LC}<em>{j} := \text{data}</em>{j,2}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Applied Bending Moment at Bolts**

$M_{j} := 0\text{-in-lbf}$

**Format of Output File**

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 64001, 64002, 64003, and 64004, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 64001 will have bolt numbers 01 thru 12 attached to the end for all 64 load cases. This brings the total number of load cases to 3072 (4 joints x 12 bolts x 64 load cases = 3072). See the array example to the right.

ID := stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5, ID + 6, ID + 7, ID + 8, ID + 9, ID + 10, ID + 11)

LC := stack(LC, LC, LC, LC, LC, LC, LC, LC, LC, LC, LC, LC)

The array example is as follows:

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>6400101</td>
<td>2001</td>
</tr>
<tr>
<td>6400101</td>
<td>2002</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6400101</td>
<td>2064</td>
</tr>
<tr>
<td>6400102</td>
<td>2001</td>
</tr>
<tr>
<td>6400102</td>
<td>2002</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6400102</td>
<td>2064</td>
</tr>
</tbody>
</table>

Array Example
Moment Distribution

\[
M_{\text{tot}}^j := \begin{pmatrix} M_{x_j} \\ M_{y_j} \\ M_{z_j} \end{pmatrix} + r_{\text{load}} \times \begin{pmatrix} F_{x_j} \\ F_{y_j} \\ F_{z_j} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg}}^j := M_{\text{tot1},j} \\
Y_{\text{boltcg}}^j := M_{\text{tot2},j} \\
M_{\text{boltcg}}^j := M_{\text{tot3},j}
\]

Tension on bolts

\[
F_{\text{direct},i,j} := \begin{cases} 0 \text{ lbf} & \text{if } F_{x_i} \leq 0 \text{ lbf} \\ \frac{F_{x_i}}{\text{num_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz,i,j} := \begin{cases} 0 \text{ lbf} & \text{if } (y_i - y_{\text{ycg}}) = 0 \text{ in} \\ \frac{M_{z_{\text{boltcg}}}(y_i - y_{\text{ycg}})}{\sum_i (y_i - y_{\text{ycg}})^2 \cdot A_t_i} & \text{otherwise} \end{cases}
\]

\[
F_{my,i,j} := \begin{cases} 0 \text{ lbf} & \text{if } (z_i - z_{\text{zcg}}) = 0 \text{ in} \\ \frac{M_{y_{\text{boltcg}}}(z_i - z_{\text{zcg}})}{\sum_i (z_i - z_{\text{zcg}})^2 \cdot A_t_i} & \text{otherwise} \end{cases}
\]

\[
F_{t,i,j} := F_{\text{direct},i,j} + F_{mz,i,j} + F_{my,i,j}
\]

Total tensile load

Shear on bolts

Secondary shear on bolts

\[
F_{s,i,j} := \frac{M_{x_{\text{boltcg}} \cdot r_{j,i}} \cdot A_s_i}{\sum_i (r_{j,i})^2 \cdot (A_s_i)}
\]

Total shear load

\[
F_{\text{tot},i,j} := F_{s,i,j}
\]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}\begin{bmatrix}
(F_t^T)^{(1)}
, (F_t^T)^{(2)}
, (F_t^T)^{(3)}
, (F_t^T)^{(4)}
, (F_t^T)^{(5)}
, (F_t^T)^{(6)}
, (F_t^T)^{(7)}
, (F_t^T)^{(8)}
, (F_t^T)^{(9)}
, (F_t^T)^{(10)}
, (F_t^T)^{(11)}
, (F_t^T)^{(12)}
\end{bmatrix}
\]

\[
V := \text{stack}\begin{bmatrix}
(F_{stot}^T)^{(1)}
, (F_{stot}^T)^{(2)}
, (F_{stot}^T)^{(3)}
, (F_{stot}^T)^{(4)}
, (F_{stot}^T)^{(5)}
, (F_{stot}^T)^{(6)}
, (F_{stot}^T)^{(7)}
, (F_{stot}^T)^{(8)}
, (F_{stot}^T)^{(9)}
\end{bmatrix}
\]

\[
M := \text{stack}\begin{bmatrix}
M
\end{bmatrix}
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

\[
\text{Output} := \text{augment}\begin{bmatrix}
\text{ID}
, \text{LC}
, \frac{P}{\text{lbf}}
, \frac{V}{\text{lbf}}
, \frac{M}{\text{in-lbf}}
\end{bmatrix}
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

\[
\begin{bmatrix}
6400101 & 2001 & 1011.17 & -358.78 & 0 \\
6400101 & 2002 & 957.81 & -465.51 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
6400101 & 2064 & 645.19 & -160.68 & 0 \\
6400102 & 2001 & 1171.64 & -100.17 & 0 \\
6400102 & 2002 & 1078.73 & -130.24 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
6400102 & 2064 & 832.25 & -86.57 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
6400112 & 2001 & -170.48 & -240.73 & 0 \\
6400112 & 2002 & -357.40 & -312.99 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
6400112 & 2064 & -155.87 & -208.06 & 0
\end{bmatrix}
\]

Size of the "Output" Array: \( \text{rows}(\text{Output}) = 3072 \) 

(12 bolts x 64 load cases) x 4 joints = 3072 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)

Example of Output Array

WRITEPRN("output_forces_upperipvcf_r2_abortland.txt") := Output
CHECK BOLTS (NAS1956C10 0.375-24UNJF-3A, Material-A-286), Insert MS51832CA-204L, Washer NAS1587-6C

The array from the text file above is read:

\[
\begin{align*}
data &= \text{READPRN}("output_forces_upperipvcf_r2_abortland.txt") \\
s &= 1.. \text{rows(data)}
\end{align*}
\]

**Flange 1: Upper Interface Plate**
Part number: SEG39135788
Material: 7050-T7451

**Flange 2: Upper Support Ring Assy**
Part number: SEG39135786
Material: 7050-T7451

**Loads from Abort Landing Load Cases**

- **Applied tensile load**
  \[ P_s := \text{data}_{s,3}, \text{lbf} \]
  
  **Element Identification**
  \[ \text{ID}_s := \text{data}_{s,1} \]

- **Applied shear load**
  \[ V_s := \text{data}_{s,4}, \text{lbf} \]
  
  **Load case number**
  \[ \text{LC}_s := \text{data}_{s,2} \]

- **Applied bending moment**
  \[ M_s := \text{data}_{s,5}, \text{in-lbf} \]

**Factors of Safety**

- **Ultimate**
  \[ SFu := 1.4 \]
  
  **Yield**
  \[ SFy := 1.1 \]

- **Joint Separation**
  \[ SFsep := 1.2 \]
  
  **Fitting factor**
  \[ FF := 1.15 \]

**Temperature Data (Ref Appendix C2), Abort Landing Case**

- **Assembly**
  \[ \text{Temp}_\text{initial} := 70 \text{ deg} \]

- **Maximum**
  \[ \text{Temp}_\text{max} := 150 \text{ deg} \]

- **Minimum**
  \[ \text{Temp}_\text{min} := 40 \text{ deg} \]

**Bolt and Insert Data**

- **Nominal diameter of bolt**
  \[ D := 0.375 \text{-in} \]

- **Number of threads/inch**
  \[ Nt := 24 \frac{\text{in}}{\text{lbf}} \]

- **Total length of bolt**
  \[ L := 1.203 \text{-in} \]

- **Length of insert**
  \[ \text{Lins} := 0.500 \text{-in} \]

- **Threaded length**
  \[ Lt := 0.578 \text{-in} \]

- **Min. external diameter of insert**
  \[ F_{\text{min}} := 0.551 \text{-in} \]

- **Depth of recess for insert**
  \[ lr := 0.02 \text{-in} \]

(If bolt is fully threaded, input Lt = L)

\[ \text{This file uses the calculations shown in } \text{escfil02/2111_mathcad/8307_bolts/thread_data.mcd} \]
Washer Data
Thickess of washer     $tw := 0.078 \text{-in}$
Outer Diameter of washer $Dw := 0.687\text{in}$
Inner Diameter of washer $Dwi := 0.378\text{-in}$
Bolt head dia. across flats $dw := 0.523\text{-in}$

Flange data
Thickness of flange 1 $tf1 := 0.410\text{-in}$
Thickness of flange 2 $tf2 := 0.500\text{-in}$ (Length of insert)
Diameter of hole $D_{hole} := 0.386\text{-in}$

Note: If there is no washer, $tw$, $Dw$, and $Dwi$ should be zero.

Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate $TS_{u\_bolt} := .97$ yield $TS_{y\_bolt} := .97$
Bolt ultimate tensile allowable stress $F_{tu\_bolt} := 180000\text{-psi}$ (Ref. NAS1956)
Bolt yield tensile allowable $F_{ty\_bolt} := 0.6F_{tu\_bolt}$
Temperature correction factor for bolt modulus $TE_{bolt} := .98$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

Modulus of elasticity of bolt $E_{bolt} := \left(29.1\times10^6\text{-psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Thermal coefficient for bolt:
$u_{bolt\_hot} := 9.1\times10^{-6} \frac{\text{in}}{\text{in}\times\text{deg}}$
$u_{bolt\_cold} := 8.9\times10^{-6} \frac{\text{in}}{\text{deg}}$
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

Insert
Temperature correction factor for insert strength $TS_{ins} := .97$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Ultimate tensile allowable stress $F_{tu\_ins} := 140000\text{-psi}$ (Ref. MS51832)
Ultimate shear allowable stress $F_{su\_ins} := 0.6F_{tu\_ins}$

Washer
Temperature correction factor for washer modulus $TE_{washer} := .97$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Modulus of elasticity of washer $E_{washer} := \left(29.1\times10^6\text{-psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1  \( T_{f1E} := .98 \) (modulus)  
Temperature correction factor for flange 2  \( T_{f2E} := .98 \) (modulus)  
\( T_{f2s} := .97 \) (strength)  
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Shear strength allowable for flanges  \( F_{su_{f2}} := 44000\text{-psi} \)  
(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Modulus of elasticity for the parts in the joint  
(Ref. MIL-HDBK-5J, table 3.7.4.0(d))  
\( E_{f\_flange1} := \left(10.2\cdot10^6\text{ psi}\right) \)  
\( E_{f\_flange2} := \left(10.2\cdot10^6\text{ psi}\right) \)

Coefficient of thermal expansion for flanges  
(Ref. MIL-HDBK-5J, table 3.7.4.0(d) and Appendix C9)  
\( u_{\_f\_flange1\_hot} := 12.8\cdot10^{-6} \frac{\text{in}}{\text{deg}} \)  
\( u_{\_f\_flange2\_hot} := 12.8\cdot10^{-6} \frac{\text{in}}{\text{deg}} \)

\( u_{\_f\_flange1\_cold} := 12.1\cdot10^{-6} \frac{\text{in}}{\text{deg}} \)  
\( u_{\_f\_flange2\_cold} := 12.1\cdot10^{-6} \frac{\text{in}}{\text{deg}} \)

Torque/Preload data

Maximum torque (60% of yield)  \( T_{max} := 392\text{-in-lbf} \)  
Minimum torque (95% of max. torque)  \( T_{min} := 372\text{-in-lbf} \)  
Loading plane factor:  \( n := .5 \)  
Preload Uncertainty:  \( := 0.25 \)

Torque coefficient:  \( k := 0.15 \)

This file uses the calculations shown in \textbackslash escfl02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Bolt/joint stiffness factor

\[ = 0.384 \]

Preload due to temperature

\[ \text{Pth}_\text{pos} = 671 \text{lbf} \]

Max. preload

\[ \text{PLD}_{\text{max}} = 9382.1 \text{lbf} \]

Uncertainty factor

\[ = 0.25 \]

Min. preload

\[ \text{PLD}_{\text{min}} = 4306.8 \text{lbf} \]

Torque coefficient

\[ k = 0.15 \]

Joint separation load

\[ \max(P_{\text{sep}}) = 4011.9 \text{lbf} \]

Loading plane factor

\[ n = 0.5 \]

Max. load on the bolt (ultimate)

\[ \max(P_b) = 10415.7 \text{lbf} \]

Thread shear pullout load of bolt or insert

\[ \text{Pths} = 30946.4 \text{lbf} \]

Max. load on the bolt (yield)

\[ \max(P_{by}) = 10194.2 \text{lbf} \]

Thread shear pullout load in parent metal

\[ \text{Ppths} = 18470 \text{lbf} \]

Bolt ultimate tensile strength

\[ P_{\text{At}} = 15003.1 \text{lbf} \]

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Component</th>
<th>Margin</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{\text{min}1,1} = 0.155</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{\text{min}2,1} = 1.787</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_{\text{min}3,1} = 1.608</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{\text{min}4,1} = 0.440</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_{\text{min}5,1} = 0.082</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{\text{bolt}} := \min(\text{MS}) \]

\[ \text{MS}_{\text{bolt}} = 0.082 \]

Failure Mode = "Total Tension Yield"

Element Identification (64002) and Bolt Number (10) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Upper Interface Plate to Vacuum Case (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-001. All 12 NAS1956 fasteners will take the direct shear load.

\[
F_{sd,i,j} = \frac{\sqrt{(F_{y,j})^2 + (F_{z,j})^2}}{\text{num_bolts}}
\]

Total shear load
\[
F_{stot,i,j} := F_{s,i,j} + F_{sd,i,j}
\]
(Note: The Fs variable is the secondary shear and calculated above.)

The stack command below is used to stack the applied shear load (V) in ascending order per bolt. The applied axial load (P) and applied moment (M) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

\[
V := \text{stack}[F_{stot}^{(1)}, F_{stot}^{(2)}, F_{stot}^{(3)}, F_{stot}^{(4)}, F_{stot}^{(5)}, F_{stot}^{(6)}, F_{stot}^{(7)}, F_{stot}^{(8)}, F_{stot}^{(9)}]
\]

\[
V := \text{stack}[V, F_{stot}^{(1)}, F_{stot}^{(1)}, F_{stot}^{(1)}, F_{stot}^{(1)}, F_{stot}^{(1)}, F_{stot}^{(1)}, F_{stot}^{(1)}]
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is written to a text file. For the format of the array see the output example array above.

Output := augment(ID, LC, P / lbf, V / lbf, M / in-lbf) (Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: rows(Output) = 3072
(12 bolts x 64 load cases) x 4 joints = 3072 load cases

WRITEPRN("output_forces_upperipvcf_r2_abortland_pinfs.txt") := Output

Fail-safe Analysis (Shear Pin Failure)

data_fsp := READPRN("output_forces_upperipvcf_r2_abortland_pinfs.txt")

s := 1 .. rows(data_fsp)
Fail-safe Loads, abort landing

Applied tensile load
\[ P_{FS_s} := \text{data}_s \times \text{lb} \]
ID \[ F_{FS_s} := \text{data}_s \]

Applied shear load
\[ V_{FS_s} := \text{data}_s \times \text{lb} \]
LC \[ F_{FS_s} := \text{data}_s \]

Applied bending moment
\[ M_{FS_s} := \text{data}_s \times \text{in} \times \text{lb} \]

This file uses the calculations shown in \escfil02\i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

Joint separation load  \[ \max(P_{sep}_{FS}) = 3343.25 \text{ lbf} \]

Max. load on the bolt (ultimate)  \[ \max(P_{b,FS}) = 10120.4 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

Joint separation  \[ MS_{minFS_{1,1}} = 0.386 \]

Direct Tension Ultimate  \[ MS_{minFS_{2,1}} = 2.902 \]

Total Tension Ultimate  \[ MS_{minFS_{3,1}} = 0.482 \]

Direct Thread shear Ultimate  \[ MS_{minFS_{4,1}} = 3.8 \]

Total Thread shear Ultimate  \[ MS_{minFS_{5,1}} = 0.825 \]

Shear Ultimate  \[ MS_{minFS_{6,1}} = 3.96 \]

Bending Ultimate  \[ MS_{minFS_{7,1}} = 10 \]

Combined shear, tension and bending ultimate  \[ MS_{minFS_{8,1}} = 0.4816 \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt,FS} := \min(MS_{FS}) \]

\[ MS_{bolt,FS} = 0.386 \]

Failure Mode \_FS = "Joint Separation"

Element Identification (64002) and Bolt Number (10) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Upper Interface Plate to Vacuum Case

Since bolt number 10 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 11, NAS1956C10 0.375-24 UNJF fasteners, holding the upper interface plate to the vacuum case. The drawing number for the Vacuum Case Assembly is SEG39135776.

\[
\text{size} \quad \text{thread/in} \\
\begin{array}{c}
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
\end{array}
\]

\[
bolt2 := \\
\begin{array}{c}
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
0.375 \ 24 \\
\end{array}
\]

\[
s := 1 \ \text{rows(bolt2)} \\
N_{2,s} := \text{bolt2}_{s,2} \times \frac{1}{\text{in}} \quad \text{pitch of bolt} \\
D_{2,s} := \text{bolt2}_{s,1} \times \text{in} \quad \text{bolt diameter}
\]

\[
A_{t,s} := \beta \left( \frac{D_{2,s} - 0.9743 \times \frac{1}{N_{2,s}}}{2} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
A_{s,s} := \beta \left( \frac{D_{2,s} - 1.299038 \times \frac{1}{N_{2,s}}}{2} \right)^2 \quad \text{Shear Area of bolt}
\]
Bolts from Upper Interface Plate to Vacuum Case

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-3.0</td>
<td>1.362</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>1.362</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.0</td>
<td>1.362</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.0</td>
<td>-1.563</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.563</td>
</tr>
<tr>
<td>6</td>
<td>x2 := 0.0-in</td>
<td>y2 := 3.0-in</td>
<td>z2 := -1.563-in</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>-1.75</td>
<td>-2.838</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>1.75</td>
<td>-2.838</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-4.5</td>
<td>1.362</td>
</tr>
<tr>
<td>11</td>
<td>0.0</td>
<td>-4.5</td>
<td>-1.563</td>
</tr>
<tr>
<td>12</td>
<td>0.0</td>
<td>4.5</td>
<td>-1.563</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[ x_{force} := 0.0 \text{in} \quad y_{force} := 0.0 \text{in} \quad z_{force} := 0.0 \text{in} \]

\[ \text{cgload} := \begin{pmatrix} x_{force} \\ y_{force} \\ z_{force} \end{pmatrix} \quad \text{cgload} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in} \]

Center of gravity of bolt group

\[ x_{cg} := \frac{\sum x_s^2}{\text{rows}(x2)} \quad x_{cg} = 0 \text{ in} \]

\[ y_{cg} := \frac{\sum y_s^2}{\text{rows}(y2)} \quad y_{cg} = -0.409 \text{ in} \]

\[ z_{cg} := \frac{\sum z_s^2}{\text{rows}(z2)} \quad z_{cg} = -0.731 \text{ in} \]

\[ \text{cgbolt} := \begin{pmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{pmatrix} \quad \text{cgbolt} = \begin{pmatrix} 0 \\ -0.409 \\ -0.731 \end{pmatrix} \text{in} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 10, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[ r_{load} := \text{cgload} - \text{cgbolt} \quad r_{load} = \begin{pmatrix} 0 \\ 0.409 \\ 0.731 \end{pmatrix} \text{in} \]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_2_s = \sqrt{(z_2_s - z_{cg})^2 + (y_2_s - y_{cg})^2} \]

\[ r_2 = \begin{pmatrix} 
3.331 \\
2.133 \\
4.000 \\
2.721 \\
0.927 \\
3.509 \\
2.497 \\
3.017 \\
4.595 \\
4.175 \\
4.979 
\end{pmatrix} \text{ in} \]

Reading database file for bolted joint, abort landing case

data := READPRN("upperipvcf_r2_abortland.txt")

q := 1..rows(data)

num_bolts2 := rows(bolt2)

Loads from 2-04 loads model, abort landing case

Axial Load \( F_{x2} \) := data\_q\_3 \text{ lbf} \n
Shear in Y axis \( F_{y2} \) := data\_q\_4 \text{ lbf} \n
Shear in Z axis \( F_{z2} \) := data\_q\_5 \text{ lbf} \n
Element Identification \( \text{ID2} \) := data\_q\_1 \n
Load Case Number \( \text{LC2} \) := data\_q\_2 \n
Applied Bending Moment at Bolts \( M_{2} \) := 0 \text{ in-lbf} \n
Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 10 is not included.

\[ \text{ID2} := \text{stack}(\text{ID2, ID2 + 1, ID2 + 2, ID2 + 3, ID2 + 4, ID2 + 5, ID2 + 6, ID2 + 7, ID2 + 8, ID2 + 10, ID2 + 11}) \]

\[ \text{LC2} := \text{stack}(\text{LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2, LC2}) \]
Moment Distribution

\[
M_{\text{tot}2}^{(q)} := \begin{pmatrix}
M_x^{(q)} \\
M_y^{(q)} \\
M_z^{(q)}
\end{pmatrix} + \sum_{\text{load}} \begin{pmatrix}
F_x^{(q)} \\
F_y^{(q)} \\
F_z^{(q)}
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x_{\text{bolt}}2}^{(q)} := M_{\text{tot}1,2}^{(q)} \quad \text{My}_{\text{bolt}}2^{(q)} := M_{\text{tot}2,2}^{(q)} \quad \text{Mz}_{\text{bolt}}2^{(q)} := M_{\text{tot}3,2}^{(q)}
\]

Tension on bolts

\[
F_{\text{direct}}2_{s,q} := \begin{cases} 
0 \text{-lbf} & \text{if } F_{x2}^{(q)} \leq 0 \text{lbf} \\
\frac{F_{x2}^{(q)}}{\text{num}_{\text{bolts}}} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation

\[
F_{mz}2_{s,q} := \begin{cases} 
0 \text{-lb} & \text{if } (y_{2s} - y_{\text{cog}}2) = 0 \text{-in} \\
\left[\frac{M_{x_{\text{bolt}}2}^{(q)} \cdot (y_{2s} - y_{\text{cog}}2)}{A_{2s}}\right] & \text{otherwise}
\end{cases}
\]

\[
F_{my}2_{s,q} := \begin{cases} 
0 \text{-lb} & \text{if } (z_{2s} - z_{\text{cog}}2) = 0 \text{-in} \\
\sum_{s} \left[\frac{(y_{2s} - y_{\text{cog}}2)^2 \cdot A_{2s}}{A_{2s}}\right] & \text{otherwise}
\end{cases}
\]

\[
F_{t2}2_{s,q} := F_{\text{direct}}2_{s,q} + F_{mz}2_{s,q} + F_{my}2_{s,q}
\]

Total Tensile load

Shear on bolts

\[
F_{s2}2_{s,q} := \frac{M_{x_{\text{bolt}}2}^{(q)} \cdot r_{2s} \cdot A_{2s}}{\sum_{s} \left[\frac{(r_{2s})^2 \cdot (A_{2s})}{A_{2s}}\right]}
\]

Total shear load

\[
F_{stot}2_{s,q} := F_{s2}2_{s,q}
\]

(Note: The direct shear is taken by the shear pin.)

3.10.6-17

ESCG-4005-05-AMS-0039
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 11 bolts, since bolt number 10 is not included.

\[
P2 := \text{stack} \left[ \left( Fr2^T \right)^{(1)}, \left( Fr2^T \right)^{(2)}, \left( Fr2^T \right)^{(3)}, \left( Fr2^T \right)^{(4)}, \left( Fr2^T \right)^{(5)}, \left( Fr2^T \right)^{(6)}, \left( Fr2^T \right)^{(7)}, \left( Fr2^T \right)^{(8)}, \left( Fr2^T \right)^{(9)}, \left( Fr2^T \right)^{(10)}, \left( Fr2^T \right)^{(11)} \right]
\]

\[
V2 := \text{stack} \left[ \left( Fstot2^T \right)^{(1)}, \left( Fstot2^T \right)^{(2)}, \left( Fstot2^T \right)^{(3)}, \left( Fstot2^T \right)^{(4)}, \left( Fstot2^T \right)^{(5)}, \left( Fstot2^T \right)^{(6)}, \left( Fstot2^T \right)^{(7)}, \left( Fstot2^T \right)^{(8)} \right]
\]

\[
V2 := \text{stack} \left[ V2, \left( Fstot2^T \right)^{(9)}, \left( Fstot2^T \right)^{(10)}, \left( Fstot2^T \right)^{(11)} \right]
\]

\[
M2 := \text{stack} (M2, M2, M2, M2, M2, M2, M2, M2, M2, M2, M2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

Output2 := augment \( \left[ ID2, LC2, \frac{P2}{\text{lbf}}, \frac{V2}{\text{lbf}}, \frac{M2}{\text{in-lbf}} \right] \) (Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: \( \text{rows(} \text{Output2} \text{)} = 2816 \)

\( (11 \text{ bolts} \times 64 \text{ load cases}) \times 4 \text{ joints} = 2816 \text{ load cases} \)

WRITEPRN("output_forces_upperipvcf_r2_abortland_fs.txt") := Output2

Bolt Fail-safe Results

data_fs := READPRN("output_forces_upperipvcf_r2_abortland_fs.txt")

s := 1..rows(data_fs)
Fail-safe Loads, abort landing

\[
P_{FS} = \text{data}_{fs,3} \text{lbf} \quad \text{ID}_{FS} = \text{data}_{fs,1}
\]

Applied tensile load

\[
V_{FS} = \text{data}_{fs,4} \text{lbf} \quad \text{LC}_{FS} = \text{data}_{fs,2}
\]

Applied shear load

\[
M_{FS} = \text{data}_{fs,5} \text{in-lbf}
\]

Applied bending moment

This file uses the calculations shown in \escri02\211_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

Fail-safe Factors of Safety

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu_{FS} := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep_{FS} := 1.0</td>
</tr>
</tbody>
</table>

Bolt Fail-safe Load data

Joint separation load \( \max(P_{sep_{FS}}) = 3942.135 \text{lbf} \)

Max. load on the bolt (ultimate) \( \max(P_{b_{FS}}) = 10252.6 \text{lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th></th>
<th>MS_{minFS,1,1} := 0.176</th>
<th>MS_{minFS,5,1} := 0.801</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>Total Thread shear Ultimate</td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>Shear Ultimate</td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>Bending Ultimate</td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>Combined shear, tension and bending ultimate</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MS_{minFS,4,1} := 0.307</th>
<th>MS_{minFS,8,1} := 0.4592</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MS_{bolt_{FS}} := \min(\text{MS}_{FS})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS_{bolt_{FS}} := 0.176</td>
<td>Failure Mode_{FS} = &quot;Joint Separation&quot;</td>
</tr>
</tbody>
</table>

Element Identification (64002) and Bolt Number (3) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Shear Pin Analysis for Upper Interface Plate to Vacuum Case

The Vacuum Case Assembly consists of four upper interface plates. Each upper interface plate has a shear pin (SDG39135755-005) installed with two bushings. The shear pin sits inside of an inner bushing SDG39135757-001 and the inner bushing sits inside of the outer bushing SDG39135757-003.

Cross Section of the Bolted Interface

Shear Pin SDG39135755-005

Inner Bushing SDG39135757-001

Outer Bushing SDG39135757-003

Inner Bushing SDG39135757-001

Outer Bushing SDG39135757-003
Geometry

Minimum Diameter of shear pin \( dp := 0.8746 \text{-in} \) (Ref. Dwg. SDG39135755-005)
Outer diameter of outer bushing \( do := 1.3685 \text{-in} \) (Ref. Dwg. SDG39135757-003)
Thickness of interface plate \( tp := 0.75 \text{-in} \) (Ref. Dwg. SDG39135788)
Length of inner bushing \( t\text{pin} := 0.78 \text{-in} \) (Ref. Dwg. SDG39135757-001)

Temperature Data

Shear Pin (Custom 455, H1000 bar, AMS5617):
Temperature correction factor for shear \( c_{sp} := 0.96 \) (Ref. MIL-HDBK-5J, table 2.6.4.1.2)

Interface Plate (Al 7050-T7451 Plate):
Temperature correction factor for ultimate \( c_{pu} := 0.91 \) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)
Temperature correction factor for yield \( c_{py} := 0.97 \)

Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):
Temperature correction factor for ultimate \( c_{bu} := 0.95 \) (Ref. Appendix C8)
Temperature correction factor for yield \( c_{by} := 0.99 \)

Material Properties

Shear Pin (Custom 455, H1000 bar, AMS5617):
Allowable shear stress \( F_{su} := 124000 \text{-psi} \) (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

Interface Plate (Al 7050-T7451 Plate):
Allowable bearing stress \( F_{bru} := 141000 \text{-psi} \) (Ref. MIL-HDBK-5J, table 3.7.4.0 (b1), 2.5 in. thick, e/D=2.0)
\( F_{bry} := 104000 \text{-psi} \)

Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):
Allowable bearing stress of bushing \( F_{bru} := 125000 \text{-psi} \) (Ref. Appendix C8, Rockwell Materials data sheet 09.12.01.01,1.0)
\( F_{bry} := 72000 \text{-psi} \)
Shear Pin Analysis

Loads in shear pin from Bolt Analysis (Direct Shear)

\[ F_{sp,j} := \sqrt{(F_{y,j})^2 + (F_{z,j})^2} \]

rows\((F_{sp}) = 256 \)

(4 joints x 64 load cases = 256 load cases)

Shear Area of pin

\[ A_{sh} := \frac{3 \cdot dp^2}{4} \]

\[ A_{sh} = 0.601 \text{ in}^2 \]

Allowable shear load

\[ P_{all} := F_{su} \cdot A_{sh} \cdot c_{sp} \]

\[ P_{all} = 71515.8 \text{ lbf} \]

Margin of safety

\[ M_{Sp,j} := \left( \frac{P_{all}}{F_{sp,j} \cdot S_{Fu}} - 1 \right) \]

\[ \min(M_{Sp}) = 1.55 \]

Bearing of Outer Bushing on Interface Plate

Bearing area

\[ A_{b} := do\cdot tp \]

\[ A_{b} = 1.026 \text{ in}^2 \]

Allowable bearing load

\[ P_{bru} := F_{bru} \cdot A_{b} \cdot c_{pu} \]

\[ P_{bru} = 116750.2 \text{ lbf} \]

\[ P_{bry} := F_{bry} \cdot A_{b} \cdot c_{py} \]

\[ P_{bry} = 71682 \text{ lbf} \]

Margin of safety

\[ M_{Su,j} := \left( \frac{P_{bru}}{F_{sp,j} \cdot S_{Fu}} - 1 \right) \]

\[ \min(M_{Su}) = 3.16 \]

\[ \min(M_{Sy}) = 2.25 \]
Bolts from Upper Interface Plate to Vacuum Case

**Bearing of Shear Pin on Inner Bushing**

**Bearing area**

\[ \text{Abp} := \text{dp}\cdot\text{tpin} \]

\[ \text{Abp} = 0.682 \text{ in}^2 \]

**Allowable bearing load**

\[ \text{Pbru} := \text{Fbru}\cdot\text{Abp}\cdot\text{cbru} \]

\[ \text{Pbru} = 81009.8 \text{ lbf} \]

\[ \text{Pbry} := \text{Fbry}\cdot\text{Abp}\cdot\text{cby} \]

\[ \text{Pbry} = 48626.4 \text{ lbf} \]

**Margin of safety**

\[ \text{MSbru} := \frac{\text{Pbru}}{\text{Fsp}\cdot\text{SFu}} - 1 \]

\[ \text{MSbry} := \frac{\text{Pbry}}{\text{Fsp}\cdot\text{SFy}} - 1 \]

\[ \min(\text{MSbru}) = 1.89 \]

\[ \min(\text{MSbry}) = 1.21 \]
3.10.7 Lower Interface Plate to Vacuum Case Bolted Interface
Lower Interface Plate to Vacuum Case Bolted Interface

The Lower Interface Plate to Vacuum Case Bolt Analysis is performed in the following report sections:

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.10.7.1</td>
<td>Lower Interface Plate to Vacuum Case - .375&quot;</td>
</tr>
<tr>
<td>3.10.7.1</td>
<td>Lower Interface Plate to Vacuum Case Fail-Safe - .375&quot;</td>
</tr>
<tr>
<td>3.10.7.1</td>
<td>Lower Interface Plate to Vacuum Case Fail-Safe - .375&quot; (Shear Pin Failure)</td>
</tr>
<tr>
<td>3.10.7.2</td>
<td>Lower Interface Plate to Vacuum Case - .500&quot;</td>
</tr>
<tr>
<td>3.10.7.2</td>
<td>Lower Interface Plate to Vacuum Case Fail-Safe - .500&quot;</td>
</tr>
<tr>
<td>3.10.7.2</td>
<td>Lower Interface Plate to Vacuum Case Fail-Safe - .500&quot; (Shear Pin Failure)</td>
</tr>
</tbody>
</table>
3.10.7.1 Lower Interface Plate to Vacuum Case - .375"
Lower Interface Plate to Vacuum Case Bolt Analysis - 0.375" Bolts

The Vacuum Case Assembly consists of four lower interface plates. There are a total of 14 fasteners attaching the lower interface plate to the Vacuum Case. The following analysis will just include analysis of 8 of the 14 fasteners. The fasteners are NAS1956C8 and NAS1956C7 (180 ksi), 0.375-24 UNJF. Fastener NAS1956C8 will experience a higher load and therefore the following bolt analysis will assume that all bolts are NAS1956C8. There is also one shear pin 0.875" in diameter. The drawing number for the Vacuum Case Assembly is SEG39135776.

Bolt Geometry

\[
\begin{array}{c|c|c}
\text{size} & \text{thread/in} \\
0.375 & 24 \\
0.375 & 24 \\
0.50 & 20 \\
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
0.50 & 24 \\
0.50 & 20 \\
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
0.50 & 20 \\
0.50 & 20 \\
0.50 & 20 \\
0.50 & 20 \\
\end{array}
\]

\[i := 1..\text{rows(bolt)}\]

\[N_i := \text{bolt}_{i,2} \times \frac{1}{\text{in}}\] pitch of bolt

\[D_i := \text{bolt}_{i,1} \times \text{in}\] bolt diameter

\[A_t_i := \beta \left( \frac{D_i - 0.9743}{N_i} \right)^2\] Tensile Area of bolt

\[A_s_i := \beta \left( \frac{D_i - 1.299038}{N_i} \right)^2\] Shear Area of bolt
Bolts from Lower Interface Plate to Vacuum Case - 0.375" Bolts

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-1.75</td>
<td>2.838</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>1.75</td>
<td>2.838</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>-4.688</td>
<td>1.563</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.0</td>
<td>1.563</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>1.563</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>3.0</td>
<td>1.563</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>4.688</td>
<td>1.563</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>-4.688</td>
<td>-1.362</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-3.0</td>
<td>-1.362</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.362</td>
</tr>
<tr>
<td>11</td>
<td>0.0</td>
<td>3.0</td>
<td>-1.362</td>
</tr>
<tr>
<td>12</td>
<td>0.0</td>
<td>4.688</td>
<td>-1.362</td>
</tr>
<tr>
<td>13</td>
<td>0.0</td>
<td>-4.688</td>
<td>-0.062</td>
</tr>
<tr>
<td>14</td>
<td>0.0</td>
<td>4.688</td>
<td>-0.062</td>
</tr>
</tbody>
</table>

In this analysis, only the 0.375" bolts will be analyzed. These bolts correspond to bolt no. 1, 2, 4, 5, 6, 9, 10, and 11. Refer to bolt geometry in previous page.

Location of applied forces and moments

\[
\text{cgload} = \begin{bmatrix} xforce \\ yforce \\ zforce \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{ in}
\]

\[
\text{xforce} := 0.0 \text{ in} \quad \text{yforce} := 0.0 \text{ in} \quad \text{zforce} := 0.0 \text{ in}
\]
Center of gravity of bolt group

\[
\begin{align*}
x_{cg} & := \frac{\sum x_i}{\text{rows}(x)} \quad x_{cg} = 0 \text{ in} \\
y_{cg} & := \frac{\sum y_i}{\text{rows}(y)} \quad y_{cg} = 0 \text{ in} \\
z_{cg} & := \frac{\sum z_i}{\text{rows}(z)} \quad z_{cg} = 0.468 \text{ in}
\end{align*}
\]

\[c_{\text{gbolt}} := \begin{pmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{pmatrix} \quad c_{\text{gbolt}} = \begin{pmatrix} 0 \\ 0 \\ 0.468 \end{pmatrix} \text{ in}\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. In the z direction the bolt pattern is unsymmetric and has a 0.468" offset from the center of gravity.

Load Vector

\[r_{\text{load}} := c_{\text{gl}} - c_{\text{gbolt}} \quad r_{\text{load}} = \begin{pmatrix} 0 \\ 0 \\ -0.468 \end{pmatrix} \text{ in}\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[r_i := \sqrt{\left(z_i - z_{cg}\right)^2 + \left(y_i - y_{cg}\right)^2} \]

\[
\begin{align*}
2.946 \\
2.946 \\
4.814 \\
3.193 \\
1.095 \\
3.193 \\
4.814 \\
5.033 \\
3.514 \\
1.830 \\
3.514 \\
5.033 \\
4.718 \\
4.718 \\
\end{align*}
\]

Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 64011, 64012, 64013, and 64014. These loads are read into an array and distributed out to the 14 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis.)
Reading database file for bolted joint, abort landing case

\[ \text{data := READPRN("lower_ipvcf_r2_abortland.txt")} \]
\[ \text{num\_bolts := rows(bolt)} \]
\[ j := 1..\text{rows(data)} \]

Loads from 2-04 loads model, abort landing case

Axial Load \[ F_x := \text{data}_j,3\text{-lbf} \]
Shear in Y axis \[ F_y := \text{data}_j,4\text{-lbf} \]
Shear in Z axis \[ F_z := \text{data}_j,5\text{-lbf} \]
Element Identification \[ ID := \text{data}_j,1 \]
Load Case Number \[ LC := \text{data}_j,2 \]
Applied Bending Moment at Bolts \[ M := 0\text{-in-lbf} \]

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 64011, 64012, 64013, and 64014, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 64001 will have bolt numbers 001 thru 002, 004 thru 006, and 009 thru 011 attached to the end for all 64 load cases. This brings the total number of load cases to 2048 (4 joints x 8 (3/8" bolts) x 64 load cases = 2048) since only 8 of the bolts will be analyzed. See the array example to the right.

\[ \text{ID := stack(ID, ID + 1, ID + 3, ID + 4, ID + 5, ID + 8, ID + 9, ID + 10)} \]
\[ \text{LC := stack(LC, LC, LC, LC, LC, LC, LC, LC)} \]

Array Example

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>64011001</td>
<td>2001</td>
</tr>
<tr>
<td>64011001</td>
<td>2002</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>64011001</td>
<td>2064</td>
</tr>
<tr>
<td>64011002</td>
<td>2001</td>
</tr>
<tr>
<td>64011002</td>
<td>2002</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>64011011</td>
<td>2001</td>
</tr>
<tr>
<td>64011011</td>
<td>2002</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>64011011</td>
<td>2064</td>
</tr>
</tbody>
</table>
Moment Distribution

\[
M_{\text{tot}j} := \begin{pmatrix} M_{xj} \\ M_{yj} \\ M_{zj} \end{pmatrix} + r_{\text{load}} \times \begin{pmatrix} F_{xj} \\ F_{yj} \\ F_{zj} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x\text{boltcg}}_j := M_{\text{tot}1,j} \quad \text{My}_{\text{boltcg}}_j := M_{\text{tot}2,j} \quad \text{Mz}_{\text{boltcg}}_j := M_{\text{tot}3,j}
\]

Tension on bolts

\[
F_{\text{direct}}_{i,j} := \begin{cases} 0 \text{-lbf} & \text{if } F_{xj} \leq 0 \text{-lbf} \\ \frac{F_{xj}}{\text{num_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
F_{mz}_{i,j} := \begin{cases} 0 \text{-lbf} & \text{if } \left( y_i - y_{\text{ycg}} \right) = 0 \text{-in} \\ \frac{M_{z\text{boltcg}}_j \left( y_i - y_{\text{ycg}} \right)}{\sum_i \left( y_i - y_{\text{ycg}} \right)^2 \cdot A_{t_i}} & \text{otherwise} \end{cases}
\]

\[
F_{my}_{i,j} := \begin{cases} 0 \text{-lbf} & \text{if } \left( z_i - z_{\text{zcg}} \right) = 0 \text{-in} \\ \frac{M_{y\text{boltcg}} \left( z_i - z_{\text{zcg}} \right) \cdot A_{t_i}}{\sum_i \left[ \left( z_i - z_{\text{zcg}} \right)^2 \cdot A_{t_i} \right]} & \text{otherwise} \end{cases}
\]

\[
F_{t_{i,j}} := F_{\text{direct}}_{i,j} + F_{mz}_{i,j} + F_{my}_{i,j}
\]

Total tensile load

Shear on bolts

Secondary shear on bolts

\[
F_{s_{i,j}} := \frac{M_{x\text{boltcg}} \cdot r_i \cdot A_{s_i}}{\sum_i \left[ r_{ij} \right]^2 \cdot A_{s_i}}
\]

Total shear load

\[
F_{\text{stot}}_{i,j} := F_{s_{i,j}}
\]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the “Output” file below.

\[
P := \text{stack}\left[\begin{array}{c}
\left(F_tT\right)^{(1)}, \left(F_tT\right)^{(2)}, \left(F_tT\right)^{(4)}, \left(F_tT\right)^{(5)}, \left(F_tT\right)^{(6)}, \left(F_tT\right)^{(9)}, \left(F_tT\right)^{(10)}, \left(F_tT\right)^{(11)}
\end{array}\right]
\]

\[
V := \text{stack}\left[\begin{array}{c}
\left(F_{stot}T\right)^{(1)}, \left(F_{stot}T\right)^{(2)}, \left(F_{stot}T\right)^{(4)}, \left(F_{stot}T\right)^{(5)}, \left(F_{stot}T\right)^{(6)}, \left(F_{stot}T\right)^{(9)}, \left(F_{stot}T\right)^{(10)}, \left(F_{stot}T\right)^{(11)}
\end{array}\right]
\]

\[
\]

The “Output” file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

\[
\text{Output} := \text{augment}\left(\begin{array}{c}
\text{ID}, \text{LC}, \frac{\text{P}}{\text{lbf}}, \frac{\text{V}}{\text{lbf}}, \frac{\text{M}}{\text{in} \cdot \text{lbf}}
\end{array}\right)
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

\[
\begin{array}{cccccc}
\text{ID} & \text{LC} & \text{P} & \text{V} & \text{M} \\
64011001 & 2001 & -1038.145 & -76.062 & 0 \\
64011001 & 2002 & -1010.549 & -73.512 & 0 \\
... & ... & ... & ... & ... \\
64011001 & 2064 & 622.985 & -532.722 & 0 \\
64011002 & 2001 & -968.239 & -76.062 & 0 \\
64011002 & 2002 & -973.376 & -73.512 & 0 \\
... & ... & ... & ... & ... \\
64011002 & 2064 & 669.148 & -532.722 & 0 \\
... & ... & ... & ... & ... \\
64011011 & 2001 & 834.805 & -90.74 & 0 \\
64011011 & 2002 & 798.073 & -87.699 & 0 \\
... & ... & ... & ... & ... \\
64011011 & 2064 & 717.04 & -635.529 & 0 \\
\end{array}
\]

Size of the “Output” Array: \(\text{rows(Output)} = 2048\)

\((8 \text{ (3/8"bolts)} \times 64 \text{ load cases}) \times 4 \text{ joints} = 2048 \text{ load cases}\)

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)

Example of Output Array

\text{WRITEPRN(“output_forces_loweripvcf_r2_abortland.txt”) := Output}
CHECK BOLTS (NAS1956C8, 0.375-24UNJF-3A, Material-A-286), Insert MS51832CA-204L, Washer NAS1587-6C

The array from the text file above is read:

```
data := READPRN("output_forces_loweripvcf_r2_abortland.txt")
```

```
s := 1..rows(data)
```

Flange 1: Lower Interface Plate
Part number: SEG39135789
Material: 7050-T7451

Flange 2: Lower Support Ring Assy
Part number: SEG39135787
Material: 7050-T7451

**Loads from Abort Landing Load Cases**

Applied tensile load

\[ P_s := \text{data}_s,3 \times \text{lbf} \]

Element Identification

\[ \text{ID}_s := \text{data}_s,1 \]

Applied shear load

\[ V_s := \text{data}_s,4 \times \text{lbf} \]

Load case number

\[ \text{LC}_s := \text{data}_s,2 \]

Applied bending moment

\[ M_s := \text{data}_s,5 \times \text{in}\times \text{lbf} \]

**Factors of Safety**

Ultimate

\[ \text{SFu} := 1.4 \]

Yield

\[ \text{SFy} := 1.1 \]

Assembly

\[ \text{Temp}_{\text{initial}} := 70 \text{ deg} \]

Joint Separation

\[ \text{SFsep} := 1.2 \]

Fitting factor

\[ \text{FF} := 1.15 \]

Maximum

\[ \text{Temp}_{\text{max}} := 150 \text{ deg} \]

Minimum

\[ \text{Temp}_{\text{min}} := 40 \text{ deg} \]

**Bolt and Insert Data**

Nominal diameter of bolt

\[ D := 0.375 \text{ in} \]

Number of threads/inch

\[ \text{Nt} := 24 \times \frac{1}{\text{in}} \]

Total length of bolt

\[ L := 1.078 \text{ in} \]

Length of insert

\[ \text{Lins} := 0.500 \text{ in} \]

Threaded length

\[ L_t := 0.578 \text{ in} \]

Min. external diameter of insert

\[ \text{Fmin} := 0.551 \text{ in} \]

(If bolt is fully threaded, input \( L_t = L \))

Depth of recess for insert

\[ l_r := 0.02 \text{ in} \]

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\thread_data.mcd`
### Washer Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of washer</td>
<td>tw := 0.078-in</td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := .687in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.378-in</td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>dw := 0.523-in</td>
</tr>
</tbody>
</table>

Note: If there is no washer, tw, Dw, and Dwi should be zero.

### Flange Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 1</td>
<td>tf1 := .410-in</td>
</tr>
<tr>
<td>Thickness of flange 2</td>
<td>tf2 := .500-in (Length of insert)</td>
</tr>
<tr>
<td>Diameter of hole</td>
<td>D_hole := 0.386-in</td>
</tr>
</tbody>
</table>

### Material Property Data

#### Bolt

- Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Bolt ultimate tensile allowable stress $F_{tu, bolt} := 180000$ psi (Ref. NAS1956)
- Bolt yield tensile allowable $F_{ty, bolt} := 132353$ psi (Ref. Appendix C10)
- Temperature correction factor for bolt modulus $T_{E, bolt} := .98$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

- Modulus of elasticity of bolt $E_{bolt} := \left(29.1 \times 10^6 \text{ psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt: $u_{bolt, hot} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{deg}}$ $u_{bolt, cold} := 8.9 \times 10^{-6} \frac{\text{in}}{\text{deg}}$ (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

#### Insert

- Temperature correction factor for insert strength $T_{S, ins} := .97$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress $F_{tu, ins} := 140000$ psi (Ref. MS51832)
- Ultimate shear allowable stress $F_{su, ins} := 0.6 F_{tu, ins}$

#### Washer

- Temperature correction factor for washer modulus $T_{E, washer} := .97$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Modulus of elasticity of washer $E_{washer} := \left(29.1 \times 10^6 \text{ psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges

(Mechanical Properties shall meet the requirements of AMS 4108)

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{1E} := 0.98 \text{ (modulus)} \]

Temperature correction factor for flange 2

\[ T_{2E} := 0.98 \text{ (modulus)} \]

\[ T_{2s} := 0.97 \text{ (strength)} \]

Shear strength allowable for flanges

\[ F_{su,f_2} := 42000 \text{ psi} \]

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange1}} := \left(10.2 \cdot 10^6 \text{ psi}\right) \]

\[ E_{\text{flange2}} := \left(10.2 \cdot 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges

\[ u_{\text{flange1, hot}} := 12.8 \cdot 10^{-6} \text{ in/deg} \]

\[ u_{\text{flange2, hot}} := 12.8 \cdot 10^{-6} \text{ in/deg} \]

\[ u_{\text{flange1, cold}} := 12.1 \cdot 10^{-6} \text{ in/deg} \]

\[ u_{\text{flange2, cold}} := 12.1 \cdot 10^{-6} \text{ in/deg} \]

Torque/Preload data

Maximum torque (62% of yield)

\[ T_{\text{max}} := 405 \text{ in-lbf} \]

Minimum torque (95% of max. torque)

\[ T_{\text{min}} := 384.75 \text{ in-lbf} \]

Torque coefficient:

\[ k := 0.15 \]

Load coefficient:

\[ n := 0.5 \]

Preload Uncertainty:

\[ := 0.25 \]

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC

Insert Stiffness File
Bolt Load data

Bolt/joint stiffness factor \( = 0.374 \)
Max. preload \( \text{PLD}_{\text{max}} = 9652.9 \text{lbf} \)
Min. preload \( \text{PLD}_{\text{min}} = 4468.2 \text{lbf} \)
Joint separation load \( \text{max}(P_{\text{sep}}) = 1651.094 \text{lbf} \)
Max. load on the bolt (ultimate) \( \text{max}(P_b) = 10066.9 \text{lbf} \)
Max. load on the bolt (yield) \( \text{max}(P_{by}) = 9978.2 \text{lbf} \)
Bolt ultimate tensile strength \( P_{\text{At}} = 15003.1 \text{lbf} \)
Preload due to temperature \( \text{P}_{\text{thr}}_{\text{pos}} = 652.9 \text{lbf} \)
Uncertainty factor \( = 0.25 \)
Torque coefficient \( k = 0.15 \)
Loading plane factor \( n = 0.5 \)
Thread shear pullout load of bolt or insert \( \text{P}_{\text{ths}} = 25380.5 \text{lbf} \)
Thread shear pullout load in parent metal \( \text{P}_{\text{pths}} = 17630.4 \text{lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation \( \text{MS}_{\text{min}}_{1,1} = 1.894 \)
Direct Thread shear Ultimate \( \text{MS}_{\text{min}}_{6,1} = 6.959 \)
Direct Tension Ultimate \( \text{MS}_{\text{min}}_{2,1} = 5.773 \)
Total Thread shear Ultimate \( \text{MS}_{\text{min}}_{7,1} = 0.751 \)
Direct Tension Yield \( \text{MS}_{\text{min}}_{3,1} = 5.338 \)
Shear Ultimate \( \text{MS}_{\text{min}}_{8,1} = 3.52 \)
Total Tension Ultimate \( \text{MS}_{\text{min}}_{4,1} = 0.490 \)
Bending Ultimate \( \text{MS}_{\text{min}}_{9,1} = 10 \)
Total Tension Yield \( \text{MS}_{\text{min}}_{5,1} = 0.106 \)
Combined shear, tension and bending ultimate \( \text{MS}_{\text{min}}_{10,1} = 0.479 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{\text{bolt}} := \min(\text{MS}) \]

\[ \text{MS}_{\text{bolt}} = 0.106 \]

Failure Mode = "Total Tension Yield"

Element Identification (64011) and Bolt Number (11) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Lower Interface Plate to Vacuum Case (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-001. All 8 NAS1956 3/8” fasteners will take the direct shear load.

Direct shear Loads

\[ F_{sd, i,j} := \sqrt{\left( F_{y, j}\right)^2 + \left( F_{z, j}\right)^2} \]

Total shear load

\[ F_{stot, i,j} := F_{s, i,j} + F_{sd, i,j} \]

(Note: The Fs variable is the secondary shear and has been calculated previously in the analysis.)

The stack command below is used to stack the applied shear load (V) in ascending order per bolt. The applied axial load (P) and applied moment (M) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

\[
V := \text{stack}\left[ F_{stot, T}^{(1)} \right]
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is written to a text file. For the format of the array see the output example array above.

Output := augment\left( ID, LC, P, V, M \right) \text{ (Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)}

Size of the "Output" Array: rows(Output) = 2048

(8 (3/8"bolts) x 64 load cases) x 4 joints = 2048 load cases

WRITEPRN("output_forces_loweripvcf_r2_abortland_pinfs.txt") := Output

Fail-safe Analysis (Shear Pin Failure)

data_fsp := READPRN("output_forces_loweripvcf_r2_abortland_pinfs.txt")

s := 1..rows(data_fsp)
Bolts from Lower Interface Plate to Vacuum Case - 0.375" Bolts

Fail-safe Loads, abort landing

| Applied tensile load | $P_{FS_s} := \text{data}_s^{3}_{fsp,1}$ lbf | $ID_{FS_s} := \text{data}_s^{1}_{fsp}$ |
| Applied shear load   | $V_{FS_s} := \text{data}_s^{4}_{fsp}$ lbf | $LC_{FS_s} := \text{data}_s^{2}_{fsp}$ |
| Applied bending moment | $M_{FS_s} := \text{data}_s^{5}_{fsp}$ in-lbf |

Fail-safe Factors of Safety

| Applied tensile load | Ultimate | $SFu_{FS} := 1.0$ |
| Applied shear load   | Joint Separation | $SF_{sep_{FS}} := 1.0$ |

This file uses the calculations shown in \escf002\2111\mathcad\8307\bolts\multi_bolt_stiffness_insert\FS_RevC

Bolt Fail-safe Load data

- Joint separation load $\max(P_{sep_{FS}}) = 1375.912$ lbf
- Max. load on the bolt (ultimate) $\max(P_{b_{FS}}) = 9948.6$ lbf

Summary of fail-safe Margins for bolt:

| Joint separation | $MS_{min_{FS1,1}} = 2.473$ | Total Thread shear Ultimate | $MS_{min_{FS5,1}} = 0.772$ |
| Direct Tension Ultimate | $MS_{min_{FS2,1}} = 8.482$ | Shear Ultimate | $MS_{min_{FS6,1}} = 2.91$ |
| Total Tension Ultimate | $MS_{min_{FS3,1}} = 0.508$ | Bending Ultimate | $MS_{min_{FS7,1}} = 10$ |
| Direct Thread shear Ultimate | $MS_{min_{FS4,1}} = 10$ | Combined shear, tension and bending ultimate | $MS_{min_{FS8,1}} = 0.4845$ |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

$MS_{bolt_{FS}} := \min(MS_{FS})$

$MS_{bolt_{FS}} = 0.485$  
Failure Mode $FS = "\text{Combined Shear Tension Bending Ultimate}"$

$MS_{min_{ID}} = 64012009$  
Element Identification (64012) and Bolt Number (9) for Minimum Margin

$MS_{min_{LC}} = 2011$  
Load Case Number for Minimum Margin

$MS_{min_{P}} = 809.4$  
Applied Tensile Load for Minimum Margin

$MS_{min_{V}} = 1881.9$  
Applied Shear Load for Minimum Margin

$MS_{min_{M}} = 0$  
Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Lower Interface Plate to Vacuum Case - 0.375" Bolts

Since bolt number 11 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 7, NAS1956C8 0.375-24 UNJF fasteners, holding the lower interface plate to the Vacuum Case. The drawing number for the Vacuum Case Assembly is SEG39135776.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.50 & \quad 20 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
0.50 & \quad 20 \\
\end{align*}
\]

\[
pitch \quad \text{of bolt} \\
D_2 := \text{bolt2} \quad 1 \text{ in} \\
bolt \quad \text{diameter}
\]

\[
A_{t2} := \beta \left( \frac{D_2 - 0.9743 \cdot \frac{1}{N_2}}{2} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
A_{s2} := \beta \left( \frac{D_2 - 1.299038 \cdot \frac{1}{N_2}}{2} \right)^2 \quad \text{Shear Area of bolt}
\]
Bolts from Lower Interface Plate to Vacuum Case - 0.375" Bolts

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>-1.75</td>
<td>2.838</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>1.75</td>
<td>2.838</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>-4.688</td>
<td>1.563</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>-3.0</td>
<td>1.563</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>1.563</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>3.0</td>
<td>1.563</td>
</tr>
<tr>
<td>7</td>
<td>x2 := 0.0 in</td>
<td>y2 := 4.688 in</td>
<td>z2 := 1.563 in</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>-4.688</td>
<td>-1.362</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-3.0</td>
<td>-1.362</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.362</td>
</tr>
<tr>
<td>12</td>
<td>0.0</td>
<td>4.688</td>
<td>-1.362</td>
</tr>
<tr>
<td>13</td>
<td>0.0</td>
<td>-4.688</td>
<td>-0.062</td>
</tr>
<tr>
<td>14</td>
<td>0.0</td>
<td>4.688</td>
<td>-0.062</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[ \text{xforce2} := 0.0 \text{in} \quad \text{yforce2} := 0.0 \text{in} \quad \text{zforce2} := 0.0 \text{in} \]

\[ \text{cgload2} = \begin{bmatrix} \text{xforce2} \\ \text{yforce2} \\ \text{zforce2} \end{bmatrix} \]

Center of gravity of bolt group

\[ \text{xcg} = 0 \text{ in} \]
\[ \text{ycg} = \frac{\sum y_2 s}{\text{rows}(y2)} \]
\[ \text{zcg} = \frac{\sum z_2 s}{\text{rows}(z2)} \]

\[ \text{cgbolt2} := \begin{bmatrix} \text{xcg} \\ \text{ycg} \\ \text{zcg} \end{bmatrix} \]

\[ \text{cgload2} = \begin{bmatrix} 0 \\ 0 \text{ in} \end{bmatrix} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 11, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[ \text{r}_{\text{load2}} := \text{cgload2} - \text{cgbolt2} \]

\[ \text{r}_{\text{load2}} = \begin{bmatrix} 0 \\ 0.231 \text{ in} \\ -0.609 \text{ in} \end{bmatrix} \]
Bolts from Lower Interface Plate to Vacuum Case - 0.375” Bolts

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\frac{r_s^2}{s} := \sqrt{\left(x_s^2 - xcg^2\right)^2 + \left(y_s^2 - ycg^2\right)^2}
\]

\[
\frac{r_s^2}{s} = \begin{pmatrix} 2.697 \\ 2.982 \\ 4.558 \\ 2.929 \\ 0.981 \\ 3.369 \end{pmatrix} \text{ in}
\]

Reading database file for bolted joint, abort landing case

data := READPRN("lower_ipvcf_r2_abortland.txt")

q := 1..rows(data)

num_bolts2 := rows(bolt2)

Loads from 2-04 loads model, abort landing case

Axial Load \( Fx_2 \) := data\_q,3 \text{lbf} 

Shear in Y axis \( Fy_2 \) := data\_q,4 \text{lbf} 

Shear in Z axis \( Fz_2 \) := data\_q,5 \text{lbf} 

Element Identification \( ID_2 \) := data\_q,1 

Load Case Number \( LC_2 \) := data\_q,2 

Applied Bending Moment at Bolts \( M_2 \) := 0 \text{in-lbf} 

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 11 is not included.

\[
ID2 := \text{stack}(ID2, ID2 + 1, ID2 + 3, ID2 + 4, ID2 + 5, ID2 + 8, ID2 + 9)
\]

\[
LC2 := \text{stack}(LC2, LC2, LC2, LC2, LC2, LC2, LC2)
\]
**Moment Distribution**

\[ M_{tot2} := \begin{bmatrix} Mx_{2} \\ My_{2} \\ Mz_{2} \end{bmatrix} + \begin{bmatrix} Fx_{2} \\ Fy_{2} \\ Fz_{2} \end{bmatrix} \times f_{load} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{x,boltcg2} := M_{tot12}, q \quad My_{boltcg2} := M_{tot22}, q \quad Mz_{boltcg2} := M_{tot32}, q \]

**Tension on bolts**

\[ F_{direct2, s, q} := \begin{cases} 0 - \text{lbf} & \text{if } Fx_{q, s} \leq 0 - \text{lbf} \\ \frac{Fx_{q, s}}{num\_bolts} & \text{otherwise} \end{cases} \]

Direct tensile load calculation

\[ F_{mz2, s, q} := \begin{cases} 0 - \text{lbf} & \text{if } (y_{2, s} - y_{cog2}) = 0 - \text{in} \\ \left[ M_{z, boltcg2, q} (y_{2, s} - y_{cog2}) \right] At_{2, s} & \sum_{s} \left[ (y_{2, s} - y_{cog2})^2 \cdot At_{2, s} \right] \end{cases} \]

\[ F_{my2, s, q} := \begin{cases} 0 - \text{lbf} & \text{if } (z_{2, s} - z_{cog2}) = 0 - \text{in} \\ \left[ My_{boltcg2, q} (z_{2, s} - z_{cog2}) \right] At_{2, s} & \sum_{s} \left[ (z_{2, s} - z_{cog2})^2 \cdot At_{2, s} \right] \end{cases} \]

\[ F_{t2, s, q} := F_{direct2, s, q} + F_{mz2, s, q} + F_{my2, s, q} \quad \text{Total Tensile load} \]

**Shear on bolts**

Secondary shear on bolts

\[ F_{s2, s, q} := \frac{M_{x,boltcg2} \cdot r_{2, s} \cdot As_{2, s}}{\sum_{s} \left[ r_{2, s}^2 \cdot As_{2, s} \right]} \]

Total shear load

\[ F_{s2, s, q} := F_{s2, s, q} \]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 7 bolts, since bolt number 11 is not included.

\[
P2 := \text{stack}\left[\left(\text{Fr2}_1^T\right)^1, \left(\text{Fr2}_2^T\right)^2, \left(\text{Fr2}_4^T\right)^4, \left(\text{Fr2}_5^T\right)^5, \left(\text{Fr2}_6^T\right)^6, \left(\text{Fr2}_9^T\right)^9, \left(\text{Fr2}_10^T\right)^{10}\right]
\]

\[
V2 := \text{stack}\left[\left(\text{Fstot}_1^T\right)^1, \left(\text{Fstot}_2^T\right)^2, \left(\text{Fstot}_4^T\right)^4, \left(\text{Fstot}_5^T\right)^5, \left(\text{Fstot}_6^T\right)^6, \left(\text{Fstot}_9^T\right)^9, \left(\text{Fstot}_10^T\right)^{10}\right]
\]

\[
M2 := \text{stack}(\text{M2}_1, \text{M2}_2, \text{M2}_2, \text{M2}_2, \text{M2}_2, \text{M2}_2, \text{M2}_2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

Output2 := augment\(\left[\text{ID2}, \text{LC2}, \frac{\text{P2}}{\text{lb}}, \frac{\text{V2}}{\text{lb}}, \frac{\text{M2}}{\text{in-lb}}\right]\) (Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: rows(Output2) = 1792

\(7 \text{ (3/8" bolts) x 64 load cases} \times 4 \text{ joints} = 1792 \text{ load cases}\)

WRITEPRN("output_forces_loweripvcf_r2_abortland_fs.txt") := Output2

Bolt Fail-safe Results

data_fs := READPRN("output_forces_loweripvcf_r2_abortland_fs.txt")

s := 1..rows(data_fs)
Fail-safe Loads, abort landing

Applied tensile load  
\[ P_{FS3} := \text{data}_{fs3}, \_s, \_3 \text{ lbf} \]

ID_{FS3} := \text{data}_{fs1}, \_s, \_1 \text{ lbf} 

Applied shear load  
\[ V_{FS3} := \text{data}_{fs4}, \_s, \_4 \text{ lbf} \]

LC_{FS3} := \text{data}_{fs2}, \_s, \_2 \text{ in-lbf} 

Applied bending moment  
\[ M_{FS3} := \text{data}_{fs5}, \_s, \_5 \text{ in-lbf} \]

This file uses the calculations shown in \escfil02\211\mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

### Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate SFu_FS3</td>
<td>1.0</td>
</tr>
<tr>
<td>Joint Separation SFsep_FS3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Bolt Fail-safe Load data

- Joint separation load  
  \[ \max(P_{sep\_FS}) = 1448.553 \text{ lbf} \]

- Max. load on the bolt(ultimate)  
  \[ \max(P_{b\_FS}) = 9964.2 \text{ lbf} \]

### Summary of fail-safe Margins for bolt:

- Joint separation  
  \[ MS_{minFS3,1,1} = 2.299 \]

- Direct Tension Ultimate  
  \[ MS_{minFS3,2,1} = 8.006 \]

- Total Tension Ultimate  
  \[ MS_{minFS3,3,1} = 0.506 \]

- Direct Thread shear Ultimate  
  \[ MS_{minFS3,4,1} = 9.58 \]

### Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt\_FS} := \text{min}(MS_{FS3}) \]

\[ MS_{bolt\_FS} = 0.505 \]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

- MS_{min\_ID} = 64012009  
  Element Identification (64012) and Bolt Number (9) for Minimum Margin

- MS_{min\_LC} = 2038  
  Load Case Number for Minimum Margin

- MS_{min\_P} = 1415.5  
  Applied Tensile Load for Minimum Margin

- MS_{min\_V} = -616.6  
  Applied Shear Load for Minimum Margin

- MS_{min\_M} = 0  
  Applied Bending Moment for Minimum Margin
Shear Pin Analysis for Lower Interface Plate to Vacuum Case

The Vacuum Case Assembly consists of four lower interface plates. Each lower interface plate has a shear pin (SDG39135755-001) installed with two bushings. The shear pin sits inside of an inner bushing SDG39135757-001 and the inner bushing sits inside of the outer bushing SDG39135757-003.

Cross Section of the Bolted Interface

Shear Pin SDG39135755-001

Inner Bushing SDG39135757-001

Outer Bushing SDG39135757-003

Inner Bushing SDG39135757-001

Outer Bushing SDG39135757-003
Bolts from Lower Interface Plate to Vacuum Case - 0.375° Bolts

### Geometry

- Minimum Diameter of shear pin: \( dp := 0.8746 \text{-in} \)  
  (Ref. Dwg. SDG39135755-001)
- Outer diameter of outer bushing: \( do := 1.3685 \text{-in} \)  
  (Ref. Dwg. SDG39135757-003)
- Thickness of interface plate: \( tp := 0.75 \text{-in} \)  
  (Ref. Dwg. SDG39135789)
- Length of inner bushing: \( tpin := 0.78 \text{-in} \)  
  (Ref. Dwg. SDG39135757-001)

### Temperature Data

**Shear Pin (Custom 455, H1000 bar, AMS5617):**

- Temperature correction factor for shear: \( csp := 0.96 \)  
  (Ref. MIL-HDBK-5J, table 2.6.4.1.2)

**Interface Plate (Al 7050-T7451 Plate):**

- Temperature correction factor for ultimate: \( cpu := 0.91 \)  
  (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)
- Temperature correction factor for yield: \( cpy := 0.97 \)

**Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):**

- Temperature correction factor for ultimate: \( cbu := 0.95 \)  
  (Ref. Appendix C8)
- Temperature correction factor for yield: \( cby := 0.99 \)

### Material Properties

**Shear Pin (Custom 455, H1000 bar, AMS5617):**

- Allowable shear stress: \( Fsu := 124000 \text{-psi} \)  
  (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

**Interface Plate (Al 7050-T7451 Plate):**

- Allowable bearing stress: \( Fbru := 131000 \text{-psi} \)  
  (Ref. MIL-HDBK-5J, table 3.7.4.0 (d))
- \( Fbry := 101000 \text{-psi} \)

**Bushings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):**

- Allowable bearing stress of bushing: \( Fbru := 125000 \text{-psi} \)  
  (Ref. Appendix C8, Rockwell Materials data sheet 09.12.01.01.1.0)
- \( Fbry := 72000 \text{-psi} \)
Shear Pin Analysis

Loads in shear pin from Bolt Analysis (Direct Shear)

\[ F_{sp,j} := \sqrt{(F_{y,j})^2 + (F_{z,j})^2} \]

rows\( (F_{sp}) = 256 \)

(4 joints x 64 load cases = 256 load cases)

Shear Area of pin

\[ A_{sh} := \frac{\beta \cdot d \cdot p^2}{4} \]

\[ A_{sh} = 0.601 \text{ in}^2 \]

Allowable shear load

\[ P_{all} := F_{su} \cdot A_{sh} \cdot c_{sp} \]

\[ P_{all} = 71515.8 \text{ lbf} \]

Margin of safety

\[ M_{Sp,j} := \left( \frac{P_{all}}{F_{sp,j} \cdot S_{fu}} - 1 \right) \]

\[ \text{min}(M_{Sp}) = 0.89 \]

Bearing of Outer Bushing on Interface Plate

Bearing area

\[ A_{b} := d \cdot o \cdot t\]

\[ A_{b} = 1.026 \text{ in}^2 \]

Allowable bearing load

\[ P_{bru} := F_{bru} \cdot A_{b} \cdot c_{pu} \]

\[ P_{bru} = 116750.2 \text{ lbf} \]

\[ P_{bry} := F_{bry} \cdot A_{b} \cdot c_{py} \]

\[ P_{bry} = 71682 \text{ lbf} \]

Margin of safety

\[ M_{Su,j} := \left( \frac{P_{bru}}{F_{sp,j} \cdot S_{fu}} - 1 \right) \]

\[ M_{Sy,j} := \left( \frac{P_{bry}}{F_{sp,j} \cdot S_{fy}} - 1 \right) \]

\[ \text{min}(M_{Su}) = 2.08 \]

\[ \text{min}(M_{Sy}) = 1.41 \]
Bearing of Shear Pin on Inner Bushing

Bearing area

\[ A_{bp} := dp\cdot tp \quad A_{bp} = 0.682 \text{ in}^2 \]

Allowable bearing load

\[ P_{bru} := F_{bru}\cdot A_{bp}\cdot cbu \quad P_{bru} = 81009.8 \text{ lb} \]
\[ P_{bry} := F_{bry}\cdot A_{bp}\cdot cby \quad P_{bry} = 48626.4 \text{ lb} \]

Margin of safety

\[ MS_{bru} := \frac{P_{bru}}{F_{sp} \cdot SF_{u}} - 1 \quad MS_{bry} := \frac{P_{bry}}{F_{sp} \cdot SF_{y}} - 1 \]

\[ \min(\text{MS}_{bru}) = 1.14 \]
\[ \min(\text{MS}_{bry}) = 0.63 \]
3.10.7.2 Lower Interface Plate to Vacuum Case - .500"
Lower Interface Plate to Vacuum Case Bolt Analysis - 0.50" Bolts

The Vacuum Case Assembly consists of four lower interface plates. There are a total of 14 fasteners attaching the lower interface plate to the Vacuum Case. The following analysis will just include analysis of 6 of the 14 fasteners. The fasteners are NAS1958C9 (180 ksi), 0.50-20 UNJF. There is also one shear pin 0.875" in diameter. The drawing number for the Vacuum Case Assembly is SEG39135776.

Bolt Geometry

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
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<tr>
<td>0.50</td>
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<td>24</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
</tbody>
</table>

\[
bolt := \begin{bmatrix} 0.375 & 24 \\ 0.375 & 24 \\ 0.50 & 20 \\ 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \\ 0.50 & 20 \\ 0.50 & 20 \\ 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \\ 0.50 & 20 \\ 0.50 & 20 \end{bmatrix}
\]

\[
i := 1..\text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{i,2} \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{i,1} \cdot \text{in} \quad \text{bolt diameter}
\]

\[
A_{ti} := \beta \left( \frac{D_i - 0.9743}{N_i} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
A_{si} := \beta \left( \frac{D_i - 1.299038}{N_i} \right)^2 \quad \text{Shear Area of bolt}
\]
Bolts from Lower Interface Plate to Vacuum Case - 0.50" Bolts

In this analysis, only the 0.50" bolts will be analyzed. These bolts correspond to bolt no. 3, 7, 8, 12, 13, and 14. Refer to bolt geometry in previous page.

Location of applied forces and moments:

\[
\begin{align*}
\text{xforce} & := 0.0\text{in} \\
\text{yforce} & := 0.0\text{in} \\
\text{zforce} & := 0.0\text{in}
\end{align*}
\]

\[
\text{cgload} = \begin{pmatrix} \text{xforce} \\ \text{yforce} \\ \text{zforce} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in}
\]
Bolts from Lower Interface Plate to Vacuum Case - 0.50" Bolts

Center of gravity of bolt group

\[ x_{cg} := \frac{\sum x_i}{\text{rows}(x)} \quad \text{in} \]
\[ y_{cg} := \frac{\sum y_i}{\text{rows}(y)} \quad \text{in} \]
\[ z_{cg} := \frac{\sum z_i}{\text{rows}(z)} \quad \text{in} \]

\[ c_{bg bolt} := \begin{bmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{bmatrix} \]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. In the z direction the bolt pattern is unsymmetric and has a 0.468" offset from the center of gravity.

Load Vector

\[ r_{load} := c_{g load} - c_{bg bolt} \]

\[ r_{load} := \begin{bmatrix} 0 \\ 0 \\ -0.468 \end{bmatrix} \quad \text{in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_i := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2} \]

\[ r := \begin{bmatrix} 2.946 \\ 2.946 \\ 4.814 \\ 3.193 \\ 1.095 \\ 3.193 \\ 4.814 \\ 5.033 \\ 3.514 \\ 1.830 \\ 3.514 \\ 5.033 \\ 4.718 \\ 4.718 \end{bmatrix} \quad \text{in} \]

Loads model 2-04 was used to retrieve loads at the four bolted interfaces. A Cbush element located at the center of each interface plate was post processed in NASPOST for forces and moments in the x, y, and z directions. The Cbush element identifications for the four bolted interfaces are 64011, 64012, 64013, and 64014. These loads are read into an array and distributed out to the 14 bolts for each interface plate.

(Note: This joint was checked for minimum margins of safety for launch, nominal landing, and abort landing load cases. The abort landing cases combined with abort landing temperature data resulted in the lowest minimum margins of safety. Therefore, the abort landing cases are used in this analysis.)
Reading database file for bolted joint, abort landing case

\[
data := \text{READPRN}(\text{"lower_ipvcf_r2_abortland.txt"})
\]
\[
\text{num_bolts} := \text{rows(bolt)}
\]
\[
j := 1..\text{rows(data)}
\]

Loads from 2-04 loads model, abort landing case

- **Axial Load**
  \[
  F_x^j := \text{data}_{j,3}\text{\,-lbf}
  \]
- **Shear in Y axis**
  \[
  F_y^j := \text{data}_{j,4}\text{\,-lbf}
  \]
- **Shear in Z axis**
  \[
  F_z^j := \text{data}_{j,5}\text{\,-lbf}
  \]
- **Element Identification**
  \[
  \text{ID}_j := \text{data}_{j,1}
  \]
- **Load Case Number**
  \[
  \text{LC}_j := \text{data}_{j,2}
  \]
- **Torsion**
  \[
  M_x^j := \text{data}_{j,6}\text{\,-\,in\,-lbf}
  \]
- **Moment about Y axis**
  \[
  M_y^j := \text{data}_{j,7}\text{\,-\,in\,-lbf}
  \]
- **Moment about Z axis**
  \[
  M_z^j := \text{data}_{j,8}\text{\,-\,in\,-lbf}
  \]
- **Counter for number of bolts in pattern**
  \[
  \text{ID} := \text{ID}_j \times 1000 + 1
  \]
- **Applied Bending Moment at Bolts**
  \[
  M_j := 0\text{\,\,-\,in\,-lbf}
  \]

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column. For each element identification, 64011, 64012, 64013, and 64014, the bolt number within the bolt pattern is added to the end of each element identification. For example, the element identification number 64001 will have bolt numbers 003, 007 thru 008, and 012 thru 014 attached to the end for all 64 load cases. This brings the total number of load cases to 1536 (4 joints x 6 (1/2" bolts) x 64 load cases = 1536) since only 6 of the bolts will be analyzed. See the array example to the right.

\[
\text{ID} := \text{stack(ID + 2, ID + 6, ID + 7, ID + 11, ID + 12, ID + 13)}
\]
\[
\text{LC} := \text{stack(LC, LC, LC, LC, LC, LC)}
\]

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<tr>
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<td>2064</td>
<td>2064</td>
<td></td>
</tr>
</tbody>
</table>

Array Example

3.10.7.2-5
ESCG-4005-05-AMS-0039
Moment Distribution

\[ M_{tot,j} := \left( \begin{array}{c} M_{x,j} \\ M_{y,j} \\ M_{z,j} \end{array} \right) + r_{load} \times \left( \begin{array}{c} F_{x,j} \\ F_{y,j} \\ F_{z,j} \end{array} \right) \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{x,boltcg,j} := M_{tot,1,j} \quad \text{My}_{boltcg,j} := M_{tot,2,j} \quad \text{Mz}_{boltcg,j} := M_{tot,3,j} \]

Tension on bolts

\[ F_{direct,1,j} := \begin{cases} 0 \text{ lbf} & \text{if } F_{x,j} \leq 0 \text{ lbf} \\ \frac{F_{x,j}}{\text{num\_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ F_{mz,j} := \begin{cases} 0 \text{ lbf} & \text{if } (y_i - y_{cg}) = 0 \text{ in} \\ \frac{[M_{z,boltcg,j} \cdot (y_i - y_{cg})] \cdot At_i}{\sum_{i}[(y_i - y_{cg})^2 \cdot At_i]^{\frac{3}{2}}} \end{cases} \]

\[ F_{my,j} := \begin{cases} 0 \text{ lbf} & \text{if } (z_i - z_{cg}) = 0 \text{ in} \\ \frac{[M_{y,boltcg,j} \cdot (z_i - z_{cg})] \cdot At_i}{\sum_{i}[(z_i - z_{cg})^2 \cdot At_i]^{\frac{3}{2}}} \end{cases} \]

\[ F_{t,j} := F_{direct,1,j} + F_{mz,j} + F_{my,j} \]

Total tensile load

Shear on bolts

Secondary shear on bolts

\[ F_{s,j} := \frac{M_{x,boltcg,j} \cdot r_i \cdot As_j}{\sum_{i}[(r_i)^2 \cdot (As_i)^{\frac{3}{2}}]} \]

Total shear load

\[ F_{stot,j} := F_{s,j} \]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}\left[\left(\text{Ft}\right)^{\left(3\right)}, \left(\text{Ft}\right)^{\left(7\right)}, \left(\text{Ft}\right)^{\left(8\right)}, \left(\text{Ft}\right)^{\left(12\right)}, \left(\text{Ft}\right)^{\left(13\right)}, \left(\text{Ft}\right)^{\left(14\right)}\right]\right]
\]

\[
V := \text{stack}\left[\left(\text{Fstot}\right)^{\left(3\right)}, \left(\text{Fstot}\right)^{\left(7\right)}, \left(\text{Fstot}\right)^{\left(8\right)}, \left(\text{Fstot}\right)^{\left(12\right)}, \left(\text{Fstot}\right)^{\left(13\right)}, \left(\text{Fstot}\right)^{\left(14\right)}\right]\right]
\]

\[
M := \text{stack}(\text{M}, \text{M}, \text{M}, \text{M}, \text{M})
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

\[
\text{Output := augment}\left(\text{ID, LC, P, V, M}\right)
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \(\text{rows(Output)} = 1536\)

(6 (1/2"bolts) x 64 load cases) x 4 joints = 1536 load cases

(Note: The output array to the left is an example of the array format. The loads in this example are for format purposes only and should NOT be used in this analysis.)
CHECK BOLTS (NAS1958C9 0.50-20UNJF-3A, Material-A-286), Insert MS51831CA-206L, Washer NAS1587-8C

The array from the text file above is read:

data := READPRN("output_forces_loweripvcf_r2_abortland.txt")

Flange 1: Lower Interface Plate
Part number: SEG39135789
Material: 7050-T7451

Flange 2: Lower Support Ring Assy
Part number: SEG39135787
Material: 7050-T7451

Loads from Abort Landing Load Cases

<table>
<thead>
<tr>
<th>Applied tensile load</th>
<th>( P_s := data_{s,3}\text{lbf} )</th>
<th>Element Identification</th>
<th>( ID_s := data_{s,1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear load</td>
<td>( V_s := data_{s,4}\text{lbf} )</td>
<td>Load case number</td>
<td>( LC_s := data_{s,2} )</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>( M_s := data_{s,5}\text{in-lbf} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Factors of Safety

<table>
<thead>
<tr>
<th>Ultimate SFu := 1.4</th>
<th>Yield SFy := 1.1</th>
<th>Assembly Temp_initial := 70\text{deg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation SFsep := 1.2</td>
<td>Fitting factor FF := 1.15</td>
<td>Maximum Temp_max := 150\text{deg}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum Temp_min := 40\text{deg}</td>
</tr>
</tbody>
</table>

Bolt and Insert Data

<table>
<thead>
<tr>
<th>Nominal diameter of bolt</th>
<th>( D := 0.50\text{-in} )</th>
<th>Number of threads/inch ( Nt := 20 \frac{1}{\text{in}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of bolt</td>
<td>( L := 1.297\text{-in} )</td>
<td>Length of insert ( Lins := 0.688\text{-in} )</td>
</tr>
<tr>
<td>Threaded length</td>
<td>( Lt := 0.735\text{-in} )</td>
<td>Min. external diameter of insert ( Fmin := 0.615\text{-in} )</td>
</tr>
<tr>
<td></td>
<td>(If bolt is fully threaded, input ( Lt = L ))</td>
<td>Depth of recess for insert ( lr := 0.02\text{-in} )</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \\escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
**Washer Data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of washer</td>
<td>tw := 0.078-in</td>
<td></td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw := 0.875-in</td>
<td></td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi := 0.504-in</td>
<td></td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>dw := 0.710-in</td>
<td>(used only if there is no washer)</td>
</tr>
</tbody>
</table>

**Flange data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 1</td>
<td>tf1 := .345-in</td>
<td>(Ref. SDG39135789)</td>
</tr>
<tr>
<td>Thickness of flange 2</td>
<td>tf2 := .688-in</td>
<td>(Length of insert)</td>
</tr>
<tr>
<td>Diameter of hole</td>
<td>D_hole := 0.516-in</td>
<td>(Ref. SDG39135789)</td>
</tr>
</tbody>
</table>

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
- Bolt ultimate tensile allowable stress
  
  \[ F_{tu\_bolt} := 180000 \text{ psi} \]  
  (Ref. NAS1958)
  
- Bolt ultimate shear allowable stress
  
  \[ F_{su\_bolt} := 0.6 F_{tu\_bolt} \]

- Bolt yield tensile allowable
  
  \[ F_{ty\_bolt} := 132353 \text{ psi} \]  
  (Ref. Appendix C10)

- Temperature correction factor for bolt modulus
  
  \[ T_E\_bolt := .98 \]  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))

- Modulus of elasticity of bolt
  
  \[ E_{\text{bolt}} := \left( 29.1 \times 10^6 \text{ psi} \right) \]  
  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt:
  
  \[ u_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \text{ in/in deg} \]  
  \[ u_{\text{bolt\_cold}} := 8.9 \times 10^{-6} \text{ in/in deg} \]  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

**Insert**

- Temperature correction factor for insert strength
  
  \[ T_S\_\text{ins} := .97 \]  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Ultimate tensile allowable stress
  
  \[ F_{tu\_\text{ins}} := 140000 \text{ psi} \]  
  (Ref. MS51831)

- Ultimate shear allowable stress
  
  \[ F_{su\_\text{ins}} := 0.6 F_{tu\_\text{ins}} \]

**Washer**

- Temperature correction factor for washer modulus
  
  \[ T_E\_\text{washer} := .97 \]  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Modulus of elasticity of washer
  
  \[ E_{\text{washer}} := \left( 29.1 \times 10^6 \text{ psi} \right) \]  
  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))
Flanges  (Mechanical Properties shall meet the requirements of AMS 4108)

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1  
$T_{1E} \equiv 0.98$ (modulus)  
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

Temperature correction factor for flange 2  
$T_{2E} \equiv 0.98$ (modulus)  
$T_{2s} \equiv 0.97$ (strength)  
(Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Shear strength allowable for flanges  
$F_{su_{f2}} \equiv 42000$-psi  
(Ref. MIL-HDBK-5J, table 3.7.4.0(d))

Modulus of elasticity for the parts in the joint  
(Ref. MIL-HDBK-5J, table 3.7.4.0(d))  
$E_{flange1} \equiv (10.2 \cdot 10^6 \text{psi})$  
$E_{flange2} \equiv (10.2 \cdot 10^6 \text{psi})$

Coefficient of thermal expansion for flanges  
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C9)  
$u_{flange1_{hot}} \equiv 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$  
$u_{flange2_{hot}} \equiv 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$

$u_{flange1_{cold}} \equiv 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$  
$u_{flange2_{cold}} \equiv 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$

Torque/Preload data

Maximum torque (62% of yield)  
$T_{max} \equiv 984$-in-lbf

Minimum torque (95% of max. torque)  
$T_{min} \equiv 934$-in-lbf

Loading plane factor:  
$n \equiv 0.5$

Preload Uncertainty:  
$\equiv 0.25$

$k \equiv 0.15$

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Bolt/joint stiffness factor \( k = 0.432 \)

Max. preload

\[ \text{PLD}_{\text{max}} = 17576.2 \text{ lbf} \]

Min. preload

\[ \text{PLD}_{\text{min}} = 8138.5 \text{ lbf} \]

Joint separation load

\[ \text{max}(P_{\text{sep}}) = 3133.493 \text{ lbf} \]

Max. load on the bolt (ultimate)

\[ \text{max}(P_b) = 18483.7 \text{ lbf} \]

Max. load on the bolt (yield)

\[ \text{max}(P_{by}) = 18289.2 \text{ lbf} \]

Bolt ultimate tensile strength

\( P_A = 27425.9 \text{ lbf} \)

Preload due to temperature

\( P_{\text{th}}^{\text{pos}} = 1176.2 \text{ lbf} \)

Uncertainty factor

\( = 0.25 \)

Torque coefficient

\( k = 0.15 \)

Loading plane factor

\( n = 0.5 \)

Thread shear pullout load of bolt or insert

\( P_{\text{ths}} = 51098.8 \text{ lbf} \)

Thread shear pullout load in parent metal

\( P_{\text{pths}} = 27077.2 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

| Joint separation | \( \text{MS}_{\min 1,1} = 1.880 \) | Direct Thread shear Ultimate | \( \text{MS}_{\min 6,1} = 5.441 \) |
| Direct Tension Ultimate | \( \text{MS}_{\min 2,1} = 5.524 \) | Total Thread shear Ultimate | \( \text{MS}_{\min 7,1} = 0.465 \) |
| Direct Tension Yield | \( \text{MS}_{\min 3,1} = 5.105 \) | Shear Ultimate | \( \text{MS}_{\min 8,1} = 2.16 \) |
| Total Tension Ultimate | \( \text{MS}_{\min 4,1} = 0.484 \) | Bending Ultimate | \( \text{MS}_{\min 9,1} = 10 \) |
| Total Tension Yield | \( \text{MS}_{\min 5,1} = 0.103 \) | Combined shear, tension and bending ultimate | \( \text{MS}_{\min 10,1} = 0.451 \) |

Determination of the smallest margin of safety for the bolt, and the failure mode:

\( \text{MS}_{\text{bolt}} := \min(\text{MS}) \)

\( \text{MS}_{\text{bolt}} = 0.103 \)

Failure Mode = "Total Tension Yield"

Element Identification (64011) and Bolt Number (12) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Lower Interface Plate to Vacuum Case (Shear Pin Failure)

This portion of the analysis assumes a failure in the shear pin. The shear pin part number is SDG39135755-001. All 6 NAS1958 1/2" fasteners will take the direct shear load.

\[
F_{sd,i,j} := \frac{\sqrt{(F_{y,j})^2 + (F_{z,j})^2}}{\text{num_bolts}}
\]

Total shear load

\[
F_{stot,i,j} := F_{s,i,j} + F_{sd,i,j}
\]

(Note: The \( F_s \) variable is the secondary shear and has been calculated previously in the analysis.)

The stack command below is used to stack the applied shear load (\( V \)) in ascending order per bolt. The applied axial load (\( P \)) and applied moment (\( M \)) are stacked above and reused in the output file below. These loads are put into an array with the element/bolt number and load case number from above.

\[
V := \text{stack}\left[\left(F_{stot}^T\right)^{(3)},\left(F_{stot}^T\right)^{(7)},\left(F_{stot}^T\right)^{(8)},\left(F_{stot}^T\right)^{(12)},\left(F_{stot}^T\right)^{(13)},\left(F_{stot}^T\right)^{(14)}\right]
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (\( P \)), applied shear on the bolt (\( V \)), and applied moment on the bolt (\( M \)). The array is written to a text file. For the format of the array see the output example array above.

\[
\text{Output} := \text{augment}\left(\text{ID}, \text{LC}, \frac{P}{\text{lb}} , \frac{V}{\text{lb}} , \frac{M}{\text{in-lbf}}\right)
\]

(Note: Since the ID and LC numbers are dimensionless, the \( P, V, \) and \( M \) values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \( \text{rows}(\text{Output}) = 1536 \)

\((6 \times 1/2"\text{bolts}) \times 64 \text{ load cases} \times 4 \text{ joints} = 1536 \text{ load cases} \)

\(\text{WRITEPRN}(\text{"output_forces_loweripvcf_r2_abortland_pinfs.txt"}) := \text{Output}\)

Fail-safe Analysis (Shear Pin Failure)

\(\text{data}_fsp := \text{READPRN}(\text{"output_forces_loweripvcf_r2_abortland_pinfs.txt"})\)

\(s := 1..\text{rows}(\text{data}_fsp)\)
Fail-safe Loads, abort landing

Applied tensile load  \[ P_{FS} := \text{data}_{fsp},3 \text{lbf} \]

Applied shear load  \[ V_{FS} := \text{data}_{fsp},4 \text{lbf} \]

Applied bending moment  \[ M_{FS} := \text{data}_{fsp},5 \text{in-lbf} \]

This file uses the calculations shown in \textbackslash escfil02/2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

Joint separation load  \[ \text{max}(P_{sep_{FS}}) = 2611.24 \text{lb} \]

Max. load on the bolt(ultimate)  \[ \text{max}(P_{b_{FS}}) = 18224.4 \text{lb} \]

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>MS,SB,1</th>
<th>MS,SB,2</th>
<th>MS,SB,3</th>
<th>MS,SB,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>2.456</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>8.133</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.505</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>8.02</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt_{FS}} := \text{min}(MS_{FS}) \]

\[ MS_{bolt_{FS}} = 0.486 \]  

Failure Mode FS = "Total Thread Shear Ultimate"

Element Identification (64011) and Bolt Number (12) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Lower Interface Plate to Vacuum Case - 0.50" Bolts

Since bolt number 12 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 5, NAS1958C9 0.50-20 UNJF fasteners, holding the lower interface plate to the Vacuum Case. The drawing number for the Vacuum Case Assembly is SEG39135776.

\[
s := 1 \ldots \text{rows(bolt2)}
\]

\[
N_2^s := \text{bolt2}_s, 2 \cdot \frac{1}{\text{in}} \text{ pitch of bolt}
\]

\[
D_2^s := \text{bolt2}_s, 1 \cdot \frac{1}{\text{in}} \text{ bolt diameter}
\]

\[
\text{At}_2^s := \beta \cdot \left( \frac{D_2^s - 0.9743 \frac{1}{N_2^s}}{2} \right)^2 \text{ Tensile Area of bolt}
\]

\[
\text{As}_2^s := \beta \cdot \left( \frac{D_2^s - 1.299038 \frac{1}{N_2^s}}{2} \right)^2 \text{ Shear Area of bolt}
\]
Bolt no.  x co-ord  y co-ord  z co-ord
1    0.0     -1.75     2.838
2    0.0      1.75     2.838
3    0.0     -4.688    1.563
4    0.0      -3.0     1.563
5    0.0       0.0     1.563
6    0.0       3.0     1.563
7  x2 := 0.0-in  y2 := 4.688-in  z2 := 1.563-in
8    0.0     -4.688   -1.362
9    0.0      -3.0     -1.362
10   0.0       0.0     -1.362
11   0.0       3.0     -1.362
13   0.0     -4.688    -0.062
14   0.0     4.688    -0.062

Location of applied forces and moments
xforce2 := 0.0in  yforce2 := 0.0in  zforce2 := 0.0in
cgload2 := \begin{pmatrix} xforce2 \\ yforce2 \\ zforce2 \end{pmatrix}
cgload2 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}\text{-in}

Center of gravity of bolt group
\begin{align*}
xcg2 := \frac{\sum x^2_s}{\text{rows}(x2)} & \quad \text{xcg} = 0\text{-in} \\
ycg2 := \frac{\sum y^2_s}{\text{rows}(y2)} & \quad \text{ycg2} = -0.361\text{-in} \\
zcg2 := \frac{\sum z^2_s}{\text{rows}(z2)} & \quad \text{zcg2} = 0.609\text{-in}
\end{align*}
\begin{pmatrix} xcg2 \\ ycg2 \\ zcg2 \end{pmatrix}
cgbolt2 := \begin{pmatrix} 0 \\ -0.361 \end{pmatrix}\text{-in}
\begin{pmatrix} 0 \\ 0.609 \end{pmatrix}\text{-in}

Note: Since the x direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 12, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector
r_{load2} := cgload2 - cgbolt2
r_{load2} = \begin{pmatrix} 0 \\ 0.361 \\ -0.609 \end{pmatrix}\text{-in}
Distance from CG of Bolts to Individual Bolts for shear calculations

\( r_2 := \sqrt{(x_2 - x_{cg2})^2 + (y_2 - y_{cg2})^2} \)

\[
\begin{align*}
2.626 \\
3.070 \\
4.431 \\
2.806 \\
1.020 \\
3.493 \\
5.138 \text{ in} \\
4.755 \\
3.294 \\
2.004 \\
3.896 \\
4.379 \\
5.093
\end{align*}
\]

Reading database file for bolted joint, abort landing case

\( \text{data} := \text{READPRN}("lower_ipvcf_r2_abortland.txt") \)
\( q := 1..\text{rows(data)} \)
\( \text{num_bolts2} := \text{rows(bolt2)} \)

Loads from 2-04 loads model, abort landing case

Axial Load
\( F_{x2} := \text{data}_{q,3}\text{-lbf} \)

Shear in Y axis
\( F_{y2} := \text{data}_{q,4}\text{-lbf} \)

Shear in Z axis
\( F_{z2} := \text{data}_{q,5}\text{-lbf} \)

Element Identification
\( \text{ID}_{2} := \text{data}_{q,1} \)

Load Case Number
\( \text{LC}_{2} := \text{data}_{q,2} \)

Applied Bending Moment at Bolts
\( M_{2} := 0\text{-in-lbf} \)

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 12 is not included.

\[
\text{ID2} := \text{stack(ID2 + 2, ID2 + 6, ID2 + 7, ID2 + 12, ID2 + 13)}
\]
\[
\text{LC2} := \text{stack(LC2, LC2, LC2, LC2, LC2)}
\]
Moment Distribution

\[ M_{\text{tot}2}(q) := \begin{pmatrix} Mx_2 \\ My_2 \\ Mz_2 \end{pmatrix} + \begin{pmatrix} Fx_2 \\ Fy_2 \\ Fz_2 \end{pmatrix} \times r_{\text{load}} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{\text{boltcg}2}(q) := M_{\text{tot}1,q}, \quad M_{\text{boltcg}2}(q) := M_{\text{tot}2,q}, \quad M_{\text{boltcg}2}(q) := M_{\text{tot}3,q} \]

Tension on bolts

\[ F_{\text{direct}2,s,q} := \begin{cases} 0 \text{-lbf} & \text{if } Fx_2 \leq 0\text{lbf} \\ \frac{Fx_2}{\text{num_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation

\[ F_{mz2,s,q} := \begin{cases} 0 \text{-lbf} & \text{if } Mz_2 \leq 0\text{-in} \\ \frac{Mz_2}{(y_2 - y_{cg2})^2 \cdot At_s} & \text{otherwise} \end{cases} \]

\[ F_{my2,s,q} := \begin{cases} 0 \text{-lbf} & \text{if } Mx_2 \leq 0\text{-in} \\ \frac{Mx_2}{(z_2 - z_{cg2})^2 \cdot At_s} & \text{otherwise} \end{cases} \]

\[ F_{s2,s,q} := F_{\text{direct}2,s,q} + F_{mz2,s,q} + F_{my2,s,q} \quad \text{Total Tensile load} \]

Shear on bolts

\[ F_{s2,s,q} := \frac{M_{\text{boltcg}2,q} \cdot r_s \cdot As_s}{\sum_s (r_s^2 \cdot (As_s))^2} \quad \text{Total shear load} \]

(Note: The direct shear is taken by the shear pin.)
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 5 bolts, since bolt number 12 is not included.

\[ P_2 := \text{stack} \left[ \left( F_{2T} \right)^3, \left( F_{2T} \right)^7, \left( F_{2T} \right)^8, \left( F_{2T} \right)^{12}, \left( F_{2T} \right)^{13} \right] \]

\[ V_2 := \text{stack} \left[ \left( F_{stot2} \right)^3, \left( F_{stot2} \right)^7, \left( F_{stot2} \right)^8, \left( F_{stot2} \right)^{12}, \left( F_{stot2} \right)^{13} \right] \]

\[ M_2 := \text{stack} (M_2, M_2, M_2, M_2, M_2) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

Output2 := augment\((\text{ID2, LC2, } \frac{\text{P2}}{\text{lbf}}, \frac{\text{V2}}{\text{lbf}}, \frac{\text{M2}}{\text{in-lbf}})\) (Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: rows(Output2) = 1280

\((5 \text{ (1/2" bolts)} \times 64 \text{ load cases}) \times 4 \text{ joints} = 1280 \text{ load cases}\)

\text{WRITEPRN("output_forces_loweripvcf_r2_abortland_fs.txt") := Output2}

\textbf{Bolt Fail-safe Results}

data_fs := \text{READPRN("output_forces_loweripvcf_r2_abortland_fs.txt")}

s := 1..rows(data_fs)
**Fail-safe Loads, abort landing**

<table>
<thead>
<tr>
<th><strong>Applied tensile load</strong></th>
<th><strong>ID</strong></th>
<th><strong>SF</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{FS3} := \text{data}_{FS3,3} \text{lbf}$</td>
<td>$\text{SF}<em>{FS3} := \text{data}</em>{FS3,1}$</td>
<td><strong>Ultimate</strong></td>
</tr>
<tr>
<td><strong>Applied shear load</strong></td>
<td><strong>LC</strong></td>
<td><strong>SF</strong></td>
</tr>
<tr>
<td>$V_{FS3} := \text{data}_{FS3,4} \text{lbf}$</td>
<td>$\text{SF}<em>{FS3} := \text{data}</em>{FS3,2}$</td>
<td><strong>Joint Separation</strong></td>
</tr>
<tr>
<td><strong>Applied bending moment</strong></td>
<td><strong>MS</strong></td>
<td><strong>SF</strong></td>
</tr>
<tr>
<td>$M_{FS3} := \text{data}_{FS3,5} \text{in-lbf}$</td>
<td></td>
<td><strong>Ultimate</strong></td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escf02\211_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`

---

**Bolt Fail-safe Load data**

- Joint separation load: $\max(P_{sep_{FS}}) = 2819.999 \text{lbf}$
- Max. load on the bolt (ultimate): $\max(P_{b_{FS}}) = 18276.2 \text{lbf}$

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th><strong>Joint separation</strong></th>
<th>$MS_{minFS3,1} = 2.200$</th>
<th><strong>Total Thread shear Ultimate</strong></th>
<th>$MS_{minFS3,5,1} = 0.482$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Tension Ultimate</strong></td>
<td>$MS_{minFS3,2} = 7.457$</td>
<td><strong>Shear Ultimate</strong></td>
<td>$MS_{minFS3,6,1} = 2.66$</td>
</tr>
<tr>
<td><strong>Total Tension Ultimate</strong></td>
<td>$MS_{minFS3,3} = 0.501$</td>
<td><strong>Bending Ultimate</strong></td>
<td>$MS_{minFS3,7,1} = 10$</td>
</tr>
<tr>
<td><strong>Direct Thread shear Ultimate</strong></td>
<td>$MS_{minFS3,4} = 7.35$</td>
<td><strong>Combined shear, tension and bending ultimate</strong></td>
<td>$MS_{minFS3,8,1} = 0.4848$</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

$MS_{bolt_{FS}} := \min(MS_{FS3})$

$MS_{bolt_{FS}} = 0.482$  
Failure Mode FS = "Total Thread Shear Ultimate"

$MS_{min\_ID} = 64012008$  
Element Identification (64012) and Bolt Number (8) for Minimum Margin

$MS_{min\_LC} = 2038$  
Load Case Number for Minimum Margin

$MS_{min\_P} = 2820$  
Applied Tensile Load for Minimum Margin

$MS_{min\_V} = -1804.8$  
Applied Shear Load for Minimum Margin

$MS_{min\_M} = 0$  
Applied Bending Moment for Minimum Margin
Shear Pin Analysis for Lower Interface Plate to Vacuum Case

The Vacuum Case Assembly consists of four lower interface plates. Each lower interface plate has a shear pin (SDG39135755-001) installed with two bushings. The shear pin sits inside of a inner bushing SDG39135757-001 and the inner bushing sits inside of the outer bushing SDG39135757-003.

Cross Section of the Bolted Interface

Shear Pin SDG39135755-001

Inner Bushing SDG39135757-001

Outer Bushing SDG39135757-003
Geometry

Minimum Diameter of shear pin \( dp := 0.8746 \text{ in} \) (Ref. Dwg. SDG39135755-001)
Outer diameter of outer bushing \( do := 1.3685 \text{ in} \) (Ref. Dwg. SDG39135757-003)
Thickness of interface plate \( tp := 0.75 \text{ in} \) (Ref. Dwg. SDG39135789)
Length of inner bushing \( t\text{pin} := 0.78 \text{ in} \) (Ref. Dwg. SDG39135757-001)

Temperature Data

Shear Pin (Custom 455, H1000 bar, AMS5617):
Temperature correction factor for shear \( csp := 0.96 \) (Ref. MIL-HDBK-5J, table 2.6.4.1.2)

Interface Plate (Al 7050-T7451 Plate):
Temperature correction factor for ultimate \( cpu := 0.91 \) (Ref. MIL-HDBK-5J, fig. 3.7.4.2.1)

Busings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):
Temperature correction factor for ultimate \( cbu := 0.95 \) (Ref. Appendix C8)
Temperature correction factor for yield \( cby := 0.99 \)

Material Properties

Shear Pin (Custom 455, H1000 bar, AMS5617):
Allowable shear stress \( F_{su} := 124000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 2.6.4.0(b))

Interface Plate (Al 7050-T7451 Plate):
Allowable bearing stress \( F_{bru} := 131000 \text{ psi} \) (Ref. MIL-HDBK-5J, table 3.7.4.0 (d))
\( F_{bry} := 101000 \text{ psi} \)

Busings (Aluminum Bronze AMS4640, ASTM B150, alloy C63000):
Allowable bearing stress of bushing \( F_{bru} := 125000 \text{ psi} \) (Ref. Appendix C8, Rockwell Materials data sheet 09.12.01.01,1.0)
\( F_{bry} := 72000 \text{ psi} \)
Shear Pin Analysis

 Loads in shear pin from Bolt Analysis (Direct Shear)

\[ F_{sp,j} := \sqrt{(F_{y,j})^2 + (F_{z,j})^2} \]
rows\((F_{sp}) = 256 \)

(4 joints x 64 load cases = 256 load cases)

Shear Area of pin

\[ A_{sh} := \frac{\beta \cdot dp^2}{4} \]

\[ A_{sh} = 0.601 \text{in}^2 \]

Allowable shear load

\[ P_{all} := F_{su} \cdot A_{sh} \cdot C_{sp} \]

\[ P_{all} = 71515.8 \text{lbf} \]

Margin of safety

\[ M_{Sp,j} := \left( \frac{P_{all}}{F_{sp,j} \cdot S_{Fu}} - 1 \right) \]

\[ \text{min}(M_{Sp}) = 0.89 \]

Bearing of Outer Bushing on Interface Plate

Bearing area

\[ A_{b} := d \cdot o \cdot t \]

\[ A_{b} = 1.026 \text{in}^2 \]

Allowable bearing load

\[ P_{bru} := F_{bru} \cdot A_{b} \cdot C_{pu} \]

\[ P_{bru} = 116750.2 \text{lbf} \]

\[ P_{bry} := F_{bry} \cdot A_{b} \cdot C_{py} \]

\[ P_{bry} = 71682 \text{lbf} \]

Margin of safety

\[ M_{Su,j} := \frac{P_{bru}}{F_{sp,j} \cdot S_{Fu}} - 1 \]

\[ M_{Sy,j} := \frac{P_{bry}}{F_{sp,j} \cdot S_{Fy}} - 1 \]

\[ \text{min}(M_{Su}) = 2.08 \]

\[ \text{min}(M_{Sy}) = 1.41 \]
## Bearing of Shear Pin on Inner Bushing

<table>
<thead>
<tr>
<th>Description</th>
<th>Equation</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing area</td>
<td>$\text{Abp} := dp \cdot \text{tpin}$</td>
<td>$\text{Abp} = 0.682 \text{ in}^2$</td>
</tr>
<tr>
<td>Allowable bearing load</td>
<td>$\text{Pbru} := F\text{bru} \cdot \text{Abp} \cdot \text{cbru}$</td>
<td>$\text{Pbru} = 81009.8 \text{ lbf}$</td>
</tr>
<tr>
<td></td>
<td>$\text{Pbry} := F\text{bry} \cdot \text{Abp} \cdot \text{cbry}$</td>
<td>$\text{Pbry} = 48626.4 \text{ lbf}$</td>
</tr>
<tr>
<td>Margin of safety</td>
<td>$\text{MSbru} := \frac{\text{Pbru}}{F_{\text{sp}, j} \cdot \text{SFu}} \cdot 1$</td>
<td>$\text{min}(\text{MSbru}) = 1.14$</td>
</tr>
<tr>
<td></td>
<td>$\text{MSbry} := \frac{\text{Pbry}}{F_{\text{sp}, j} \cdot \text{SFy}} \cdot 1$</td>
<td>$\text{min}(\text{MSbry}) = 0.63$</td>
</tr>
</tbody>
</table>


4.0 Strength Assessment of Payload Attach System Assembly
4.0  AMS-02 Passive Payload Attach System (PAS)

4.0.1  Introduction

The PAS is used to hold the AMS-02 payload to the ISS by means of an active claw on the station that holds the PAS capture bar, pulling the PAS down where the three PAS guide pins rest in the ISS guide vanes. The figure below shows the AMS-02 payload attached to the station truss.

Figure 4.0-1: AMS-02 Attached to ISS

SSP 57003 gives a stiffness requirement of 13500 +/- 10% for the overall PAS/payload stiffness as measured at the center of the capture bar. When under load, 57003 also require that the capture bar must be able to be manually lowered by EVA astronauts.

The AMS-02 PAS is designed with two “bridge beams” the center of which are connected at each end of the capture bar through bearings. These two beams will be simply supported at each end. Pinning the beams at different locations will change the beam’s length, which will then vary the overall system stiffness. The system will be tested in various configurations until the desired stiffness is reached, and then the pins will be fixed in those locations.
4.0.1.1 Description

An overview of the PAS assembly is shown below in three views, with some of the major components labeled.

Figure 4.0-2 PAS Assembly
The PAS consists of

1. Platform. Roughly triangular in shape, machined out of three inch thick 7050 plate.
2. Guidepins. Machined out of 7050 plate. Attached to the vertices of the triangle. The
forward guide pin takes Y and Z translational forces. The two rear pins take X and Z translational forces. (Axis refer to the analysis coordinate system)


4. Bridge beam brackets. Steel “U” shaped brackets that the bridge beams ride in. Mounting pins attach the bridge to the brackets. The brackets then sit on the platform. The brackets and bridge beams have six mounting holes, allowing the effective length of the bridge beam to be changed.

5. Release mechanism. A machined box with a cover. The actual mechanism has a triangular wedge upon which rides a triangular washer/nut that holds the capture bar bearing shaft. An EVA astronaut moves the wedge in the Y direction by means of a screw that is turnable. This lowers the capture bar, releasing it from the active PAS claw.

6. Bearing housing/shaft. Spherical bearing for the capture bar to sit in. The bearing housing is machined into the end of an A286 shaft.

7. Capture bar. Round bar of A286 steel. The bar has a groove that is used to retain the bar and prevent it from being totally removed from the bearing/housing. There is a handle attached to one end of the bar that allows the EVA astronauts to remove the bar once it has been lowered by the EVA release screws.

8. BCS Bracket/camera. The berthing camera is mounted to two brackets, which are attached to the rear of the PAS platform.

4.0.2 Loading

The hardware will see three loading conditions:

1. Capture bar loading. Maximum applied loading at the AMS-02 location is 6430 lbs in the negative Z direction. Nominal loading is 5650 lbs. Analysis will be performed using the maximum loading. The first figure below shows the active PAS. The second figure shows the PAS platform in the berthed condition with the active PAS claw closed.
2. On-orbit loading. These loads result from Berthing Load (latch disengaged) and operational loads (latched+ EVA misc. events). For analysis it is assumed that the capture bar is engaged during these loads. Forces are given in ISS DAC-8 at the capture bar. These forces were moved to the AMS payload c.g. and converted to acceleration load factors so they could be applied to the AMS-02 model. This is explained below. These on-orbit loads result in slight increases in the maximum load that the capture bar sees.

3. Liftoff/landing load factors. The PAS is connected to the AMS-02 thru the lower USS structure. During liftoff/landing the PAS sees accelerations loads due to its weight, plus loads imparted due to movement of the USS hardware.
4.0.2.1 Load Factor Derivation of On-Orbit Loads for AMS-02

The loads for the PAS are derived from ISS DAC-8 Structural Loads Report; Document D684-10019-02-01-02 Rev E (shown in Figure 4.0-7 and Figure 4.0-8). The ISS DAC-8 loads require the following additional operations before they can be used on the PAS.

1. The loads have to be transformed to the C.G. of the AMS-02.
2. Various combinations of the loads are used to generate 64 load cases by utilizing the translational and rotational accelerations.

The detailed derivations are shown in Appendix C16.

### Peak Load Cases

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Axial (lbs)</th>
<th>RSS Shear (lbs)</th>
<th>RSS Moment (in-lbs)</th>
<th>Torsion (in-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D858BEP10464</td>
<td>776.6</td>
<td>615.3</td>
<td>18,686.9</td>
<td>19,150.5</td>
</tr>
<tr>
<td>D860PJM20602</td>
<td>126.8</td>
<td>764.2</td>
<td>17,621.3</td>
<td>3,579.5</td>
</tr>
<tr>
<td>D882PDM20557</td>
<td>161.4</td>
<td>342.3</td>
<td>32,479.5</td>
<td>3,527.0</td>
</tr>
<tr>
<td>D858BEP10467</td>
<td>525.9</td>
<td>726.3</td>
<td>20,594.7</td>
<td>32,417.7</td>
</tr>
</tbody>
</table>

*Figure 4.0-7 Peak On-Orbit Load Cases from page 7-434*

### Resultant Berthing Contact Forces

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Axial (lbs)</th>
<th>RSS Shear (lbs)</th>
<th>RSS Moment (in-lbs)</th>
<th>Torsion (in-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D858BEPB0001</td>
<td>662</td>
<td>610</td>
<td>18995</td>
<td>10415</td>
</tr>
<tr>
<td>D858BEPB0002</td>
<td>748</td>
<td>650</td>
<td>21680</td>
<td>9029</td>
</tr>
<tr>
<td>D858BEPB0003</td>
<td>496</td>
<td>460</td>
<td>14350</td>
<td>13491</td>
</tr>
<tr>
<td>D858BEPB0004</td>
<td>862</td>
<td>439</td>
<td>24960</td>
<td>8956</td>
</tr>
</tbody>
</table>

*Figure 4.0-8 Peak Berthing Contact Load Cases from page 7-716*
4.0.2.2  Factors of Safety

The hardware is designed with a yield factor of 1.25 and ultimate factor of 2.0 against limit loads except for the Vertex Bracket.

The design of the Vertex bracket was based on a yield factor of safety of 1.25 and an ultimate factor of safety of 2.0 for untested hardware. A static test of the vertex bracket is done and the stress analysis for the vertex bracket will use a yield factor of safety of 1.10 and an ultimate factor of safety of 1.4 for tested hardware.

Ref. AMS-02 :"Structural Verification Plan" JSC 28792 REV. E

4.0.3  Analysis Technique

A FEM model was built of the PAS hardware using FEMAP.

1. Platform was modeled as quad and tri plate elements, with RBEs representing thick regions. In some high stress areas tapered shell elements were used in order to attempt to model the change in thickness between areas.
2. Guidepins were modeled as beam elements and attached to the platform with RBEs.
3. The bridge beams were modeled as beam elements. Since the bridge beams are truly simply supported beams, the RBEs connecting them to the U brackets were released in all DOF except for the PAS Z DOF. There are six of these 1 DOF RBEs on each end of the beams. Depending on what analysis case is being run, 5 of each six RBEs is commented out, leaving one representing the actual pin location.
4. Attached to the bridge beams are beams representing the release mechanism. RBEs attach the bridge beams to the release mechanism beams, which are then attached to the PAS platform.
5. Beams representing the capture bar bearing shafts are then attached to the release mechanism beams.
6. The capture bar is modeled as beams attached to the spherical bearings with only Y and Z translations fixed.
7. Attached on one end of the capture bar is an RBE connected to a CONM2 card representing the capture bar handle.
8. Berthing camera is modeled as a lumped mass CONM2 card with two RBE “spiders”

Figure 4.0-9 The Following Load Derivations And Load Cases Can Be Found In Appendix C16.
connecting it to the PAS platform.

9. The scuff plates and BCS bracket are not included in this model.

Note that the coordinate system used for analysis is rotated 90 about the Z as compared to the UCCAS coordinate system.
This model was then attached to the full AMS-02 model using RBE and CBUSH elements. The CBUSH elements were adjusted for stiffness to represent the actual joint stiffness. The CBUSH stiffness may be adjusted once the static testing is performed in order to correlate the model to the test results.

The capture bar load was applied using a FORCE card of 6430 pounds. Six separate cases were run, one for the bridge pins in each location. For these cases the PAS was constrained at the three guide pins.

Deflections were recovered and the stiffness in both configurations was calculated. New load cases were run with on-orbit loads applied as accelerations to the FEM, with capture bar deflections applied using a SPCD card. This is necessary since for these load cases the capture itself must be constrained in the Z DOF.

Figure 4.0-11  FEMAP Model of Bridge Beams with Capture Bar Assembly
4.0.3.1 Model Checks

Rigid body checks were performed using NASTRAN. Results from the check .f06 file are shown below. The KGG, KNN and KFF matrices all pass with low strain energy.

- **USER INFORMATION MESSAGE 7570 (GPWGID)**
  RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
  PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.041040E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>5.159429E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.911161E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>3.191360E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>8.701639E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.851847E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

- **USER INFORMATION MESSAGE 7570 (GPWGID)**
  RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
  PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.614816E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.016599E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>9.60342E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.63542E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>7.701034E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.701003E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

- **USER INFORMATION MESSAGE 7570 (GPWGID)**
  RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
  PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.614816E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.016599E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>9.60342E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.63542E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>7.701034E-04</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.701003E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

A further check is that of rigid body modes. The first 7 unconstrained modes are shown below. There are six rigid body modes (\( \sim 0.0 \)), and then good separation with the first non-rigid body mode.
This table gives the natural frequencies of the entire AMS-02 payload while attached to the ISS. Note that for this calculation, as per SSP 57003, the PAS is fully constrained (all six DOF) at the guidepins. As required, the first frequency is greater than 1.5 Hz.

**Table 4.0-1: Natural Modes of AMS/PAS On-orbit**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Extraction</th>
<th>Eigenvalues</th>
<th>Radians</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>106.96</td>
<td>10.34</td>
<td>1.65</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>188.45</td>
<td>13.73</td>
<td>2.18</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>269.41</td>
<td>16.41</td>
<td>2.61</td>
</tr>
</tbody>
</table>
4.0.4 Analysis

4.0.4.1 Stiffness

The PAS is used to hold the AMS-02 payload to the ISS by means of an active claw on the station that holds the PAS capture bar, pulling the PAS down where the three PAS guide pins rest in the ISS guide vanes.

SSP 57003 gives a stiffness requirement of 13500 +/- 10% for the overall PAS/payload stiffness as measured at the center of the capture bar. When under load, 57003 also require that the capture bar must be able to be manually lowered by EVA astronauts. Since this model was changed the stiffness needs to be rechecked to confirm it has not been affected significantly. This comparison is shown in Table 4.0-2 Stiffness calculations of PAS.

The AMS-02 PAS is designed with two “bridge beams” the centers of which are connected at each end of the capture bar through bearings. These two beams will be simply supported at each end. Pinning the beams at different locations will change the beam’s length, which will then vary the overall system stiffness. The system will be tested in various configurations until the desired stiffness is reached, and then the pins will be fixed in those locations.

Capture bar loading. Maximum applied loading at the AMS-02 location is 6430 lbs in the negative Z direction. Nominal loading is 5650 lbs. Analysis will be performed using the maximum loading.

The model has to simulate the combined inertia and static claw load as well as the constraints. In the Nastran simulation the method used, was to first run the model, unconstrained at the Claw location and with the static load applied. The results of this run are shown in case 1119 in Table 4.0-2 Stiffness calculations of PAS. The deflection from this load case was input into the inertia run as a SPCD constraint.
### Table 4.0-2  Stiffness calculations of PAS

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Case 1120</th>
<th>Case 1119</th>
<th>Units</th>
<th>Percent Difference</th>
<th>Data Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Point ID.</strong></td>
<td>802112</td>
<td>802112</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied Load</td>
<td></td>
<td></td>
<td>Load (lbf)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Applied Load</strong></td>
<td></td>
<td></td>
<td>Load (lbf)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1 (cd1)</td>
<td>0.00000</td>
<td>0.0</td>
<td>(in) or (lbf)</td>
<td>NA</td>
<td>NASTRAN input</td>
</tr>
<tr>
<td>T2 (cd2)</td>
<td>0.00000</td>
<td>0.0</td>
<td>(in) or (lbf)</td>
<td>NA</td>
<td>NASTRAN input</td>
</tr>
<tr>
<td>T3 (ccd3)</td>
<td>-0.49278</td>
<td>-6430.0</td>
<td>(in) or (lbf)</td>
<td>NA</td>
<td>NASTRAN input</td>
</tr>
<tr>
<td><strong>Load in Claw Cord. System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.00000</td>
<td>0.0</td>
<td>(in) or (lbf)</td>
<td>NA</td>
<td>=-1*cd2</td>
</tr>
<tr>
<td>T2</td>
<td>-0.10245</td>
<td>-1336.9</td>
<td>(in) or (lbf)</td>
<td>NA</td>
<td>=cd1<em>c12+cd3</em>s12</td>
</tr>
<tr>
<td>T3</td>
<td>-0.48201</td>
<td>-6289.5</td>
<td>(in) or (lbf)</td>
<td>NA</td>
<td>=-1<em>cd1</em>s12+cd3*c12</td>
</tr>
<tr>
<td><strong>Load lbf (P)</strong></td>
<td>-6430.0</td>
<td>-6430.0</td>
<td>(lbf)</td>
<td>NA</td>
<td>Per. Requirements</td>
</tr>
<tr>
<td><strong>Translation in Orbiter Cord. System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.07534</td>
<td>0.08089</td>
<td>(in)</td>
<td>-7.1%</td>
<td>From NASTRAN</td>
</tr>
<tr>
<td>T2</td>
<td>-0.00041</td>
<td>-0.00048</td>
<td>(in)</td>
<td>-15.6%</td>
<td>From NASTRAN</td>
</tr>
<tr>
<td>T3</td>
<td>-0.48778</td>
<td>-0.50566</td>
<td>(in)</td>
<td>-3.6%</td>
<td>From NASTRAN</td>
</tr>
<tr>
<td><strong>Translation in Claw Cord. System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>-0.00009</td>
<td>-0.00009</td>
<td>(rad)</td>
<td>-5.5%</td>
<td>From NASTRAN</td>
</tr>
<tr>
<td>R2</td>
<td>0.00975</td>
<td>0.01009</td>
<td>(rad)</td>
<td>-3.4%</td>
<td>From NASTRAN</td>
</tr>
<tr>
<td>R3</td>
<td>-0.00004</td>
<td>-0.00004</td>
<td>(rad)</td>
<td>-2.4%</td>
<td>From NASTRAN</td>
</tr>
<tr>
<td><strong>Translation in Claw Cord.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.00041</td>
<td>0.00048</td>
<td>(in)</td>
<td>-15.6%</td>
<td>=-1*od2</td>
</tr>
<tr>
<td>T2</td>
<td>-0.02772</td>
<td>-0.02601</td>
<td>(in)</td>
<td>6.38%</td>
<td>=od1<em>c12+od3</em>s12</td>
</tr>
<tr>
<td>T3</td>
<td>-0.49278</td>
<td>-0.51143</td>
<td>(in)</td>
<td>-3.7%</td>
<td>=-1<em>od1</em>s12+od3*c12</td>
</tr>
<tr>
<td><strong>Stiffness (k)</strong></td>
<td>13048.419</td>
<td>12572.707</td>
<td>(lbf/in)</td>
<td>3.71%</td>
<td>=P/d</td>
</tr>
<tr>
<td><strong>Target Stiffness (Tark)</strong></td>
<td>13500</td>
<td>13500</td>
<td>(lbf/in)</td>
<td>NA</td>
<td>Per. Requirements</td>
</tr>
<tr>
<td><strong>Min Targ</strong></td>
<td>12150</td>
<td>12150</td>
<td>(lbf/in)</td>
<td>NA</td>
<td>=0.9*Tark</td>
</tr>
<tr>
<td><strong>Max targ</strong></td>
<td>14850</td>
<td>14850</td>
<td>(lbf/in)</td>
<td>NA</td>
<td>=1.1*Tark</td>
</tr>
<tr>
<td><strong>Percent Error</strong></td>
<td>-3.35%</td>
<td>-6.87%</td>
<td>%</td>
<td>-69.00%</td>
<td>= (k-Tark)/Tark</td>
</tr>
<tr>
<td><strong>Cos(12)</strong></td>
<td>0.978147601</td>
<td>0.978147601</td>
<td>NA</td>
<td>NA</td>
<td>=cos(12deg)</td>
</tr>
<tr>
<td><strong>Sin(12)</strong></td>
<td>0.207911691</td>
<td>0.207911691</td>
<td>NA</td>
<td>NA</td>
<td>=sin(12deg)</td>
</tr>
</tbody>
</table>

Note: Percent difference is (“case 1120” - “case 1119”)/Average(“case 1120” and “case 1119”)
4.1 Vertex Bracket
4.1 AMS-02 PAS Vertex Bracket

4.1.1 Margins of Safety

Table 4.1-1 Minimum Margin Of Safety Summary

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135813</td>
<td>PAS Vertex Bracket</td>
<td>AL ALY 7050-T7451</td>
<td>Consistent On-Orbit Load Factor</td>
<td>Solid Min Prin Stress</td>
<td>0.02 (u)</td>
<td>4.1-13</td>
</tr>
</tbody>
</table>

Notes:
1. See Table 4.1.7-6, Set 139, ID 1056000
2. Factors of Safety are 1.5 for Ultimate and 1.1 for Yield for tested hardware.
3. Boundary condition is at PAS Guide Pins and PAS handle locations.
4. 16 on-orbit load cases are applied.
5. \( u = \text{ultimate}, \ y = \text{yield} \)

4.1.2 Factors of Safety

The design of the Vertex bracket was based on a yield factor of safety of 1.25 and an ultimate factor of safety of 2.0 for untested hardware. A static test of the vertex bracket is done and the stress analysis for the vertex bracket will use a yield factor of safety of 1.10 and an ultimate factor of safety of 1.5 for tested hardware.

Ref. AMS-02 :"Structural Verification Plan" JSC 28792 REV. E and “Structural Design and Verification Requirements, International Space Station” SSP 30559 Rev. C.

4.1.3 Description of Structure

Figure 4.1-1 below shows the locations of the vertex bracket in AMS-02. The bracket was machined out of 7050-T7451 Aluminum Alloy plate. The base of the vertex bracket bolts to the PAS platform and the other end which consists of the two clevis joint bolts to the 4.0 x 4.0 tube of the lower center body tube of the USS-02.
Figure 4.1-1  Location Of PAS Vertex Bracket In AMS-02

4.1.4  Description of Model

A FEM model was built for the vertex bracket hardware using FEMAP.

1. The part was modeled primarily of Mid-side node CTETA elements.
2. At the bolt holes, RBE2 rigid elements with DOF's 1, 2 & 3 are represented.
3. The interface between the Vertex Bracket and the Lower USS-02 are represented by RBE2 rigid elements with DOF's 1, 2 & 3.
4. The interface between the Vertex Bracket and the PAS Platform is represented by a CBUSH spring element with DOF's 1, 2, 3, 4, 5, and 6.
5. The interface between the Vertex Bracket and the PAS Platform is represented by individual CBUSH spring element with DOF's 1, 2, and 3 at each of the bolt locations.
6. The AMS-02 model was then constrained by the three PAS guide pins and the PAS Handle. The two aft guide pins were constrained with SPCs in DOF 2 and 3. The forward guide pin was constrained with a SPC in DOF 1 and 3. The PAS Handle was constrained with a SPC in DOF 1, 2, and 3.

7. All of the Flight, Abort Landing and On-Orbit Load Cases were run. For the On-Orbit Load Cases the PAS Handle was also constrained with a SPCD to represent the force due to the Claw pull down force.

Figure 4.1-2 View Of Vertex Bracket Model
MSC/NASTRAN v.2005.0 was used as a solver for analyzing the complete math model of AMS-02 version 2-06.

Solid stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in the Vertex Bracket using a combination of FEMAP and Excel.

(Note: The elements around the bolt holes connected to the RBEs were removed from the stress sort since the stresses at these locations are artificially high as shown thought the bearing analysis preformed in the bolt analysis section.)

File locations for NASTRAN runs, results were stored in .xdb files and compressed in to .zip file for archive purposes. the runs used in this analysis all end in "f.dat". Files are listed in Figure 4.1-4.

---

**Figure 4.1-3  Second View Showing Bottom Of Vertex Bracket.**
4.1.5 Model Checks

Rigid body checks were performed using MSC/NASTRAN for the constrained and unconstrained models. A third run was made with the Model fixed in all six directions at the constraints. Table 4.1.5-1 shows results for the constrained model, these strain energy results show the G and N set as unconstrained but the F and A set as constrained so this model passes. Table 4.1.5-2 translational strain energy above below 6E-6 and rotational below 3E-3 while this is higher then performed, this is a large model with a significant number of solid elements. These results were judged acceptable. A final check of the fully fixed model is shown in Table 4.1.5-3.

| Table 4.1.5-1 Fixed Strain Energy Check |
|------------------|---|---|---|---|
| **DOF** | **G-SET** | **N-SET** | **F-SET** | **A-SET** |
| 1 | 3.40E-06 | 3.28E-06 | 1.48E+08 | 1.48E+08 |
| 2 | 1.25E-06 | 1.21E-06 | 5.06E+07 | 5.06E+07 |
| 3 | 5.12E-06 | 5.73E-06 | 6.95E+07 | 6.95E+07 |
| 4 | 5.24E-05 | 5.28E-04 | 2.26E+11 | 2.26E+11 |
A further check is that of rigid body modes. The first 7 unconstrained modes are shown in Table 4.1.5-5. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode. The fixed modes run shown in Table 4.1.5-4 shows there are no unconstrained DOF. Table 4.1.5-6 shows the model fully fixed at the guide pins this run shows that the first mode is above 1.5 Hz as required in SSP 57003.
Table 4.1.5-5  Free Free Modes

<table>
<thead>
<tr>
<th>Cycles(Hz)</th>
<th>Tran X</th>
<th>Tran Y</th>
<th>Tran Z</th>
<th>Rot X</th>
<th>Rot Y</th>
<th>Rot Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.1698</td>
<td>0.3042</td>
<td>0.0448</td>
<td>0.3270</td>
<td>0.1478</td>
<td>0.0096</td>
</tr>
<tr>
<td>0.00</td>
<td>0.1992</td>
<td>0.0901</td>
<td>0.0437</td>
<td>0.0686</td>
<td>0.1541</td>
<td>0.4381</td>
</tr>
<tr>
<td>0.00</td>
<td>0.1468</td>
<td>0.1235</td>
<td>0.0103</td>
<td>0.0856</td>
<td>0.0857</td>
<td>0.5493</td>
</tr>
<tr>
<td>0.00</td>
<td>0.0723</td>
<td>0.0009</td>
<td>0.8980</td>
<td>0.0008</td>
<td>0.0255</td>
<td>0.0021</td>
</tr>
<tr>
<td>0.00</td>
<td>0.0455</td>
<td>0.4484</td>
<td>0.0008</td>
<td>0.4705</td>
<td>0.0379</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.00</td>
<td>0.3664</td>
<td>0.0328</td>
<td>0.0023</td>
<td>0.0475</td>
<td>0.5490</td>
<td>0.0009</td>
</tr>
<tr>
<td>4.19</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table 4.1.5-6  Fully Fixed Modes

<table>
<thead>
<tr>
<th>Cycles(Hz)</th>
<th>Tran X</th>
<th>Tran Y</th>
<th>Tran Z</th>
<th>Rot X</th>
<th>Rot Y</th>
<th>Rot Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.02</td>
<td>0.7729</td>
<td>0.0109</td>
<td>0.0003</td>
<td>0.0034</td>
<td>0.1912</td>
<td>0.0042</td>
</tr>
<tr>
<td>2.13</td>
<td>0.0134</td>
<td>0.6613</td>
<td>0.0006</td>
<td>0.2288</td>
<td>0.0044</td>
<td>0.0717</td>
</tr>
<tr>
<td>3.00</td>
<td>0.0002</td>
<td>0.0466</td>
<td>0.0001</td>
<td>0.0190</td>
<td>0.0004</td>
<td>0.7459</td>
</tr>
<tr>
<td>4.70</td>
<td>0.0000</td>
<td>0.0040</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0022</td>
<td>0.1533</td>
</tr>
<tr>
<td>4.81</td>
<td>0.0000</td>
<td>0.0203</td>
<td>0.0003</td>
<td>0.1555</td>
<td>0.0002</td>
<td>0.0056</td>
</tr>
<tr>
<td>4.99</td>
<td>0.0115</td>
<td>0.0000</td>
<td>0.0055</td>
<td>0.0001</td>
<td>0.1638</td>
<td>0.0054</td>
</tr>
<tr>
<td>5.51</td>
<td>0.0001</td>
<td>0.0090</td>
<td>0.0014</td>
<td>0.0091</td>
<td>0.0002</td>
<td>0.0079</td>
</tr>
<tr>
<td>5.76</td>
<td>0.0209</td>
<td>0.0001</td>
<td>0.0042</td>
<td>0.0002</td>
<td>0.0099</td>
<td>0.0022</td>
</tr>
<tr>
<td>6.07</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.4448</td>
<td>0.0011</td>
<td>0.0002</td>
<td>0.0000</td>
</tr>
<tr>
<td>9.52</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Last the Mass and CG are shown for each model. As expected the Mass is the same for all three configurations. Note the CG is about grid point 999999 which is close to the model CG location. Ideally the grid point would be at the CG location but due to portions of the model that can not be read into FEMAP correctly the cg as calculated by FEMAP is slightly different. This difference is shown below.

Table 4.1.5-7  Fixed Mass Information

<table>
<thead>
<tr>
<th>MASS</th>
<th>CG X</th>
<th>CG Y</th>
<th>CG Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.14737</td>
<td>0.02973518</td>
<td>-0.004117</td>
<td>-0.056474</td>
</tr>
</tbody>
</table>

Table 4.1.5-8  Free Free Mass Information

<table>
<thead>
<tr>
<th>MASS</th>
<th>CG X</th>
<th>CG Y</th>
<th>CG Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.14737</td>
<td>0.029735</td>
<td>-0.00412</td>
<td>-0.056474</td>
</tr>
</tbody>
</table>
4.1.5  Fully Fixed in all 6 DOF S MASS Information

<table>
<thead>
<tr>
<th>MASS</th>
<th>CG X</th>
<th>CG Y</th>
<th>CG Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.14737</td>
<td>0.02973518</td>
<td>-0.004117</td>
<td>-0.056474</td>
</tr>
</tbody>
</table>

4.1.6  Material and Temperature

The Vertex Bracket is made of 7050-T7451 Aluminum Alloy. Material properties of 7050-T7451 are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5H. Temperature limits at the interface of the PAS platform and vertex bracket are provided by the Thermal Analysis Group. For on-orbit condition, the temperature of 151°F is applied, see Appendix C2.

4.1.7  Stress Analysis of the Vertex Bracket

The critical stresses for the Vertex Bracket are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. All margins of safety are positive.

<table>
<thead>
<tr>
<th>Allowable</th>
<th>Value (psi)</th>
<th>Factor of Safety (Untested)</th>
<th>Temp. Reduction Factor</th>
<th>Factor of Safety (Tested)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ftu</td>
<td>65000</td>
<td>2</td>
<td>0.91</td>
<td>1.5</td>
</tr>
<tr>
<td>Fry</td>
<td>55000</td>
<td>1.25</td>
<td>0.97</td>
<td>1.1</td>
</tr>
<tr>
<td>Fsu</td>
<td>44000</td>
<td>2</td>
<td>0.91</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Since the model was created using Midside node tetrahedral elements NASPOST could not be used to sort the data. FEMAP's post processing capabilities were utilized instead. Results from On-Orbit cases are shown in Table 4.1.7-2. Results for Liftoff cases and Landing cases are shown in Table 4.1.7-3 and Table 4.1.7-4 respectively.

<table>
<thead>
<tr>
<th>Stress</th>
<th>Max</th>
<th>Min</th>
<th>Set</th>
<th>ID</th>
<th>Value</th>
<th>Margin Untested</th>
<th>Margin Tested</th>
<th>Stress Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid X Normal Stress</td>
<td></td>
<td>Minimum</td>
<td>23</td>
<td>1084297</td>
<td>-20615</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>1096353</td>
<td>15746</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid XY Shear Stress</td>
<td></td>
<td>Minimum</td>
<td>31</td>
<td>1159796</td>
<td>-13250</td>
<td>0.51</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
<td>23</td>
<td>1056823</td>
<td>13366</td>
<td>0.50</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Solid Max Prin Stress</td>
<td></td>
<td>Minimum</td>
<td>31</td>
<td>1078809</td>
<td>-5957</td>
<td>3.96</td>
<td>5.62</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>1103844</td>
<td>28953</td>
<td>0.02</td>
<td>0.36</td>
<td>0.49</td>
</tr>
<tr>
<td>Solid Mean Stress</td>
<td></td>
<td>Minimum</td>
<td>23</td>
<td>1181166</td>
<td>-11166</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>1049148</td>
<td>14638</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid Von Mises Stress</td>
<td></td>
<td>Minimum</td>
<td>37</td>
<td>1067044</td>
<td>6</td>
<td>7562.22</td>
<td>8593.57</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>1056000</td>
<td>40744</td>
<td>0.05</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>
### Stress Analysis For Liftoff Load Cases

<table>
<thead>
<tr>
<th>Stress</th>
<th>Max</th>
<th>Min</th>
<th>Set</th>
<th>ID</th>
<th>Value</th>
<th>Margin Untested</th>
<th>Margin Tested</th>
<th>Stress Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Y Normal Stress</td>
<td>Minimum</td>
<td>23</td>
<td>1115720</td>
<td>-25890</td>
<td>0.25</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>1080126</td>
<td>17999</td>
<td>0.25</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid YZ Shear Stress</td>
<td>Minimum</td>
<td>31</td>
<td>1153225</td>
<td>-16120</td>
<td>0.24</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>23</td>
<td>1110381</td>
<td>16031</td>
<td>0.25</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Min Prin Stress</td>
<td>Minimum</td>
<td>31</td>
<td>1056000</td>
<td>-41683</td>
<td>(0.29)</td>
<td>(0.05)</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>23</td>
<td>1000190</td>
<td>6739</td>
<td>3.39</td>
<td>4.85</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Solid Z Normal Stress</td>
<td>Minimum</td>
<td>31</td>
<td>1056000</td>
<td>-40955</td>
<td>Not checked</td>
<td>Not checked</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>1024496</td>
<td>21071</td>
<td>Not checked</td>
<td>Not checked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid ZX Shear Stress</td>
<td>Minimum</td>
<td>23</td>
<td>1067223</td>
<td>-13065</td>
<td>0.53</td>
<td>1.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
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### Stress Analysis For Landing Load Cases

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AMS-02 PAS Vertex Bracket

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<th>Value</th>
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Note: On-Orbit cases had negative margins with tested and untested factors of safety. For this configuration all load cases are shown with negative margins highlighted in red are shown in Table 4.1.7-5. This was a worst worst enveloping set of load cases. Because of the negative margins, a further analysis was completed using consistent load cases.

Table 4.1.7-5 Vertex Bracket Low Margin Table

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Element ID</th>
<th>Minimum Principal Stress (psi)</th>
<th>Margin with FS=2</th>
<th>Margin with FS=1.5</th>
<th>Stress Ratio</th>
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<tbody>
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## AMS-02 PAS Vertex Bracket

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For all load cases with negative margins the corresponding cases with consistent load factor cases (from Appendix C16, Table C16-7, p. C16-7) were run. Results were sorted using FEMAP and are shown in Table 4.1.7-6.

Stresses shown in Table 4.1.7-6 shows negative margin only for Min principle stress with the untested factor of safety of 2.0. With the tested factor of safety of 1.5 the margin is positive. A Static test will be performed on the vertex bracket to confirm model accuracy and allow the use of the lowered factor of safety.

Also note the Max stress ratio is above 30% which indicates that fatigue analysis will be required for this part.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Element ID</th>
<th>Minimum Principal Stress (psi)</th>
<th>Margin with FS=2</th>
<th>Margin with FS=1.5</th>
<th>Stress Ratio</th>
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<td>0.59</td>
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Table 4.1.7-6: Table Of Margins For Consistent On-Orbit Load Factor Cases

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<th>Margin Tested</th>
<th>Stress Ratio</th>
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Stress contours of high stress areas for load case 5031 are shown in Figure 4.1-5 and Figure 4.1-6. Figure 4.1-7 shows both stress and deflection for this load case. Figure 4.1-8 through Figure 4.1-12 show areas with a stress ratio above 30%. The fatigue analysis will be an enveloping case covering all areas shown in these figures.

Figure 4.1-5 Stress Contour Vertex Bracket
Figure 4.1-6  Stress Contour Vertex Bracket High Stress Area

Figure 4.1-7  Stress Contour Vertex Bracket With Deflection
Figure 4.1-8  Red Areas Have Stress Ratio Above 30% For At Least One Load Case

Figure 4.1-9  High Stress Area On "U" Shaped Area
**Title**

AMS-02 PAS Vertex Bracket

---

*Figure 4.1-10 Several Areas With Stress Ratio Above 30%*
**Figure 4.1-11 Second View Of Areas With Stress Ratio Above 30%**

**Figure 4.1-12 Areas With Stress Ratios Above 30% On Base Of Vertex Bracket**
4.2 Aft Bracket
4.2 AMS-02 PAS Aft Bracket

4.2.1 Margins of Safety

Table 4.2-1 Minimum Margin Of Safety Summary

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135814</td>
<td>PAS Aft Bracket</td>
<td>AL ALY 7050-T7451</td>
<td>On-Orbit</td>
<td>Solid Min Prin Stress</td>
<td>0.01 (u)</td>
<td>4.2-13</td>
</tr>
</tbody>
</table>

Note:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Boundary condition is at PAS Guide Pins and PAS handle locations.
3. 16 on-orbit load cases are applied.
4. $u = \text{ultimate, } y = \text{yield}$
5. See Table 4.2-10, Set 56, ID 702957

4.2.2 Factors of Safety

The hardware is designed with a yield factor of 1.25 and an ultimate factor of 2.0 against limit loads for on-orbit.

4.2.3 Description of Structure

Figure 4.2-1 below shows the locations of the aft brackets in AMS-02. The brackets were machined out of 7050-T7451 Aluminum Alloy plate. The base of the aft brackets bolt to the PAS platform and the other ends of the aft brackets bolt to the center body on the Lower USS-02.
The same finite element NASTRAN model was used for this Aft Bracket (s4.2) as was used for the Vertex Bracket (s4.1). For a description of the model, see Section 4.1.4. For model checks, see Section 4.1.5. The aft bracket is shown in Figure 4.2-2.
4.2.5 **Material and Temperature**

The Aft brackets are made of 7050-T7451 Aluminum Alloy. These properties are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5J. Temperature limits at the interface of the PAS platform and aft brackets are provided by the Thermal Analysis Group. For on-orbit conditions, the temperature of 151°F is applied, see Appendix C2.

4.2.6 **Stress analysis Aft bracket**

The same methodology as for the analysis of the Vertex bracket was used with the exception of the Factor of safety. Since this part will not be tested, only the margins using the untested factors of safety will be calculated. The method of calculation as well as material allowable is shown in Section 4.1.7, in Table 4.1.7-1 Results are shown in Table 4.2-1 through table 4.2-10.

<table>
<thead>
<tr>
<th>Stress</th>
<th>Max Min</th>
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<th>ID</th>
<th>Stress (psi)</th>
<th>Margin Untested</th>
<th>Stress Ratio</th>
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</thead>
<tbody>
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<td>Solid X Normal Stress</td>
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<tr>
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### Table 4.2-3 Landing Plate Element Stress Sort

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<th>Stress (psi)</th>
<th>Margin Untested</th>
<th>Stress Ratio</th>
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# Stress Analysis

## Table 4.2-4  Liftoff Solid Element Stress Sort

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## Table 4.2-5  Liftoff Plate Element Stress Sort

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<th>ID</th>
<th>Stress (psi)</th>
<th>Margin Untested</th>
<th>Stress Ratio</th>
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### Table 4.2-6 On-Orbit Solid Element Stress Sort

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<th>Set</th>
<th>ID</th>
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<th>Margin Untested</th>
<th>Stress Ratio</th>
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Last Saved 3/20/2009 2:48 PM  4.2-7  ESCG-4005-05-AMS-0039
### Stress Table

#### Solid Min Prin Stress
- **Minimum:** 702957, -29332 psi, Margin = 0.01
- **Maximum:** 600024, 6411 psi, Margin = 0.11

#### Solid Z Normal Stress
- **Minimum:** 702957, -18418 psi, Not checked
- **Maximum:** 602854, 25787 psi, Not checked

#### Solid ZX Shear Stress
- **Minimum:** 702957, -11461 psi, Margin = 0.75
- **Maximum:** 703552, 4710 psi, 3.25

#### Solid Int Prin Stress
- **Minimum:** 600001, -14489 psi, Margin = 1.04
- **Maximum:** 600024, 12113 psi, Margin = 1.44

---

### Plate Bottom Fiber
- **Minimum:** 706665, 0 psi, Not checked
- **Maximum:** 706665, 0 psi, Not checked

### Plate Bot X Normal Stress
- **Minimum:** 706879, -23773 psi, Not checked
- **Maximum:** 706878, 35622 psi, Not checked

### Plate Bot Y Normal Stress
- **Minimum:** 600501, -11490 psi, Not checked
- **Maximum:** 600526, 8332 psi, Not checked

### Plate Bot XY Shear Stress
- **Minimum:** 700502, -7922 psi, 1.53
- **Maximum:** 600502, 8276 psi, 1.42

### Plate Bot PrinStress Angle
- **Minimum:** 706879, -24201 psi, 0.22
- **Maximum:** 708009, 4710 psi, 3.25

### Plate Bot MajorPrn Stress
- **Minimum:** 600501, -6371 psi, 3.64
- **Maximum:** 706878, 36636 psi, *(0.19)*

### Plate Bot MinorPrn Stress
- **Minimum:** 706879, -24201 psi, 0.22
- **Maximum:** 600502, 8276 psi, 1.42

### Plate Bot VonMises Stress
- **Minimum:** 706879, 11111 psi, 0.06
- **Maximum:** 707431, 26470 psi, 0.61

---

### Table 4.2-7 On-Orbit Plate Element Stress Sort

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Note there are negative margins for On-Orbit load cases for both Solid and Plate elements. Figure 4.2-3 shows the locations of the two elements on one bracket, the other bracket is a mirror image.

![Figure 4.2-3 Areas With Negative Margins On Aft-Bracket.](image)

Table 4.2-8 lists the elements with negative margins, the adjusted stress, the rationale for the correction and the new margins. For the Plate elements the thickness is modeled as 0.375". The element is fully in the curved area as shown in Figure 4.2-4. The thickness at this location is actually bigger. Since the area represented by the element is at least 25% thicker, the stresses in the elements are scaled to account for the difference between the model and the drawing.

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<th>New Margin</th>
<th>Note</th>
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Note:
1.) Stress Lowered by 25% to account for difference between modeled thickness and actual thickness
2.) Stress of next lowest element at same location used for analysis
Figure 4.2-4  Location Of High Stress Plate Element In Red Green Is Actual Part Thickness.

Table 4.2-9  Plate Element Sort Excluding The Two Elements With Negative Margins

<table>
<thead>
<tr>
<th>Stress</th>
<th>Max</th>
<th>Min</th>
<th>Set</th>
<th>ID</th>
<th>Stress (psi)</th>
<th>Margin</th>
<th>Stress Ratio</th>
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<td>600526</td>
<td>8332</td>
<td>Not checked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Bot XY Shear Stress</td>
<td>Minimum</td>
<td>56</td>
<td>700502</td>
<td>-7922</td>
<td>1.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>60</td>
<td>600502</td>
<td>8276</td>
<td>1.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Bot PrnStress Angle</td>
<td>Minimum</td>
<td>26</td>
<td>607937</td>
<td>-90</td>
<td>Not checked</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>31</td>
<td>708009</td>
<td>90</td>
<td>Not checked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Bot MajorPrn Stress</td>
<td>Minimum</td>
<td>60</td>
<td>600501</td>
<td>-6371</td>
<td>3.64</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>63</td>
<td>706866</td>
<td>26610</td>
<td>0.11</td>
<td>*0.45</td>
<td></td>
</tr>
<tr>
<td>Plate Bot MinorPrn Stress</td>
<td>Minimum</td>
<td>61</td>
<td>706879</td>
<td>-24201</td>
<td>0.22</td>
<td>*0.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>3</td>
<td>600526</td>
<td>6361</td>
<td>3.65</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Plate Bot VonMises Stress</td>
<td>Minimum</td>
<td>28</td>
<td>707162</td>
<td>11</td>
<td>3957.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>63</td>
<td>706866</td>
<td>26406</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Top Fiber</td>
<td>Minimum</td>
<td>1</td>
<td>600501</td>
<td>0</td>
<td>Not checked</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>1</td>
<td>600501</td>
<td>0</td>
<td>Not checked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Top X Normal Stress</td>
<td>Minimum</td>
<td>56</td>
<td>707431</td>
<td>-27693</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>63</td>
<td>706782</td>
<td>17732</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Top Y Normal Stress</td>
<td>Minimum</td>
<td>3</td>
<td>605135</td>
<td>-10452</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>11</td>
<td>600523</td>
<td>7721</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Top XY Shear Stress</td>
<td>Minimum</td>
<td>51</td>
<td>607411</td>
<td>-6127</td>
<td>2.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>60</td>
<td>600501</td>
<td>6401</td>
<td>2.13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Stress** | **Max** | **Min** | **Set** | **ID** | **Stress (psi)** | **Margin** | **Stress Ratio**
---|---|---|---|---|---|---|---
Plate Top PrnStress Angle | Minimum | 61 | 608081 | -90 | Not checked |
| Maximum | 5 | 608057 | 90 | Not checked |
Plate Top MajorPrn Stress | Minimum | 11 | 600548 | -8045 | 2.68 | 0.14 |
| Maximum | 63 | 706782 | 17846 | 0.66 *0.30 |
Plate Top MinorPrn Stress | Minimum | 56 | 707431 | -28016 | 0.06 *0.47 |
| Maximum | 3 | 600523 | 7672 | 2.85 | 0.13 |
Plate Top VonMises Stress | Minimum | 46 | 607226 | 8 | 5104.43 |
| Maximum | 56 | 707431 | 26470 | 0.61 |

*V: Untitled
G: Aft no hole

**Figure 4.2-5** Location Of Solid Element With Negative Margin.
For the two solid elements listed in Figure 4.2-6 the high stress is in a malformed element. Further this element is at the corner connection between solid and plate elements. If you exclude these two misshaped elements the stress is shown in Table 4.2-10. This next highest stress is at the same location in another malformed element. Averaging the elements surrounding the solid element with negative margins a stress lower than the closest elements is obtained. The stress of the closest element was used as the more conservative solution.

**Figure 4.2-6 Plot Showing Malformed Element.**

**Table 4.2-10 On-Orbit Solid Element Stress Sort, Excluding Misshaped Elements Connected With RESSCON Cards.**

<table>
<thead>
<tr>
<th>Stress</th>
<th>Max</th>
<th>Min</th>
<th>Set</th>
<th>ID</th>
<th>Stress (psi)</th>
<th>Margin</th>
<th>Stress Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid X Normal Stress</td>
<td>Minimum</td>
<td>56</td>
<td>702957</td>
<td>-16847</td>
<td></td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid XY Shear Stress</td>
<td>Minimum</td>
<td>56</td>
<td>702663</td>
<td>-5850</td>
<td>2.42</td>
<td>2.41</td>
<td></td>
</tr>
<tr>
<td>Solid Max Prin Stress</td>
<td>Minimum</td>
<td>60</td>
<td>602663</td>
<td>-6702</td>
<td>3.41</td>
<td>0.11</td>
<td>0.45</td>
</tr>
<tr>
<td>Solid Mean Stress</td>
<td>Minimum</td>
<td>11</td>
<td>600024</td>
<td>-11705</td>
<td>0.11</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid Von Mises Stress</td>
<td>Minimum</td>
<td>45</td>
<td>703693</td>
<td>12</td>
<td>3562.59</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid Y Normal Stress</td>
<td>Minimum</td>
<td>60</td>
<td>601042</td>
<td>-10036</td>
<td>0.81</td>
<td>Not checked</td>
<td></td>
</tr>
<tr>
<td>Solid YZ Shear Stress</td>
<td>Minimum</td>
<td>3</td>
<td>602853</td>
<td>-9969</td>
<td>1.01</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>8</td>
<td>702853</td>
<td>9964</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For the fracture analysis the areas with a stress ratio greater than 30% need to be considered. Figure 4.2-7 and Figure 4.2-8 show these locations.

![Image of aft bracket]

**Figure 4.2-7  Aft Bracket Areas With Stress Ratio Greater Than 30%**
Figure 4.2-8  Aft Bracket Areas With Stress Ratio Greater Than 30%
4.3 PAS Platform Assembly
4.3  AMS-02 PAS Platform Assembly

4.3.1  Margins of Safety

Table 4.3-1  Minimum Margin Of Safety Summary

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/ Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135817</td>
<td>PAS Platform Assembly</td>
<td>AL ALY 7050-T7451</td>
<td>Consistent On-Orbit Load Factor</td>
<td>Tensile Ultimate</td>
<td>0.27</td>
<td>4.3-7</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. 64 Liftoff, 64 On-Orbit, and 64 Landing load cases were analyzed.

4.3.2  Factors of Safety

The untested hardware is designed with a yield factor of safety 1.25 and an ultimate factor of safety 2.0 against limit loads.

Ref. AMS-02 :"Structural Verification Plan" JSC 28792 REV. E

4.3.3  Description of Structure

Figure 4.3-1 shows the PAS Platform Assy, PAS Base Assembly drawing.
4.3.4  **Materials and Temperature**

The PAS Platform is made of 7050-T7451 Aluminum Alloy. The material properties are taken from Boeing Material Specification of BMS 7-323C, and MIL-HDBK-5J. Temperature limits are provided by the Thermal Analysis Group. For on-orbit conditions, the temperature of 151 F is applied, see Appendix C2.

4.3.5  **Summary of Analysis**

Stresses were recovered from the NASTRAN run for the platform base. Figure 4.3-2 shows the areas of highest stress concentration.

![High Stress Areas of PAS](image)

**Figure 4.3-2  High Stress Areas of PAS**

Table 4.3-2 shows the elements and load cases with the maximum absolute value of Principal, Von Mises, and Shear stresses. For comparison, the CTRIA3 with the highest stresses is shown along with the CQUAD4 with the highest stresses. The highlighted row represents the highest stresses.
Table 4.3-2  PAS Platform Stresses For Liftoff, On-Orbit, and Landing

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Element Number</th>
<th>Load Case</th>
<th>Principal Stress (psi)</th>
<th>Von Mises Stress (psi)</th>
<th>Shear Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liftoff</td>
<td>CTRIA</td>
<td>1031</td>
<td>12,742</td>
<td>11,099</td>
<td>6,371</td>
</tr>
<tr>
<td></td>
<td>CQUAD</td>
<td>1027</td>
<td>6,395</td>
<td>6,404</td>
<td>3,206</td>
</tr>
<tr>
<td>On-Orbit</td>
<td>CTRIA</td>
<td>5035</td>
<td>26,339</td>
<td>25,905</td>
<td>13,170</td>
</tr>
<tr>
<td></td>
<td>CQUAD</td>
<td>5050</td>
<td>25,385</td>
<td>25,401</td>
<td>12,708</td>
</tr>
<tr>
<td>Landing</td>
<td>CTRIA</td>
<td>2031</td>
<td>10,706</td>
<td>9,322</td>
<td>5,353</td>
</tr>
<tr>
<td></td>
<td>CQUAD</td>
<td>2031</td>
<td>6,471</td>
<td>6,369</td>
<td>3,236</td>
</tr>
</tbody>
</table>

Table 4.3-3, Table 4.3-4, and Table 4.3-5, show a summary of the lowest margins of safety for Tensile Ultimate, Tensile Yield, and Shear Ultimate for the Liftoff, On-Orbit, and Landing load cases respectively.

Table 4.3-3  PAS Platform Liftoff Minimum Margins

<table>
<thead>
<tr>
<th>Allowable Stress (psi)</th>
<th>Thermal Reduction Coefficient</th>
<th>Factor of Safety</th>
<th>Element Stress (psi)</th>
<th>Margin of Safety</th>
<th>Stress Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>73,000</td>
<td>0.92</td>
<td>2.00</td>
<td>12,742</td>
<td>1.64</td>
<td>Tensile Ultimate</td>
</tr>
<tr>
<td>63,000</td>
<td>0.97</td>
<td>1.25</td>
<td>11,099</td>
<td>3.40</td>
<td>Tensile Yield</td>
</tr>
<tr>
<td>43,000</td>
<td>0.92</td>
<td>2.00</td>
<td>6,371</td>
<td>2.10</td>
<td>Shear Ultimate</td>
</tr>
</tbody>
</table>

Table 4.3-4  PAS Platform On-Orbit Minimum Margins

<table>
<thead>
<tr>
<th>Allowable Stress (psi)</th>
<th>Thermal Reduction Coefficient</th>
<th>Factor of Safety</th>
<th>Element Stress (psi)</th>
<th>Margin of Safety</th>
<th>Stress Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>73,000</td>
<td>0.92</td>
<td>2.00</td>
<td>26,339</td>
<td>0.27</td>
<td>Tensile Ultimate</td>
</tr>
<tr>
<td>63,000</td>
<td>0.97</td>
<td>1.25</td>
<td>25,905</td>
<td>0.89</td>
<td>Tensile Yield</td>
</tr>
<tr>
<td>43,000</td>
<td>0.92</td>
<td>2.00</td>
<td>13,170</td>
<td>0.50</td>
<td>Shear Ultimate</td>
</tr>
</tbody>
</table>

Table 4.3-5: PAS Platform Landing Minimum Margins

<table>
<thead>
<tr>
<th>Allowable Stress (psi)</th>
<th>Thermal Reduction Coefficient</th>
<th>Factor of Safety</th>
<th>Element Stress (psi)</th>
<th>Margin of Safety</th>
<th>Stress Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>73,000</td>
<td>0.92</td>
<td>2.00</td>
<td>10,706</td>
<td>2.14</td>
<td>Tensile Ultimate</td>
</tr>
<tr>
<td>63,000</td>
<td>0.97</td>
<td>1.25</td>
<td>9,322</td>
<td>4.24</td>
<td>Tensile Yield</td>
</tr>
<tr>
<td>43,000</td>
<td>0.92</td>
<td>2.00</td>
<td>5,353</td>
<td>2.70</td>
<td>Shear Ultimate</td>
</tr>
</tbody>
</table>
4.3.6  Analysis

CHECK of Assembly Drawing, #SEG39135816
PAS Platform Assy PAS Base Assy, #SDG39135817-001

Allowables

Material Properties

AL ALY, 7050-T7451, BMS-7-323-C, Plate, 2.001-3.000, A

\[
F_{u} := 73000 \text{ psi} \\
F_{y} := 63000 \text{ psi} \\
F_{su} := 43000 \text{ psi}
\]

Factors of Safety

\[
FS_{u} := 2.0 \\
FS_{y} := 1.25
\]

Temperature Reduction Factors

+ At 151°F: (These temperature reduction factors are conservative for liftoff/landing conditions)

\[
\beta_{u} := 0.92 \\
\beta_{y} := 0.97
\]

(Ref. MMPDS-03, Figure 3.7.4.2.1(a))

(Ref. MMPDS-03, Figure 3.7.4.2.1(b))

Allowable Stresses

\[
F_{tu} := F_{u} \cdot \beta_{u} \\
F_{ty} := F_{y} \cdot \beta_{y} \\
F_{su} := F_{su} \cdot \beta_{u}
\]

\[
F_{tu} = 67160 \text{ psi} \\
F_{ty} = 61110 \text{ psi} \\
F_{su} = 39560 \text{ psi}
\]

Omitted Elements

No element were excluded.
PAS Platform Assy PAS Base Assy, #SDG39135817-001

Liftoff Loads

For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected from 64 Liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across all load cases.

NASTRAN Punch Filename: Platform-Tran (Liftoff).lis

Maximum Stresses

\[ u_{tu} = 12742 \, \text{psi} \]
\[ u_{ty} = 11099 \, \text{psi} \]
\[ u_{su} = 6371 \, \text{psi} \]

LC# 1031, ELEM# 22800791

(Maximum Principal Stress)
(Maximum Von-Mises Stress)
(Maximum Shear Stress)

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_{u} \cdot u_{tu}} - 1 \]
\[ MS_{tyg} := \frac{F_{tyg}}{FS_{y} \cdot u_{ty}} - 1 \]
\[ MS_{sug} := \frac{F_{sug}}{FS_{u} \cdot u_{su}} - 1 \]

MS\(_{tug} = 1.64 \]
MS\(_{tyg} = 3.40 \]
MS\(_{sug} = 2.10 \]

... Margin of Safety Tensile Ultimate
... Margin of Safety Tensile Yield
... Margin of Safety Shear Ultimate
PAS Platform Assy PAS Base Assy, #SDG39135817-001

On-Orbit Loads

For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected from 64 On-Orbit load cases (Load Case 5001 - 5064). NASPOST V.2.2 is used to sort the maximum stresses across all load cases.

NASTRAN Punch Filename: Platform-15 (On-Orbit).lis

Maximum Stresses

\[ \sigma_{tu} = 26339 \text{ psi} \quad \text{LC# 5035, ELEM# 22804428} \quad (\text{Maximum Principal Stress}) \]

\[ \sigma_{ty} = 25905 \text{ psi} \quad \text{LC# 5035, ELEM# 22804428} \quad (\text{Maximum Von-Mises Stress}) \]

\[ \sigma_{su} = 13170 \text{ psi} \quad \text{LC# 5035, ELEM# 22804428} \quad (\text{Maximum Shear Stress}) \]

Margins of Safety

\[ MS_{tu} = \frac{F_{tu}}{FS_{u} \cdot \sigma_{tu}} - 1 \quad MS_{tu} = 0.27 \quad \ldots \text{Margin of Safety Tensile Ultimate} \]

\[ MS_{ty} = \frac{F_{ty}}{FS_{y} \cdot \sigma_{ty}} - 1 \quad MS_{ty} = 0.89 \quad \ldots \text{Margin of Safety Tensile Yield} \]

\[ MS_{su} = \frac{F_{su}}{FS_{u} \cdot \sigma_{su}} - 1 \quad MS_{su} = 0.50 \quad \ldots \text{Margin of Safety Shear Ultimate} \]
PAS Platform Assy PAS Base Assy, #SDG39135817-001

Landing Loads

For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected from 64 Landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across all load cases.

NASTRAN Punch Filename: Platform-Landing.lis

Maximum Stresses

\[ \sigma_{tu} = 10706 \text{ psi} \]
\[ \sigma_{ty} = 9322 \text{ psi} \]
\[ \sigma_{su} = 5353 \text{ psi} \]

LC# 2031, ELEM# 22800793  \( (\text{Maximum Principal Stress}) \)

LC# 2031, ELEM# 22800793  \( (\text{Maximum Von-Mises Stress}) \)

LC# 2031, ELEM# 22800793  \( (\text{Maximum Shear Stress}) \)

Margins of Safety

\[ \frac{F_{tu}}{F_{S_u} \cdot \sigma_{tu}} - 1 = MS_{tu} \]
\[ MS_{tu} = 2.14 \]  \( \ldots \text{Margin of Safety Tensile Ultimate} \)

\[ \frac{F_{ty}}{F_{S_y} \cdot \sigma_{ty}} - 1 = MS_{ty} \]
\[ MS_{ty} = 4.24 \]  \( \ldots \text{Margin of Safety Tensile Yield} \)

\[ \frac{F_{su}}{F_{S_u} \cdot \sigma_{su}} - 1 = MS_{su} \]
\[ MS_{su} = 2.70 \]  \( \ldots \text{Margin of Safety Shear Ultimate} \)
4.4 Guide Pins
4.4 AMS-02 Guide Pins, PAS Base Assembly

4.4.1 Margins of Safety

Table 4.4-1 Minimum Margin Of Safety Summary

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/ Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135818</td>
<td>Guide Pins</td>
<td>AL ALY 7050-T7451</td>
<td>Consistent On-Orbit Load Factor</td>
<td>Shear Ultimate</td>
<td>17.67</td>
<td>4.4-10</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. The way the AMS is stowed during Liftoff and Landing, the Guide Pins are not loaded.
3. 64 On-Orbit load cases, combined with the preload of the capture bar, were analyzed.
4. Boundary conditions are at the PAS Guide Pins and PAS handle locations.

4.4.2 Factors of Safety

The untested hardware is designed with a yield factor of safety 1.25 and an ultimate factor of safety 2.0 against limit loads for on-orbit.

Ref. AMS-02 :"Structural Verification Plan" JSC 28792 REV. E

4.4.3 Description of Structure

Figure 4.4-2 shows the Aft and Apex Guide Pins along with the PAS Base Assembly. There are a total of three Guide Pins (Figure 4.4-1) that are fastened with four 3/8” bolts to the PAS Base Assembly. The Guide Pins can not react loads axially along their length (L).
Figure 4.4-2   Guide Pins, PAS Base Assembly

4.4.3.1   Moment Arm Along the length of the Guide Pins to Section AA

**Apex Guide Pin**

Active PAS, Distance From the Centerline of the Aft Guide Vanes to the Inner Edge of the Apex Guide Vane, Figure 4.4-3.

\[ L_{001} := 0.570 \text{ in} \]

**Aft Guide Pin**

Active PAS, Distance From the Centerline of the Apex Guide Vane to the Inner Edges of the Aft Guide Vanes, Figure 4.4-3.

\[ L_{003} := 0.550 \text{ in} \]

Figure 4.4-5   Trimetric View of the Active PAS, labels the primary interfacing parts of the Active PAS.
Figure 4.4-3  Top View of the Active PAS
Figure 4.4-4  Bottom View of the Passive PAS
The Guide Pins are made of 7050-T7451 Aluminum Alloy. The material properties are taken from Boeing Material Specification of BMS-7-323-C, and MIL-HDBK-5J. Temperature limits are provided by the Thermal Analysis Group. For on-orbit conditions, the maximum temperature of 151 ºF is applied, see Appendix C2.

4.4.5 Description of Model and Model Checks

The same finite element model was used for the PAS Base, Guide Pins, Aft and Vertex Brackets. For a detailed description of the model see Section 4.1.4. For a detailed description of the model checks, see Section 4.1.5.

The worst case loading for the guide pins was determined by taking the highest resultant reaction load (SPCFORCE) at any single Guide Pin (Figure 4.4-3) for the combined preload and on-orbit loading. The nodal SPCFORCES, from the corresponding Guide Pin reaction, along with the moment arm
corresponding to that Guide Pin (either L001 or L003, Figure 4.4-1) were used to calculate maximum Tensile Ultimate stresses and the maximum Shear Ultimate stresses.

Figure 4.4-6 shows the finite element model of the Aft and Apex Guide Pins, the PAS Base Assembly, and the Aft and Vertex brackets. The origin of the black arrows show the location of the constraints (SPCs) and their corresponding Node IDs. The black arrow heads show the positive axis directions for those SPCFORCES.
4.4.6 Detailed Stress Analysis

Material and Allowables

**AL Alloy 7050-T7451, 12.6" x 3.75" x 3.00", BMS-7-323-C**

- **Ftu** := 73000 psi  
  Tensile Ultimate Strength
- **Fcy** := 63000 psi  
  Compressive Yield Strength
- **Fsu** := 43000 psi  
  Shear Ultimate Strength
- **FSy** := 1.25  
  Yield Factor of Safety
- **FSu** := 2.0 
  Ultimate Factor of Safety
- **β** := .97 
  Thermal Expansion Coefficient @151°F, App.C2

Apex Guide Pin SDG39135818-001

Section AA Properties as Calculated in FEMAP V9.3.1

- **A** := 3.51334 in²  
  Area of guide pin
- **Izz** := 0.77625 in⁴  
  Weak axis moment of inertia
- **Ixx** := 3.50011 in⁴  
  Strong axis moment of inertia
- **cx** := 0.725 in  
  Centroid distance x
- **cz** := 2.21839 in  
  Centroid distance z

![](image)

**Figure 4.4-4a Section AA for Apex Guide Pin -001**

Distance Along Length (L) to Section AA on the Apex Guide Pin -001

See Figure 4.4-1
Loads from SPC's for the Apex Guide Pin, SDG39135818-001

Note: The finite element "Model" (M) uses the coordinate system shown in Figure 4.4-3. But for the purpose of Loads definitions, the "Section" coordinate system shown in Figure 4.4-4 will be utilized. The file `guidepin-sangster.dat` contains SPCFORCES (Node ID, Load Case, Fx (lbf), Fy (lbf), Fz (lbf)) in the Model's coordinate system. These SPCFORCES must be translated into the local Section coordinate system for both the Apex Guide Pin -001 and for the Aft Guide Pins -003.

data := READPRN("guidepin-sangster.dat")  
SPCFORCES File Being Read Into Array "data"

ORIGIN := 1  
i := 1..rows(data)  
Set Origin of Array to 1, Set "i" as Row Counter

The SPCFORCES file, `guidepin-sangster.dat`, contains the reaction forces for Nodes 800259 (Aft), 801559 (Apex), 801564 (Aft) for Load Cases 5001-5064 and has the following columnwise structure:

<table>
<thead>
<tr>
<th>Column</th>
<th>Header Row Data</th>
<th>Node ID</th>
<th>Load Case</th>
<th>Fx(M) lbf</th>
<th>Fy(M) lbf</th>
<th>Fz(M) lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>data_i,1</td>
<td>data_i,2</td>
<td>data_i,3</td>
<td>data_i,4</td>
<td>data_i,5</td>
<td></td>
</tr>
<tr>
<td>ID_i</td>
<td>:= data_i,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LC_i</td>
<td>:= data_i,2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ID_i := data_i,1  
Node ID Counter for Column 1

LC_i := data_i,2  
Load Case ID Counter for Column 2

Fx001_i := data_i,3 lbf  
Axial Load

Fy001_i := data_i,4 lbf  
Shear along X Axis

Fz001_i := data_i,5 lbf  
Shear along Z Axis

Mx001_i := data_i,5 lbf \cdot L001  
Moment about X Axis Caused by Fz

M001_i := data_i,3 lbf \cdot L001  
Moment about Z Axis Caused by Fx

Bending Stresses for the Apex Guide Pin, SDG39135818-001

Calculate Stresses at Section AA Resulting from the Preload of the Capture Bar Combined With On-Orbit Loading, for Apex Guide Pin -001

\[
u001 := \sqrt{\left(\frac{Mx001 \cdot c_x}{Ixx}\right)^2 + \left(\frac{Mx001 \cdot c_z}{Izz}\right)^2} \\
\max(u001) = 1234.1 \text{ psi}
\]

\[
001 := \sqrt{\frac{Fx001^2 + Fz001^2}{A}} \\
\max(001) = 931.5 \text{ psi}
\]
Maximum Shear Stress for Apex Guide Pin -001

\[ \text{max}_{001} := \sqrt{\left( \frac{u_{001}}{2} \right)^2 + 001^2} \]

\[ \max(\text{max}_{001}) = 1117.3 \text{ psi} \]

Maximum Principal Stress for Apex Guide Pin -001

\[ u_{\text{max}001} := \frac{u_{001}}{2} + \text{max}_{001} \]

\[ \max(u_{\text{max}001}) = 1734.4 \text{ psi} \]

Margins of Safety for Apex Guide Pin -001

\[ M_{\text{Stu001}_i} := \left[ \frac{F_{\text{t}} \cdot \beta}{FSu \cdot u_{\text{max}001_i}} \right] - 1 \quad \text{if } u_{\text{max}001_i} > 0 \]

\[ 999 \text{ otherwise} \]

\[ \min(M_{\text{Stu001}}) = 19.41 \text{ Tensile Ultimate} \]

\[ \text{NodeID}_{\text{Stu001}} := \text{lookup}(\min(M_{\text{Stu001}}), M_{\text{Stu001}}, \text{ID}) = (801559) \text{ Node ID} \]

\[ \text{LC}_{\text{Stu001}} := \text{lookup}(\min(M_{\text{Stu001}}), M_{\text{Stu001}}, \text{LC}) = (5040) \text{ Load Case} \]

\[ M_{\text{Su001}_i} := \left[ \frac{F_{\text{s}} \cdot \beta}{FSu \cdot \text{max}_{001_i}} \right] - 1 \quad \text{if } \text{max}_{001_i} > 0 \]

\[ 999 \text{ otherwise} \]

\[ \min(M_{\text{Su001}}) = 17.67 \text{ Shear Ultimate} \]

\[ \text{NodeID}_{\text{Su001}} := \text{lookup}(\min(M_{\text{Su001}}), M_{\text{Su001}}, \text{ID}) = (801559) \text{ Node ID} \]

\[ \text{LC}_{\text{Su001}} := \text{lookup}(\min(M_{\text{Su001}}), M_{\text{Su001}}, \text{LC}) = (5040) \text{ Load Case} \]
**Aft Guide Pin SDG39135818-003**

*Section AA Properties as Calculated in FEMAP V9.3.1*

\[
\begin{align*}
A &:= 3.51334 \text{in}^2 \quad \text{Area of guide pin} \\
I_{zz} &:= 0.77625 \text{in}^4 \quad \text{Weak axis moment of inertia} \\
I_{yy} &:= 3.50011 \text{in}^4 \quad \text{Strong axis moment of inertia} \\
c_Y &:= 0.725 \text{in} \quad \text{centroid distance y} \\
c_Z &:= 2.21839 \text{in} \quad \text{centroid distance z}
\end{align*}
\]

\[L_{003} := 0.55 \text{ in} \quad \text{Distance Along Length (L) to Section AA on the Aft Guide Pins -003}
\]

See Figure 4.4-1

**Loads from SPC’s for the Aft Guide Pin, , SDG39135818-003**

- \(F_{x003} := \text{data1}_3 \cdot \text{lbf}\)  \(\text{Axial Load}\)
- \(F_{y003} := \text{data1}_4 \cdot \text{lbf}\)  \(\text{Shear along Y Axis}\)
- \(F_{z003} := \text{data1}_5 \cdot \text{lbf}\)  \(\text{Shear along Z Axis}\)
- \(M_{y003} := \text{data1}_5 \cdot \text{lbf} \cdot L_{003}\)  \(\text{Moment about Y Axis Caused by FZ}\)
- \(M_{z003} := \text{data1}_4 \cdot \text{lbf} \cdot L_{003}\)  \(\text{Moment about Z Axis Caused by FY}\)
**Bending Stresses for the Aft Guide Pins, SDG39135818-003**

Calculate Stresses at Section AA Resulting from the Preload of the Capture Bar Combined With On-Orbit Loading, for Aft Guide Pins -003

\[ u_{003} := \sqrt{\left( \frac{M_{y003} \cdot c_y}{I_{zz}} \right)^2 + \left( \frac{M_{y003} \cdot c_z}{I_{yy}} \right)^2} \]

\[ 003 := \sqrt{F_{y003}^2 + F_{z003}^2} \]

\[ \text{max}(u_{003}) = 1129.5 \text{ psi} \]

\[ \text{max}(003) = 900.5 \text{ psi} \]

**Maximum Shear Stress for Aft Guide Pins -003**

\[ \text{max}003 := \sqrt{\left( \frac{u_{003}}{2} \right)^2 + 003^2} \]

\[ \text{max}(\text{max}003) = 1059.2 \text{ psi} \]

**Maximum Principal Stress for Aft Guide Pins -003**

\[ u_{\text{max}003} := \frac{u_{003}}{2} + \text{max}003 \]

\[ \text{max}(u_{\text{max}003}) = 1623.9 \text{ psi} \]

**Margins of Safety for Aft Guide Pins -003**

\[ M_{\text{stu003}} := \left( \frac{F_{tu} \cdot \beta}{F_{SU} \cdot u_{\text{max}003}} \right) - 1 \text{ if } u_{\text{max}003} > 0 \]

\[ 999 \text{ otherwise} \]

\[ \text{min}(M_{\text{stu003}}) = 20.80 \text{ Tensile Ultimate} \]

**Node ID**

NodeIDtu003 := lookup(min(Mstu003), Mstu003, ID) = (801564)

**Load Case**

LCtu003 := lookup(min(Mstu003), Mstu003, LC) = (5056)

\[ M_{\text{susu003}} := \left( \frac{F_{su} \cdot \beta}{F_{SU} \cdot \text{max}003} \right) - 1 \text{ if } \text{max}003 > 0 \]

\[ 999 \text{ otherwise} \]

\[ \text{min}(M_{\text{susu003}}) = 18.69 \text{ Shear Ultimate} \]

**Node ID**

NodeIDsu003 := lookup(min(Msusu003), MSusu003, ID) = (801564)

**Load Case**

LCSu003 := lookup(min(Msusu003), MSusu003, LC) = (5056)
4.5 BCS Avionics Bracket
4.5 BCS Avionics Bracket, SDG39135822

The maximum load camera weight is: camera := 25 lb

Camera Bracket, is made of 7075-T7351 and is good by engineering judgement, based upon the 25 lbf load and the significant cross section.
4.6 PAS Bridge Bracket
4.6  AMS-02 PAS Bridge, PAS Bridge Assembly, SDG39135837-001

4.6.1  Margins of Safety

**Table 4.6-1  Minimum Margin Of Safety Summary**

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135837-001</td>
<td>PAS Bridge</td>
<td>AL ALY 7050-T7451</td>
<td>On-Orbit Inertia Steady State</td>
<td>Shear Ultimate</td>
<td>0.04</td>
<td>4.6-16</td>
</tr>
</tbody>
</table>

**Notes:**
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. 64 Liftoff, On-Orbit, and Landing load cases were analyzed.

4.6.2  Factors of Safety

The untested hardware is designed with a yield factor of safety 1.25 and an ultimate factor of safety 2.0 against limit loads for on-orbit.

Ref. AMS-02 :"Structural Verification Plan" JSC 28792 REV. E

4.6.3  Description of Structure

Figure 4.6-1 shows the PAS Bridge and the PAS Bridge Assembly. Figure 4.6-2 shows the Bridge Beam in relation to the PAS Base Assembly.
Figure 4.6-1 Bridge Assy PAS Bridge Assy SDG39135837 and PAS Bridge Assy AMS Passive PAS Assy SEG39135836

Figure 4.6-2 AMS Passive PAS Base Assy, PAS Assy SEG39135815
4.6.4  
**Materials and Temperature**

The Bridge Beam is made of 7050-T7451 Aluminum Alloy. The material properties are taken from Boeing Material Specification of BMS-7-323-C, and MIL-HDBK-5J. Temperature limits are provided by the Thermal Analysis Group. For on-orbit conditions, the maximum temperature of 151 °F is applied, see Appendix C2.

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Allowables</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135837-001</td>
<td>PAS Bridge</td>
<td>AL ALY</td>
<td>( F_{tu} = 73,000 \text{ psi} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7050-T7451</td>
<td>( F_{ty} = 63,000 \text{ psi} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BMS-7-323-C</td>
<td>( F_{cy} = 61,000 \text{ psi} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plate 2.001-3.000</td>
<td>( F_{sz} = 43,000 \text{ psi} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A basis</td>
<td>( E = 10.3E06 \text{ psi} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( E_c = 10.6E06 \text{ psi} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( G = 3.9E06 \text{ psi} )</td>
</tr>
</tbody>
</table>

4.6.5  
**Description of Model and Model Checks**

Figure 4.6-3 shows the finite element model used for the Bridge Beam. The same finite element model was used for the Bridge Beam, PAS Base, Guide Pins, Aft and Vertex Brackets. For a detailed description of the model see Section 4.1.4. For a detailed description of the model checks, see Section 4.1.5.

![Figure 4.6-3](image-url)
4.6.6 Detailed Stress Analysis

Summary of Load Conditions

The bridge beam was analyzed for four load conditions:
- Flight (Liftoff)
- On-Orbit
- On-Orbit Steady State
- Landing

Factors of Safety

\[ F_{SU} := 2.0 \]
\[ F_{SV} := 1.25 \]

Materials and Temperature

Material Allowables

**AL ALY, 7050-T7451, BMS-7-323-C, Plate, 37.575 x 3.650 x 2.070, A**

\[ F_{tu} := 73000 \text{ psi} \]
\[ F_{ty} := 63000 \text{ psi} \]
\[ F_{su} := 43000 \text{ psi} \]

Temperature Degradation

\[ \beta_{tu} := 0.92 \]
\[ \beta_{ty} := 0.97 \]

Detailed Stress Analysis

Section Properties

![Diagram of bridge assembly](image)

**Figure 4.6-1** ISO View of Bridge Assembly, PAS Bridge Assembly, SDG39135837
Calculation of Section Properties for Irregular Section

This calculation is based on information given in the Jan 22, 1976 Machine Design in "Properties of Plane Cross Sections" by Fleix Wojciechowski

Assumptions (Figure 4.6-4):
1. The entire cross section is contained in the first quadrant.
2. Small curved boundaries are approximated by straight line segments.
3. Centroid of the section is a small distance from the origin of the coordinate system.
4. Order of entry for vertices is clockwise.
5. For holes in section, enter coordinates going counterclockwise.
Enter the \( y \) and \( z \) coordinates of the vertices of the cross section.

Note: The last two vertices are the same as the first \((0,0)\).

<table>
<thead>
<tr>
<th></th>
<th>( y )</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.325</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>0.325</td>
<td>2.070</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>2.07</td>
</tr>
<tr>
<td>6</td>
<td>1.1</td>
<td>1.6825</td>
</tr>
<tr>
<td>7</td>
<td>2.55</td>
<td>1.6825</td>
</tr>
<tr>
<td>8</td>
<td>2.55</td>
<td>2.07</td>
</tr>
<tr>
<td>9</td>
<td>3.325</td>
<td>2.07</td>
</tr>
<tr>
<td>10</td>
<td>3.325</td>
<td>0.2</td>
</tr>
<tr>
<td>11</td>
<td>3.65</td>
<td>0.2</td>
</tr>
<tr>
<td>12</td>
<td>3.65</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>3.075</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>3.075</td>
<td>1.6825</td>
</tr>
<tr>
<td>15</td>
<td>2.55</td>
<td>1.6825</td>
</tr>
<tr>
<td>16</td>
<td>1.1</td>
<td>1.6825</td>
</tr>
<tr>
<td>17</td>
<td>0.575</td>
<td>1.6825</td>
</tr>
<tr>
<td>18</td>
<td>0.575</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Define \( n \), used in the summations

\[
\text{max value} := \begin{cases} 
\max(y) & \text{if } \max(y) \geq \max(z) \\
\max(z) & \text{otherwise}
\end{cases}
\]

\[
\text{max}(y) = 3.650 \text{ in} \quad \text{max}(z) = 2.070 \text{ in}
\]

The area is found by using the summation

\[
\text{Area} := -\sum_{i=1}^{n} \left( z_{i+1} - z_i \right) \frac{y_{i+1} + y_i}{2}
\]

\[
\text{Area} = 1.572 \text{ in}^2
\]
Next, find the y and z coordinates of the centroid of the section

\[
y_{\text{bar}} := \frac{1}{\text{Area}} \sum_{i=1}^{n} \left[ \frac{z_{i+1} - z_i}{8} \left( \frac{y_{i+1} + y_i}{2} \right)^2 + \frac{(y_{i+1} - y_i)^2}{3} \right]
\]
\[
z_{\text{bar}} := \frac{1}{\text{Area}} \sum_{i=1}^{n} \left[ \frac{y_{i+1} - y_i}{8} \left( \frac{z_{i+1} + z_i}{2} \right)^2 + \frac{(z_{i+1} - z_i)^2}{3} \right]
\]

\[
y_{\text{bar}} = 1.825 \text{ in}
\]
\[
z_{\text{bar}} = 1.175 \text{ in}
\]

Find the maximum distance from the centroid to the outer fiber

\[
c_y := y - y_{\text{bar}} \quad \max(c_y) = 1.825 \text{ in} \quad \min(c_y) = -1.825 \text{ in}
\]
\[
c_z := z - z_{\text{bar}} \quad \max(c_z) = 0.895 \text{ in} \quad \min(c_z) = -1.175 \text{ in}
\]

Next, find the moment of inertias of the cross section with respect to the coordinate axes

\[
I_{y_{\text{a}}} := \sum_{i=1}^{n} \left[ \frac{(y_{i+1} - y_i)(z_{i+1} + z_i)}{24} \left( \frac{(z_{i+1} + z_i)^2}{2} + (z_{i+1} - z_i)^2 \right) \right]
\]
\[
I_{z_{\text{a}}} := -\sum_{i=1}^{n} \left[ \frac{(z_{i+1} - z_i)(y_{i+1} + y_i)}{24} \left( \frac{(y_{i+1} + y_i)^2}{2} + (y_{i+1} - y_i)^2 \right) \right]
\]
\[
I_{y_{\text{a}}} = 2.917 \text{ in}^4
\]
\[
I_{z_{\text{a}}} = 7.964 \text{ in}^4
\]

\[
I_{y_{\text{a}}} := \sum_{i=1}^{n} \left[ \begin{array}{c}
0 \text{ in}^4 \quad \text{if } y_{i+1} = y_i \\
\frac{1}{8} (z_{i+1} - z_i)^2 \left( y_{i+1} + y_i \right)^2 + (y_i)^2 \\
\frac{1}{3} (z_{i+1} - z_i) \left( y_{i+1} - y_i \right) (z_{i+1}^2 + z_i^2) \\
\frac{1}{4} (y_{i+1}^2 - y_i^2) (z_{i+1}^2 + z_i^2) \\
\end{array} \right]
\]
\[
I_{y_{\text{a}}} = 3.372 \text{ in}^4
\]

**Note: The if statement to check if \(y_{i+1}\) is equal to \(y_i\)**

Now, find the moments of inertia about the centroidal axes

\[
I_y := I_{y_{\text{a}}} - \text{Area} \cdot z_{\text{bar}}^2 \quad I_y = 0.7457 \text{ in}^4
\]
\[
I_z := I_{z_{\text{a}}} - \text{Area} \cdot y_{\text{bar}}^2 \quad I_z = 2.7288 \text{ in}^4
\]
\[
I_{yz} := I_{y_{\text{a}}} - \text{Area} \cdot y_{\text{bar}} \cdot z_{\text{bar}} 
\]
\[
I_{yz} = 0.0000 \text{ in}^4
\]
Calculate the angle that the neutral axes make with the centroidal axes

\[ u := \begin{cases} \text{90 deg if } I_y = I_z \\ \frac{1}{2} \tan \left( -\frac{2 I_{yz}}{I_y - I_z} \right) \text{ otherwise} \end{cases} \]

\[ u = 0 \text{ deg} \]

Prepare equations for graph

\[ i := 1..(n) \]

\[ z_{neutral} := \begin{cases} \text{zbar if } u = 0 \\ \text{zbar} + \tan(u) \cdot (y_{bar} - y_{bar}) \text{ otherwise} \end{cases} \]

\[ y_{neutral} := \begin{cases} \max(z) \cdot 2 \cdot i \text{ if } u < .0001 \\ \text{zbar} + \tan(u + 90 \text{ deg}) \cdot (y_{bar} - y_{bar}) \text{ otherwise} \end{cases} \]

\[ y_{yyneutral} := \begin{cases} \text{ybar if } u < .0001 \\ y_{bar} \text{ otherwise} \end{cases} \]

---

U shaped cross section, from NASTRAN card, match the calculated values above

\[ I_z = 2.729 \text{ in}^4 \quad I_y = 7.457 \text{ in}^4 \quad J_z = 0.0442752 \text{ in}^4 \quad \text{Area} = 1.572 \text{ in}^2 \]

\[ c_z = 0.895 \text{ in} \quad c_y = 1.825 \text{ in} \quad r = 1.91919 \text{ in} \]

---

**Figure 4.6-5  Section Properties From the NASTRAN PBEAM Card**
Figure 4.6-6 NASTRAN CBEAM Element Coordinate System

Figure 4.6-7 NASTRAN CBEAM Element Internal Forces and Moments

Our $F_y$ is the negative of NASTRAN's $M_2$

Figure 4.6-8 Bridge Beam FEM Showing $x_{elem}$ Direction (red) and $y_{elem}$ Direction (green)
Match Analysis Force and Moment Inputs to CBEAM Element Internal Directions

<table>
<thead>
<tr>
<th></th>
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</tr>
</tbody>
</table>

Fx (axial) = Fx (Column 7)
Fy (shear) = V1 (Columns 5 and 11)
Fz (shear) = V2 (Columns 6 and 12)
My = -M2 (Columns 4 and 10)
Mz = M1 (Columns 3 and 9)
T (torque) = Tx (Column 8)

Liftoff/Flight Loads, Minimum Cross Section w/Bearing Thru Hole

Read formatted Naspost output, Naspost file called PASBridgeBeam-SortFlight.nas.lis

forces := READPRN("beams-Flight.txt")

\[
\begin{array}{cccccccccccc}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\
\end{array}
\]

Load data from first end of beam

\[
\begin{align*}
F_{x1} & := \text{forces}_{1,7} \text{ lbf} \\
F_{y1} & := \text{forces}_{1,5} \text{ lbf} \\
F_{z1} & := \text{forces}_{1,6} \text{ lbf} \\
T_{i} & := \text{forces}_{1,8} \text{ in lbf} \\
M_{y1} & := -\text{forces}_{1,4} \text{ in lbf} \\
M_{z1} & := \text{forces}_{1,3} \text{ in lbf}
\end{align*}
\]

Load data from second end of beam

\[
\begin{align*}
F_{x2}(\text{forces}) & := \text{forces}_{1,7} \text{ lbf} \\
F_{y2}(\text{forces}) & := \text{forces}_{1,11} \text{ lbf} \\
F_{z2}(\text{forces}) & := \text{forces}_{1,12} \text{ lbf} \\
T_{i}(\text{forces}) & := \text{forces}_{1,8} \text{ in lbf} \\
M_{y2}(\text{forces}) & := -\text{forces}_{1,10} \text{ in lbf} \\
M_{z2}(\text{forces}) & := \text{forces}_{1,9} \text{ in lbf}
\end{align*}
\]
Calculate Stresses

\[ i := 1, \text{ rows (forces) 2} \]
\[ i,j := \frac{F_{xi}}{\text{Area}} + \frac{M_{yi} c_{ji}}{I_y} - \frac{M_{zi} c_{ij}}{I_z} \]
\[ \text{max( )} = 1422 \text{ psi} \quad \text{Normal is direct axial plus bending} \]
\[ \sqrt{\frac{F_{yi}}{\text{Area}}}^2 + \left(\frac{F_{zi}}{\text{Area}}\right)^2 \]
\[ \text{max( =v) } = 82 \text{ psi} \quad \text{Shear due to transverse loading} \]
\[ \text{max( =t) } = 1214 \text{ psi} \quad \text{Shear due to torsion} \]
\[ \text{max( = ) } = 1260 \text{ psi} \quad \text{Combined shear} \]
\[ p_{1i,j} := \frac{i,j}{2} + \left[ \left(\frac{i,j}{2}\right)^2 + (\epsilon)^2 \right]^\frac{1}{2} \]
\[ \text{max( p1) } = 1638 \text{psi} \quad \text{Principal Stresses} \]
\[ \text{min( p1) } = 0.000 \text{psi} \]
\[ p_{2i,j} := \frac{i,j}{2} - \left[ \left(\frac{i,j}{2}\right)^2 + (\epsilon)^2 \right]^\frac{1}{2} \]
\[ \text{max( p2) } = 0.000 \text{psi} \]
\[ \text{min( p2) } = -1771 \text{psi} \]
\[ \text{RES_i} := \sqrt{(F_{xi})^2 + (F_{yi})^2 + (F_{zi})^2} \]
\[ \text{max(RES) } = 128.565 \text{ lb} \]
\[ \text{max( Flight max := max( max( | p1)|, max( | p2)|) )} \quad f_{tu} := \text{Flight max } = 1771 \text{ psi} \quad \text{Maximum Principal} \]
\[ \text{vm_{i,j} := ( p1_{i,j})^2 + ( p2_{i,j})^2 - (p1_{i,j}) p_{2i,j} \]
\[ f_{ty} := \text{max( vm) } = 2240 \text{ psi} \quad \text{Von-Mises Stress} \]
\[ \text{max( =max) } = 1281 \text{ psi} \quad \text{Maximum shear} \]
\[ \text{output := augment}\left(\text{cases}, \frac{p_1}{\text{psi}}, \frac{p_2}{\text{psi}}\right) \quad \text{WRITEPRN\("\text{bridgebeambout-Flight.txt"} \) := output} \]

Margins of Safety for Liftoff, Minimum Cross Section w/Bearing Thru Hole

\[ MS_{tu} := \frac{f_{tu}}{f_{su} f_{tu}} - 1 = 17.97 \quad \text{Tensile Ultimate} \]
\[ MS_{ty} := \frac{f_{ty}}{f_{sy} f_{ty}} - 1 = 20.83 \quad \text{Tensile Yield} \]
\[ MS_{su} := \frac{f_{su}}{f_{su} f_{su}} - 1 = 14.44 \quad \text{Shear Ultimate} \]
**Landing Loads, Minimum Cross Section w/Bearing Thru Hole**

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortLanding.nas.lis

```plaintext
forces := READPRN("beams-Landing.txt")
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Load data from first end of beam

- $F_{x1} := forces_{i, 7}$ lbf
- $F_{y1} := forces_{i, 5}$ lbf
- $F_{z1} := forces_{i, 6}$ lbf
- $T_{i} := forces_{i, 8}$ in lbf
- $M_{y1} := -forces_{i, 4}$ in lbf
- $M_{z1} := forces_{i, 3}$ in lbf

Load data from second end of beam

- $F_{x1} := forces_{i, 7}$ lbf
- $F_{y1} := forces_{i, 11}$ lbf
- $F_{z1} := forces_{i, 12}$ lbf
- $T_{i} := forces_{i, 8}$ in lbf
- $M_{y1} := -forces_{i, 10}$ in lbf
- $M_{z1} := forces_{i, 9}$ in lbf

Calculate Stresses

- $i := 1..\text{rows}(forces)$
- $i,j := \frac{F_{x} \cdot c_{j}}{A} + \frac{M_{y} \cdot c_{j}}{I_{y}} - \frac{M_{z} \cdot c_{j}}{I_{z}}$
- $\max(\cdot) = 2249.404$ psi  
  *Normal is direct axial plus bending*

- $\sigma_{i} := \sqrt{\left(\frac{F_{i} \cdot c_{j}}{A}\right)^{2} + \left(\frac{F_{z} \cdot c_{j}}{A}\right)^{2}}$
- $\max(\sigma) = 104$ psi  
  *Shear due to transverse loading*

- $\tau := \frac{T_{i}}{J}$
- $\max(\tau) = 1821$ psi  
  *Shear due to torsion*

- $\theta := \sigma + \tau$
- $\max(\theta) = 1890$ psi  
  *Combined shear*

- $p_{1,j} := \frac{-1}{2} \left[ \left(\frac{i,j}{2}\right)^{2} + (\tau)^{2} \right]^{1/2}$
- $\max(p_{1}) = 3201$ psi  
  *Principal Stresses*

- $\min(p_{1}) = 0.000$ psi

- $p_{2,j} := \frac{1}{2} \left[ \left(\frac{i,j}{2}\right)^{2} + (\tau)^{2} \right]^{1/2}$
- $\max(p_{2}) = 0.000$ psi  
  *Principal Stresses*

- $\min(p_{2}) = -3732$ psi

- $\text{RES}_{i} := \sqrt{\left(F_{x}\right)^{2} + \left(F_{y}\right)^{2} + \left(F_{z}\right)^{2}}$
- $\max(\text{RES}) = 162.718$ lbf
Landings max := \( \max(\max(\frac{p_1}{p_1}, \max(\frac{p_2}{p_2}))) \) \( f_{tu} := \text{Landing max} = 3732 \text{ psi} \) \text{Maximum Principal}

\( v_{mi,j} := \sqrt{\left(\frac{p_{1i,j}}{p_{1i,j}}\right)^2 + \left(\frac{p_{2i,j}}{p_{2i,j}}\right)^2 - \frac{p_{1i,j}}{p_{2i,j}}} \) \( f_{ty} := \max(\text{vm}) = 4228 \text{ psi} \) \text{Von-Mises Stress}

\( = \max_{i,j} := \sqrt{\frac{1}{4} \left(\frac{i}{i}j\right)^2 + \left(\frac{i}{i}j\right)^2} \) \( f_{su} := \max(=\max) = 2296 \text{ psi} \) \text{Maximum Shear}

output := augment\left(\text{cases}, \frac{p_1}{\text{psi}}, \frac{p_2}{\text{psi}}\right) \text{ WRITEPRN("bridgebeamout-Landing.txt") := output}

**Margins of Safety, Minimum Cross Section w/Bearing Thru Hole**

\[
\begin{align*}
MS_{tu} &= \left(\frac{f_{tu}}{f_{tu}}\right)^2 - 1 = 8.00 & \text{Tensile Ultimate} \\
MS_{ty} &= \left(\frac{f_{ty}}{f_{ty}}\right)^2 - 1 = 10.56 & \text{Tensile Yield} \\
MS_{su} &= \left(\frac{f_{su}}{f_{su}}\right)^2 - 1 = 7.62 & \text{Shear Ultimate}
\end{align*}
\]
On-Orbit Inertial Steady State Combined Loads, Min. Cross Section w/Bearing Thru Hole

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortOn-Orbit.nas.lis

\[
\text{forces} := \text{READPRN("beams-Onorbit.txt")}
\]

\[
i := 1, \ \text{rows(forces)} \quad \text{cases} := \text{forces}, \ 2
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Load data from first end of beam

\[
F_{x_i} := \text{forces}_{i,7} \ \text{lbf}
\]

\[
F_{y_i} := \text{forces}_{i,5} \ \text{lbf}
\]

\[
T_i := \text{forces}_{i,8} \ \text{in lbf}
\]

\[
M_{y_i} := -\text{forces}_{i,4} \ \text{in lbf}
\]

\[
M_{z_i} := \text{forces}_{i,9} \ \text{in lbf}
\]

Load data from second end of beam

\[
F_{x_{i+\text{rows(forces)}}} := \text{forces}_{i,7} \ \text{lbf}
\]

\[
F_{y_{i+\text{rows(forces)}}} := \text{forces}_{i,11} \ \text{lbf}
\]

\[
T_{i+\text{rows(forces)}} := \text{forces}_{i,8} \ \text{in lbf}
\]

\[
M_{y_{i+\text{rows(forces)}}} := -\text{forces}_{i,10} \ \text{in lbf}
\]

\[
M_{z_{i+\text{rows(forces)}}} := \text{forces}_{i,9} \ \text{in lbf}
\]

Calculate Stresses

\[
i := 1, \ \text{rows(forces)} \ 2
\]

\[
\frac{i,j}{\text{Area}} + \frac{My_i cz_j}{Iy} + \frac{Mz_i cy_j}{Iz}
\]

\[
\text{max(} \gamma \text{) := 28825.467 psi}
\]

Normal is direct axial plus bending

\[
\eta := \left( \frac{F_{y_i}}{\text{Area}} \right) \gamma + \left( \frac{F_{z_i}}{\text{Area}} \right) \gamma^2
\]

\[
\text{max(} \eta \text{) := 1046 psi}
\]

Shear due to transverse loading

\[
\tau := T \cdot \frac{r}{J}
\]

\[
\text{max(} \tau \text{) := 3164 psi}
\]

Shear due to torsion

\[
\text{max(} \phi \text{) := 4175 psi}
\]

Combined shear

\[
p_{1,i,j} := \frac{i,j}{2} + \left( \frac{i,j}{2} \right)^2 + \left( \gamma \right)^2
\]

\[
\text{max(} p_1 \text{) := 28892 psi}
\]

Principal Stresses

\[
p_{2,i,j} := \frac{i,j}{2} - \left( \frac{i,j}{2} \right)^2 + \left( \gamma \right)^2
\]

\[
\text{min(} p_1 \text{) := 0.000 psi}
\]

\[
\text{max(} p_2 \text{) := 0.000 psi}
\]

\[
\text{min(} p_2 \text{) := -37847 psi}
\]

\[
\text{max(RES) := 1644 lbf}
\]

Last Saved 7/27/2009 1:37 PM
OnOrbit $\max := \max \left( \max \left( \left| \frac{p_1}{L} \right|, \max \left( \left| \frac{p_2}{L} \right| \right) \right) \right)$

\[ f_{\text{tu}} := \text{OnOrbit} \max = \textbf{37847} \text{ psi} \quad \text{Maximum Principal} \]

\[ v_{m_{i,j}} := \sqrt{\left( \frac{p_{1_{i,j}}}{L} \right)^2 + \left( \frac{p_{2_{i,j}}}{L} \right)^2 - \frac{p_{1_{i,j}}}{p_{2_{i,j}}}} \]

\[ f_{\text{ty}} := \max (\text{vm}) = \textbf{37873} \text{ psi} \quad \text{Von-Mises Stress} \]

\[ = \max_{i,j} := \sqrt{\frac{1}{4} \left( \frac{p_1}{L} \right)^2 + \left( \frac{p_2}{L} \right)^2} \]

\[ f_{\text{SU}} := \max (-\max) = \textbf{18949} \text{ psi} \quad \text{Maximum shear} \]

\[ \text{output} := \text{augment} \left( \text{cases}, \frac{p_1}{\text{psi}}, \frac{p_2}{\text{psi}} \right) \quad \text{WRITEPRN("bridgebeamout-On-Orbit.txt") := output} \]

**Margins of Safety, Inertial Steady State Combined, Min Cross Section w/Bearing Thru Hole**

\[ M_{\text{SU}} := \frac{f_{\text{tu}}}{f_{\text{SU}}} - 1 = -0.11 \]  

\textit{Tensile Ultimate}

*Note: Because of the negative margin for Tensile Ultimate, a Plastic Bending check (Section 4.6.7) and a Buckling check (Section 4.6.8) will be performed.*

\[ M_{\text{SY}} := \frac{f_{\text{ty}}}{f_{\text{SU}}} - 1 = 0.29 \]  

\textit{Tensile Yield}

\[ M_{\text{SU}} := \frac{f_{\text{SU}}}{f_{\text{SU}}} - 1 = 0.04 \]  

\textit{Shear Ultimate}
On-Orbit Steady State Loads, Minimum Cross Section w/Bearing Thru Hole

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortOn-OrbitSS.nas.lis

forces2 := READPRN("beams-OnorbitSS.txt")

\[ i := 1.. \text{rows (forces)} \]
\[ \text{cases}_i \text{ := forces}_i, 2 \]

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Data is modified in the below embedded excel file. Result is for the Max stress - Steady State Stress

forces3 := Sort Excel

\[ \text{cases}_{1, \text{rows (forces3)}} := \text{forces3}_{1, 2} \]

( forces forces2 )

Load data from first end of beam

\[ F_{x_i} := \text{forces3}_{i, 7} \text{ lbf} \]
\[ F_{y_i} := \text{forces3}_{i, 5} \text{ lbf} \]
\[ F_{z_i} := \text{forces3}_{i, 6} \text{ lbf} \]
\[ \text{T}_{i} := \text{forces3}_{i, 8} \text{ in lb}f \]
\[ M_{y_i} := -\text{forces3}_{i, 4} \text{ in lb}f \]
\[ M_{z_i} := \text{forces3}_{i, 3} \text{ in lb}f \]

Load data from second end of beam

\[ F_{x_i} := \text{forces3}_{i, 7} \text{ lbf} \]
\[ F_{y_i} := \text{forces3}_{i, 11} \text{ lbf} \]
\[ F_{z_i} := \text{forces3}_{i, 12} \text{ lbf} \]
\[ \text{T}_{i} := \text{forces3}_{i, 8} \text{ in lb}f \]
\[ M_{y_i} := -\text{forces3}_{i, 10} \text{ in lb}f \]
\[ M_{z_i} := \text{forces3}_{i, 9} \text{ in lb}f \]

Calculate Stresses

\[ i := 1.. \text{rows (forces3)} \]
\[ \text{max}(\ldots) = 1047.210 \text{ psi} \]

Normal is direct axial plus bending

\[ \nu := \frac{F_{y_i}}{\text{Area}} + \frac{M_{z_i}}{I_y} - \frac{M_{z_i}}{I_z} \]
\[ \max(\nu) = 62 \text{ psi} \]

Shear due to transverse loading

\[ \epsilon := T \frac{r}{j} \]
\[ \max(\epsilon) = 1864 \text{ psi} \]

Shear due to torsion

\[ \gamma := \nu + \epsilon \]
\[ \max(\gamma) = 1890 \text{ psi} \]

Combined shear

\[ p_{1, j} := -\frac{i_{1, j}}{2} + \left(\frac{i_{1, j}^2}{2} + (\gamma)^2\right)^{\frac{1}{2}} \]
\[ \max(\ p_{1}) = 2317 \text{ psi} \]
\[ \min(\ p_{1}) = 0.000 \text{ psi} \]

Principal Stresses
AMS-02 PAS Bridge, PAS Bridge Assembly

\[
p_{2i,j} := \frac{i_j}{\sqrt{\left(\frac{i_j}{2}\right)^2 + \left(\frac{j}{2}\right)^2}}\]

\[
\sqrt{\max\left(\frac{p_{1i,j}}{\text{psi}}, \frac{p_{2i,j}}{\text{psi}}\right)}
\]

\[
\text{max}(p_2) = 0.000\text{ psi}
\]

\[
\text{min}(p_2) = -2351\text{ psi}
\]

\[
\text{OnOrbitd max} := \max\left(\max\left(\frac{p_{1i,j}}{\text{psi}}, \frac{p_{2i,j}}{\text{psi}}\right)\right)
\]

\[
f_{tu} := \text{OnOrbitd max} = 2351\text{ psi}
\]

\[
\text{Von-Mises Stress}
\]

\[
\text{output} := \text{augment}\left(\frac{p_{1i,j}}{\text{psi}}, \frac{p_{2i,j}}{\text{psi}}\right)
\]

Margins of Safety, On-Orbit Steady State Loads, Min Cross Section w/Bearing Thru Hole

\[
MS_{tu} := \left(\frac{F_{tu}}{F_{tu}^{\beta_{tu}}}\right) - 1 = 13.28
\]

Tensile Ultimate

\[
MS_{ty} := \left(\frac{F_{ty}}{F_{ty}^{\beta_{ty}}}\right) - 1 = 13.61
\]

Tensile Yield

\[
MS_{su} := \left(\frac{F_{su}}{F_{su}^{\beta_{tu}}}\right) - 1 = 9.30
\]

Shear Ultimate
4.6.7 Plastic Bending, Inelastic Bending, Ultimate Allowable Bending Stress

At Ultimate Design Loads there can be no rupture/failure from tension or local crippling from compression. Stresses are in the inelastic range, above the proportional limit. Once a structure has exceeded the proportional limit of a material, the simplified elastic stress distribution method (Mc/I) is usually too conservative and will predict maximum fiber stresses that are too high for practical design use or cause a weight penalty.

For materials fully capable of plastic behavior, excluding local instability, failure of a member in bending will occur above the proportional limit of the material in the inelastic range of stresses. A redistribution of load (a nonlinear variation of stress) will occur such that the extreme fiber stresses of an actual structure in bending will begin to yield, while interior points of that structure will experience increases in stress. The member will collapse when the maximum moment equals the plastic moment which is developed when the stress throughout the section becomes equal to the tensile yield strength (plastic yielding throughout the section).

To predict the ultimate failure of a member in bending in the inelastic range of stresses, we use the Ultimate Allowable Bending Stress \( F_{bu} \) in place of \( F_{tu} \) in the Margin of Safety calculation.

\[
MS_{bu} := \frac{(F_{bu} \times v_{tu})}{(FS_{u} \times f_{u})} - 1
\]

The On-Orbit Inertial Steady State Combined Loads, Maximum Principal Stress, at the minimum cross section resulted in a negative Margin of Safety for Tensile Ultimate. Therefore that stress and cross section will now be checked using the Ultimate Plastic Bending Allowable.

Factors of Safety

\[
FS_{u} := 2.0 \quad FS_{y} := 1.25
\]

Materials and Temperature

**Material Allowables**

**Material and Temperature**

AL ALY, 7050-T7451, BMS-7-323-C, Plate, 37.575 x 3.650 x 2.070, A

\[
F_{tu} := 73000 \text{ psi} \quad F_{ty} := 63000 \text{ psi} \quad F_{cy} := 61000 \text{ psi} \quad F_{su} := 43000 \text{ psi}
\]

**Temperature Degradation**

\[
\beta_{tu} := 0.92 \quad \beta_{ty} := 0.97
\]
### Section Properties

#### Section Properties About Y Axis

<table>
<thead>
<tr>
<th>Element</th>
<th>b_i</th>
<th>h_i</th>
<th>A_i</th>
<th>z_i</th>
<th>A_i z_i</th>
<th>z_i</th>
<th>A_i z_i^2</th>
<th>I_{0yl}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5750</td>
<td>0.2000</td>
<td>0.11500</td>
<td>0.1000</td>
<td>0.01150</td>
<td>-1.0754</td>
<td>0.13301</td>
<td>0.00038</td>
</tr>
<tr>
<td>2</td>
<td>0.2500</td>
<td>1.8700</td>
<td>0.46750</td>
<td>1.1350</td>
<td>0.53061</td>
<td>-0.0404</td>
<td>0.00076</td>
<td>0.13623</td>
</tr>
<tr>
<td>3</td>
<td>0.5250</td>
<td>0.3875</td>
<td>0.20344</td>
<td>1.8763</td>
<td>0.38171</td>
<td>0.7009</td>
<td>0.09993</td>
<td>0.00255</td>
</tr>
<tr>
<td>4</td>
<td>0.5250</td>
<td>0.3875</td>
<td>0.20344</td>
<td>1.8763</td>
<td>0.38171</td>
<td>0.7009</td>
<td>0.09993</td>
<td>0.00255</td>
</tr>
<tr>
<td>5</td>
<td>0.2500</td>
<td>1.8700</td>
<td>0.46750</td>
<td>1.1350</td>
<td>0.53061</td>
<td>-0.0404</td>
<td>0.00076</td>
<td>0.13623</td>
</tr>
<tr>
<td>6</td>
<td>0.5750</td>
<td>0.2000</td>
<td>0.11500</td>
<td>0.1000</td>
<td>0.01150</td>
<td>-1.0754</td>
<td>0.13301</td>
<td>0.00038</td>
</tr>
<tr>
<td>Sum</td>
<td>1.57188</td>
<td>1.84764</td>
<td>1.84764</td>
<td>1.57188</td>
<td>1.57188</td>
<td>1.57188</td>
<td>0.46740</td>
<td>0.27832</td>
</tr>
</tbody>
</table>

Where:
- i = element number
- b = breadth, parallel to the axis of bending
- h = height, value of function f(x) at any point
- z_i = distance from reference axis to element centroid
- Zbar_i = distance from reference axis to section centroid
- Zbar = ? A_i z_i / ? A_i
- z_i = distance from neutral axis to element centroid
- I_{0yl} = bh^2/12 for a rectangular element
- I_y = ? A_i z_i^2 + ? I_{0yl} (Second Moment of Area)

**Zbar = 1.1754 inches**

**I_y = 0.74572 inches**
AMS-02 PAS Bridge, PAS Bridge Assembly

**Q_{yBottom} - First Moment of Area**

<table>
<thead>
<tr>
<th>i</th>
<th>b_i</th>
<th>h_i</th>
<th>A_i</th>
<th>z_i'</th>
<th>z_i</th>
<th>A_i z_i</th>
<th>A_i z_i^2</th>
<th>I_{y, i}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5750</td>
<td>0.2000</td>
<td>0.11500</td>
<td>0.1000</td>
<td>-1.0754</td>
<td>-0.12368</td>
<td>0.13301</td>
<td>0.00038</td>
</tr>
<tr>
<td>2</td>
<td>0.2500</td>
<td>0.9750</td>
<td>0.24375</td>
<td>0.6877</td>
<td>-0.4877</td>
<td>-0.11889</td>
<td>0.05799</td>
<td>0.01931</td>
</tr>
<tr>
<td>3</td>
<td>0.2500</td>
<td>0.9750</td>
<td>0.24375</td>
<td>0.6877</td>
<td>-0.4877</td>
<td>-0.11889</td>
<td>0.05799</td>
<td>0.01931</td>
</tr>
<tr>
<td>4</td>
<td>0.5750</td>
<td>0.2000</td>
<td>0.11500</td>
<td>0.1000</td>
<td>-1.0754</td>
<td>-0.12368</td>
<td>0.13301</td>
<td>0.00038</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.48512</td>
<td>0.38198</td>
<td>0.03939</td>
<td></td>
</tr>
</tbody>
</table>

\[ Q_{yBottom} = 0.4851 \text{ inches}^2 \]

\[ I_{yBottom} = 0.42137 \text{ inches}^4 \]

**Q_{yTop} - First Moment of Area**

<table>
<thead>
<tr>
<th>i</th>
<th>b_i</th>
<th>h_i</th>
<th>A_i</th>
<th>z_i'</th>
<th>z_i</th>
<th>A_i z_i</th>
<th>A_i z_i^2</th>
<th>I_{y, i}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5250</td>
<td>0.8946</td>
<td>0.22365</td>
<td>1.6227</td>
<td>0.4473</td>
<td>0.10003</td>
<td>0.04474</td>
<td>0.01492</td>
</tr>
<tr>
<td>2</td>
<td>0.5250</td>
<td>0.8946</td>
<td>0.22365</td>
<td>1.6227</td>
<td>0.4473</td>
<td>0.10003</td>
<td>0.04474</td>
<td>0.01492</td>
</tr>
<tr>
<td>3</td>
<td>0.5250</td>
<td>0.8946</td>
<td>0.22365</td>
<td>1.6227</td>
<td>0.4473</td>
<td>0.10003</td>
<td>0.04474</td>
<td>0.01492</td>
</tr>
<tr>
<td>4</td>
<td>0.2500</td>
<td>0.9750</td>
<td>0.23444</td>
<td>1.8763</td>
<td>0.7008</td>
<td>0.14257</td>
<td>0.09992</td>
<td>0.00255</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.48520</td>
<td>0.28931</td>
<td>0.03492</td>
<td></td>
</tr>
</tbody>
</table>

\[ Q_{yTop} = 0.4852 \text{ inches}^2 \]

\[ I_{yTop} = 0.32423 \text{ inches}^4 \]

\[ C_z = \text{Distance from the Neutral Axis to the Extreme Fiber} \]

\[ I = \text{Moment of Inertia of an Area (Second Moment of an Area)} \]

\[ Q = \text{Static First Moment, About the Neutral Axis, of the Cross-Sectional Area on the Tension Side of the Neutral Axis} \]

\[ Z = \text{Q is the Plastic Section Moduli (from Roark)} \]

\[ Zbar = 1.1754 \text{ in} \]

**NASTRAN Section Properties**

\[ I_z = 2.729 \text{ in}^4 \]

\[ I_y = 0.7457 \text{ in}^4 \]

\[ J = 0.0442752 \text{ in}^4 \]

\[ \text{Area} = 1.572 \text{ in}^2 \]

\[ cz = 0.895 \text{ in} \]

\[ cy = 1.825 \text{ in} \]

\[ r = 1.91919 \text{ in} \]
Plastic Bending Allowable For the Bottom Portion of the Flange

\[ K := \frac{Q_y \text{Bottom}}{F_y \text{Bottom}} = 1.35 \]

*\( K \) is the Beam Section Shape Factor (also shown as SF in Roark). Varies between 1.0 - 2.0

\[ f_m := F_{tu} = 73000 \text{ psi} \]

*\( f_m \) is the Maximum Stress Permitted in the Outer most Fiber, \((F_y = f_m =< F_{tu}) \) but usually \( f_m \sim F_{tu} \)

\[ f_o := \min(F_{ty}, F_{cy}) \]

*\( f_o \) is the Fictitious Stress at the Neutral Axis Assuming Zero Strain.
Can be Approximated as the Lower of \( F_{cy} \) or \( F_{ty} \)

\[ f_o = 61000 \text{ psi} \]

\[ F_{bu} := f_m + f_o (K - 1) \]

*\( F_{bu} \) is the Fictitious Failing Bending Stress, Ultimate Modulus of Rupture, Ultimate Allowable Bending Stress.

\[ F_{bu} = 94544 \text{ psi} \]

\[ f_{tu} = 37847 \text{ psi} \]

\[ \frac{F_{bu}}{F_{tu}} = 1 = 0.15 \]

...Margin of Safety for Plastic Bending Bottom

Plastic Bending Allowable For the Top Portion of the Flange

\[ K := \frac{Q_y \text{Top}}{F_y \text{Top}} = 1.34 \]

*\( K \) is the Beam Section Shape Factor (also shown as SF in Roark). Varies between 1.0 - 2.0

\[ F_{bu} := f_m + f_o (K - 1) \]

*\( F_{bu} \) is the Fictitious Failing Bending Stress, Ultimate Modulus of Rupture, Ultimate Allowable Bending Stress.

\[ F_{bu} = 93663 \text{ psi} \]

\[ \frac{F_{bu}}{F_{tu}} = 1 = 0.14 \]

...Margin of Safety for Plastic Bending Top
4.6.8 Bucking of PAS Bridge Beam Flanges

Table 34 Formulas for Elastic Stability of Bars, Rings and Beams
Case 11 Straight Uniform Beam of Narrow Rectangular Section Under Pure Bending

Straight uniform beam of narrow rectangular section under pure bending

Notation file

Provides a description of Table 34 and the notation used.

- $E_c := 10.6 \times 10^6$ psi
  - Modulus of Elasticity
- $G := 3.9 \times 10^6$ psi
  - Modulus of Rigidity
- $d := 0.200$ in
  - Height of Cross-Sectional Rectangle
- $b := 0.575$ in
  - Width of Cross-Sectional Rectangle
- $L := \frac{2}{3} \times 25.450$ in = 16.97 in
  - Beam Length:
- $\beta_{tu} := 0.92$
  - Temperature Degradation
- $\beta_{ty} := 0.97$
  - Factor of Safety
- $FS_u := 2.00$
- $FS_Y := 1.25$

For ends held vertical, but not fixed in a horizontal plane, the critical bending is

$$M'_{SS} := \frac{u \cdot b^3 \cdot d}{6 \cdot L} \cdot \sqrt{E_c \cdot G \left(1 - \frac{.063 \cdot b}{d}\right)} = 6827 \text{ in lbf}$$

Maximum Allowed Moment
Assuming Simply Supported

For ends held vertical and fixed in a horizontal plane, the critical bending is

$$M'_{ff} := \frac{2 \cdot u \cdot b^3 \cdot d}{6 \cdot L} \cdot \sqrt{E_c \cdot G \left(1 - \frac{.063 \cdot b}{d}\right)} = 13654 \text{ in lbf}$$

Maximum Allowed Moment
Assuming Fixed
Margin of Safety for Buckling

\[ f_{tu} = 37847 \text{ psi} \]

\[ I_{bd} := \frac{1}{12} bd^3 = 383.333 \times 10^{-6} \text{ in}^3 \]

\[ c_{bd} := \frac{d}{2} = 0.10 \text{ in} \]

\[ m_{y,\text{Applied}} := f_{tu} \frac{I_{bd}}{c_{bd}} = 145.08 \text{ in lb} \]

\[ MS_{BucklingU} := \frac{M'ss}{FSu m_{y,\text{Applied}}} \beta_{tu} - 1 = 21 \]

\[ MS_{BucklingU} := \frac{M'ff}{FSu m_{y,\text{Applied}}} \beta_{tu} - 1 = 42 \]

...Margin of Safety for Flange Bucking, SS

...Margin of Safety for Flange Bucking, Fixed
4.7 Bridge Flat Bearing
4.7 Bridge Flat Bearing, SDG39135825

Bridge Flat Bearing, is made of CRES15-5 PH H1025 and is good by engineering judgement, based upon the compressive loads and the significant cross section.
4.8 Bridge Pin
4.8 Bridge Pin, AMS Passive PAS Assy, SDG39135826-001

Minimum Margins of Safety

Table 4.8-1 Minimum Margin Of Safety Summary

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135826-001</td>
<td>Bridge Pin</td>
<td>CRES A286 AMS 5737</td>
<td>Landing</td>
<td>Shear Ultimate</td>
<td>34.36</td>
<td>4.8-8</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Liftoff, On-Orbit, and Landing load cases, combined with the preload of the capture bar, were analyzed.
3. Boundary conditions are at the PAS Guide Pins and PAS handle locations.

Structural Description

Pin has a threaded end for retention. Primary loads are from the capture bar resulting in double shear on the pin. No moment.

Figure 4.8-1 Bridge Pin, AMS Passive PAS Assy, SDG39135826-001

Section Properties

\[
\text{dia} := .420 \text{ in} \\
\text{Area} := \beta \left( \frac{\text{dia}}{2} \right)^2 \\
\text{Area} = 0.139 \text{ in}^2
\]
Figure 4.8-2  Bridge Pin in Relation to PAS Base Assy

Figure 4.8-3  Cross Section View of Bridge Beam and Platform
Summary of Load Conditions

The Liftoff, On-Orbit, and Landing loads from the Bridge Beam (section 4.6) were used for the stress analysis of the Bridge Pin.

Factors of Safety

\[
FS_u := 2.0 \quad \text{Ultimate} \quad \quad \quad FS_y := 1.25 \quad \text{Yield}
\]

Materials and Temperature

Material Allowables

CRES A286, AMS 5737, .705 X 4.620 LG, Passivate

\[
F_{tu} := 140000 \text{ psi} \quad F_{ty} := 95000 \text{ psi} \quad F_{su} := F_{tu} \times 0.60 = 84000.00 \text{ psi}
\]

Temperature Degradation

\[
u := 0.96 \quad a_{tu} = a_{ty} = a \text{ at } 151 \degree F \text{ Thermal Reduction Coefficient}
\]

Finite Element Model

The same finite element model was used for the Bridge Pin, Bridge Beam, PAS Base, Guide Pins, Aft and Vertex Brackets.

For a detailed description of the model see Section 4.1.4.

For a detailed description of the model checks, see Section 4.1.5.
Liftoff/Flight Loads

From the Bridge Beam (Section 4.6)

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortFlight.nas.lis

```
forces := READPRN("beams-Flight.txt") ORIGIN := 1
i := 1..rows(forces) cases_i := forces_i,2

Load data from first end of beam

M_i := forces_i,4 in lbf M_z := forces_i,3 in lbf T_i := forces_i,8 in lbf cases_i,rows(forces) := forces_i,2
F_yi := forces_i,5 lbf F_zi := forces_i,6 lbf F_xi := forces_i,7 lbf

Load data from second end of beam

M_i,rows(forces) := forces_i,10 in lbf M_z,rows(forces) := forces_i,9 in lbf T_i,rows(forces) := forces_i,8 in lbf
F_yi,rows(forces) := forces_i,11 lbf F_zi,rows(forces) := forces_i,12 lbf F_xi,rows(forces) := forces_i,7 lbf

i := 1..rows(forces) 2
```

Detailed Stress Analysis

Bridge Pin (circular diameter) is Loaded in Double Shear. No Moment.

\[
i := \sqrt{\frac{F_{zi}}{\text{Area}}}\]

\[\text{max}(i) = 505.25 \text{ psi}\]

\[=p_{i,1} = \left[\left(\frac{1}{i}\right)^2\right] \quad \text{max} = 505.25 \text{ psi}\]

\[=p_{i,2} = \left[\left(\frac{1}{i}\right)^2\right] \quad \text{max} = 505.25 \text{ psi}\]

\[\text{Maximum Principal}\]

\[=\text{vm}_i := \sqrt{(=p_{i,1})^2 + (=p_{i,2})^2} - =p_{i,1} = =p_{i,2} \quad \text{max} = 875.13 \text{ psi}\]

\[\text{Maximum Von-Mises}\]

\[\text{max} := \sqrt{\left(\frac{1}{i}\right)^2} \quad \text{max} = 505.25 \text{ psi}\]

\[\text{Maximum Shear}\]
Margins of Safety for Liftoff/Flight Loads

\[ M_{Stu} := \left( \frac{F_{tu}}{F_{Su} \max(\text{max})} \right) - 1 \quad M_{Stu} = 132.00 \quad \text{Tensile Ultimate} \]

\[ M_{Sty} := \left( \frac{F_{ty}}{F_{Sy} \max(\text{max})} \right) - 1 \quad M_{Sty} = 82.37 \quad \text{Tensile Yield} \]

\[ M_{Ssu} := \left( \frac{F_{su}}{F_{Su} \max(\text{max})} \right) - 1 \quad M_{Ssu} = 78.80 \quad \text{Shear Ultimate} \]
Landing Loads

From the Bridge Beam (Section 4.6)

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortLanding.nas.lis

\[
\text{forces} := \text{READPRN}(\text{"beams-Landing.txt"}) \quad i := 1 \ldots \text{rows(foreces)} \quad \text{cases}_i := \text{forces}_{i, 2}
\]

Load data from first end of beam

\[
\begin{align*}
M_y_i &:= -\text{forces}_{i, 4} \text{ in lbf} \\
M_z_i &:= \text{forces}_{i, 3} \text{ in lbf} \\
T_i &:= \text{forces}_{i, 8} \text{ in lbf} \\
\text{cases}_i \cdot \text{rows(foreces)} &:= \text{forces}_{i, 2}
\end{align*}
\]

Load data from second end of beam

\[
\begin{align*}
M_y_{i+\text{rows(foreces)}} &:= -\text{forces}_{i, 10} \text{ in lbf} \\
M_z_{i+\text{rows(foreces)}} &:= \text{forces}_{i, 9} \text{ in lbf} \\
T_{i+\text{rows(foreces)}} &:= \text{forces}_{i, 8} \text{ in lbf} \\
\text{cases}_{i+\text{rows(foreces)}} &:= \text{forces}_{i, 2}
\end{align*}
\]

i := 1..\text{rows(foreces)}

Detailed Stress Analysis

Bridge Pin (circular diameter) is Loaded in Double Shear. No Moment.

\[
i := \sqrt{\left(\frac{F_{z_i}}{\text{Area}}\right)^2} \quad \max(\ ) = 1140.43 \text{ psi}
\]

\[
\text{p}_{i, 1} := \left[\left(\frac{1}{i^2}\right)^2\right] \quad \max(=p) = 1140.43 \text{ psi}
\]

\[
\text{p}_{i, 2} := -\left[\left(\frac{1}{i^2}\right)^2\right] \quad \max(=p) = 1140.43 \text{ psi} \quad \max\left(\frac{\left|-p\right|}{=p}\right) = 1140.43 \text{ psi}
\]

\[
v_{m_i} := \sqrt{\left(\text{p}_{i, 1}\right)^2 + \left(\text{p}_{i, 2}\right)^2} = \text{p}_{i, 1} \cdot \text{p}_{i, 2} \quad \max(=\text{vm}) = 1975.28 \text{ psi}
\]

\[
\max = \sqrt{\left(\right)^2} \quad \max(\text{max}) = 1140.43 \text{ psi}
\]
Margins of Safety for the Landing Loads

\[
M_{Stu} := \left( \frac{F_{tu} - u}{FS_{u \max} - p} \right) - 1 \quad M_{Stu} = 57.93 \quad \text{Tensile Ultimate}
\]

\[
M_{Sty} := \left( \frac{F_{ty} - u}{FS_{y \max} - v} \right) - 1 \quad M_{Sty} = 35.94 \quad \text{Tensile Yield}
\]

\[
M_{Sus} := \left( \frac{F_{su} - u}{FS_{u \max} - m} \right) - 1 \quad M_{Sus} = 34.36 \quad \text{Shear Ultimate}
\]
On-Orbit Inertial and Steady State Combined Loads

From the Bridge Beam (Section 4.6)

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortOn-Orbit.nas.lis

\[
\text{forces} := \text{READPRN}("\text{beams-Onorbit.txt}")
\]

\[
i := 1\ldots \text{rows(forces)}
\]

\[
\text{cases}_i := \text{forces}_i, 2
\]

\[
\text{cases}_n\text{rows(forces)} := \text{forces}_i, 2
\]

Load data from first end of beam

\[
\text{My}_i := -\text{forces}_i, 4 \text{ in lbf}
\]

\[
\text{Mz}_i := \text{forces}_i, 3 \text{ in lbf}
\]

\[
\text{T}_i := \text{forces}_i, 8 \text{ in lbf}
\]

\[
\text{id}_i := \text{forces}_i, 1
\]

\[
\text{Fy}_i := \text{forces}_i, 6 \text{ lbf}
\]

\[
\text{Fz}_i := \text{forces}_i, 5 \text{ lbf}
\]

\[
\text{Fx}_i := \text{forces}_i, 7 \text{ lbf}
\]

\[
\text{id}_n\text{rows(forces)} := \text{forces}_i, 1
\]

Load data from second end of beam

\[
\text{My}_n\text{rows(forces)} := -\text{forces}_i, 10 \text{ in lbf}
\]

\[
\text{Mz}_n\text{rows(forces)} := \text{forces}_i, 9 \text{ in lbf}
\]

\[
\text{T}_n\text{rows(forces)} := \text{forces}_i, 8 \text{ in lbf}
\]

\[
\text{Fy}_n\text{rows(forces)} := \text{forces}_i, 12 \text{ lbf}
\]

\[
\text{Fz}_n\text{rows(forces)} := \text{forces}_i, 11 \text{ lbf}
\]

\[
\text{Fx}_n\text{rows(forces)} := \text{forces}_i, 7 \text{ lbf}
\]

\[
i := 1\ldots \text{rows(forces)}
\]

Detailed Stress Analysis

Bridge Pin (circular diameter) is Loaded in Double Shear. No Moment.

\[
i := \sqrt{\frac{\text{Fz}_i}{\text{Area}}}
\]

\[
\max(\ ) = 822.84 \text{ psi}
\]

\[
\sigma_{1,1} := \left(\frac{1}{i}\right)^2
\]

\[
\max(\sigma) = 822.84 \text{ psi}
\]

\[
\sigma_{1,2} := \left(\frac{1}{i}\right)^2
\]

\[
\max(\sigma) = 822.84 \text{ psi}
\]

\[
\sigma_{n} := \sqrt{\left(\sigma_{1,1}\right)^2 + \left(\sigma_{1,2}\right)^2 - \sigma_{1,1}\cdot\sigma_{1,2}}
\]

\[
\max(\sigma) = 1425.20 \text{ psi}
\]

\[
\max(\text{Transverse Shear}) = 822.84 \text{ psi}
\]

\[
\max(\text{Principal Stresses}) = 822.84 \text{ psi}
\]

\[
\max(\text{Maximum Principal}) = 822.84 \text{ psi}
\]

\[
\max(\text{Maximum Von-Mises}) = 1425.20 \text{ psi}
\]

\[
\max(\text{Maximum Shear}) = 822.84 \text{ psi}
\]
Margins of Safety for On-Orbit Inertial and Steady State Combined Loads

\[ M_{Stu} := \left( \frac{F_{tu}}{F_{S_{u} \max(\lvert -p \rvert)}} \right) - 1 \]  
\[ M_{Sty} := \left( \frac{F_{ty}}{F_{S_{y} \max(\lvert -vm \rvert)}} \right) - 1 \]  
\[ M_{Ssu} := \left( \frac{F_{su}}{F_{S_{u} \max(\max)}} \right) - 1 \]

\[ M_{Stu} = 80.67 \text{  Tensile Ultimate} \]
\[ M_{Sty} = 50.19 \text{  Tensile Yield} \]
\[ M_{Ssu} = 48.00 \text{  Shear Ultimate} \]
On-Orbit Steady State Loads

From the Bridge Beam (Section 4.6)

Read formatted Naspost output. Naspost file called PASBridgeBeam-SortOn-OrbitSS.nas.lis

\[
\text{forces2} := \text{READPRN("beams-OnorbitSS.txt")}
\]

\[i := 1..\text{rows(forces)}\]

Data is modified in the below embedded excel file. Result is for the Max stress - Steady State Stress

\[
\text{forces3} := \text{Sort Excel}
\]

( \text{forces forces2} )

Load data from first end of beam

\[M_{yi} := -\text{forces}_{i,4} \text{ in-lbf} \quad M_{zi} := \text{forces}_{i,3} \text{ in-lbf} \quad T_{i} := \text{forces}_{i,8} \text{ in-lbf} \quad \text{cases}_{i} := \text{forces}_{i,2}\]

\[F_{yi} := \text{forces}_{i,6} \text{ lbf} \quad F_{zi} := \text{forces}_{i,5} \text{ lbf} \quad F_{xi} := \text{forces}_{i,7} \text{ lbf} \quad \text{cases}_{i\cdot\text{rows(forces3)}} := \text{forces}_{i,2}\]

Load data from second end of beam

\[M_{yi\cdot\text{rows(forces3)}} := -\text{forces}_{i,10} \text{ in-lbf} \quad M_{zi\cdot\text{rows(forces3)}} := \text{forces}_{i,9} \text{ in-lbf} \quad T_{i\cdot\text{rows(forces3)}} := \text{forces}_{i,8} \text{ in-lbf}\]

\[F_{yi\cdot\text{rows(forces3)}} := \text{forces}_{i,12} \text{ lbf} \quad F_{zi\cdot\text{rows(forces3)}} := \text{forces}_{i,11} \text{ lbf} \quad F_{xi\cdot\text{rows(forces3)}} := \text{forces}_{i,7} \text{ lbf}\]

\[i := 1..\text{rows(forces3)}\]

Detailed Stress Analysis

Bridge Pin (circular diameter) is Loaded in Double Shear. No Moment.

\[
i := \sqrt{\left(\frac{F_{zi}}{\text{Area}}\right)^2} \quad \text{max( } ) = 288.72 \text{ psi} \quad \text{Transverse Shear}
\]

\[
\pm_{i,1} := \left[\left(\frac{1}{i}\right)^2\right]^\frac{1}{2} \quad \text{max}(\pm) = 288.72 \text{ psi} \quad \text{Principal Stresses}
\]

\[
\pm_{i,2} := -\left[\left(\frac{1}{i}\right)^2\right]^\frac{1}{2} \quad \text{max}(\pm) = 288.72 \text{ psi} \quad \text{Maximum Principal}
\]

\[
\text{vm}_{i} := \sqrt{\left(\pm_{i,1}\right)^2 + \left(\pm_{i,2}\right)^2 - \pm_{i,1} \pm_{i,2}} \quad \text{max}(\text{vm}) = 500.07 \text{ psi} \quad \text{Maximum Von-Mises}
\]

\[
\text{max}_{i} := \sqrt{\left(\pm\right)^2} \quad \text{max}(\text{max}) = 288.72 \text{ psi} \quad \text{Maximum Shear}
\]
Margins of Safety for On-Orbit Steady State Loads

\[
\begin{align*}
M_{Stu} & := \left( \frac{F_{tu} u}{F_{Su} \max(\|p\|)} \right) - 1 \\
M_{Sty} & := \left( \frac{F_{ty} u}{F_{Sy} \max(=vm)} \right) - 1 \\
M_{Su} & := \left( \frac{F_{su} u}{F_{Su} \max( \max)} \right) - 1
\end{align*}
\]

- Tensile Ultimate: \( M_{Stu} = 231.75 \)
- Tensile Yield: \( M_{Sty} = 144.90 \)
- Shear Ultimate: \( M_{Su} = 138.65 \)
4.9 Bridge Assembly
4.9 PAS Bridge Assembly, SEG39135836
Bridge Assembly

Cross section of platform with bridge beam assembly and release mechanism showing capture bar loading.

Cross section of bridge beam showing capture bar loading.

See PAS report sections 4.6, 4.7, 4.8, 4.10, 4.11, and 4.13 for analysis of individual components.
4.10 Bearing Housing
4.10 Bearing Housing, Bearing Assembly, SDG39135845-001

Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135845-001</td>
<td>Bearing Housing</td>
<td>15-5PH</td>
<td>Ressultant Preload</td>
<td>Section N-N</td>
<td>0.20</td>
<td>4.10-14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMS5659</td>
<td>Combined</td>
<td>Tensile</td>
<td></td>
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<td></td>
<td></td>
<td>H1025</td>
<td>On-Orbit/Mating</td>
<td>Ultimate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Structural Description

The Bearing Housings (BH) are used to support the PAS capture bar at both ends. The housing contains a spherical bearing that allows the capture bar to rotate at the ends making it simply supported. The BH is held in place with a hex-nut and two belville washers at the top of the bearing shaft. Without this the housing would be free to slide out from the bridge beam assembly. Refer to the figures shown below for both the location of the housing on the PAS along with an iso. view of the bearing housing itself.

![Figure 4.10-1 View Bearing Housing in the PAS Assembly](image-url)
Summary of Load Conditions

There are three load cases being examined.
1. Resultant preload combined with Flight loads.
2. Resultant preload combined with Landing loads.
3. Resultant preload combined with On-Orbit/mating envelope loads.

Factors of Safety

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS_y</td>
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</tr>
<tr>
<td>FS_u</td>
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</tbody>
</table>

Yield Factor of Safety
Ultimate Factor of Safety

Materials and Temperature

Material Allowables

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRES 15-5PH, H1025, 6.930 x 3.000 x 1.500, AMS5659</td>
<td>Tensile Ultimate Strength</td>
<td>155000 psi</td>
</tr>
<tr>
<td></td>
<td>Tensile Yield Strength</td>
<td>145000 psi</td>
</tr>
<tr>
<td></td>
<td>Shear Ultimate strength</td>
<td>97000 psi</td>
</tr>
</tbody>
</table>

Temperature Degradation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Temperature Correction Factor for 140 °F, $\alpha_{tu} = \alpha_{ty} = \alpha$

Figure 2.6.6.1.1 p. 2-162 MIL-HDBK-5H

Description of Finite Element Model and Model Checks

The same finite element model was used for the Bridge Beam, PAS Base, Guide Pins, Aft and Vertex Brackets. For a detailed description of the model see Section 4.1.4. For a detailed description of the model checks, see Section 4.1.5.
Detailed Stress Analysis

Section Properties

Figure 4.10-2 Configuration of Bearing Housing Inside of the Capture Bar Assembly.

Figure 4.10-3 ISO View of Bearing Housing Assembly
Section Properties for Bearing Housing at Section S-S

To be conservative, a shaft diameter of 0.675" will be used for Section S-S

\[ d := 0.675 \text{ in} \]
\[ c := \frac{1}{2} d \]
\[ c = 0.338 \text{ in} \]
\[ A_{\text{bear}} := \frac{u \cdot d^2}{4} \]
\[ A_{\text{bear}} = 0.358 \text{ in}^2 \]
\[ I_{\text{bh}} := \frac{u \cdot d^4}{64} \]
\[ I_{\text{bh}} = 0.010 \text{ in}^4 \]
\[ J_{\text{bh}} := 2 \cdot I_{\text{bh}} \]
\[ J_{\text{bh}} = 0.020 \text{ in}^4 \]

Thread/Joint Section Properties on the Bearing Housing Shaft

\[ FF := 1.15 \]
\[ N := 20 \frac{1}{\text{in}} \]
\[ D := 0.5 \text{ in} \]
\[ A_t := u \left( \frac{D - 0.9743}{2} \right)^2 \]
\[ A_t = 0.160 \text{ in}^2 \]
\[ \text{ctu} := 0.98 \]
\[ \text{cty} := 0.98 \]
\[ \text{ftu} := \text{Ftu} \cdot A_t \cdot \text{ctu} \]
\[ \text{fty} := \text{Fty} \cdot A_t \cdot \text{cty} \]
\[ F_{\text{max}} := 0.75 \text{ Fty} \]
\[ F_{\text{min}} := 0.85 \cdot F_{\text{max}} \]
\[ n := 1.0 \]
\[ n := 0.111 \]

Section Properties for Bearing Housing at Section N-N

\[ D_s := 0.426 \text{ in} \]
\[ A_{\text{shoulder}} := \frac{u \cdot D_s^2}{4} \]
\[ A_{\text{shoulder}} = 0.143 \text{ in}^2 \]

Thread and Joint Section Properties on the Bearing Housing Shaft:

- **FF**: 1.15
- **N**: 20 in
- **D**: 0.5 in
- **A_t**: 0.160 in^2
- **ctu**: 0.98
- **cty**: 0.98
- **ftu**: Ftu \cdot A_t \cdot ctu
- **fty**: Fty \cdot A_t \cdot cty
- **F_{max}**: 0.75 \cdot Fty
- **F_{min}**: 0.85 \cdot F_{max}
- **n**: 1.0
- **n**: 0.111

**Diameter of Bearing Housing Shaft**

\[ D_s := 0.426 \text{ in} \]

**Area of Bearing Housing Shaft**

\[ A_{\text{shoulder}} := \frac{u \cdot D_s^2}{4} \]

\[ A_{\text{shoulder}} = 0.143 \text{ in}^2 \]
Resultant Preload Combined With Flight Loads

Check Bearing Housing at Section S-S

Loads

forces := READPRN("Beams-Flight.txt")

\[ i := 1 \text{.. rows(} \text{forces} \text{)} \quad \text{cases}_i := \text{forces}_{i,2} \quad \text{cases}_i\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,2} \]

Load data from first end of beam

\[ M_{1i} := \text{forces}_{i,3} \text{ in lbf} \quad M_{2i} := \text{forces}_{i,4} \text{ in lbf} \]
\[ S_{1i} := \text{forces}_{i,5} \text{ lbf} \quad S_{2i} := \text{forces}_{i,6} \text{ lbf} \]
\[ T_{xi} := \text{forces}_{i,8} \text{ in lbf} \quad F_{xi} := \text{forces}_{i,7} \text{ lbf} \]

Load data from second end of beam

\[ M_{1_{1i}}\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,9} \text{ in lbf} \quad M_{2_{1i}}\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,10} \text{ in lbf} \]
\[ S_{1_{1i}}\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,11} \text{ lbf} \quad S_{2_{1i}}\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,12} \text{ lbf} \]
\[ T_{x_{1i}}\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,8} \text{ in lbf} \quad F_{x_{1i}}\text{-rows(} \text{forces} \text{)} := \text{forces}_{i,7} \text{ lbf} \]

Stresses

\[ i := 1 \text{.. rows(} \text{forces} \text{)} \quad j := i \]

\[ \gamma_j := \sqrt{\left( \frac{M_{1j}}{J_{bh}} \right)^2 + \left( \frac{M_{2j}}{J_{bh}} \right)^2 + \frac{F_{xj}}{A_{\text{bear}}} \sqrt{ \frac{T_{xi}}{J_{bh}} } } \]

\[ \nu_{yj} := \frac{4}{3} \sqrt{ \left( S_{1j} \right)^2 + \left( S_{2j} \right)^2 } \]

\[ \nu_{y_{\text{max}}} := \sqrt{ \frac{\gamma_j^2}{2} + \nu_{yj}^2 } \quad \nu_{\gamma_{\text{max}}} := \sqrt{ \frac{2}{2} } \]

\[ \nu_{\gamma_{\text{max}}} := \frac{\gamma_j}{2} + \nu_{y_{\text{max}}} \quad \max(\nu_{y_{\text{max}}}) = 12.30 \text{ ksi} \]
\[ \min(\nu_{y_{\text{max}}}) = 0.11 \text{ ksi} \]

Maximum Shear Stress

Minimum Principle Stress

Maximum Principle Stress
Margin of Safety of Bearing Housing at Section S-S

\[ MS_{tu} = \frac{F_{tu}}{F_{max}} - 1 \quad \min(\text{MS}_{tu}) = 5.11 \quad \text{Tensile Ultimate} \]

\[ MS_{ty} = \frac{F_{ty}}{F_{max}} - 1 \quad \min(\text{MS}_{ty}) = 8.14 \quad \text{Tensile Yield} \]

\[ MS_{su} = \frac{F_{su}}{F_{max}} - 1 \quad \min(\text{MS}_{su}) = 5.86 \quad \text{Shear Ultimate} \]

output1 := augment(stack(forces, forces), \text{MS}_{tu})
output2 := augment(output1, \text{MS}_{ty})
output3 := augment(output2, \text{MS}_{su})
L := 1 .. cols(output3)

\[ \text{worstMS}_{\text{Su}}_{\text{1}, \text{L}} := \left[ (\text{csort(output3, 1 + 12)}^T)^{\text{1}}\right]_{\text{L}} \quad \text{Sort using lowest MSu} \]

\[ \text{worstMS}_{\text{Sy}}_{\text{1}, \text{L}} := \left[ (\text{csort(output3, 1 + 13)}^T)^{\text{1}}\right]_{\text{L}} \quad \text{Sort using lowest MSy} \]

\[ \text{worstMS}_{\text{S}}_{\text{1}, \text{L}} := \left[ (\text{csort(output3, 1 + 14)}^T)^{\text{1}}\right]_{\text{L}} \quad \text{Sort using lowest MSs} \]
**Check Threads on the Bearing Housing Shaft**

**Loads**

\[ W_{jsj} := \frac{F_{\text{min}}}{1 - n}, \quad \text{min}(W_{jsj}) = 16299.121 \text{ lbf} \]

**Stresses**

Check for joint separation (if ratio is > 1.0, separation occurs)

\[ \text{check\_ratio}_j := \frac{F_{axj}}{F_{\text{min}}} \quad \text{max}(\text{check\_ratio}) = 0.001 \]

\[ F_{\text{normal}_j} := F_{\text{max}} + n \cdot (FS_u \cdot F_{axj}) \]

\[ \text{max}(\frac{F_{\text{normal}_j}}{F_{tu}}) = 0.074 \]

\[ \text{max}(\frac{F_{\text{max}} + n \cdot (FS_u \cdot F_{axj})}{At}) = 106610.14 \text{ psi} \]

\[ \text{min}(\text{max}) = 106551.059 \text{ psi} \]

\[ \text{Max normal stress on threaded region} \]

\[ \text{Min normal stress on threaded region} \]

\[ =q_{nj} := \frac{F_{axj}}{At} \]

\[ \text{max}(\frac{F_{axj}}{At}) = 137.541 \text{ psi} \]

\[ \text{min}(\text{max}) = -93.778 \text{ psi} \]

**Margin of Safety for Threads on the Bearing Housing Shaft**

\[ M_{su_j} := \frac{F_{tu}}{\beta} - 1 \]

\[ \text{min}(M_{su}) = 0.41 \]

\[ \max(\frac{F_{tu}}{\beta}) = 0.688 \]

**Check Bearing Housing at Section N-N**

**Stresses**

\[ =sh_j := \frac{F_{\text{normal}_j}}{A_{\text{shoulder}}} \]

\[ \text{max}(\frac{F_{\text{normal}_j}}{A_{\text{shoulder}}}) = 119641.268 \text{ psi} \]

\[ \text{min}(\text{max}) = 119574.994 \text{ psi} \]

**Margin of Safety of Bearing Housing at Section N-N**

\[ M_{su_j} := \frac{F_{tu}}{\beta} - 1 \]

\[ \text{min}(M_{su}) = 0.26 \]
Resultant Preload Combined With Landing Loads

*Check Bearing Housing at Section S-S*

**Loads**

\[
\text{forces} := \text{READPRN("Beams-Landing.txt")}
\]

\[
i := 1 \ldots \text{rows(forces)} \quad \text{cases}_i := \text{forces}^i_1 \quad \text{cases}_{i+1:\text{rows(forces)}} := \text{forces}^i_2
\]

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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Load data from first end of beam

\[
\begin{align*}
M_1 & := \text{forces}_1^3 \text{ in lbf} \\
S_1 & := \text{forces}_1^5 \text{ lbf} \\
T_x & := \text{forces}_1^8 \text{ in lbf}
\end{align*}
\]

Load data from second end of beam

\[
\begin{align*}
M_{1+1:\text{rows(forces)}} & := \text{forces}_{1+1}^9 \text{ in lbf} \\
M_{2+1:\text{rows(forces)}} & := \text{forces}_{1+2}^{10} \text{ in lbf} \\
S_{1+1:\text{rows(forces)}} & := \text{forces}_{1+1}^{11} \text{ lbf} \\
S_{2+1:\text{rows(forces)}} & := \text{forces}_{1+2}^{12} \text{ lbf} \\
T_{x+1:\text{rows(forces)}} & := \text{forces}_{1+1}^8 \text{ in lbf} \\
F_{x+1:\text{rows(forces)}} & := \text{forces}_{1+1}^{7} \text{ lbf}
\end{align*}
\]

**Stresses**

\[
i := 1 \ldots \text{rows(forces)} \quad j := i
\]

\[
\begin{align*}
\epsilon_j &= \sqrt{\left(\frac{M_1^c}{lbh}\right)^2 + \left(\frac{M_2^c}{lbh}\right)^2} + \frac{F_{x_j}}{A_{\text{bear}}} \\
y_j &= \sqrt{\left(\frac{S_1}{A_{\text{bear}}}\right)^2 + \left(\frac{S_2}{A_{\text{bear}}}\right)^2} + \frac{T_{x_j}}{J_{bh}} \\
\gamma_{\text{max},j} &= \sqrt{\left(\frac{\epsilon_j}{2}\right)^2 + \left(y_j\right)^2} \\
\gamma_{\min,j} &= \frac{\epsilon_j}{2} + \gamma_{\text{max},j} \\
\max(\gamma_{\max}) &= 15.35 \text{ ksi} \\
\min(\gamma_{\min}) &= 0.01 \text{ ksi}
\end{align*}
\]

*Maximum Shear Stress*

*Maximum Principle Stress*

*Minimum Principle Stress*
### Margin of Safety of Bearing Housing at Section S-S

\[
MS_{tu} := \frac{F_{tu}}{\max_j F_{Su}} - 1 \quad \min(\text{MS}_{tu}) = 3.90 \quad \text{Tensile Ultimate} \\
MS_{ty} := \frac{F_{ty}}{\max_j F_{Sy}} - 1 \quad \min(\text{MS}_{ty}) = 6.33 \quad \text{Tensile Yield} \\
MS_{su} := \frac{F_{su}}{\gamma_{\max} F_{Su}} - 1 \quad \min(\text{MS}_{su}) = 4.94 \quad \text{Shear Ultimate}
\]

\[
\text{output1 := augment(\text{stack(forces, forces)}, \text{MS}_{tu})} \\
\text{output2 := augment(output1, \text{MS}_{ty})} \\
\text{output3 := augment(output2, \text{MS}_{su})} \\
L := 1 \ldots \text{cols(output3)}
\]

\[
\text{worstMSu}_{1,L} := \left[\text{csort(output3, 1 + 12)^T(1)}\right]_L \quad \text{Sort using lowest MSu} \\
\text{worstMSy}_{1,L} := \left[\text{csort(output3, 1 + 13)^T(1)}\right]_L \quad \text{Sort using lowest MSy} \\
\text{worstMSs}_{1,L} := \left[\text{csort(output3, 1 + 14)^T(1)}\right]_L \quad \text{Sort using lowest MSs}
\]

<table>
<thead>
<tr>
<th>MSu</th>
<th>MSy</th>
<th>MSs</th>
</tr>
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<tr>
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<tr>
<td>S1</td>
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<tr>
<td>S2</td>
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<td>-66.000</td>
</tr>
<tr>
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<td>49.000</td>
</tr>
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<td>Tz</td>
<td>-198.000</td>
<td>-198.000</td>
</tr>
<tr>
<td>M1</td>
<td>426.000</td>
<td>426.000</td>
</tr>
<tr>
<td>M2</td>
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<td>128.000</td>
</tr>
<tr>
<td>S1</td>
<td>-132.000</td>
<td>-132.000</td>
</tr>
<tr>
<td>S2</td>
<td>-66.000</td>
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</tr>
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<tr>
<td>MSy</td>
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</tr>
<tr>
<td>MSs</td>
<td>4.940</td>
<td>4.940</td>
</tr>
</tbody>
</table>
**Check Threads on the Bearing Housing Shaft**

**Loads**

\[ W_{js} := \frac{F_{\text{min}}}{1-n} \quad \text{min}(W_{js}) = 16299.121 \text{ lbf} \quad \text{Joint Separation Load} \]

**Stresses**

Check for joint separation (if ratio is > 1.0, separation occurs)

\[ \text{check\_ratio}_j := \frac{F_{ax}}{F_{\text{min}} \times (1-n)} \quad \text{max(\text{check\_ratio})} = 0.003 \quad \text{Joint Separation} \]

\[ F_{\text{normal}} := F_{\text{max}} + \cdot n \cdot (F_{\text{Su}} \cdot F_{ax}) \quad \text{Combined Axial Load} \]

\[ \text{max} \left( \frac{=} {F_{tu}} \right) = 0.096 \]

\[ \text{max} \left( \frac{=} {F_{tu}} \right) = 106653.209 \text{ psi} \quad \text{Max normal stress on threaded region} \]

\[ \text{min} (\text{=}) = 106539.886 \text{ psi} \quad \text{Min normal stress on threaded region} \]

\[ \text{=} \text{qq}_j := \frac{F_{ax}}{A_t} \]

\[ \text{max(=qq)} = 306.340 \text{ psi} \quad \text{Max normal stress on threaded region} \]

\[ \text{min(=qq)} = -137.541 \text{ psi} \quad \text{Min normal stress on threaded region} \]

**Margin of Safety for Threads on the Bearing Housing Shaft**

\[ M_{stuj} := \frac{F_{tu}}{\beta} - 1 \quad \text{min} (M_{stuj}) = 0.41 \quad \text{Ultimate} \]

\[ \text{max} \left( \frac{=} {F_{tu}} \right) = 0.688 \]

**Check Bearing Housing at Section N-N**

**Stresses**

\[ \text{=} \text{sh}_j := \frac{F_{\text{normal}}}{A_{\text{shoulder}}} \quad \text{max(=sh)} = 119689.630 \text{ psi} \]

\[ \text{min(=sh)} = 119562.456 \text{ psi} \]

**Margin of Safety of Bearing Housing at Section N-N**

\[ M_{stuj} := \frac{F_{tu}}{\beta} - 1 \quad \text{min} (M_{stuj}) = 0.26 \quad \text{Ultimate} \]
Resultant Preload Combined With On-Orbit/Mating Envelope Loads

Check Bearing Housing at Section S-S

Loads

\[
\text{forces} := \text{READPRN("Beams-Onorbit.txt")}
\]

\[
i := 1 \ldots \text{rows(forces)}
\]

\[
cases_i := \text{forces}_{i, 2}
\]

\[
cases_{i+\text{rows(forces)}} := \text{forces}_{i, 2}
\]

Load data from first end of beam

\[
M_1 := \text{forces}_{i, 3} \text{ in lbf}
\]

\[
M_2 := \text{forces}_{i, 4} \text{ in lbf}
\]

\[
S_1 := \text{forces}_{i, 5} \text{ lbf}
\]

\[
S_2 := \text{forces}_{i, 6} \text{ lbf}
\]

\[
T_x := \text{forces}_{i, 8} \text{ in lbf}
\]

\[
F_{ax} := \text{forces}_{i, 7} \text{ lbf}
\]

Load data from second end of beam

\[
M_{1+\text{rows(forces)}} := \text{forces}_{i, 9} \text{ in lbf}
\]

\[
M_{2+\text{rows(forces)}} := \text{forces}_{i, 10} \text{ in lbf}
\]

\[
S_{1+\text{rows(forces)}} := \text{forces}_{i, 11} \text{ lbf}
\]

\[
S_{2+\text{rows(forces)}} := \text{forces}_{i, 12} \text{ lbf}
\]

\[
T_{x+\text{rows(forces)}} := \text{forces}_{i, 8} \text{ in lbf}
\]

\[
F_{ax+\text{rows(forces)}} := \text{forces}_{i, 7} \text{ lbf}
\]

Stresses

\[
i := 1 \ldots \text{rows(forces)}
\]

\[
j := i
\]

\[
\varepsilon_j := \sqrt{\left(\frac{M_1 c}{lbh}\right)^2 + \left(\frac{M_2 c}{lbh}\right)^2 + \frac{F_{ax}}{A_{bear}}}
\]

\[
\gamma_j := \frac{4}{3} \sqrt{\left(S_1\right)^2 + \left(S_2\right)^2 + \frac{T_x}{J_{bh}} \cdot \frac{1}{2} d}
\]

\[
\gamma_{\max} := \sqrt{\left(\frac{\varepsilon_j}{2}\right)^2 + \left(\gamma_j\right)^2}
\]

\[
\gamma_{\max} := \frac{\varepsilon_j}{2} + \gamma_{\max}
\]

\[
\max(\gamma_{\max}) = 30.86 \text{ ksi}
\]

\[
\min(\gamma_{\max}) = 8.81 \text{ ksi}
\]

Maximum Shear Stress

Maximum Principle Stress

Minimum Principle Stress
Margin of Safety of Bearing Housing at Section S-S

\[
MS_{tu} := \frac{Ftu \cdot \beta}{\text{max}_j FSu} - 1 \quad \min(\text{MS}_{tu}) = 1.44 \quad \text{Tensile Ultimate}
\]

\[
MS_{ty} := \frac{Fty \cdot \beta}{\text{max}_j FSy} - 1 \quad \min(\text{MS}_{ty}) = 2.65 \quad \text{Tensile Yield}
\]

\[
MS_{su} := \frac{FSu \cdot \beta}{\text{max}_j FSu} - 1 \quad \min(\text{MS}_{su}) = 1.99 \quad \text{Shear Ultimate}
\]

output1 := augment(stack(forces, forces), MS_{tu})
output2 := augment(output1, MS_{ty})
output3 := augment(output2, MS_{su})
L := 1..cols(output3)

\[
\text{worstMS}_{su, L} := \left[\text{csort(output3, 1 + 12)^T}\right]_L \quad \text{Sort using lowest MSu}
\]

\[
\text{worstMS}_{sy, L} := \left[\text{csort(output3, 1 + 13)^T}\right]_L \quad \text{Sort using lowest MSy}
\]

\[
\text{worstMS}_{ss, L} := \left[\text{csort(output3, 1 + 14)^T}\right]_L \quad \text{Sort using lowest MSs}
\]

<table>
<thead>
<tr>
<th>MSu</th>
<th>MSy</th>
<th>MSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>worstMS_{su, L}</td>
<td>worstMS_{sy, L}</td>
<td>worstMS_{ss, L}</td>
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<td>case</td>
<td>ID</td>
</tr>
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<td>22.802 \cdot 10^6</td>
<td>22.802 \cdot 10^6</td>
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<td>1.986</td>
<td>1.986</td>
<td>1.986</td>
</tr>
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</table>
Check Threads on the Bearing Housing Shaft

Loads

\[
W_{js_j} := \frac{F_{\text{min}}}{1 - n}. \quad \text{min}(W_{js}) = 16299.121 \text{ lbf} \quad \text{Joint Separation Load}
\]

Stresses

Check for joint separation (if ratio is > 1.0, separation occurs)

\[
\text{check\_ratio}_j := \frac{F_{ax_j}}{F_{\text{min}}} \quad \max(\text{check\_ratio}) = 0.200 \quad \text{Joint Separation}
\]

\[
F_{\text{Normal}_j} := F_{\text{max}} + n \cdot (F_{\text{Su}} \cdot F_{ax_j}) \quad \text{Combined Axial Load}
\]

\[
\max\left(\frac{F_{\text{max}}}{F_{tu}}\right) = 0.195
\]

\[
\sigma_j := \frac{F_{\text{max}} + n \cdot (F_{\text{Su}} \cdot F_{ax_j})}{A_t} \quad \max(\sigma) = 111786.255 \text{ psi} \quad \text{Max normal stress on threaded region}
\]

\[
\min(\sigma) = 111607.492 \text{ psi} \quad \text{Min normal stress on threaded region}
\]

\[
=qq_j := \frac{F_{ax_j}}{A_t} \quad \max(=qq) = 20412.280 \text{ psi} \quad \text{Max normal stress on threaded region}
\]

\[
\min(=qq) = 19712.073 \text{ psi} \quad \text{Min normal stress on threaded region}
\]

Margin of Safety for Threads on the Bearing Housing Shaft

\[
MS_{tu_j} := \frac{F_{tu} \beta}{\sigma_j} - 1 \quad \min(MS_{tu}) = 0.34 \quad \text{Ultimate}
\]

\[
\max\left(\frac{F_{tu}}{\sigma_j}\right) = 0.721
\]

Check Bearing Housing at Section N-N

Stresses

\[
=sh_j := \frac{F_{\text{normal}_j}}{A_{\text{shoulder}}} \quad \max(=sh) = 125450.098 \text{ psi}
\]

\[
\min(=sh) = 125249.485 \text{ psi}
\]

Margin of Safety of Bearing Housing at Section N-N

\[
MS_{tu_j} := \frac{F_{tu} \beta}{=sh_j} - 1 \quad \min(MS_{tu}) = 0.20 \quad \text{Ultimate}
\]
4.11 Capture Bar Assembly
4.11 Capture Bar Handle Assembly

Capture Bar
4.11.1 Capture Bar
4.11.1 Capture Bar, SDG39135850-001

Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Part/Dwg Number</th>
<th>Part Name/Description</th>
<th>Material Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
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<tbody>
<tr>
<td>SDG39135850-001</td>
<td>Capture Bar</td>
<td>CRES A-286 AMS 5737</td>
<td>On-Orbit</td>
<td>Tensile</td>
<td>0.01</td>
<td>4.11.1-7</td>
</tr>
</tbody>
</table>

Structural Description

Figure 4.11.1-1 shows and exploded ISO view of the Capture Bar Assembly which includes the Capture Bar, Handle Base, Handle, and Handle Extension Assembly along with their associated fasteners.

![Capture Bar Assembly Diagram]

Figure 4.11.1-1  Capture Bar Assembly, AMS Passive PAS Assy, SEG39135849

Summary of Load Conditions

There are three load cases being examined.
1. Resultant preload combined with Flight loads.  "Beams-Flight.txt"
2. Resultant preload combined with Landing loads.  "Beams-Landing.txt"
3. Resultant preload combined with On-Orbit/mating envelope loads.  "Beams-On-Orbit.txt"

Capture bar can be treated as a simply supported beam with two applied point loads from the capture claw (Figure 4.11.1-2). Forces are taken from the NASTRAN results and then applied using beam equations
Factors of Safety

$FS_u := 2.0$
$FS_y := 1.25$

Materials and Temperature

Material Allowables

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>$F_{tu}$</th>
<th>$F_{ty}$</th>
<th>$F_{su}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRES A-286, AMS 5737, Bar, 1.50 Dia x 16.25 LG, S</td>
<td></td>
<td>140000 psi</td>
<td>95000 psi</td>
<td>91000 psi</td>
</tr>
</tbody>
</table>

Temperature Degradation

$\beta := 0.96$
$\beta_u = \beta_y = \beta$

Finite Element Model - Description, Model Checks

The same finite element model was used for the Capture Bar, Bridge Beam, PAS Base, Guide Pins, Aft and Vertex Brackets.
For a detailed description of the model see Section 4.1.4.
For a detailed description of the model checks, see Section 4.1.5.
Detailed Stress Analysis

Section Properties

Section A-A (Figure 4.11.1-2) cross section is a circle with a groove as shown in Figure 4.11.1-3.

![Cross Sectional Views of the Capture Bar](image)

\[
d := 1.5 \text{ in}
\]

\[
groove\_width := 0.1 \text{ in}
\]

\[
groove\_depth := 0.25 \text{ in}
\]

\[
Area := \left(\frac{\pi}{4}\right) \left(d^2\right) - \text{groove\_width \times grove\_depth}
\]

\[
Area = 1.74 \text{ in}^2
\]

\[
y_c := \frac{d}{2}
\]

\[
y_c = 0.75 \text{ in}
\]

\[
z_c := \frac{d}{2}
\]

\[
z_c = 0.75 \text{ in}
\]

\[
c_y := y_c
\]

\[
c_y = 0.75 \text{ in}
\]

\[
c_z := z_c
\]

\[
c_z = 0.75 \text{ in}
\]

\[
J := \frac{1}{32} \pi \left(d^4\right)
\]

\[
Torsional Constant
\]

\[
r := \frac{d}{2}
\]

\[
Radius of Gyration
\]
Moments of Inertia About Centroid

\[ I_y := \left( \frac{e}{64} \right) d^4 - \left( \frac{1}{12} \right) \text{groove_width} \times \text{groove_depth}^3 + \text{groove_width} \times \text{groove_depth} \left( z_c - \frac{\text{groove_depth}}{2} \right)^2 \]

\[ I_y = 0.23861 \text{ in}^4 \]

\[ I_z := \left( \frac{e}{64} \right) d^4 - \left( \frac{1}{12} \right) \text{groove_width} \times \text{groove_depth}^3 \]

\[ I_z = 0.24837 \text{ in}^4 \]

\[ I_{yz} := 0 \text{ in}^4 \quad (I_y \text{ and } I_z \text{ are About the Principle Axes}) \]

Now, rotate the cross section about q

\[ I_{yrot}(\beta) := I_y \cos^2(\beta) + I_z \sin^2(\beta) - I_{yz} \sin(2\beta) \quad I_{yrot}(50 \text{ deg}) = 0.24434 \text{ in}^4 \]

\[ I_{zrot}(\beta) := I_z \cos^2(\beta) + I_y \sin^2(\beta) + I_{yz} \sin(2\beta) \quad I_{zrot}(50 \text{ deg}) = 0.24264 \text{ in}^4 \]

\[ I_{yzrot}(\beta) := \frac{I_y - I_z}{2} \sin(2\beta) + I_{yz} \cos(2\beta) \]

\[ z(\beta) := \frac{d}{2} \cos(\beta) \quad y(\beta) := \frac{d}{2} \sin(\beta) \]

\[ I_y := I_{yrot}(50 \text{ deg}) \]

\[ I_z := I_{zrot}(50 \text{ deg}) \]
Check Capture Bar at Section A-A, On-Orbit Loads

Loads

Forces and moments for the beam elements used for the capture bar are in the file beams-on-orbit.txt

\[
\text{forces := READPRN("beams-on-orbit.txt") i := 1.. rows(forces)}
\]

\[
V_1 := \text{forces}_{i,5} \text{ lbf} \quad \max(V_1) = 510.00 \text{ lbf} \quad F_a := \text{forces}_{i,7} \text{ lbf} \quad \max(F_a) = 452.00 \text{ lbf}
\]

\[
V_2 := \text{forces}_{i,6} \text{ lbf} \quad \max(V_2) = 3266 \text{ lbf} \quad T_i := \text{forces}_{i,8} \text{ in lbf} \quad \max(T) = 469 \text{ in lbf}
\]

\[
M_{1a} := \text{forces}_{i,3} \text{ in lbf} \quad M_{2a} := \text{forces}_{i,4} \text{ in lbf}
\]

\[
M_{1b} := \text{forces}_{i,10} \text{ in lbf} \quad M_{2b} := \text{forces}_{i,11} \text{ in lbf}
\]

\[
M_1 := \begin{cases} 
M_{1a} & \text{if } |M_{1a}| \geq |M_{1b}| \\
M_{1b} & \text{otherwise}
\end{cases} \quad 
M_2 := \begin{cases} 
M_{2a} & \text{if } |M_{2a}| \geq |M_{2b}| \\
M_{2b} & \text{otherwise}
\end{cases}
\]

\[
\max(M_1) = 2268.00 \text{ in lbf} \quad \max(M_2) = 267.00 \text{ in lbf}
\]

\[
\min(M_1) = -2267.00 \text{ in lbf} \quad \min(M_2) = -19388.00 \text{ in lbf}
\]

Stresses

\[
\sigma_i := \frac{F_a}{\text{Area}} + \frac{|M_{1i}| \cdot c_z}{I_y} + \frac{|M_{2i}| \cdot c_y}{I_z} \quad \max(\{\sigma\}) = 66453 \text{ psi} \quad \text{Axial plus Bending}
\]

\[
\sigma_v := \sqrt{\left(\frac{V_1}{\text{Area}}\right)^2 + \left(\frac{V_2}{\text{Area}}\right)^2} \quad \max(\{\sigma_v\}) = 1890 \text{ psi} \quad \text{Shear due to Transverse}
\]

\[
\sigma_i := \frac{T_i}{J} \quad \max(\{\sigma\}) = 786 \text{ psi} \quad \text{Shear due to Torsion}
\]

\[
\sigma_i := \sigma_v + \sigma_t \quad \max(\{\sigma\}) = 2644 \text{ psi} \quad \text{Combined Shear}
\]

\[
\sigma_{p,1} := \frac{\sigma_i}{2} + \left(\frac{\sigma_v}{2}\right)^2 + \left(\sigma_t\right)^2 \quad \sigma_{p,2} := \frac{\sigma_i}{2} + \left(\frac{\sigma_v}{2}\right)^2 + \left(\sigma_t\right)^2 \quad \sigma_{p,1} \text{ or } \sigma_{p,2} \quad \max(\{\sigma_{p}\}) = 66520.42 \text{ psi} \quad \text{Principal Stresses}
\]

\[
f_{tu} := \max(\{\sigma_p\}) = 66520.42 \text{ psi} \quad \text{Maximum Absolute Principal}
\]

\[
\max(\{\sigma_{p,1}\}) = 66520 \text{ psi} \quad \text{Maximum Principal}
\]

\[
\sigma_{vm} := \sqrt{\left(\sigma_{p,1}\right)^2 + \left(\sigma_{p,2}\right)^2 - 2\sigma_{p,1}\sigma_{p,2}} \quad f_{ty} := \max(\{\sigma_{vm}\}) = 66554.17 \text{ psi} \quad \text{Von-Mises}
\]
Margins of Safety - Capture Bar at Section A-A, On-Orbit Loads

\[ \text{MS}_{tu} := \left( \frac{F_{tu}}{F_{tu}^U} \right) - 1 = 0.01 \]  
\[ \text{MS}_{ty} := \left( \frac{F_{ty}}{F_{ty}^Y} \right) - 1 = 0.10 \]  
\[ \text{MS}_{su} := \left( \frac{F_{su}}{F_{su}^U} \right) - 1 = 0.31 \]

**Tensile Ultimate**

**Tensile Yield**

**Shear Ultimate**
Check Capture Bar at Section A-A, Flight Loads

Loads
Forces and moments for the beam elements used for the capture bar are in the file beams-flight.txt

\[ \text{forces} := \text{READPRN("beams-flight.txt") \ \ i := 1.. \ \ \text{rows(forces)} } \]

\[ V_1 := \text{forces}_i \text{, 5 lbf} \quad \max(V_1) = 111.00 \text{ lbf} \quad F_a := \text{forces}_i \text{, 7 lbf} \quad \max(F_a) = 120.00 \text{ lbf} \]

\[ V_2 := \text{forces}_i \text{, 6 lbf} \quad \max(V_2) = 7 \text{ lbf} \quad T_i := \text{forces}_i \text{, 8 in lbf} \quad \max(T) = 185 \text{ in lbf} \]

\[ M_{1a} := \text{forces}_i \text{, 3 in lbf} \]

\[ M_{1b} := \text{forces}_i \text{, 10 in lbf} \]

\[ M_1 := \begin{cases} M_{1a} & \text{if } |M_{1a}| \geq |M_{1b}| \\ M_{1b} & \text{otherwise} \end{cases} \quad \max(M_1) = 176.00 \text{ in lbf} \]

\[ \min(M_1) = -251.00 \text{ in lbf} \]

\[ M_{2a} := \text{forces}_i \text{, 4 in lbf} \]

\[ M_{2b} := \text{forces}_i \text{, 11 in lbf} \]

\[ M_2 := \begin{cases} M_{2a} & \text{if } |M_{2a}| \geq |M_{2b}| \\ M_{2b} & \text{otherwise} \end{cases} \quad \max(M_2) = 114.00 \text{ in lbf} \]

\[ \min(M_2) = -293.00 \text{ in lbf} \]

Stresses

\[ \sigma_i := \frac{F_a}{\text{Area}} + \frac{|M_{1a}| \cdot cz}{I_y} + \frac{|M_{2a}| \cdot cy}{I_z} \quad \max(\sigma_i) = 1688 \text{ psi} \quad \text{Axial plus Bending} \]

\[ \sigma_x := \frac{1}{\sqrt{\left(\frac{V_1}{\text{Area}}\right)^2 + \left(\frac{V_2}{\text{Area}}\right)^2}} \quad \max(\sigma_v) = 67 \text{ psi} \quad \text{Shear Due to Transverse} \]

\[ \tau_{ij} := \frac{T_i}{J} \quad \max(\tau) = 349 \text{ psi} \quad \text{Shear Due To Torsion} \]

\[ \sigma := \sigma_v + \sigma_t \quad \max(\sigma) = 398 \text{ psi} \quad \text{Combined Shear} \]

\[ \sigma_{p,1} := \frac{\sigma}{2} + \left(\frac{\sigma}{2}\right)^2 + \left(\frac{\sigma}{2}\right)^2 \quad \sigma_{p,2} := \frac{\sigma}{2} + \left(\frac{\sigma}{2}\right)^2 + \left(\frac{\sigma}{2}\right)^2 \quad \max(\sigma_{p,1}) = 1688.37 \text{ psi} \quad \max(\sigma_{p,2}) = 1688 \text{ psi} \quad \text{Principal Stresses} \]

\[ f_{tu} := \max\left(\frac{f_{tu}}{\sigma}\right) = 1688.37 \text{ psi} \quad \max(\sigma_{p,1}) = 1688 \text{ psi} \quad \text{Maximum Absolute Principal} \]

\[ \max(\sigma_{p,1}) = 1688 \text{ psi} \quad \text{Maximum Principal} \]

\[ \sigma_{vm} := \sqrt{\sigma_{p,1}^2 + \sigma_{p,2}^2} \quad \max(\sigma_{vm}) = 1688.40 \text{ psi} \quad \text{Von-Mises} \]
\[
\gamma_{\text{max}} := \sqrt{\frac{1}{4} (\gamma_1)^2 + (\gamma_2)^2}
\]

\[f_{SU} := \max(\gamma) = 844.22 \text{ psi} \quad \text{Maximum Shear} \]

**Margins of Safety - Capture Bar at Section A-A, Flight Loads**

\[
MS_{tu} := \left( \frac{F_{tu} \beta}{FS_{U} f_{tu}} \right) - 1 = 38.80 \quad \text{Tensile Ultimate}
\]

\[
MS_{ty} := \left( \frac{F_{ty} \beta}{FS_{Y} f_{ty}} \right) - 1 = 42.21 \quad \text{Tensile Yield}
\]

\[
MS_{su} := \left( \frac{F_{su} \beta}{FS_{U} f_{su}} \right) - 1 = 50.74 \quad \text{Shear Ultimate}
\]
Check Capture Bar at Section A-A, Landing Loads

Loads
Forces and moments for the beam elements used for the capture bar are in the file beams-landing.txt

\[
\text{forces} := \text{READPRN("beams-landing.txt")}
\]

\[
i := 1.. \text{rows(forces)}
\]

\[
V_{i1} := \text{forces}_{i,5} \text{ lbf}, \quad \max(V_{i1}) = 82.00 \text{ lbf} \quad F_{a_i} := \text{forces}_{i,7} \text{ lbf}, \quad \max(F_{a_i}) = 150.00 \text{ lbf}
\]

\[
V_{i2} := \text{forces}_{i,6} \text{ lbf}, \quad \max(V_{i2}) = 17.00 \text{ lbf} \quad T_i := \text{forces}_{i,8} \text{ in lbf}, \quad \max(T_i) = 131.00 \text{ in lbf}
\]

\[
M_{1a_i} := \text{forces}_{i,3} \text{ in lbf}, \quad M_{1b_i} := \text{forces}_{i,10} \text{ in lbf}
\]

\[
M_{1i} := \begin{cases} M_{1a_i} \text{ if } |M_{1a_i}| \geq |M_{1b_i}| \\ M_{1b_i} \text{ otherwise} \end{cases}
\]

\[
\max(M_{1i}) = 222.00 \text{ in lbf} \quad \min(M_{1i}) = -430.00 \text{ in lbf}
\]

\[
M_{2i} := \begin{cases} M_{2a_i} \text{ if } |M_{2a_i}| \geq |M_{2b_i}| \\ M_{2b_i} \text{ otherwise} \end{cases}
\]

\[
\max(M_{2i}) = 56.00 \text{ in lbf} \quad \min(M_{2i}) = -209.00 \text{ in lbf}
\]

Stresses

\[
\sigma_i := \frac{|F_{a_i}|}{\text{Area}} + \frac{|M_{1i}| \cdot \text{cz}}{I_y} + \frac{|M_{2i}| \cdot \text{cy}}{I_z}
\]

\[
\max(\sigma_i) = 2005 \text{ psi} \quad \text{Axial plus Bending}
\]

\[
\sigma_{yi} := \sqrt{\left(\frac{V_{i1}}{\text{Area}}\right)^2 + \left(\frac{V_{i2}}{\text{Area}}\right)^2}
\]

\[
\max(\sigma_{yi}) = 48 \text{ psi} \quad \text{Shear Due to Transverse}
\]

\[
\sigma_i := \frac{r}{J}
\]

\[
\max(\sigma_i) = 237 \text{ psi} \quad \text{Shear Due To Torsion}
\]

\[
\sigma := \sigma_{yi} + \sigma_i
\]

\[
\max(\sigma) = 246 \text{ psi} \quad \text{Combined Shear}
\]

\[
\sigma_{p,1} := \frac{\sigma_i}{2} + \left[\frac{\sigma_{yi}}{2}\right]^2
\]

\[
\sigma_{p,2} := \frac{\sigma_i}{2} + \left[\frac{\sigma_{yi}}{2}\right]^2
\]

\[
\max(\sigma_{p,1}) = \frac{1}{2} \text{ Principal Stresses}
\]

\[
f_{tu} := \max\left(\sigma_{p,1}\right) = 2005.24 \text{ psi} \quad \text{Maximum Absolute Principal}
\]

\[
\max(\sigma_{p,1}) = 2005 \text{ psi} \quad \text{Maximum Principal}
\]

\[
\sigma_{vm} := \sqrt{\left(\sigma_{p,1}\right)^2 + \left(\sigma_{p,2}\right)^2 - \sigma_{p,1} \cdot \sigma_{p,2}}
\]

\[
f_{ty} := \max(\sigma_{vm}) = 2005.28 \text{ psi} \quad \text{Von-Mises}
\]
AMS-02 Capture Bar, Capture Bar Assembly

\[ \gamma_{\text{max}} := \frac{1}{4} \left( \gamma_1 \right)^2 + \left( \gamma_2 \right)^2 \]

\[ f_{SU} := \max(\gamma_{\text{max}}) = 1002.67 \text{ psi} \quad \text{Maximum Shear} \]

**Margins of Safety - Capture Bar at Section A-A, Landing Loads**

\[ \text{MS}_{tu} := \left( \frac{F_{tu} \beta}{FSU \cdot f_{tu}} \right) - 1 = 32.51 \quad \text{Tensile Ultimate} \]

\[ \text{MS}_{ty} := \left( \frac{F_{ty} \beta}{FSY \cdot f_{ty}} \right) - 1 = 35.38 \quad \text{Tensile Yield} \]

\[ \text{MS}_{su} := \left( \frac{F_{su} \beta}{FSU \cdot f_{su}} \right) - 1 = 42.56 \quad \text{Shear Ultimate} \]
4.11.2 Handle Base
Section 4.11.2  PAS Handle Base

Handle Base, SDG39135851, is made of 15-5 PH and is good by engineering judgement, based upon the 50 lbf load and the significant cross section.

Capture bar threaded portion is a 1/2-20 thread, and will also be good for the 50 lbf load.

The capture bar threaded portion threads into the handle base. This analysis is performed in Section 4.12.4 of this report.
4.11.3 Handle Extension Assembly
Section 4.11.3  

PAS Handle Extension

Check Handle Extension, SDG39135853

Material properties—6061-T651 plate

Temperature reduction \( \beta := 0.96 \)

Tensile allowable, ultimate, and yield 

\[ F_{tu} := 42000 \cdot \beta \quad F_{ty} := 35000 \cdot \beta \]

Shear allowable 

\[ F_{su} := 27000 \cdot \beta \]

Factors of Safety 

\[ F_{Su} := 2.0 \quad F_{Sy} := 1.25 \]

Moment will be carried by the extension until it contacts the camera mounting bracket.

Section Properties:  Section A-A

Cross section is a rectangle

Width of base:  \( b := 0.5 \text{ in} \)

Height:  \( h := 0.75 \text{ in} \)

Area is: 

\[ \text{Area} := b \cdot h \quad \text{Area} = 0.375 \text{ in}^2 \]

Distance to centroid is:

\[ y_c := \frac{b}{2} \quad y_c = 0.25 \text{ in} \]

\[ z_c := \frac{h}{2} \quad z_c = 0.375 \text{ in} \]
**Distance from centroid to outer fiber:**
\[ cy := yc, \quad cy = 0.25 \text{ in} \]
\[ cz := zc, \quad cz = 0.375 \text{ in} \]

**Moments of inertia about centroid:**
\[ I_y := \frac{b \cdot h^3}{12}, \quad I_y = 0.018 \text{ in}^4 \]
\[ I_z := \frac{h \cdot b^3}{12}, \quad I_z = 7.812 \times 10^{-3} \text{ in}^4 \]

**Torsional constant:**
\[ J := \begin{cases} 
\frac{b \cdot h^3}{3} \left( 1 - 0.063 \frac{h}{b} + 0.052 \frac{h^5}{b^5} \right) & \text{if } b \geq h \\
\frac{h \cdot b^3}{3} \left( 1 - 0.063 \frac{b}{h} + 0.052 \frac{b^5}{h^5} \right) & \text{otherwise}
\end{cases} \]
\[ J = 0.03 \text{ in}^4 \]

**Stresses on cross section:**

**Assume that the maximum handle load is:**
\[ \text{Handle force} := 50 \text{ lbf} \]

**If handle is treated as a simple beam (worst case for handle itself):**
\[ M := \frac{\text{Handle force} \cdot \text{length}}{4}, \quad M = 113 \text{ in} \cdot \text{lbf} \]

**Normal is direct axial plus bending:**
\[ u_h := \frac{|M| \cdot cy}{I_z} + \frac{\text{Handle force}}{\text{Area}}, \quad u_h = 3747 \text{ psi} \]

**Shear due to transverse loading**
\[ v_h := 0 \text{ psi} \]

**Shear due to torsion**
\[ t_h := 0 \text{ psi} \]

**Combined shear:**
\[ h := v_h + t_h, \quad h = 0 \text{ psi} \]

**Principal Stresses:**
\[ u_{ph1} := \frac{u_h}{2} + \left[ \left( \frac{u_h}{2} \right)^2 + h^2 \right]^{\frac{1}{2}}, \quad u_{ph1} = 3747 \text{ psi} \]
\[ u_{ph2} := \frac{u_h}{2} - \left[ \left( \frac{u_h}{2} \right)^2 + h^2 \right]^{\frac{1}{2}}, \quad u_{ph2} = 0 \text{ psi} \]
Maximum principal stress is:

$$umax := \max \left( \left\{ \sqrt{\frac{1}{2} \left( (uph_1)^2 + (uph_2)^2 - uph_1 \cdot uph_2 \right)} \right\} \right)$$

$$umax = 3747 \text{ psi}$$

Von-Mises Stress:

$$vmh := \sqrt{\left(\frac{1}{2} \cdot uph_1\right)^2 + \left(\frac{1}{2} \cdot uph_2\right)^2 - uph_1 \cdot uph_2}$$

$$vmh = 3747 \text{ psi}$$

Maximum shear:

$$maxh := \sqrt{\frac{1}{4} \cdot uh^2 + h^2}$$

$$maxh = 1873 \text{ psi}$$

Margins of safety:

Ultimate

$$MSu := \left( \frac{Ftu}{FSu \cdot umaxh} \right) - 1$$

$$MSu = 4.38$$

Ultimate, shear

$$MSsu := \left( \frac{Fsu}{FSu \cdot maxh} \right) - 1$$

$$MSsu = 5.918$$

Yield (using von-Mises)

$$MSy := \left( \frac{Fty}{FSy \cdot vmh} \right) - 1$$

$$MSy = 6.174$$
4.11.4 Handle
Section 4.11.4    PAS Handle

Handle, SDG39135854 in Assembly SEG39135849

\[
FS_u := 2.0 \quad \text{FSy} := 1.25
\]

Assume that the maximum handle load is: \( \text{Handle}_\text{force} := 50\text{-lbf} \)

\[
\text{length} := 9.034\text{-in}
\]

If handle is treated as a simple beam (worst case for handle itself):

\[
M := \frac{\text{Handle}_\text{force} \times \text{length}}{4} \quad M = 113\text{-in-lbf}
\]
Section Properties: Section A-A
Cross section is a rectangle

Width of base: \( b := 0.625 \text{-in} \)
Height: \( h := 1.376 \text{-in} \)

Area is: \[ \text{Area} := bh \]
Area = 0.86 \text{-in}^2

Distance to centroid is:
\[ yc := \frac{b}{2} \]
\( yc = 0.313 \text{-in} \)
\[ zc := \frac{h}{2} \]
\( zc = 0.688 \text{-in} \)

Distance from centroid to outer fiber:
\[ cy := yc \]
\( cy = 0.313 \text{-in} \)
\[ cz := zc \]
\( cz = 0.688 \text{-in} \)

Moments of inertia about centroid:
\[ Iy := \frac{bh^3}{12} \]
\( Iy = 0.136 \text{-in}^4 \)
\[ Iz := \frac{bh^3}{12} \]
\( Iz = 0.028 \text{-in}^4 \)

Torsional constant:
\[ J := \frac{bh^3}{3} \left( 1 - 0.063 \frac{h}{b} + 0.52 \frac{h^5}{b^5} \right) \]
if \( b \geq h \)
\[ J = 0.109 \text{-in}^4 \]
\[ J := \frac{bh^3}{3} \left( 1 - 0.063 \frac{b}{h} + 0.52 \frac{b^5}{h^5} \right) \]
otherwise

4.11.4-3 ESCG-4005-05-AMS-0039
**Stresses on cross section:**

Normal is direct axial plus bending: \[ \beta_h := \frac{M \cdot cy}{Lz} \] \[ \beta_h = 1261 \text{ psi} \]

Shear due to transverse loading \[ \text{uvh} := \sqrt{\left(\frac{\text{Handle\_force}}{\text{Area}}\right)^2} \] \[ \text{uvh} = 58.14 \text{ psi} \]

Shear due to torsion: \[ u_{th} := 0 \text{ psi} \] \[ u_{th} = 0 \text{ psi} \]

Combined shear: \[ u_h := \text{uvh} + u_{th} \] \[ u_h = 58.14 \text{ psi} \]

Principal Stresses:
\[ \beta_{ph_1} := \frac{\beta_h}{2} + \left[\left(\frac{\beta_h}{2}\right)^2 + u_h^2\right]^{1/2} \] \[ \beta_{ph_1} = 1263 \text{ psi} \]
\[ \beta_{ph_2} := \frac{\beta_h}{2} - \left[\left(\frac{\beta_h}{2}\right)^2 + u_h^2\right]^{1/2} \] \[ \beta_{ph_2} = -3 \text{ psi} \]

Maximum principal stress is: \[ \beta_{maxh} := \max\left(\beta_{ph_1}\right) \] \[ \beta_{maxh} = 1263 \text{ psi} \]

Von-Mises Stress:
\[ \beta_{vmh} := \sqrt{\left(\beta_{ph_1}\right)^2 + \left(\beta_{ph_2}\right)^2 - \beta_{ph_1} \beta_{ph_2}} \] \[ \beta_{vmh} = 1265 \text{ psi} \]

Maximum shear:
\[ u_{maxh} := \sqrt{\frac{1}{4} \cdot \beta_h^2 + u_h^2} \] \[ u_{maxh} = 633 \text{ psi} \]

**Material properties—6061-T651 plate**
\[ := .90 \] temperature effect for 140 deg F

Tensile allowable, ultimate and yield \[ F_{tu} := 42000 \text{ psi} \] \[ F_{ty} := 35000 \text{ psi} \]

Shear allowable \[ F_{su} := 27000 \text{ psi} \]
Margins of safety:

Ultimate

\[ MS_u := \left( \frac{F_{tu}}{F_{su} \cdot \beta_{maxh}} \right) - 1 \]

\[ MS_u = 13.962 \]

Ultimate, shear

\[ MS_{su} := \left( \frac{F_{su}}{F_{su} \cdot \beta_{umaxh}} \right) - 1 \]

\[ MS_{su} = 18.196 \]

Yield (using von-Mises)

\[ MS_y := \left( \frac{F_{ty}}{F_{sy} \cdot \beta_{vmh}} \right) - 1 \]

\[ MS_y = 18.928 \]

Now, assume one fastener fails, and treat handle as a cantilever. Moment is worst at the thinned out area.

\[ M := \text{Handle}_\text{force} \cdot \frac{\text{length}}{2} \]

Section Properties:

Cross section is an I-beam

Width of base flange:

\[ b := 0.625 - \text{in} \]

Height:

\[ h := 1.376 - \text{in} \]

Flange thickness:

\[ tf := 0.25 - \text{in} \]

Web thickness:

\[ tw := 0.16 - \text{in} \]

Define:

\[ d := h - tf \]

\[ f := h - 2 \cdot tf \]

Area is:

\[ \text{Area} := 2 \cdot b \cdot tf + f \cdot tw \]

\[ \text{Area} = 0.453 - \text{in}^2 \]

4.11.4-5

ESCG-4005-05-AMS-0039
Distances to centroid are:
\[ y_c := \frac{1}{2}b \quad \quad z_c := \frac{1}{2}h \]

Distance from centroid to outer fiber:
\[ c_y := y_c \quad \quad c_y = 0.313\text{\,in} \]
\[ c_z := z_c \quad \quad c_z = 0.688\text{\,in} \]

Moments of inertia about centroid:
\[ I_y := \frac{1}{12} \left( b \cdot h^3 - (b - tw) \cdot f^3 \right) \quad \quad I_y = 0.11\text{\,in}^4 \]
\[ I_z := \frac{1}{12} \left( f \cdot tw^3 + 2tf \cdot b^3 \right) \quad \quad I_z = 0.01\text{\,in}^4 \]

Torsional constant:
\[ J := \frac{1}{3} \left( 2b \cdot tf^3 + d \cdot tw^3 \right) \quad \quad J = 8.048 \times 10^{-3}\text{\,in}^4 \]

Stresses on cross section:

Normal is direct axial plus bending:
\[ \beta_h := \frac{|M| \cdot c_y}{I_z} \quad \quad \beta_h = 6740\text{\,psi} \]

Shear due to transverse loading
\[ u_{vh} := \sqrt{\left( \frac{\text{Handle\_force}}{\text{Area}} \right)^2} \quad \quad u_{vh} = 110\text{\,psi} \]

Shear due to torsion:
\[ u_{th} := 0\text{\,psi} \quad \quad u_{th} = 0\text{\,psi} \]

Combined shear:
\[ u_h := u_{vh} + u_{th} \quad \quad u_h = 110\text{\,psi} \]

Principal Stresses:
\[ \beta_{ph_1} := \frac{\beta_h}{2} + \left[ \left( \frac{\beta_h}{2} \right)^2 + u_h^2 \right]^{\frac{1}{2}} \quad \quad \beta_{ph_1} = 6742\text{\,psi} \]
\[ \beta_{ph_2} := \frac{\beta_h}{2} - \left[ \left( \frac{\beta_h}{2} \right)^2 + u_h^2 \right]^{\frac{1}{2}} \quad \quad \beta_{ph_2} = -1.81\text{\,psi} \]

Maximum principal stress is:
\[ \beta_{maxh} := \max(\beta_{ph}) \quad \quad \beta_{maxh} = 6742\text{\,psi} \]
Von-Mises Stress: 
\[ \beta_{vmh} := \sqrt{\left(\beta ph_1\right)^2 + \left(\beta ph_2\right)^2 - \beta ph_1 \beta ph_2} \]
\[ \beta_{vmh} = 6743 \text{ psi} \]

Maximum shear: 
\[ umaxh := \frac{1}{4} \left( \beta h^2 + uh^2 \right) \]
\[ umaxh = 3372 \text{ psi} \]

Margins of safety:

Ultimate 
\[ MSu := \left( \frac{Ftu}{FSu \cdot \beta_{maxh}} \right) - 1 \]
\[ MSu = 1.803 \]

Ultimate, shear 
\[ MSsu := \left( \frac{Fsu}{FSu \cdot umaxh} \right) - 1 \]
\[ MSsu = 2.603 \]

Yield (using von-Mises) 
\[ MSy := \left( \frac{Fty}{FSy \cdot \beta_{vmh}} \right) - 1 \]
\[ MSy = 2.737 \]

Note, we used FSu = 2.0. This is conservative, since a fastener has failed.
4.12 PAS Bolt Analysis
Section 4.12 PAS Bolt Analysis

The PAS Bolt Analysis is performed in the following report sections.

| 4.12.1 | Handle Assembly Bolted Interfaces |
| 4.12.2 | PAS Handle to PAS Handle Extension |
| 4.12.3 | Handle Extension to Handle Base |
| 4.12.4 | Handle Base to Capture Bar |
| 4.12.5 | PAS Guide Pin Bolted Interface |
| 4.12.5.1 | PAS Guide Pin to PAS Base |
| 4.12.5.1 | PAS Guide Pin to PAS Base Fail Safe |
| 4.12.6 | Vertex Bracket to PAS Platform Bolted Interface |
| 4.12.6.1 | Vertex Bracket to PAS Platform |
| 4.12.6.1 | Vertex Bracket to PAS Platform Fail Safe |
| 4.12.6.2 | Vertex Bracket to PAS Platform Shear Bolt Analysis |
| 4.12.6.2 | Vertex Bracket to PAS Platform Shear Bolt Analysis - Fail Safe |
| 4.12.7 | Aft Brackets to PAS Platform Bolted Interface |
| 4.12.7.1 | Aft Brackets to PAS Platform |
| 4.12.7.1 | Aft Brackets to PAS Platform Fail Safe |
| 4.12.7.2 | Aft Brackets to PAS Platform Shear Bolt Analysis |
| 4.12.7.2 | Aft Brackets to PAS Platform Shear Bolt Analysis - Fail Safe |
| 4.12.8 | BCS Avionics Bracket to Bridge Assembly |
| 4.12.9 | Vertex Bracket to Lower USS-02 Bolted Interface |
| 4.12.9.1 | Vertex Bracket to Lower USS-02 Assembly |
| 4.12.9.1 | Vertex Bracket to Lower USS-02 Assembly Fail Safe |
| 4.12.10 | Aft Bracket to Lower USS-02 Bolted Interface |
| 4.12.10.1 | Aft Brackets to Lower USS-02 Assembly |
| 4.12.10.1 | Aft Brackets to Lower USS-02 Assembly Fail Safe |
4.12.1 Handle Assembly Bolted Interfaces
Section 4.12.1  Handle Assembly Bolted Interfaces

The Handle Assembly Bolt Analysis is performed in the following report sections.

| 4.12.2  | PAS Handle to PAS Handle Extension |
| 4.12.3  | Handle Extension to Handle Base    |
| 4.12.4  | Handle Base to Capture Bar         |
4.12.2 PAS Handle to PAS Handle Extension
4.12.2  PAS Handle to PAS Handle Extension Bolt Analysis

Assume that the maximum handle load is:  \( \text{Handle\_force} := 50\text{-lbf} \)

Now, assume one fastener fails, and treat handle as a cantilever. Moment is worst at the thinned out area

\[
M := \frac{\text{Handle\_force} \times \text{length}}{2}
\]

Now, check fastener. Joint has to take moment, which will be coupled out heel toe

The Mapp moment will be assumed to couple out in a heel-toe effect. The moment arm will be \( \frac{2}{3} \) of the \( dl_1 \) distance, as shown in the figure.

\[
dl_1 := 0.45\text{-in}
\]

Now, the tension will be

\[
F_{\text{ten}} := \frac{M}{\left( \frac{2}{3} \times dl_1 \right)}
\]

\[
F_{\text{ten}} = 753\text{-lbf}
\]
CHECK BOLTS (NAS1351N4-8 bolts 0.25-28UNRF-3A, Material-A-286), Insert MS21209F4-20L

Flange 1: PAS Handle
Part number: SDG39135854
Material: 6061-T651

Flange 2: PAS Handle Extension
Part number: SDG39135853
Material: 6061-T651

Loads

\[ P := \text{Handle}_\text{force} + F_{\text{ten}} \]

Applied tensile load \[ P = 802.8 \text{ lbf} \]

Applied shear load \[ V := 0 \text{ lbf} \]

Applied bending moment \[ M := 0 \text{ in-lbf} \]

Factors of Safety

Factors of Safety

\[ \text{Ultimate } S_{Fu} := 2.0 \quad \text{Yield } S_{Fy} := 1.25 \quad \text{Assembly } \]

\[ \text{Joint Separation } S_{Fsep} := 1.2 \quad \text{Fitting factor } F_F := 1.15 \quad \text{Maximum } \]

\[ \text{Minimum } \]

\[ \text{Temperature data} \]

(Ref. Appendix C2)

\[ \text{Temp}_{\text{initial}} := 70 \text{ deg} \]

\[ \text{Temp}_{\text{max}} := 149 \text{ deg} \]

\[ \text{Temp}_{\text{min}} := -27 \text{ deg} \]

Bolt and Insert Data

Nominal diameter of bolt \[ D := 0.250 \text{ in} \]

Number of threads/\text{inch} \[ N_t := \frac{1}{16} \text{ in} \]

Total length of bolt \[ L := 0.500 \text{ in} \]

Length of insert \[ L_{\text{ins}} := 0.500 \text{ in} \]

Threaded length \[ L_t := 0.500 \text{ in} \]

Min. external diameter of insert \[ F_{\text{min}} := 0.306 \text{ in} \]

Depth of recess for insert \[ l_r := 0.02 \text{ in} \]

(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in `\escfil02\211\mathcad\8307_bolts\thread_data.mcd`

\[ \text{Washer Data} \]

Thickness of washer \[ t_w := 0 \text{ in} \]

Outer Diameter of washer \[ D_w := 0 \text{ in} \]

Inner Diameter of washer \[ D_{wi} := 0 \text{ in} \]

Bolt head dia. across flats \[ d_w := 0.365 \text{ in} \]

(used only if there is no washer)

\[ \text{Flange data} \]

Thickness of flange 1 \[ t_{f1} := 0.100 \text{ in} \]

(Ref. SDG39135854)

Thickness of flange 2 \[ t_{f2} := 0.500 \text{ in} \]

(insert length)

(Ref. SDG39135853)

Diameter of hole \[ D_{\text{hole}} := 0.272 \text{ in} \]
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

\( T_{Su,bolt} := .97 \) yield \( T_{Sy,bolt} := .97 \)

Bolt ultimate tensile allowable stress \( F_{tu,bolt} := 160000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su,bolt} := 0.6 F_{tu,bolt} \)

Bolt yield tensile allowable \( F_{ty,bolt} := 120000 \text{ psi} \)

Temperature correction factor for bolt modulus (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a)) \( \beta_{bolt,hot} := 9.1 \times 10^{-6} \text{ in}^{-1} \text{ deg} \)

Modulus of elasticity of bolt \( E_{bolt} := \left( 29.1 \times 10^6 \text{ psi} \right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

温度 coefficient for bolt: \( \beta_{bolt,cold} := 8.9 \times 10^{-6} \text{ in}^{-1} \text{ deg} \)

Insert

Temperature correction factor for insert strength (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Ultimate tensile allowable stress \( F_{tu,ins} := 150000 \text{ psi} \) (Ref. NASM8846)

Ultimate shear allowable stress \( F_{su,ins} := 0.6 F_{tu,ins} \)

Washer

Temperature correction factor for washer modulus \( T_{Es,washer} := .97 \) (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer \( E_{w,asher} := \left( 29.1 \times 10^6 \text{ psi} \right) \) (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{f1E} := .99 \) (modulus) \( T_{f1s} := .95 \) (strength)

Temperature correction factor for flange 2 \( T_{f2E} := .99 \) (modulus) \( F_{su,f2} := 27000 \text{ psi} \)

Modulus of elasticity for the parts in the joint \( E_{flange1} := \left( 9.9 \times 10^6 \text{ psi} \right) \) \( E_{flange2} := \left( 9.9 \times 10^6 \text{ psi} \right) \)

Coefficient of thermal expansion for flanges \( \beta_{flange1,hot} := 12.7 \times 10^{-6} \text{ in}^{-1} \text{ deg} \) \( \beta_{flange2,hot} := 12.7 \times 10^{-6} \text{ in}^{-1} \text{ deg} \)

\( \beta_{flange1,cold} := 12.4 \times 10^{-6} \text{ in}^{-1} \text{ deg} \) \( \beta_{flange2,cold} := 12.4 \times 10^{-6} \text{ in}^{-1} \text{ deg} \)

Torque/Preload data (Ref. SDG39135849)

Maximum torque \( T_{max} := 97.3 \text{ in-lbf} \)

Minimum torque \( T_{min} := 82.7 \text{ in-lbf} \)

Torque coefficient: \( k := 0.15 \)

Loading plane factor: \( n := 0.5 \)

Preload Uncertainty: \( u := 0.25 \)

4.12.2 -4
Bolt Load data

Bolt/joint stiffness factor = 0.523  
Preload due to temperature  
Pthr_pos = 217.9-lbf

Max. preload  
PLDmax = 3461.2-lbf  
Pthr_neg = -260.1-lbf

Min. preload  
PLDmin = 1231.8-lbf  
Uncertainty factor  
u = 0.25

Joint separation load  
Psep = 963.4-lbf  
Torque coefficient  
k = 0.15

Max. load on the bolt(ultimate)  
Pb = 3944.2-lbf  
Loading plane factor  
n = 0.5

Max. load on the bolt(yield)  
Pby = 3763.1-lbf  
Thread shear pullout load of bolt or insert  
Pths = 11818.5-lbf

Bolt ultimate tensile strength  
PA_t = 5475.9-lbf  
Thread shear pullout load in parent metal  
Ppths = 6164.5-lbf

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation  
MS_1 = 0.506  
Direct Thread shear Ultimate  
MS_6 = 2.34

Direct Tension Ultimate  
MS_2 = 1.97  
Total Thread shear Ultimate  
MS_7 = 0.56

Direct Tension Yield  
MS_3 = 2.56  
Shear Ultimate  
MS_8 = 10

Total Tension Ultimate  
MS_4 = 0.388  
Bending Ultimate  
MS_9 = 10

Total Tension Yield  
MS_5 = 0.091  
Combined shear, tension and bending ultimate  
MS_10 = 0.388

Determination of the smallest margin of safety for the bolt, and the failure mode:

MS_bolt := min(MS)

MS_bolt = 0.091  
Failure_Mode = "Total Tension Yield"
4.12.3 Handle Extension to Handle Base
4.12.3 PAS Handle Extension to Handle Base Bolt Analysis

Assume that the maximum handle load is: \( \text{Handle\_force} := 50\text{-lbf} \)

Assume one bolt takes the entire load.

Note, moment has been coupled out into the camera bracket.
CHECK BOLTS (NAS1351N-16 0.250"-28 x 1.0 L Material-A-286), Nut NAS1291C4M, Washer NAS1149E0432R

Flange 1: PAS Handle Extension (Handle Bushing)
Part number: SDG39135852
Material: Aluminum Bronze AMS 4640

Flange 2: Pas Handle Base
Part number: SEG39135851
Material: CRES 15-5PH H1025 AMS 5659

**Loads**
- Applied tensile load \( P := 0 \text{lbf} \)
- Applied shear load \( V := 50 \text{lbf} \)
- Applied bending moment \( M := 0 \text{in-lbf} \)

**Factors of Safety**

<table>
<thead>
<tr>
<th>Factor</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>2.0</td>
</tr>
<tr>
<td>Yield</td>
<td>1.25</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>1.2</td>
</tr>
<tr>
<td>Fitting factor</td>
<td>1.15</td>
</tr>
</tbody>
</table>

**Temperature data**
(Ref. Appendix C2)
- \( \text{Temp}_{\text{initial}} := 70\text{-deg} \)
- \( \text{Temp}_{\text{max}} := 183\text{-deg} \)
- \( \text{Temp}_{\text{min}} := -27\text{-deg} \)

**Bolt and Nut Data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter of bolt</td>
<td>( D := .250\text{-in} )</td>
</tr>
<tr>
<td>Number of threads/inch</td>
<td>( N_t := 28 \frac{1}{\text{in}} )</td>
</tr>
<tr>
<td>Total length of bolt</td>
<td>( L := 1.0\text{-in} )</td>
</tr>
<tr>
<td>Height of nut</td>
<td>( H := 0.204\text{-in} )</td>
</tr>
<tr>
<td>Threaded length</td>
<td>( L_t := 1.0\text{-in} )</td>
</tr>
</tbody>
</table>

(If bolt is fully threaded, input \( Lt = L \))

This file uses the calculations shown in `escfil02\2i11_mathcad\8307_bolts\thread_data.mcd`

**Washer Data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of washers</td>
<td>( tw := 0.032\text{-in} )</td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>( Dw := 0.500\text{in} )</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>( Dwi := 0.265\text{-in} )</td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>( dw := 0.365\text{-in} )</td>
</tr>
</tbody>
</table>

**Flange data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 1</td>
<td>( tf1 := 0.475\text{-in} )</td>
</tr>
<tr>
<td>(Ref. SDG39135852)</td>
<td></td>
</tr>
<tr>
<td>Thickness of flange 2</td>
<td>( tf2 := 0.25\text{-in} )</td>
</tr>
<tr>
<td>(Ref. SDG39135851)</td>
<td></td>
</tr>
<tr>
<td>Diameter of hole</td>
<td>( D_{\text{hole}} := 0.264\text{-in} )</td>
</tr>
</tbody>
</table>

4.12.3 -3  
ESCG-4005-05-AMS-0039
Material Property Data

**Bolt**

- Temperature correction factor for bolt strength ultimate. (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
  - $TS_{u,\text{bolt}} := 0.95$
  - Yield $TS_{y,\text{bolt}} := 0.95$

- Bolt ultimate tensile allowable stress $F_{tu,\text{bolt}} := 160000$ psi

- Bolt ultimate shear allowable stress $F_{su,\text{bolt}} := 0.6 \times F_{tu,\text{bolt}}$

- Bolt yield Tensile allowable stress $F_{ty,\text{bolt}} := 120000$ psi

- Temperature correction factor for bolt modulus (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))
  - $TE_{\text{bolt}} := 0.95$

- Modulus of elasticity of bolt $E_{\text{bolt}} := \left(29.1 \times 10^6\ \text{psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt $\beta_{\text{bolt,\ hot}} := 9.1 \times 10^{-6}\ \frac{\text{in}}{\text{deg}}$

- Nut

- Temperature correction factor for nut strength $TS_{\text{nut}} := 0.95$

- Ultimate tensile allowable stress $F_{tu,\text{nut}} := 125000$ psi

- Ultimate Shear allowable stress: $F_{su,\text{nut}} := 0.6 \times F_{tu,\text{nut}}$

- Ultimate axial strength of nut $P_{tu,\text{nut}} := 4580\ \text{lbf}$ (Ref. NAS1291)

- Washer

- Temperature correction factor for washer modulus $TE_{\text{washer}} := 0.95$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Modulus of elasticity of washer: $E_{\text{washer}} := \left(29.1 \times 10^6\ \text{psi}\right)$ (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

**Flanges**

- Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

- Temperature correction factor for flange 1 $T_{11}\text{E} := 0.96$ (modulus) (Ref. Appendix C8 for Flange 1)

- Temperature correction factor for flange 2 $T_{12}\text{E} := 0.99$ (modulus) (Ref. MIL-HDBK-5J Figure 2.6.7.1.4)

- Modulus of elasticity for the parts in the joint $E_{\text{flange1}} := \left(16 \times 10^6\ \text{psi}\right)$ $E_{\text{flange2}} := \left(28.5 \times 10^6\ \text{psi}\right)$ (Ref. MIL-HDBK-5J Table 2.6.7.0(b))

- Coefficient of thermal expansion for flanges $\beta_{\text{flange1,\ hot}} := 9.8 \times 10^{-6}\ \frac{\text{in}}{\text{deg}}$ $\beta_{\text{flange2,\ hot}} := 5.9 \times 10^{-6}\ \frac{\text{in}}{\text{deg}}$

- $\beta_{\text{flange1,\ cold}} := 9.1 \times 10^{-6}\ \frac{\text{in}}{\text{deg}}$ $\beta_{\text{flange2,\ cold}} := 5.8 \times 10^{-6}\ \frac{\text{in}}{\text{deg}}$

**Torque/Preload data**

- (Ref. SDG39135849)

- Maximum torque $T_{\text{max}} := 97.3\ \text{in-lbf}$

- Minimum torque $T_{\text{min}} := 82.7\ \text{in-lbf}$

- Torque coefficient $k := 0.15$

- Loading plane factor $n := 0.5$

- Preload Uncertainty $u := 0.25$

---

4.12.3 -4 ESCG-4005-05-AMS-0039
Bolt Load data

- Bolt/joint stiffness factor: 0.15
- Preload due to temperature: \( P_{\text{thr\_pos}} = 72.2 \text{ lbf} \)
- Max. preload: \( PLD_{\text{max}} = 3315.6 \text{ lbf} \)
- Min. preload: \( PLD_{\text{min}} = 1434 \text{ lbf} \)
- Uncertainty factor: \( u = 0.25 \)
- Joint separation load: \( P_{\text{sep}} = 0 \text{ lbf} \)
- Torque coefficient: \( k = 0.15 \)
- Max. load on the bolt (ultimate): \( P_b = 3315.6 \text{ lbf} \)
- Max. load on the bolt (yield): \( P_{by} = 3315.6 \text{ lbf} \)
- Bolt ultimate tensile strength: \( P_{At} = 4351 \text{ lbf} \)
- Nut ultimate tensile strength: \( P_{tu\_nut} = 4351 \text{ lbf} \)

Length check = "Bolt length should be increased!"

Note: Bolt length is sufficient, one full thread remains past the nut.

Summary of Margins for bolt:

- Joint separation: \( MS_1 = 10 \)
- Direct Tension Ultimate: \( MS_2 = 10 \)
- Direct Tension Yield: \( MS_3 = 10 \)
- Total Tension Ultimate: \( MS_4 = 0.312 \)
- Total Tension Yield: \( MS_5 = 0.213 \)
- Combined shear, tension and bending ultimate: \( MS_{10} = 0.312 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt}} = \min(\text{MS}) \]

\[ MS_{\text{bolt}} = 0.213 \]

Failure Mode = "Total Tension Yield"
4.12.4 Handle Base to Capture Bar
Section 4.12.4  PAS Handle Base to Capture Bar Bolt Analysis

Capture bar threaded portion is a 1/2-20 thread, and will also be good for the 50 lbf load.

Note there is only one fastener holding the handle to the capture bar, so we cannot show the fastener fail safe.
CHECK BOLTS (SDG39135850 0.500-20 A286)
Washer (NAS1149E0863R, CRES A286, 160 KSI)
Nut (NAS1291C8M, CRES A286)

Flange 1: Handle Base, Capture Bar Assembly
Part number: SDG39135851-001
Material: 15-5PH 8.264 x 2.84 x 2.50, AMS 5659, Bar, (H1025 specified in Flag 1 on drawing)

Note: Capture Bar, Capture Bar Assembly
Part number: SDG39135850-001
Material: CRES A286, 1.50 dia x 16.25 LG AMS 5737, Bar

Loads
- Applied tensile load: \( P := 50 \text{ lbf} \)
- Applied shear load: \( V := 0 \text{ lbf} \)
- Applied bending moment: \( M := 0 \text{ in lbf} \)

Factors of Safety
- Ultimate: \( SFu := 2.0 \)
- Joint Separation: \( SFsep := 1.2 \)

Temperature data
(Ref. Appendix C2)
- Assembly temperature: \( \text{Temp}_{\text{initial}} := 70 \text{ deg} \)
- Maximum temperature: \( \text{Temp}_{\text{max}} := 183 \text{ deg} \)
- Minimum temperature: \( \text{Temp}_{\text{min}} := -11 \text{ deg} \)

Bolt and Nut Data
- Nominal diameter of bolt: \( D := 0.500 \text{ in} \)
- Number of threads/inch: \( Nt := 20 \text{ in}^{-1} \)
- Total length of bolt: \( L := 1.375 \text{ in} \)
- Height of nut: \( H := 0.350 \text{ in} \)
- Threaded length: \( L_t := 0.750 \text{ in} \)

(If bolt is fully threaded, input \( L_t = L \))
This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Tue Feb 15 10:54:02 AM 2005

Washer Data

- Thickness of washers \(tw := 0.063\) in
- Outer Diameter of washer \(D_w := 0.875\) in
- Inner Diameter of washer \(D_{wi} := 0.515\) in
  
  (used only if there is no washer)

- Bolt head dia. across flats \(d_w := 0.786\) in
  
  (Since there is no bolt head, the nut dimension "Fmin" is used
  Ref. NAS1291 Specification.

Flange data

- 1/2 Thickness of flange 1 \(t_f := 0.4205\) in (Ref. SDG39135851)
- 1/2 Thickness of flange 1 \(t_f := 0.4205\) in (Ref. SDG39135851)

  (Single flange thickness divided into flange 1 and flange 2.)

- Diameter of hole \(D_{hole} := 0.516\) in
  
  (used only if there is no washer)

Material Property Data

Bolt

- Temperature correction factor for bolt strength ult
  \(TS_{u} := 0.96\)
  \(TS_{y} := 0.96\)

  (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

- Bolt ultimate tensile allowable stress
  \(F_{tu} := 140000\ psi\)

- Bolt ultimate shear allowable stress
  \(F_{su} := 0.6\ F_{tu}\)

- Bolt yield Tensile allowable stress
  \(F_{ty} := 95000\ psi\)

- Temperature correction factor for bolt modulus
  \(T\ E := 0.98\)
  \(E := 29.1 \times 10^6\ psi\)
  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.4(a))

- Modulus of elasticity of bolt
  
  (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

- Thermal coefficient for bolt
  
  (Ref. MIL-HDBK-5J, fig. 6.2.1.0)

\[\beta_{hot} := 9.15 \times 10^{-6} \text{ in/in deg}\]

\[\beta_{cold} := 8.8 \times 10^{-6} \text{ in/in deg}\]
**Nut**

Temperature correction factor for nut strength

\[ T_{S, nut} = 0.96 \]

Ultimate tensile allowable stress

\[ F_{tu, nut} = 125000 \text{ psi} \]

Ultimate Shear allowable stress:

\[ F_{su, nut} = 0.6 \times F_{tu, nut} \]

Ultimate axial strength of nut

\[ F_{tu, nut} = 21110 \text{ lbf} \quad \text{(Ref. NAS1291)} \]

**Washer**

Temperature correction factor washer modulus

\[ T_{E, washer} = 0.96 \quad \text{(Ref MIL-HDBK-5J fig. 6.2.1.1.1)} \]

Modulus of elasticity of washer:

\[ E_{washer} = \left(29.1 \times 10^6 \text{ psi} \right) \quad \text{(Ref MIL-HDBK-5J table 6.2.1.0(b))} \]

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{F1}\text{E} = 0.99 \quad \text{(modulus)} \]

Temperature correction factor for flange 2

\[ T_{F2}\text{E} = 0.99 \quad \text{(modulus)} \]

(Ref. MIL-HDBK-5J Figure 2.6.7.1.4)

Modulus of elasticity for the parts in the joint

\[ E_{flange1} = \left(28.5 \times 10^6 \text{ psi} \right) \quad E_{flange2} = \left(28.5 \times 10^6 \text{ psi} \right) \]

(Ref. MIL-HDBK-5J Table 2.6.7.0(b))

Coefficient of thermal expansion for flanges

\[ \beta_{flange1, hot} = 6.3 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{flange2, hot} = 6.3 \times 10^{-6} \text{ in/in deg} \]

(Ref. MIL-HDBK-5J Figure 2.6.7.0, use H1075 curve)

(Ref. Appendix C11)

\[ \beta_{flange1, cold} = 6.3 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{flange2, cold} = 6.3 \times 10^{-6} \text{ in/in deg} \]

**Torque/Preload data**

Maximum torque (66.2% of yield)

\[ T_{\max} = 741 \text{ in-lbf} \]

Minimum torque (85% of max. torque)

\[ T_{\min} = 630 \text{ in-lbf} \]

Torque coefficient

\[ k = 0.15 \]

Loading plane factor

\[ n = 0.5 \]

Preload Uncertainty

\[ \eta = 0.25 \]

---

This file uses the calculations shown in \escfi\mathcad\8307\bolts\bolt_stiffness_nut_RevC
**Bolt Load data**  
(The stiffness calculation \( \phi \) needs to be updated to a cylindrical load pattern.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.22</td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLD_{\text{max}} = 13118 lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLD_{\text{min}} = 4461.1 lbf</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>P_{\text{sep}} = 60.00 lbf</td>
</tr>
<tr>
<td>Max load on bolt (ultimate)</td>
<td>P_{\text{b}} = 13128.8 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>P_{\text{by}} = 13124.7 lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>P_{\text{at}} = 20265.6 lbf</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td>P_{\text{thr _ pos}} = 768 lbf</td>
</tr>
<tr>
<td>Uncertainty factor</td>
<td>( \mu = 0.25 )</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>( k = 0.15 )</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>( n = 0.50 )</td>
</tr>
<tr>
<td>Thread pullout strength required to develop full strength of bolt</td>
<td>( P_{\text{As}} = 25333.6 ) lbf</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>( P_{\text{tu _ nut}} = 20265.6 ) lbf</td>
</tr>
</tbody>
</table>

**Summary of Margins for bolt**

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{1} = 82.34</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{2} = 201.66</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_{3} = 228.21</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{4} = 0.54</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_{5} = 0.09</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{6} = 252.34</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS_{7} = 0.93</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS_{8} = 10.00</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS_{9} = 10.00</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_{10} = 0.54</td>
</tr>
</tbody>
</table>

**Determination of the smallest margin of safety for the bolt, and the failure mode**

\[
\text{MS}_{\text{bolt}} := \min(\text{MS})
\]

\[
\text{MS}_{\text{bolt}} = 0.09
\]

Failure Mode = "Total Tension Yield"
4.12.5  PAS Guide Pin Bolted Interface
Section 4.12.5  PAS Guide Pin Bolted Interface

The PAS Guide Pin Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>4.12.5.1</th>
<th>PAS Guide Pin to PAS Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12.5.1</td>
<td>PAS Guide Pin to PAS Base Fail Safe</td>
</tr>
</tbody>
</table>
4.12.5.1 PAS Guide Pin to PAS Base
4.12.5.1 Aft Guide Pin to PAS Platform Bolt Analysis

Geometry and Dimensions for the Aft Guide Pin Assembly

Exploded view of Aft Guide Pin to PAS Platform Installation

Guide Pin Dimensions, SDG39135818 Guide Pins, PAS Base Assy
Note
The Nodes are in the Definition Coordinate System C800001.
The SPC Forces are in the Output Coordinate System C800001.
The Analysis coordinate system is aligned with CS C800001, but with its origin at the CG of the bolt pattern.

Coordinates of the Applied SPC Forces in Coordinate System 800001

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Def CS</th>
<th>Out CS</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
</tr>
</thead>
<tbody>
<tr>
<td>801564</td>
<td>800001</td>
<td>800001</td>
<td>-24.</td>
<td>-13.857</td>
<td>0.3864</td>
</tr>
</tbody>
</table>

Coordinates of the Center of Gravity for the Bolt Group in Coordinate System 800001

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Def CS</th>
<th>Out CS</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>800001</td>
<td>800001</td>
<td>-20.075</td>
<td>-13.857</td>
<td>0.54229</td>
</tr>
</tbody>
</table>

Note: The X1, X2, X3 column labels are taken from NASTRAN SPC Force printed output nomenclature.
**Bolt Section Properties**

The Guide Pins attach to the PAS Platform with a four bolt pattern.

<table>
<thead>
<tr>
<th>Diam</th>
<th>Number of Threads/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
</tbody>
</table>

\[ i := 1 \text{ ... rows(bolt)} \]

\[ D_i := \text{bolt}_i, 1 \text{ in} \]

\[ N_i := \text{bolt}_i, 2 \frac{1}{\text{in}} \]

Set "i" as Row Counter for Array "bolt", i.e. # of Bolts

Assign Diameter of Bolt to Variable \( D \)

Assign Number of Threads per Inch to Variable \( N \)

**Tensile Area of Bolt**

\[ A_{t_i} := \beta \cdot \left( \frac{D_i - 0.9743 \cdot \frac{1}{N_i}}{2} \right)^2 \]

\[ A_t = \left[ \begin{array}{c} 0.088 \\ 0.088 \\ 0.088 \end{array} \right] \text{ in}^2 \]

**Shear Area of Bolt**

\[ A_{s_i} := \beta \cdot \left( \frac{D_i - 1.299038 \cdot \frac{1}{N_i}}{2} \right)^2 \]

\[ A_s = \left[ \begin{array}{c} 0.081 \\ 0.081 \\ 0.081 \end{array} \right] \text{ in}^2 \]
**Bolt Pattern Geometry (Assuming Origin of Coordinate System is at CG of Pattern)**

**Cord Sys 800001**

Note: For local Coordinate System 800001, the z axis direction is axial and the x and y axis directions are shear.

<table>
<thead>
<tr>
<th>Bolt No.</th>
<th>X Coordinates</th>
<th>Y Coordinates</th>
<th>Z Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>0.750</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-1.5</td>
<td>0.750</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-1.5</td>
<td>-0.750</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>-0.750</td>
<td>0</td>
</tr>
</tbody>
</table>

**Location of SPC Forces in Coordinate System 800001**

Note: The original parasolid geometry used to create the FEM no longer exists in the FEM file. So, it is being assumed that the CBARs representing the Guide Pins are located at the centroid of the actual Guide Pin part.

\[ X_{1_{spc}} := -3.92498 \text{ in} \]
\[ X_{2_{spc}} := 0.0 \text{ in} \]
\[ X_{3_{spc}} := -0.15589 \text{ in} \]

\[ L_{spc} := \begin{bmatrix} X_{1_{spc}} \\ X_{2_{spc}} \\ X_{3_{spc}} \end{bmatrix} = \begin{bmatrix} -3.92 \\ 0.00 \\ -0.16 \end{bmatrix} \text{ in} \]
**Location of the Center of Gravity of Bolt Pattern in Coordinate System 800001**

Analysis assumes origin is located at the CG of the bolt pattern.

\[
X_{cg} := \frac{\sum_{i} x_i}{\text{rows}(x)} \quad X_{cg} = 0.00 \text{-in}
\]

\[
Y_{cg} := \frac{\sum_{i} y_i}{\text{rows}(y)} \quad Y_{cg} = 0.00 \text{-in}
\]

\[
Z_{cg} := \frac{\sum_{i} z_i}{\text{rows}(z)} \quad Z_{cg} = 0.00 \text{-in}
\]

\[
\text{CG}_{bolt} := \begin{pmatrix} X_{cg} \\ Y_{cg} \\ Z_{cg} \end{pmatrix}
\]

\[
\text{CG}_{bolt} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{-in}
\]

Note Since the z direction is perpendicular to the plane of the bolt pattern, it is assumed the direct axial loads are shared equally among the bolts. The x and y directions have a zero offset from the CG of the pattern.

**Resultant Vector Distance from CG of Pattern to Location of SPC Force**

\[
r_{load} := L_{spc} - \text{CG}_{bolt}
\]

\[
r_{load} = \begin{pmatrix} -3.925 \\ 0.000 \\ -0.156 \end{pmatrix} \text{-in}
\]

**RMS Distance from CG of the Bolt Pattern to Each Individual Bolt for Shear Calculations**

\[
r_{i} := \sqrt{(x_i - X_{cg})^2 + (y_i - Y_{cg})^2}
\]

\[
r = \begin{pmatrix} 1.677 \\ 1.677 \\ 1.677 \end{pmatrix} \text{-in}
\]
Applied Loads

Applied Loads - SPC's for the Aft Guide Pins, SDG39135818-003

FEM of Guide Pins, PAS Base Assembly, Aft and Vertex Brackets

The picture above shows the finite element model of the Aft and Apex Guide Pins, the PAS Base Assembly, and the Aft and Vertex brackets. The origin of the black arrows show the location of the constraints (SPCs) and their corresponding Node IDs. The black arrow heads show the positive axis directions for those SPCFORCES.

The Picture below shows selected nodes and CBEAM elements that represent the Aft and Vertex Guide Pins.

Guide Pin Nodes
Read SPC Force File Into an Array

Note: The file guidepin-sangster.dat contains SPC FORCES (Node ID, Load Case, Fx (lbf), Fy (lbf), Fz (lbf)) in Coordinate System 800001 for Nodes 800259 (Aft), 801564 (Aft), and 801559 (Apex), for On-Orbit Load Cases 5001-50064, and has the following columnwise structure:

<table>
<thead>
<tr>
<th>Column Header Row</th>
<th>(1) Node ID</th>
<th>(2) Load Case</th>
<th>(3) T1 lbf</th>
<th>(4) T2 lbf</th>
<th>(5) T3 lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>data_{j,1}</td>
<td>data_{j,2}</td>
<td>data_{j,3}</td>
<td>data_{j,4}</td>
<td>data_{j,5}</td>
</tr>
</tbody>
</table>

data := READPRN("guidepin-sangster.dat")  
SPC FORCES File Being Read Into Array "data"

ORIGIN := 1  
Set Origin of all Arrays to 1

Note  "i" was defined earlier and is a counter for the bolt #.

j := 1..rows(data)
num_bolts := rows(bolt)
IDj := data_{j,1}
LCj := data_{j,2}
IDj := IDj 1000 + 1
Mj := 0 in \cdot lbf

Bolt CG Forces  MPC Forces
Fz_BoltCGj := data_{j,5} lbf
Fx_BoltCGj := data_{j,3} lbf
Fy_BoltCGj := data_{j,4} lbf

Direct Axial Load at CG of Bolt Pattern along Z Axis
Direct Shear Load at CG of Bolt Pattern along X Axis
Direct Shear Load at CG of Bolt Pattern along Y Axis

Set "j" as Row Counter for Array "data"
Number of Bolts in the Pattern
Assign Node IDs to Column 1 of Array
Assign Load Case # to Column 2 of Array
Incremental Counter for Each Loop
Set Applied Bending Moment at Bolts to Zero
Transform MPC Forces into Axial and Shear Bolt Loads

**Moment Distribution at the CG of the Bolt Pattern**

\[
M_{\text{tot} j} := r_{\text{load}} \times \begin{pmatrix}
F_{x_{\text{BoltCG} j}} \\
F_{y_{\text{BoltCG} j}} \\
F_{z_{\text{BoltCG} j}}
\end{pmatrix}
\]

*Use the cross-product to determine the additional moments acting on the fasteners.*

\[M_{x_{\text{BoltCG} j}} := M_{\text{tot} j} \times 1, j\]

*Moment at CG of Bolt Pattern about X Axis*

\[M_{y_{\text{BoltCG} j}} := M_{\text{tot} j} \times 2, j\]

*Moment at CG of Bolt Pattern about Y Axis*

\[M_{z_{\text{BoltCG} j}} := M_{\text{tot} j} \times 3, j\]

*Torsion at CG of Bolt Pattern about Z Axis*

**Tensile Force on Each Bolt Due to Direct Axial Loading, and Moments at the CG of the Pattern**

\[F_{\text{direct} i, j} := \frac{F_{z_{\text{BoltCG} j}}}{\text{num_bolts}}\]

*Direct Axial Tensile Load*

\[F_{\text{mx} i, j} := \begin{cases} 
0 \text{ lbf} & \text{if } (y_i - Y_{\text{cg}}) = 0 \cdot \text{in} \\
\frac{M_{x_{\text{BoltCG} j}} (y_i - Y_{\text{cg}})}{\sum_i [(y_i - Y_{\text{cg}})^2 \cdot A_t]} & \text{otherwise}
\end{cases}\]

*Tensile Due to the Moment about X*

\[F_{\text{my} i, j} := \begin{cases} 
0 \text{ lbf} & \text{if } (x_i - X_{\text{cg}}) = 0 \cdot \text{in} \\
\frac{-M_{y_{\text{BoltCG} j}} (x_i - X_{\text{cg}}) \cdot A_t}{\sum_i [(x_i - X_{\text{cg}})^2 \cdot A_t]} & \text{otherwise}
\end{cases}\]

*Tensile Due to the Moment about Y*

\[F_i, j := F_{\text{direct} i, j} + F_{\text{mx} i, j} + F_{\text{my} i, j}\]

*Total Tensile Load*

**Shear Force on Each Bolt Due to Direct Shear, and Torsion at the CG of the Bolt Pattern**

\[F_{s i, j} := \frac{M_{z_{\text{BoltCG} j}} r_i A_s}{\sum_i [(r_i)^2 \cdot (A_s)]}\]

*Secondary Shear Due to Torsion at CG of Bolt Pattern*

\[u_i := \text{atan2}(x_i - X_{\text{cg}}, y_i - Y_{\text{cg}})\]

\[S_{y i, j} := \sin\left(\frac{\beta}{2} - u_i\right) F_{s i, j} \quad S_{x i, j} := -\cos\left(\frac{\beta}{2} - u_i\right) F_{s i, j}\]

\[u = \begin{pmatrix} 26.6 \\ 153.4 \\ -153.4 \\ -26.6 \end{pmatrix} \text{ deg}\]
Guide Pin to PAS Platform Bolt Analysis

\[
S_x^{(1)} = \begin{bmatrix}
-141.25 \\
-141.25 \\
141.25 \\
141.25 \\
\end{bmatrix} \text{ lbf} \quad \text{Sy}^{(1)} = \begin{bmatrix}
282.50 \\
-282.50 \\
-282.50 \\
282.50 \\
\end{bmatrix} \text{ lbf}
\]

\[
\text{FsTot}_{i,j} := \sqrt{\left( \frac{S_x}{2} + \frac{F_{x,BoltCG}}{2} \right)^2 + \left( \frac{S_y}{2} + \frac{F_{y,BoltCG}}{2} \right)^2}
\]

\[
\text{max(FsTot)} = 757.84 \text{ lbf} \\
\text{min(FsTot)} = 3.01 \text{ lbf}
\]

Create Input for Bolt Template

**Stack Node ID, Load Case, Axial Force, Shear Force, and Moment**

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

ID := stack(ID, ID + 1, ID + 2, ID + 3) \\
LC := stack(LC, LC, LC, LC)

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P := \text{stack}\left[\left(F_T^T\right)^{(1)}, \left(F_T^T\right)^{(2)}, \left(F_T^T\right)^{(3)}, \left(F_T^T\right)^{(4)}\right]
\]

\[
V := \text{stack}\left[\left(FsTot^T\right)^{(1)}, \left(FsTot^T\right)^{(2)}, \left(FsTot^T\right)^{(3)}, \left(FsTot^T\right)^{(4)}\right]
\]

\[
M := \text{stack}(M, M, M, M)
\]

Create an Array of Bolt Forces and Moments

The "Output" file outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied axial load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

Output := augment(ID, LC, P / lbf, V / lbf, M / in·lb) \quad \text{Note Since the ID and LC numbers are dimensionless,} \\
\text{the P, V, and M values are divided by their units} \\
\text{in order to make the array dimensionless.}

Size of the "Output" Array rows(\text{Output}) = 768 \\
(4 \text{ bolts} \times 64 \text{ load cases}) \times 3 \text{ joint} = 768 \text{ rows}

\text{WRITEPRN( "output_Gdpin_onorbit.txt" ) := Output}
CHECK
Bolts (NAS1351N6-28, 0.375-24 x 1.75 L, CRES A286)
Nut (NAS1291C6M, .375-24)
Washer (NAS1149E0663R, .390 ID x .625 OD x .063 THK)

data := Output
s := 1 .. rows(data)

Flange 1: Guide Pins, PAS Base Assy
Part number: SDG39135818
Material: 7050-T7451, BMS-7-323-C, 12.6 x 3.75 x 3.00

Flange 2: PAS Platform
Part number: SDG39135817
Material: 7050-T7451, BMS-7-323-C, Plate 2001-3.000, A

Loads

Applied tensile load
P_s := data_s, 3-lbf
ID_s := data_s, 1

Applied shear load
V_s := data_s, 4-lbf
LC_s := data_s, 2

Applied bending moment
M_s := data_s, 5-in-lbf

Factors of Safety

Ult
SFu := 2.0
Yield
SFy := 1.25

Joint Separation
SFsep := 1.2
Fitting factor
FF := 1.15

Temperature data

(Ref. Appendix C2)
Assembly
Temp_initial := 70-deg

Maximum
Temp_max := 153-deg

Minimum
Temp_min := -44-deg
Bolt and Nut Data

Nominal diameter of bolt \( D := 0.375 \text{ in} \)
Total length of bolt \( L := 1.75 \text{ in} \)
Threaded length \( L_t := 1.25 \text{ in} \)
Number of threads/inch \( N_t := 24 \frac{1}{4} \text{ in} \)
Height of nut \( H := 0.267 \text{ in} \)

(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \\escf{11\_mathcad\_8307\_bolts\_thread\_data.mcd}

Washer Data

Thickness of washers \( t_w := 0.063 \text{ in} \)
Outer Diameter of washer \( D_w := 0.625 \text{ in} \)
Inner Diameter of washer \( D_{wi} := 0.390 \text{ in} \)
Bolt head dia. across flats \( d_w := 0.457 \text{ in} \)

(used only if there is no washer)

Flange data

Thickness of flange 1 \( t_1 := 0.500 \text{ in} \) (Ref. SDG39135818)
Thickness of flange 2 \( t_2 := 0.500 \text{ in} \) (Ref. SDG39135817)
Diameter of hole \( D_{\text{hole}} := 0.428 \text{ in} \)

Material Property Data

Bolt

Temperature correction factor for bolt strength Ult. (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1) \( T_{Su} := 0.96 \) Yield \( T_{Sy} := 0.96 \)
Bolt Ult tensile allowable stress \( F_{tu} := 160000 \text{ psi} \)
Bolt Ult shear allowable stress \( F_{su} := 0.6 \cdot F_{tu} \)
Bolt yield Tensile allowable stress \( F_{ty} := 120000 \text{ psi} \)
Temperature correction factor for bolt modulus (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a)) \( T_{E} := 0.96 \)
Guide Pin to PAS Platform Bolt Analysis

Modulus of elasticity of bolt
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

\[ E_{\text{bolt}} := \left(29.1 \times 10^6\right) \text{ psi} \]

Thermal coefficient for bolt
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

\[ \beta_{\text{bolt}} := \left(9.1 \times 10^{-6}\right) \left(\frac{\text{in}}{\text{in} \cdot \text{deg}}\right) \]

\[ \beta_{\text{bolt, cold}} := \left(8.9 \times 10^{-6}\right) \left(\frac{\text{in}}{\text{in} \cdot \text{deg}}\right) \]

**Nut**

Temperature correction factor for nut strength
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

\[ T_{\text{S nut}} := 0.96 \]

Ult tensile allowable stress
Ult Shear allowable stress
Ult axial strength of nut

\[ F_{\text{tu nut}} := 125000 \text{ psi} \]

\[ F_{\text{s nut}} := 0.6 \cdot F_{\text{tu nut}} \]

\[ P_{\text{tu nut}} := 11450 \text{ lbf} \]

**Washer**

Temperature correction factor for washer modulus
TE\_washer := 0.96 (Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer
E\_washer := 29.1 \times 10^6 \text{ psi} (Ref. MIL-HDBK-5J, table 6.2.1.0(b))

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
Tf1E := 0.98 (modulus) (Ref. Appendix C9)

Temperature correction factor for flange 2
Tf2E := 0.98 (modulus)

Modulus of elasticity for the parts in the joint
E\_flange1 := \left(10.3 \times 10^6\right) \text{ psi} \quad E\_flange2 := \left(10.3 \times 10^6\right) \text{ psi}

Coefficient of thermal expansion for flanges
(Ref. Appendix C9)

\[ \beta_{\text{flange1, hot}} := \left(12.8 \times 10^{-6}\right) \left(\frac{\text{in}}{\text{in} \cdot \text{deg}}\right) \]

\[ \beta_{\text{flange1, cold}} := \left(12.1 \times 10^{-6}\right) \left(\frac{\text{in}}{\text{in} \cdot \text{deg}}\right) \]

\[ \beta_{\text{flange2, hot}} := \left(12.8 \times 10^{-6}\right) \left(\frac{\text{in}}{\text{in} \cdot \text{deg}}\right) \]

\[ \beta_{\text{flange2, cold}} := \left(12.1 \times 10^{-6}\right) \left(\frac{\text{in}}{\text{in} \cdot \text{deg}}\right) \]
Torque/Preload data
(Ref. SDG39135815)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum torque</td>
<td>( T_{\text{max}} := 377 \text{ in-lbf} )</td>
</tr>
<tr>
<td>Minimum torque</td>
<td>( T_{\text{min}} := 320 \text{ in-lbf} )</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>( k := 0.15 )</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>( n := 0.5 )</td>
</tr>
<tr>
<td>Preload Uncertainty</td>
<td>( = := 0.25 )</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in "\( \text{\textbackslash\textbackslash escf\textbackslash02\textbackslash211\_mathcad\textbackslash8307\_bolts\textbackslashmulti\_bolt\_stiffness\_nut\_RevC} \)

Bolt Load data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>( y = 0.386 )</td>
</tr>
<tr>
<td>Max preload</td>
<td>( \text{PLD}_{\text{max}} = 8853 \text{ lbf} )</td>
</tr>
<tr>
<td>Min preload</td>
<td>( \text{PLD}_{\text{min}} = 3283 \text{ lbf} )</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>( \text{max}(P_{\text{sep}}) = 3450 \text{ lbf} )</td>
</tr>
<tr>
<td>Max bolt load (Ult)</td>
<td>( \text{max}(P_b) = 10131 \text{ lbf} )</td>
</tr>
<tr>
<td>Max bolt load (yield)</td>
<td>( \text{max}(P_{by}) = 9651 \text{ lbf} )</td>
</tr>
<tr>
<td>Bolt tensile Ult strength</td>
<td>( P_{\text{At}} = 10992 \text{ lbf} )</td>
</tr>
<tr>
<td>Temperature Preload</td>
<td>( P_{\text{thr_pos}} = 475.1 \text{ lbf} )</td>
</tr>
<tr>
<td>Uncertainty factor</td>
<td>( = = 0.25 )</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>( k := 0.15 )</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>( n := 0.50 )</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>( P_{\text{As}} = 15838 \text{ lbf} )</td>
</tr>
<tr>
<td>required to develop full strength of bolt</td>
<td></td>
</tr>
<tr>
<td>Nut tensile Ult strength</td>
<td>( P_{\text{tu_nut}} = 10992 \text{ lbf} )</td>
</tr>
</tbody>
</table>

Summary of Margins for Bolt

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>( \text{MS}_{\text{min}}1,1 = 0.03 )</td>
</tr>
<tr>
<td>Direct Tension Ult</td>
<td>( \text{MS}_{\text{min}}2,1 = 0.66 )</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>( \text{MS}_{\text{min}}3,1 = 1.40 )</td>
</tr>
<tr>
<td>Total Tension Ult</td>
<td>( \text{MS}_{\text{min}}4,1 = 0.09 )</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>( \text{MS}_{\text{min}}5,1 = 0.03 )</td>
</tr>
<tr>
<td>Direct Thread Shear Ult</td>
<td>( \text{MS}_{\text{min}}6,1 = 1.40 )</td>
</tr>
<tr>
<td>Total Thread Shear Ult</td>
<td>( \text{MS}_{\text{min}}7,1 = 0.56 )</td>
</tr>
<tr>
<td>Shear Ult</td>
<td>( \text{MS}_{\text{min}}8,1 = 3.28 )</td>
</tr>
<tr>
<td>Bending Ult</td>
<td>( \text{MS}_{\text{min}}9,1 = 10.00 )</td>
</tr>
<tr>
<td>Combined Shear, Tension, and Bending Ult</td>
<td>( \text{MS}_{\text{min}}10,1 = 0.08 )</td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"
Smallest Margin of Safety for the Bolt, and the Failure Mode

\[ MS_{\text{bolt}} := \min(\text{MS}) \]

\[ MS_{\text{bolt}} = 0.03 \]

Minimum Margin of Safety

Failure Mode = "Total Tension Yield"

\[ \text{MS\_min\_ID} = 801559002 \]

Element Identification (801559) and Bolt Number (2) for Minimum Margin

\[ \text{MS\_min\_LC} = 5032 \]

Load Case Number for Minimum Margin

\[ \text{MS\_min\_P} = 2874.9 \]

Applied Tensile Load for Minimum Margin

\[ \text{MS\_min\_V} = 273.8 \]

Applied Shear Load for Minimum Margin

\[ \text{MS\_min\_M} = 0 \]

Applied Bending Moment for Minimum Margin
Fail-Safe Analysis for Aft Guide Pin to PAS Platform Removing Bolt 2

Geometry and Dimensions for the Aft Guide Pin Assembly

Exploded view of Aft Guide Pin to PAS Platform Installation

Guide Pin Dimensions, SDG39135818 Guide Pins, PAS Base Assy
Guide Pin to PAS Platform Bolt Analysis

Note
The Nodes are in the Definition Coordinate System C800001. The SPC Forces are in the Output Coordinate System C800001. The Analysis coordinate system is aligned with CS C800001, but with it's origin at the CG of the bolt pattern.

Coordinates of the Applied SPC Forces in Coordinate System 800001

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Def CS</th>
<th>Out CS</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
</tr>
</thead>
<tbody>
<tr>
<td>801564</td>
<td>800001</td>
<td>800001</td>
<td>-24.</td>
<td>-13.857</td>
<td>0.3864</td>
</tr>
</tbody>
</table>

Coordinates of the Center of Gravity for the Bolt Group in Coordinate System 800001

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Def CS</th>
<th>Out CS</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>800001</td>
<td>800001</td>
<td>-20.075</td>
<td>-13.857</td>
<td>0.54229</td>
</tr>
</tbody>
</table>

Note: The X1, X2, X3 column labels are taken from NASTRAN SPC Force printed output nomenclature.
Bolt Section Properties

Note  The Guide Pins attach to the PAS Platform with a four bolt pattern. Since bolt number 2 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 3 (NAS1351N6-28, 0.375-24 x 1.75 L, CRES A286) bolts, holding the Guide Pin to the PAS Platform. A new bolt pattern CG and load distribution must be calculated using the remaining 3 bolts.

ORIGIN := 1

Note For local Coordinate System 800001, the z axis direction is axial and the x and y axis directions are shear.

<table>
<thead>
<tr>
<th>Diam</th>
<th>Number of Threads/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
</tbody>
</table>

\[ s := 1 \quad \text{rows(bolt2)} \quad \text{Set "s" as Row Counter for Array "bolt2", i.e. # of Bolts} \]

\[ D_{2s} := \text{bolt2s, 1-in} \quad \text{Assign Diameter of Bolt to Variable D2} \]

\[ N_{2s} := \text{bolt2s, 2-in} \quad \text{Assign Number of Threads per Inch to Variable N2} \]

### Tensile Area of Bolt

\[ At_{2s} := \beta \left( \frac{D_{2s} - 0.9743}{N_{2s}} \right)^2 \quad \text{At2} = \left( 0.088 \quad 0.088 \right)^2 \text{in}^{2.000} \]
Shear Area of Bolt

\[ A_{s2} = \beta \left( \frac{D_{2s} - 1.299038 \frac{1}{N_{2s}}}{2} \right)^2 \]

Bolt Pattern Geometry (Assuming Origin of Coordinate System is at CG of Original Pattern)

<table>
<thead>
<tr>
<th>Bolt No.</th>
<th>X Coordinates</th>
<th>Y Coordinates</th>
<th>Z Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>0.75</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-1.5</td>
<td>-0.75</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>-0.75</td>
<td>0</td>
</tr>
</tbody>
</table>

Note  Bolt 2 is removed from the bolt pattern.

Location of SPC Forces in Coordinate System 800001

Note: The original parasolid geometry used to create the FEM no longer exists in the FEM file. So, it is being assumed that the CBEAMS representing the Guide Pins are located at the centroid of the actual Guide Pin part.

Section Properties from FEMAP

Orientation of Section Properties:

| Origin: X= 0. Y= 0. Z= 0. |
| Y Axis: X= 0. Y= 1. Z= 0. |
| Z Axis: X= 0. Y= 0. Z= -1. |

Section Properties:

- Area: A= 3.51334
- Centroid (from Origin): Cy= +0.725, Cz= -1.53161

Location of Centroid of Guide Pin
\[ X_{1_{spc}} := -3.92498 \text{ in} \]
\[ X_{2_{spc}} := 0.0 \text{ in} \]
\[ X_{3_{spc}} := -0.15589 \text{ in} \]

\[ L_{spc} := \begin{pmatrix} X_{1_{spc}} \\ X_{2_{spc}} \\ X_{3_{spc}} \end{pmatrix} \]

\[ L_{spc} = \begin{pmatrix} -3.92 \\ 0.00 \\ -0.16 \end{pmatrix} \text{ in} \]
**Location of the Center of Gravity of Bolt Pattern in Coordinate System 800001**

Analysis assumes origin is located at the CG of the original bolt pattern.

\[ X_{2cg} : = \sum_{s} \frac{x_{2s}}{\text{rows}(x_{2})} \quad X_{2cg} = 0.50 \text{ in} \]

\[ Y_{2cg} : = \sum_{s} \frac{y_{2s}}{\text{rows}(y_{2})} \quad Y_{2cg} = -0.25 \text{ in} \]

\[ Z_{2cg} : = \sum_{s} \frac{z_{2s}}{\text{rows}(z_{2})} \quad Z_{2cg} = 0.00 \text{ in} \]

\[
\begin{bmatrix}
    X_{2cg} \\
    Y_{2cg} \\
    Z_{2cg}
\end{bmatrix}
= \begin{bmatrix}
    0.50 \\
    -0.25 \\
    0.00
\end{bmatrix} \text{ in}
\]

*Note Since the z direction is perpendicular to the plane of the bolt pattern, it is assumed the direct axial loads are shared equally among the bolts. However, because of the assumed failure of Bolt 2, the CG of the new 3-Bolt pattern is offset from the original 4-Bolt pattern.*

**Resultant Vector Distance from CG of Pattern to Location of SPC Force**

\[ r_{load} : = L_{spc} - CG_{2bolt} \]

\[
\begin{bmatrix}
    r_{load1} \\
    r_{load2} \\
    r_{load3}
\end{bmatrix}
= \begin{bmatrix}
    -4.425 \\
    0.250 \\
    -0.156
\end{bmatrix} \text{ in}
\]

**RMS Distance from CG of the Bolt Pattern to Each Individual Bolt for Shear Calculations**

\[ r_2 : = \sqrt{(x_{2s} - x_{2cg})^2 + (y_{2s} - y_{2cg})^2} \]

\[
\begin{bmatrix}
    r_2 \\
    r_2 \\
    r_2
\end{bmatrix}
= \begin{bmatrix}
    1.414 \\
    2.062 \\
    1.118
\end{bmatrix} \text{ in}
\]
Applied Loads

Forces from SPC's for the Aft Guide Pins, SDG39135818-003

FEM of Guide Pins, PAS Base Assembly, Aft and Vertex Brackets

The picture above shows the finite element model of the Aft and Apex Guide Pins, the PAS Base Assembly, and the Aft and Vertex brackets. The origin of the black arrows show the location of the constraints (SPCs) and their corresponding Node IDs. The black arrow heads show the positive axis directions for those SPCFORCES.

The Picture below shows selected nodes and CBEAM elements that represent the Aft and Vertex Guide Pins.

Guide Pin Nodes
Last Saved 8/21/2009 11:14 AM
Read SPC Force File Into an Array

Note: The file guidepin-sangster.dat contains SPC FORCES (Node ID, Load Case, Fx (lbf), Fy (lbf), Fz (lbf)) in Coordinate System 800001 for Nodes 800259 (Aft), 801564 (Aft), and 801559 (Apex), for On-Orbit Load Cases 5001-5064, and has the following columnwise structure:

<table>
<thead>
<tr>
<th>Column Header Row</th>
<th>(1) Node ID</th>
<th>(2) Load Case</th>
<th>(3) T1 lbf</th>
<th>(4) T2 lbf</th>
<th>(5) T3 lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>data_{qi,1}</td>
<td>data_{qi,2}</td>
<td>data_{qi,3}</td>
<td>data_{qi,4}</td>
<td>data_{qi,5}</td>
</tr>
</tbody>
</table>

\[
data2 := \text{READPRN}("\text{guidepin-sangster.dat}")\]

SPC FORCES File Being Read Into Array "data2"

ORIGIN := 1  
Set Origin of all Arrays to 1

Note  "s" was defined earlier and is a counter for the bolt #.

\[
q := 1 \ldots \text{rows(data2)}\]

Set "q" as Row Counter for Array "data2"

num_bolts2 := \text{rows(bolt2)}

Number of Bolts in the Pattern

ID2q := data2q.1

Assign Node IDs to Column 1 of Array

LC2q := data2q.2

Assign Load Case # to Column 2 of Array

ID2q := ID2q.1000 + 1

Incremental Counter for Each Loop

M2q := 0 \text{ in-lbf}

Set Applied Bending Moment at Bolts to Zero

<table>
<thead>
<tr>
<th>Bolt CG Forces</th>
<th>MPC Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz2_BoltCGq := data2q.5 \text{ lbf}</td>
<td>Direct Axial Load at CG of Bolt Pattern along Z Axis</td>
</tr>
<tr>
<td>Fx2_BoltCGq := data2q.3 \text{ lbf}</td>
<td>Direct Shear Load at CG of Bolt Pattern along X Axis</td>
</tr>
<tr>
<td>Fy2_BoltCGq := data2q.4 \text{ lbf}</td>
<td>Direct Shear Load at CG of Bolt Pattern along Y Axis</td>
</tr>
</tbody>
</table>
Transform MPC Forces into Axial and Shear Bolt Loads

**Moment Distribution at the CG of the Bolt Pattern**

\[
M_{2_{tot}} = r_2 \times \left( \frac{F_{x_2 \cdot BoltCGq}}{num\_bolts} + \frac{F_{y_2 \cdot BoltCGq}}{num\_bolts} + \frac{F_{z_2 \cdot BoltCGq}}{num\_bolts} \right)
\]

Use the cross-product to determine the additional moments acting on the fasteners.

- **Moment at CG of Bolt Pattern about X Axis**
- **Moment at CG of Bolt Pattern about Y Axis**
- **Torsion at CG of Bolt Pattern about Z Axis**

**Tensile Force on Each Bolt Due to Direct Axial Loading, and Moments at the CG of the Pattern**

\[
F_{t_{direct}} = \frac{F_{z_2 \cdot BoltCGq}}{num\_bolts}
\]

**Direct Axial Tensile Load**

\[
F_{t_{x}} = \begin{cases} \text{0 lbf if } (y_{2s} - Y_{cg}) = 0 \text{ in} \\ \frac{(M_{x_2 \cdot BoltCGq}(y_{2s} - Y_{cg}))}{\text{At}_{2s}} \sum_{s} \left( (y_{2s} - Y_{cg})^2 \cdot \text{At}_{2s} \right) \\ \text{0 lbf if } (x_{2s} - X_{cg}) = 0 \text{ in} \\ -\frac{M_{y_2 \cdot BoltCGq}(x_{2s} - X_{cg})}{\text{At}_{2s}} \sum_{s} \left( (x_{2s} - X_{cg})^2 \cdot \text{At}_{2s} \right) 
\end{cases}
\]

**Tensile Due to the Moment about X**

**Tensile Due to the Moment about Y**

\[
F_{t_{s}} = F_{t_{direct}} + F_{t_{x}} + F_{t_{y}}
\]

**Total Tensile Load**

**Shear Force on Each Bolt Due to Direct Shear, and Torsion at the CG of the Bolt Pattern**

\[
F_{s_{2s}} = \frac{M_{z_2 \cdot BoltCGq} \cdot r_{2s} \cdot As_{2s}}{\sum_{s} \left( r_{2s}^2 \cdot (As_{2s}) \right)}
\]

**Secondary Shear Due to Torsion at CG of Bolt Pattern**

\[
\theta_{2s} = \text{atan2}(x_{2s} - X_{cg}, y_{2s} - Y_{cg})
\]

\[
S_{y_{2s}} = \sin \left( \frac{\beta}{2} - \theta_{2s} \right) \cdot F_{s_{2s}}
\]

\[
S_{x_{2s}} = -\cos \left( \frac{\beta}{2} - \theta_{2s} \right) \cdot F_{s_{2s}}
\]

\[
\theta_{2} = \begin{bmatrix} 45 \\ 166 \\ -26.6 \end{bmatrix} \text{ deg}
\]

Last Saved 8/21/2009 11:14 AM
Guide Pin to PAS Platform Bolt Analysis

\[
S_{x2}^{(1)} = \begin{bmatrix} -318.49 \\ 159.24 \\ 159.24 \end{bmatrix} \text{ lbf} \quad S_{y2}^{(1)} = \begin{bmatrix} 318.49 \\ -636.97 \\ 318.49 \end{bmatrix} \text{ lbf}
\]

\[
F_{s Tol2s,q} := \sqrt{\left(\frac{S_{x2s,q}}{2} + \frac{F_{x2\_BoltCGq}}{2}\right)^2 + \left(\frac{S_{y2s,q}}{2} + \frac{F_{y2\_BoltCGq}}{2}\right)^2}
\]

\[
\max(F_{s Tol2}) = 1223.80 \text{ lbf} \\
\min(F_{s Tol2}) = 3.53 \text{ lbf}
\]

Create Input for Bolt Template

**Stack Node ID, Load Case, Axial Force, Shear Force, and Moment**

Note bolt number 2 is not included.

The stack commands below are used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

**ID2 := stack>ID2, ID2 + 2, ID2 + 3**  
**Stack Must be Changed to Reflect Bolt 2 Being Removed**

**LC2 := stack>LC2, LC2, LC2**

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

**P2 := stack>Ft2\_T\(1\), Ft2\_T\(2\), Ft2\_T\(3\)**

**V2 := stack>FsTol2\_T\(1\), FsTol2\_T\(2\), FsTol2\_T\(3\)**

**M2 := stack>M2, M2, M2**

Create an Array of Bolt Forces and Moments

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied axial load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). The array is written to a text file.

**Output2 := augment>ID2, LC2, P2, V2, M2**  
Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.

Size of the "Output2" Array  
rows(Output2) = 576

(3 bolts x 64 load cases) x 3 joint = 576 rows

**WRITEPRN("output_Gdpin_onorbit_FS.txt") := Output2**
Bolt Fail-Safe Results

CHECK

Bolts (NAS1351N6-28, 0.375-24 x 1.75 L, CRES A286)
Nut (NAS1291C6M, .375-24)
Washer (NAS1149E0663R, .390 ID x .625 OD x .063 THK)

\[
data_{fs} := \text{Output2}
\]
\[
s := 1 \quad \text{rows}(data_{fs})
\]

Flange 1: Guide Pins, PAS Base Assy
Part number: SDG39135818
Material: 7050-T7451, BMS-7-323-C, 12.6 x 3.75 x 3.00

Flange 2: PAS Platform
Part number: SDG39135817
Material: 7050-T7451, BMS-7-323-C, Plate 2.001-3.000, A

Fail-Safe Loads, On-Orbit Loads

\[
\text{Applied tensile load} \quad P_{FS} := data_{fs}, 3 \quad \text{lbf}
\]
\[
\text{Applied shear load} \quad V_{FS} := data_{fs}, 4 \quad \text{lbf}
\]
\[
\text{Applied bending moment} \quad M_{FS} := data_{fs}, 5 \quad \text{in} \cdot \text{lbf}
\]

Fail-safe Factors of Safety

\[
\text{Ultimate} \quad SF_{u,FS} := 1.0
\]
\[
\text{Joint Separation} \quad SF_{sep,FS} := 1.0
\]

\[
\text{Yield} \quad SFy := 1.00
\]
\[
\text{Fitting factor} \quad FF := 1.15
\]

Temperature data
(Ref. Appendix C2)

\[
\text{Assembly} \quad \text{Temp}_{\text{initial}} := 70 \quad \text{deg}
\]
\[
\text{Maximum} \quad \text{Temp}_{\text{max}} := 153 \quad \text{deg}
\]
\[
\text{Minimum} \quad \text{Temp}_{\text{min}} := -44 \quad \text{deg}
\]
Bolt and Nut Data

Nominal diameter of bolt $D := \text{.375 in}$
Number of threads/inch $N_t := 24 \cdot \frac{1}{\text{in}}$
Total length of bolt $L := \text{1.75 in}$
Height of nut $H := \text{0.267 in}$
Threaded length $Lt := \text{1.25 in}$

(If bolt is fully threaded, input $Lt = L$)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Washer Data

Thickness of washers $tw := \text{0.063 in}$
Outer Diameter of washer $D_w := \text{0.625 in}$
Inner Diameter of washer $D_{wi} := \text{0.390 in}$
Bolt head dia. across flats $dw := \text{0.457 in}$ (used only if there is no washer)

Flange data

Thickness of flange 1 $t_{f1} := \text{0.500 in}$ (Ref. SDG39135818)
Thickness of flange 2 $t_{f2} := \text{0.500 in}$ (Ref. SDG39135817)
Diameter of hole $D_{hole} := \text{0.428 in}$

Material Property Data

Bolt

Temperature correction factor for bolt strength Ult. $\text{TSu_bolt} := \text{.96}$
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
Bolt Ult tensile allowable stress $\text{Ftu_bolt} := \text{160000 psi}$
Bolt Ult shear allowable stress $\text{Fsu_bolt} := \text{0.6 \cdot Ftu_bolt}$
Bolt yield Tensile allowable stress $\text{Fty_bolt} := \text{120000 psi}$
Temperature correction factor for bolt modulus $\text{TE_bolt} := \text{.96}$ (Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))
Modulus of elasticity of bolt
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

\[ E_{\text{bolt}} := (29.1 \times 10^6 \text{ psi}) \]

Thermal coefficient for bolt
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

\[ \_\text{bolt}_\text{hot} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{in deg}} \]
\[ \_\text{bolt}_\text{cold} := 8.9 \times 10^{-6} \frac{\text{in}}{\text{in deg}} \]

**Nut**

Temperature correction factor for nut strength
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

\[ T_{S_{\text{nut}}} := .96 \]

Ult tensile allowable stress

\[ F_{t_{\text{nut}}} := 125000 \text{ psi} \]

Ult Shear allowable stress

\[ F_{s_{\text{nut}}} := 0.6 \cdot F_{t_{\text{nut}}} \]

Ult axial strength of nut

\[ P_{t_{\text{nut}}} := 11450 \text{ lbf} \]

**Washer**

Temperature correction factor for washer modulus

\[ T_{E_{\text{washer}}} := .96 \]

(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

Modulus of elasticity of washer

\[ E_{\text{washer}} := 29.1 \times 10^6 \text{ psi} \]

(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{F1E} := .98 \] (modulus) (Ref. Appendix C9)

Temperature correction factor for flange 2

\[ T_{F2E} := .98 \] (modulus)

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange1}} := (10.3 \times 10^6 \text{ psi}) \]
\[ E_{\text{flange2}} := (10.3 \times 10^6 \text{ psi}) \]

Coefficient of thermal expansion for flanges

(Ref. Appendix C9)

\[ _\text{flange1}_\text{hot} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in deg}} \]
\[ _\text{flange2}_\text{hot} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in deg}} \]

\[ _\text{flange1}_\text{cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in deg}} \]
\[ _\text{flange2}_\text{cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in deg}} \]
**Guide Pin to PAS Platform Bolt Analysis**

**Torque/Preload data**

(Ref. SDG39135815)

- Maximum torque: $T_{\text{max}} := 377 \text{ in \cdot lbf}$
- Minimum torque: $T_{\text{min}} := 320 \text{ in \cdot lbf}$
- Torque coefficient: $k := 0.15$
- Loading plane factor: $n := 0.5$
- Preload Uncertainty: $\delta := 0.25$

This file uses the calculations shown in \esclib02\2111_mathcad\8307_bolts\multi_bolt_stiffness_nut_RevC

**Bolt Fail-safe Load data**

- Joint separation load: $\max(P_{\text{sep FS}}) = 5486.101 \text{ lbf}$
- Max bolt load (Ult): $\max(P_{\text{b FS}}) = 1007.2 \text{ lbf}$
- $\max(P_{\text{FS}}) = 5486.101 \text{ lbf}$
- $\max(V_{\text{FS}}) = 1223.799 \text{ lbf}$

**Summary of Fail-Safe Margins Removing Bolt 2**

- Joint separation: $\text{MS}_{\text{min FS1,1}} = -0.35$
- Total Thread shear Ult: $\text{MS}_{\text{min FS5,1}} = 0.57$
- Direct Tension Ult: $\text{MS}_{\text{min FS2,1}} = 0.74$
- Shear Ult: $\text{MS}_{\text{min FS6,1}} = 4.30$
- Total Tension Ult: $\text{MS}_{\text{min FS3,1}} = 0.09$
- Bending Ult: $\text{MS}_{\text{min FS7,1}} = 10.00$
- Direct Thread shear Ult: $\text{MS}_{\text{min FS4,1}} = 1.51$
- Combined shear, tension and bending Ult: $\text{MS}_{\text{min FS8,1}} = 0.09$

**Smallest Fail-Safe Margin of Safety for the Bolt, and the Failure Mode**

- $\text{MS}_{\text{bolt FS}} := \min(\text{MS}_{\text{FS}})$
- $\text{MS}_{\text{bolt FS}} = -0.35$
- Failure Mode _FS_ = "Joint Separation"

*Element Identification (801559) and Bolt Number (3) for Minimum Margin*

*Load Case Number for Minimum Margin*

*Applied Tensile Load for Minimum Margin*

*Applied Shear Load for Minimum Margin*

*Applied Bending Moment for Minimum Margin*
4.12.6 Vertex Bracket to PAS Platform Bolted Interface
Section 4.12.6  Vertex Bracket to PAS Platform Bolted Interface

The Vertex Bracket to PAS Platform Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>4.12.6.1</th>
<th>Vertex Bracket to PAS Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12.6.1</td>
<td>Vertex Bracket to PAS Platform Fail Safe</td>
</tr>
<tr>
<td>4.12.6.2</td>
<td>Vertex Bracket to PAS Platform Shear Bolt Analysis</td>
</tr>
<tr>
<td>4.12.6.2</td>
<td>Vertex Bracket to PAS Platform Shear Bolt Analysis - Fail Safe</td>
</tr>
</tbody>
</table>
4.12.6.1 Vertex Bracket to PAS Platform
Section 4.12.6.1

PAS Vertex Bracket to PAS Platform Bolt Analysis

There are a total of 4 fasteners attaching one end of the vertex bracket to the PAS platform. Three fasteners are NAS1956C30 (180 ksi), 0.375-24 UNFJ and 1 fastener is NAS1160-6 (shear bolt). The drawing number for the Vertex Bracket Installation is SGG39135873.

Bolt Geometry

size thread/in

\[
\begin{array}{l}
0.375 \quad 24 \\
0.375 \quad 24 \\
0.375 \quad 24 \\
0.375 \quad 24
\end{array}
\]

\[i := 1... rows(bolt)\]

\[N_i := \text{bolt}\_i, \quad \frac{1}{2} \text{in} \] pitch of bolt

\[D_i := \text{bolt}\_i, \quad 1 \text{in} \] bolt diameter

Tensile Area of bolt

\[A_{ti} := \beta \left( \frac{D_i - 0.9743 \left( \frac{1}{N_i} \right)}{2} \right)^2\]

Shear Area of bolt

\[A_{si} := \beta \left( \frac{D_i - 1.299038 \left( \frac{1}{N_i} \right)}{2} \right)^2\]
Bolts from PAS Vertex Bracket to PAS Platform

(Bolt Pattern)

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinates</th>
<th>y coordinates</th>
<th>z coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.75</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-2.75</td>
<td>-1.25</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2.75</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2.75</td>
<td>-1.25</td>
<td>0</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[ x_{\text{force}} := 0.0 \text{in} \quad y_{\text{force}} := 0.0 \text{in} \quad z_{\text{force}} := 0.0 \text{in} \]

\[ \begin{bmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix} \text{in} \]

Center of gravity of bolt group

\[ x_{\text{cg}} := \frac{\sum x_i}{\text{rows}(x)} \quad x_{\text{cg}} = 0.00 \text{ in} \]
\[ y_{\text{cg}} := \frac{\sum y_i}{\text{rows}(y)} \quad y_{\text{cg}} = 0.00 \text{ in} \]
\[ z_{\text{cg}} := \frac{\sum z_i}{\text{rows}(z)} \quad z_{\text{cg}} = 0.00 \text{ in} \]

\[ \begin{bmatrix} x_{\text{cg}} \\ y_{\text{cg}} \\ z_{\text{cg}} \end{bmatrix} = \begin{bmatrix} 0.00 \\ 0.00 \\ 0.00 \end{bmatrix} \text{in} \]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. The x and y axis have a zero offset from the center of gravity.
Load Vector

\[ \mathbf{r}_{\text{load}} := \mathbf{c}_{\text{load}} - \mathbf{c}_{\text{bolt}} \]

\[
\begin{bmatrix}
0.00 \\
0.00 \\
0.00
\end{bmatrix}
\text{in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(x_i - x_{cg})^2 + (y_i - y_{cg})^2}
\]

\[
\begin{bmatrix}
3.021 \\
3.021 \\
3.021 \\
3.021
\end{bmatrix}
\text{in}
\]

Loads model 2-06 with the detailed PAS was used to retrieve loads at the bolted interface. These loads are read into an array and distributed out to the 4 bolts for the Vertex Bracket.

Note: In the FEA model the loads are recovered from CBUSH element. End B is connected to the PAS Platform and end A is connected to the Vertex bracket. Using equation shown in remark 10 of the MSC nastran reference manual Ke=(UB-UA) if UA > UB a tensile force will be present. This template is derived in the reverse direction and input loads are adjusted accordingly.

Note This joint was checked for minimum margins of safety for on-orbit, liftoff, abort landing and berthing load cases.

Reading database file for bolted joint

See Appendix A22 for NASPOST data.

data := READPRN("boltsVertPlatform.txt")

\[ j := 1 \text{.. rows(data)} \]

\[ \text{num_bolts} := \text{rows(bolt)} \]

Note that "boltsVertPlatform.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files, see Appendix A22.

Element Identification \[ \text{ID}_j := \text{(data)}_{j.1} \]

Load Case Number \[ \text{LC}_j := \text{(data)}_{j.2} \]

Applied Bending Moment at Bolts \[ M_j := 0 \text{ in.lbf} \]

Shear in X axis \[ F_{xj} := -\text{(data)}_{j.3} \text{ lbf} \]

Shear in Y axis \[ F_{yj} := -\text{(data)}_{j.4} \text{ lbf} \]

Axial Load \[ F_{zj} := -\text{(data)}_{j.5} \text{ lbf} \]

Moment about X axis \[ M_{xj} := -\text{(data)}_{j.6} \text{ in.lbf} \]

Moment about Y axis \[ M_{yj} := -\text{(data)}_{j.7} \text{ in.lbf} \]

Torsion \[ M_{zj} := -\text{(data)}_{j.8} \text{ in.lbf} \]
**Format of Output File**

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\[
\text{ID} := \text{stack}(\text{ID}, \text{ID} + 1, \text{ID} + 2, \text{ID} + 3)
\]

\[
\text{LC} := \text{stack}(\text{LC}, \text{LC}, \text{LC}, \text{LC})
\]

**Moment Distribution**

\[
\begin{align*}
M_{\text{tot}}^{(j)} & := \\
& \begin{pmatrix}
M_x \\
M_y \\
M_z
\end{pmatrix} + \text{load} \times
\begin{pmatrix}
F_x \\
F_y \\
F_z
\end{pmatrix}
\end{align*}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
\begin{align*}
M_{x,\text{bolts}}^{(j)} & := M_{\text{tot}}^{1,j} \\
M_{y,\text{bolts}}^{(j)} & := M_{\text{tot}}^{2,j} \\
M_{z,\text{bolts}}^{(j)} & := M_{\text{tot}}^{3,j}
\end{align*}
\]

**Tension on bolts**

\[
F_{\text{direct}i,j} := \frac{F_{zj}}{\text{num_bolts}}
\]

Direct tensile load calculation

\[
F_{x,ij} := \begin{cases}
0 \text{ lbf} & \text{if } (y_i - yc) = 0 \text{ in} \\
\left( M_{x,\text{bolts}}^{j}(y_i - yc) \right) / A_{t_i} & \text{if not equal to zero}
\end{cases}
\]

Tensile due to the moment about X

\[
F_{y,ij} := \begin{cases}
0 \text{ lbf} & \text{if } (x_i - xc) = 0 \text{ in} \\
-\left( M_{y,\text{bolts}}^{j}(x_i - xc) \right) / A_{t_i} & \text{if not equal to zero}
\end{cases}
\]

Tensile due to the moment about Y

\[
F_{t,j} := F_{\text{direct}i,j} + F_{x,ij} + F_{y,ij}
\]
Shear on bolts

Secondary shear on bolts
\[ F_{s_{i,j}} := \frac{M_{z_{-bolts}} + \frac{1}{n} A_s}{\sum_i \left( \frac{y_i}{A_s} \right)^2} \]
\[ u_i := \tan(\pi - \pi - x_{cg} \cdot y_{i} - y_{cg}) \]

Shear
\[ S_{y_{i,j}} := \sin\left( \frac{\beta}{2} - u_i \right) \cdot F_{s_{i,j}} \]
\[ S_{x_{i,j}} := -\cos\left( \frac{\beta}{2} - u_i \right) \cdot F_{s_{i,j}} \]
\[ u = \begin{pmatrix} 155.6 \\ -155.6 \\ 24.4 \\ -24.4 \end{pmatrix} \text{ deg} \]

Loads of first case
\[ S_x \begin{pmatrix} 1 \\ 48.90 \\ -48.90 \\ 48.90 \end{pmatrix} \text{ lbf} \]
\[ S_y \begin{pmatrix} 107.59 \\ -107.59 \\ 107.59 \\ -107.59 \end{pmatrix} \text{ lbf} \]

\[ F_{\text{stot}_{i,j}} := \sqrt{ \left( \frac{S_{x_{i,j}} + P_j}{2} \right)^2 + \left( \frac{S_{y_{i,j}} + P_j}{2} \right)^2 } \]
\[ \max(F_{\text{stot}}) = 1343.05 \text{ lbf} \]
\[ \min(F_{\text{stot}}) = 3.04 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[ P := \text{stack}\left( \begin{pmatrix} F_{t1}^T \end{pmatrix}, \begin{pmatrix} F_{t2}^T \end{pmatrix}, \begin{pmatrix} F_{t3}^T \end{pmatrix}, \begin{pmatrix} F_{t4}^T \end{pmatrix} \right) \]
\[ V := \text{stack}\left( \begin{pmatrix} F_{\text{stot}1}^T \end{pmatrix}, \begin{pmatrix} F_{\text{stot}2}^T \end{pmatrix}, \begin{pmatrix} F_{\text{stot}3}^T \end{pmatrix}, \begin{pmatrix} F_{\text{stot}4}^T \end{pmatrix} \right) \]
\[ M := \text{stack}(M, M, M, M) \]

The "Output" file outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

Output := augment(\( ID \), LC, \( P \), \( V \), \( M \))

Note Since the ID and LC numbers are dimensionless, the \( P \), \( V \), and \( M \) values are divided by their units in order to make the array dimensionless.

Size of the "Output" Array: \( \text{rows(Output)} = 1024 \)
(4 bolts x 256 load cases) x 1 joint = 1024 rows

WRITEPRN("\textbf{output\_vertpas\_r5\_onorbit.txt}\) := Output
CHECK Bolts (NAS1956C30 0.375"-24 x 2.453 L Material-A-286),
Nut (NAS1805-6), Washer (NAS1587-6C)

Flange 1 Vertex Bracket
Part number SDG39135813
Material 7050-T7451

Flange 2 PAS Platform
Part number SDG39135817
Material 7050-T7451

Loads
- Applied tensile load
- Applied shear load
- Applied bending moment

Factors of Safety
- Ultimate

Temperature data
- Assembly
- Maximum
- Minimum

Bolt and Nut Data
- Nominal diameter of bolt
- Total length of bolt
- Threaded length

Washer Data
- Thickness of washers
- Outer Diameter of washer
- Inner Diameter of washer
- Bolt head dia. across flats

Flange data
- Thickness of flange
- Diameter of hole

(If bolt is fully threaded, input Lt = L)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
Material Property Data

Bolt

Temperature correction factor bolt strength \( TS_{u,bolt} := 0.96 \)

Bolt ultimate tensile allowable stress \( F_{tu,bolt} := 180000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su,bolt} := 0.6 \times F_{tu,bolt} \)

Bolt yield Tensile allowable stress \( F_{ty,bolt} := 132353 \text{ psi} \)

Temperature correction factor for bolt modulus \( TE_{bolt} := 0.96 \)

Modulus of elasticity of bolt \( E_{bolt} := 29.1 \times 10^6 \text{ psi} \)

Yield \( TS_{y,bolt} := 0.96 \)

Nut

Temperature correction factor for nut strength \( TS_{nut} := 0.96 \)

Ultimate tensile allowable stress \( F_{tu,nut} := 180000 \text{ psi} \)

Ultimate Shear allowable stress \( F_{su,nut} := 0.6 \times F_{tu,nut} \)

Ultimate axial strength of nut \( F_{tu,nut} := 16488 \text{ lbf} \)

Washer

Temperature correction factor for washer modulus \( TE_{washer} := 0.96 \)

Modulus of elasticity of washer \( E_{washer} := 29.1 \times 10^6 \text{ psi} \)

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{f1E} := 0.98 \)

Temperature correction factor for flange 2 \( T_{f2E} := 0.98 \)

Modulus of elasticity for the parts in the joint \( E_{flange1} := 10.3 \times 10^6 \text{ psi} \)

\( E_{flange2} := 10.3 \times 10^6 \text{ psi} \)

Coefficient of thermal expansion for flanges

\( \frac{\text{in}}{\text{in}} \times \frac{\text{deg}}{\text{deg}} \)

\( \frac{\text{in}}{\text{in}} \times \frac{\text{deg}}{\text{deg}} \)

Torque/Preload data

Maximum torque (66% of yield) \( T_{max} := 420 \text{ in lbf} \)

Minimum torque (95% of max. torque) \( T_{min} := 399 \text{ in lbf} \)

Loading plane factor \( n := 0.5 \)

Preload Uncertainty \( \varepsilon := 0.25 \)

Torque coefficient \( k := 0.15 \)
Bolts from PAS Vertex Bracket to PAS Platform

This file uses the calculations shown in \escf\211\math\8307_bolts\multi_bolt_stiffness_nut_RevC

Bolt Load data

Bolt/joint stiffness factor

\( y = 0.290 \)

Max preload

PLD_{max} = 9929.2 \text{ lbf}

Min preload

PLD_{min} = 4089 \text{ lbf}

Joint separation load

max(P_{sep}) = 4109 \text{ lbf}

Max bolt load (ultimate)

max(P_b) = 11070 \text{ lbf}

Max bolt load (yield)

max(P_{by}) = 10643 \text{ lbf}

Bolt tensile ult strength

P_{At} = 14848 \text{ lbf}

Temperature Preload

P_{thr_{pos}} = 595.9 \text{ lbf}

P_{thr_{neg}} = -763.9 \text{ lbf}

Uncertainty factor

\( \sigma = 0.25 \)

Torque coefficient

\( k = 0.15 \)

Loading plane factor

\( n = 0.50 \)

Thread pullout strength required to develop full strength of bolt

PAs = 17818 \text{ lbf}

Nut tensile ult strength

P_{tu_{nut}} = 15828 \text{ lbf}

Summary of Margins for bolt

Joint separation

Length check = "Bolt length is sufficient"

Direct Thread shearUlt

MS_{min}_{6.1} = 1.26

Total Thread shearUlt

MS_{min}_{7.1} = 0.61

Shear Ultimate

MS_{min}_{8.1} = 2.71

Bending Ultimate

MS_{min}_{9.1} = 10.00

Combined shear, tension and bending ultimate

MS_{min}_{10.1} = 0.32

Determination of the smallest margin of safety for the bolt, and the failure mode

MS_{bbolt} = \text{min}(\text{MS})

MS_{bbolt} = 0.01

Failure Mode = "Joint Separation"

Element Identification (710008) and Bolt Number (2) for Minimum Margin

MS_{min_{ID}} = 710008002

Load Case Number for Minimum Margin

MS_{min_{LC}} = 5031

Applied Tensile Load for Minimum Margin

MS_{min_{P}} = 3424

Applied Shear Load for Minimum Margin

MS_{min_{V}} = 1218.6

Applied Bending Moment for Minimum Margin

MS_{min_{M}} = 0
Bolt Fail-Safe Analysis for Vertex Bracket to PAS Platform Removing Bolt 4

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, NAS1956C30 (180 ksi), 0.375-24 UNFJ fasteners, holding the Vertex Bracket to the PAS platform. The drawing number for the Vertex Bracket Installation is SGG39135873.

\[
\begin{array}{c|c|c}
\text{size} & \text{thread/in} \\
\hline
\text{bolt2} & 0.375 & 24 \\
\hline
\text{bolts} & 0.375 & 24 \\
\hline
\end{array}
\]

\[
s := 1 \times \text{rows(bolt2)}
\]

\[
N_2s := \text{bolt2}_s \times \frac{1}{\text{in}}
\]

\[
D_2s := \text{bolt2}_s \times \frac{1}{\text{in}}
\]

**Tensile Area of bolt**

\[
A_{t2s} := \beta \left( \frac{D_2s - 0.9743}{N_2s} \right)^2
\]

**Shear Area of bolt**

\[
A_{s2s} := \beta \left( \frac{D_2s - 1.299038}{N_2s} \right)^2
\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>x2 := -2.75</td>
<td>y2 := -1.25</td>
<td>z2 := 0</td>
</tr>
<tr>
<td>3</td>
<td>x2 := -2.75</td>
<td>y2 := -1.25</td>
<td>z2 := 0</td>
</tr>
</tbody>
</table>

Note Bolt 4 is removed from the bolt pattern.
Location of applied forces and moments

\[ x_{\text{force2}} := 0.0 \text{ in} \quad y_{\text{force2}} := 0.0 \text{ in} \quad z_{\text{force2}} := 0.0 \text{ in} \]

\[ \text{cgload2} := \begin{pmatrix} x_{\text{force2}} \\ y_{\text{force2}} \\ z_{\text{force2}} \end{pmatrix} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{ in} \]

Center of gravity of bolt group

\[ x_{\text{cg2}} := \frac{\sum x_{2s}}{\text{rows}(x2)} \quad y_{\text{cg2}} := \frac{\sum y_{2s}}{\text{rows}(y2)} \quad z_{\text{cg2}} := \frac{\sum z_{2s}}{\text{rows}(z2)} \]

\[ x_{\text{cg2}} = -0.92 \text{ in} \quad y_{\text{cg2}} = 0.42 \text{ in} \quad z_{\text{cg2}} = 0.00 \text{ in} \]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 4, the x and y directions in the bolt pattern are unsymmetric and have a offset from the center of gravity.

Load Vector

\[ \eta_{\text{load2}} := \text{cgload2} - \text{cgbolt2} \]

\[ \eta_{\text{load2}} = \begin{pmatrix} 0.92 \\ -0.42 \\ 0.00 \end{pmatrix} \text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_{2s} := \sqrt{(x_{2s} - x_{\text{cg2}})^2 + (y_{2s} - y_{\text{cg2}})^2} \]

\[ r_{2s} = \begin{pmatrix} 2.014 \\ 2.478 \\ 3.760 \end{pmatrix} \text{ in} \]

Reading database file for bolted joint

```plaintext
\text{data} := \text{READPRN("boltsVertPlatform.txt")}
\text{q} := 1..\text{rows(data)} \quad \text{num_bolts2} := \text{rows(bolt2)}
```
## Loads from 2-06 loads model

Shear in X axis \( F_{x,q} := - \text{data}_{q,3} \text{ lbf} \)

Shear in Y axis \( F_{y,q} := - \text{data}_{q,4} \text{ lbf} \)

Axial Load \( F_{z,q} := - \text{data}_{q,5} \text{ lbf} \)

Moment about X axis \( M_{x,q} := - \text{data}_{q,6} \text{ in lbf} \)

Moment about Y axis \( M_{y,q} := - \text{data}_{q,7} \text{ in lbf} \)

Torsion \( M_{z,q} := - \text{data}_{q,8} \text{ in lbf} \)

Element Identification \( \text{ID2}_{q} := \text{data}_{q,1} \)

Load Case Number \( \text{LC2}_{q} := \text{data}_{q,2} \)

\( \text{ID2}_{q} := \text{ID2}_q \textbf{1000} + 1 \) Counter for number of bolts in pattern

\[ M_{2,q} := 0 \text{ in lbf} \]

### Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

**Note bolt number 4 is not included.**

\[
\text{ID2} := \text{stack(ID2, ID2 + 1, ID2 + 2)}
\]

\[
\text{LC2} := \text{stack(LC2, LC2, LC2)}
\]

### Moment Distribution

\[
M_{\text{tot2}} \left( q \right) := \begin{pmatrix} M_{x,q} \\ M_{y,q} \\ M_{z,q} \end{pmatrix} + \eta_{\text{load2}} \times \begin{pmatrix} F_{x,q} \\ F_{y,q} \\ F_{z,q} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg2,q}} := M_{\text{tot2 \_q} 1} \\
M_{\text{boltcg2,q}} := M_{\text{tot2 \_q} 2} \\
M_{\text{boltcg2,q}} := M_{\text{tot2 \_q} 3}
\]

### Tension on bolts

\[
F_{\text{direct2,s,q}} := \frac{F_{z,q}}{\text{num\_bolts2}} \quad \text{Direct tensile load calculation}
\]

\[
F_{\text{mx,s,q}} := \begin{cases} 0 \text{ lbf} & \text{if } \left( y_{s,q} - y_{cg2} \right) = 0 \\ \frac{M_{\text{boltcg2,q}} \left( y_{s,q} - y_{cg2} \right) \text{At}_{2s}}{ \sum_{s} \left( y_{s,q} - y_{cg2} \right)^2 \text{At}_{2s}} & \text{otherwise} \end{cases}
\]

\[
F_{\text{my,s,q}} := \begin{cases} 0 \text{ lbf} & \text{if } \left( x_{s,q} - x_{cg2} \right) = 0 \\ \frac{-M_{\text{boltcg2,q}} \left( x_{s,q} - x_{cg2} \right) \text{At}_{2s}}{ \sum_{s} \left( x_{s,q} - x_{cg2} \right)^2 \text{At}_{2s}} & \text{otherwise} \end{cases}
\]

\[
F_{\text{t,s,q}} := F_{\text{direct2,s,q}} + F_{\text{mx,s,q}} + F_{\text{my,s,q}} \quad \text{Total Tensile load}
\]
Shear on bolts

Secondary shear on bolts

\[ Fs_{2,s,q} := \frac{M_{z\_bolt\_cg_2,q} \cdot r_{2,s} \cdot A_{s_2}}{\sum_s \left( r_{2,s} \right)^2 \left( A_{s_2} \right)} \]

\[ \gamma_{s} := \arctan2\left( x_{s_2} - x_{cg_2}, y_{s_2} - y_{cg_2} \right) \]

Shear

\[ S_x := 0 \quad S_y := 0 \]

\[ S_{y,s,q} := \sin\left( \frac{\beta}{2} - \gamma_{s} \right) \cdot F_{s_2,s,q} \]

\[ S_{x,s,q} := -\cos\left( \frac{\beta}{2} - \gamma_{s} \right) \cdot F_{s_2,s,q} \]

Loads of first case

\[ S_x \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} -106.99 \\ 213.99 \\ -106.99 \end{bmatrix} \text{ lbf} \quad S_y \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} -235.39 \\ 470.78 \end{bmatrix} \text{ lbf} \quad \gamma_{s} = \begin{bmatrix} 155.6 \deg \\ 12.8 \deg \end{bmatrix} \]

\[ F_{tot_{s_2,q}} := \sqrt{\left( S_{x,s,q} + \frac{F_{x,q}}{2} \right)^2 + \left( S_{y,s,q} + \frac{F_{y,q}}{2} \right)^2} \]

\[ \text{max}(F_{tot_{s_2,q}}) = 1735.91 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

\[ \text{min}(F_{tot_{s_2,q}}) = 9.34 \text{ lbf} \]

The stack commands below are used to stack applied axial load (\( P_2 \)), applied shear load (\( V_2 \)), and applied moment (\( M_2 \)) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 4 is not included.

\[ P_2 := \text{stack} \left( \begin{bmatrix} F_{t_2}^T \end{bmatrix}^{1}, \begin{bmatrix} F_{t_2}^T \end{bmatrix}^{2}, \begin{bmatrix} F_{t_2}^T \end{bmatrix}^{3} \right) \]

\[ V_2 := \text{stack} \left( \begin{bmatrix} F_{tot_2}^T \end{bmatrix}^{1}, \begin{bmatrix} F_{tot_2}^T \end{bmatrix}^{2}, \begin{bmatrix} F_{tot_2}^T \end{bmatrix}^{3} \right) \]

\[ M_2 := \text{stack} (M_2, M_2, M_2) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

Output2 := augment \( \left( \begin{bmatrix} P_2 \\ V_2 \\ M_2 \end{bmatrix} \right) \)

Size of the "Output2" Array \( \text{rows}(\text{Output2}) = 768 \)

(3 bolts x 256 load cases) x 1 joint = 768 rows

\[ \text{WRITEPRN}(\text{"output_vertpas_r5_onorbit_fs1.txt"}) := \text{Output2} \]

Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.
Bolt Fail-safe Results

The array from the text file above is read

```
data_fs := REAPRN("output_vertpas_r5_onorbit_fs1.txt")
s := 1..rows(data_fs)
```

**Fail-safe Loads**

- Applied tensile load \( P_{FS} := data_{fs,3} \) lbf
- Applied shear load \( V_{FS} := data_{fs,4} \) lbf
- Applied bending moment \( M_{FS} := data_{fs,5} \) in-lbf

**Fail-safe Factors of Safety**

- Ultimate \( SF_{u,FS} := 1.0 \)
- Joint Separation \( SF_{sep,FS} := 1.0 \)
This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC

**Bolt Fail-safe Load data**

Joint separation load \( \max(P_{sep\_FS}) = 6882.36 \text{ lbf} \) \( \max(P_b\_FS) = 11076.2 \text{ lbf} \)

Max bolt load (ultimate) \( \max(P\_FS) = 6882.362 \text{ lbf} \)
\( \max(V\_FS) = 1735.907 \text{ lbf} \)

**Summary of fail-safe Margins Removing Bolt 4**

<table>
<thead>
<tr>
<th></th>
<th>( MS_{minFS1.1} = -0.40 )</th>
<th>( MS_{minFS2.1} = 0.88 )</th>
<th>( MS_{minFS3.1} = 0.34 )</th>
<th>( MS_{minFS4.1} = 1.25 )</th>
<th>( MS_{minFS5.1} = 0.61 )</th>
<th>( MS_{minFS6.1} = 4.74 )</th>
<th>( MS_{minFS7.1} = 10.00 )</th>
<th>( MS_{minFS8.1} = 0.34 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{minFS2.1} = 0.88 )</td>
<td>( MS_{minFS2.1} = 0.88 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{minFS3.1} = 0.34 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{minFS4.1} = 1.25 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension and Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode**

\[ MS_{b Bolt\_FS} := \min(\text{MS\_FS}) \]
\[ MS_{b Bolt\_FS} = -0.40 \]
Failure Mode FS = "Joint Separation"

(Note: A negative margin of safety for joint separation is acceptable for fail-safe.)

\[ MS\_min\_ID = 710008002 \] Element Identification (710008) and Bolt Number (2) for Minimum Margin
\[ MS\_min\_LC = 5031 \] Load Case Number for Minimum Margin
\[ MS\_min\_P = 6882.4 \] Applied Tensile Load for Minimum Margin
\[ MS\_min\_V = 1083.1 \] Applied Shear Load for Minimum Margin
\[ MS\_min\_M = 0 \] Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 3

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, NAS1956C30 (180 ksi), 0.375-24 UNFJ fasteners, holding the Vertex Bracket to the PAS platform. The drawing number for the Vertex Bracket Installation is SGG39135873.

- size	thread/in
  - bolt2 := 0.375 24
  - 0.375 24
  - 0.375 24

\[ s := 1 \text{ rows(bolt2)} \]

\[ N_{2s} := \text{bolt2} \cdot \frac{1}{2} \text{ in} \]

\[ D_{2s} := \text{bolt2} \cdot 1 \text{ in} \]

\[ \text{pitch of bolt} \]

\[ \text{bolt diameter} \]

**Tensile Area of bolt**

\[ A_{t2s} := \beta \left( \frac{D_{2s} - 0.9743}{N_{2s}} \right)^2 \]

**Shear Area of bolt**

\[ A_{s2s} := \beta \left( \frac{D_{2s} - 1.299038}{N_{2s}} \right)^2 \]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-2.75)</td>
<td>(1.25)</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>(-2.75)</td>
<td>(-1.25)</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>(2.75)</td>
<td>(-1.25)</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>(-2.75)</td>
<td>(-1.25)</td>
<td>0</td>
</tr>
</tbody>
</table>

Note Bolt 3 is removed from the bolt pattern.
**Location of applied forces and moments**

\[
x_{force2} := 0.0 \text{ in} \quad y_{force2} := 0.0 \text{ in} \quad z_{force2} := 0.0 \text{ in}
\]

\[
cgload2 := \begin{pmatrix} x_{force2} \\ y_{force2} \\ z_{force2} \end{pmatrix} \quad cgload2 = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{ in}
\]

**Center of gravity of bolt group**

\[
x_{cg2} := \frac{\sum x_{2s}}{\text{rows}(x2)} \quad x_{cg2} = -0.92 \text{ in} \quad y_{cg2} := \frac{\sum y_{2s}}{\text{rows}(y2)} \quad y_{cg2} = -0.42 \text{ in} \quad z_{cg2} := \frac{\sum z_{2s}}{\text{rows}(z2)} \quad z_{cg2} = 0.00 \text{ in}
\]

\[
cgbolt2 := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} \quad cgbolt2 = \begin{pmatrix} -0.92 \\ -0.42 \\ 0.00 \end{pmatrix} \text{ in}
\]

Note Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 3, the x and y directions in the bolt pattern are unsymmetric and have a offset from the center of gravity.

**Load Vector**

\[
r_{load2} := cgload2 - cgbolt2 \quad r_{load2} = \begin{pmatrix} 0.92 \\ 0.42 \\ 0.00 \end{pmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_{2s} := \sqrt{(x_{2s} - x_{cg2})^2 + (y_{2s} - y_{cg2})^2} \quad r_{2s} = \begin{pmatrix} 2.478 \\ 2.014 \\ 3.760 \end{pmatrix} \text{ in}
\]

**Reading database file for bolted joint**

\[
ID2 := 0 \quad LC2 := 0 \quad M2 := 0
\]

\[
data := \text{READPRN("boltsVertPlatform.txt")}
\]

\[
q := 1 \cdot \text{rows}(data) \quad \text{num_bolts2} := \text{rows}(bolt2)
\]
Loads from 2-06 loads model

Shear in X axis \( Fx_{2q} := \text{data}_{q,3} \) lbf

Shear in Y axis \( Fy_{2q} := \text{data}_{q,4} \) lbf

Axial Load \( Fz_{2q} := \text{data}_{q,5} \) lbf

Moment about X axis \( Mx_{2q} := \text{data}_{q,6} \) in lbf

Moment about Y axis \( My_{2q} := \text{data}_{q,7} \) in lbf

Torsion \( Mz_{2q} := \text{data}_{q,8} \) in lbf

Element Identification \( ID_{2q} := \text{data}_{q,1} \) \( ID_{2q} := ID_{2q} \ 1000 + 1 \) Counter for number of bolts in pattern

Load Case Number \( LC_{2q} := \text{data}_{q,2} \) Applied Bending Moment at Bolts \( M2_{q} := 0 \) in lbf

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

Note bolt number 3 is not included.

\( ID2 := \text{stack}(ID2, ID2 + 1, ID2 + 3) \)

\( LC2 := \text{stack}(LC2, LC2, LC2) \)

Moment Distribution

\[ M_{tot2}^{(q)} := \left( \begin{array}{c} Mx_{2q} \\ My_{2q} \\ Mz_{2q} \end{array} \right) + \eta_{load2} \times \left( \begin{array}{c} Fx_{2q} \\ Fy_{2q} \\ Fz_{2q} \end{array} \right) \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg2}} := M_{\text{tot2}}_{1, q} \\
M_{\text{boltcg2}} := M_{\text{tot2}}_{2, q} \\
M_{\text{boltcg2}} := M_{\text{tot2}}_{3, q}
\]

Tension on bolts

\[ F_{\text{direct2}}_{s, q} := \frac{Fz_{2q}}{\text{num_bolts2}} \]

Direct tensile load calculation

\[
F_{mx_{2, q}} := \begin{cases} 0 \text{ lbf} & \text{if } (y_{2s} - ycg)^2 = 0 \\ \sum_s (y_{2s} - ycg)^2 \cdot At_{2s} \end{cases}
\]

\[ F_{my_{2, q}} := \begin{cases} 0 \text{ lbf} & \text{if } (x_{2s} - xcg)^2 = 0 \\ -My_{\text{boltcg2}} \cdot (x_{2s} - xcg)^2 \cdot At_{2s} \end{cases} \]

\[ F_{t2, q} := F_{\text{direct2}}_{s, q} + F_{mx_{2, q}} + F_{my_{2, q}} \]

Total Tensile load
Shear on bolts

Secondary shear on bolts

\[ Fs_{2s, q} := \frac{M_{z, bolt cg 2q}}{r_{2s} A s_{2s}} \sum_s (r_{2s})^2 \left( A s_{2s} \right) \]

\[ u_s := \text{atan2}(x_{2s} - x_{cg2}, y_{2s} - y_{cg2}) \]

Shear

\[ S_x := 0 \]
\[ S_y := 0 \]

\[ S_{ys, q} := \sin \left( \frac{\beta}{2} - u_s \right) \cdot Fs_{2s, q} \]
\[ S_{xs, q} := -\cos \left( \frac{\beta}{2} - u_s \right) \cdot Fs_{2s, q} \]

Loads of first case

\[ S_x^1 = \begin{pmatrix} -226.49 \\ 113.24 \\ 113.24 \end{pmatrix} \text{ lbf} \]
\[ S_y^1 = \begin{pmatrix} -249.14 \\ -249.14 \\ 498.28 \end{pmatrix} \text{ lbf} \]
\[ u_s = \begin{pmatrix} 137.7 \\ -155.6 \\ -12.8 \end{pmatrix} \text{ deg} \]

\[ F_{stot 2s, q} := \sqrt{\left( S_{xs, q} + F_{xq} \right)^2 + \left( S_{ys, q} + F_{yq} \right)^2} \]

\[ \max(F_{stot 2}) = 1769.21 \text{ lbf} \]
\[ \min(F_{stot 2}) = 8.26 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

Note there are only 3 bolts, since bolt number 3 is not included.

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.

Output2 := augment \[ \begin{pmatrix} \text{ID2, LC2} & P2 & V2 & M2 \end{pmatrix} \text{ lbf, lbf, lbf} \]

Size of the "Output2" Array \( \text{rows(Output2)} = 768 \)

(3 bolts x 256 load cases) x 1 joint = 768 rows

WRITEPRN("output_vertpas_r5_onorbit_fs2.txt") := Output2
Bolt Fail-safe Results

The array from the text file above is read

\[
data_fs := \text{READPRN}("output_vertpas_r5_onorbit_fs2.txt")
\]
\[
s := 1..\text{rows}(data_fs)
\]

**Fail-safe Loads**

- Applied tensile load \( P_{FS_s} := data_{fs_s,3} \text{ lbf} \)
- Applied shear load \( V_{FS_s} := data_{fs_s,4} \text{ lbf} \)
- Applied bending moment \( M_{FS_s} := data_{fs_s,5} \text{ in-lbf} \)

**Fail-safe Factors of Safety**

- Ultimate \( SFu_{FS} := 1.0 \)
- Joint Separation \( SFsep_{FS} := 1.0 \)
This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC

Fail-Safe Stiffness File

Bolt Fail-safe Load data

Joint separation load  \( \text{max}(P_{\text{sep\_FS}}) = 3529.912 \text{ lbf} \)
Max bolt load (ult)  \( \text{max}(P_{\text{b bolt\_FS}}) = 10517.5 \text{ lbf} \)

Summary of fail-safe Margins Removing Bolt 3

<table>
<thead>
<tr>
<th></th>
<th>( MS_{\text{min_FS}} )</th>
<th>Total Thread shear Ult</th>
<th>Shear Ultimate</th>
<th>Bending Ultimate</th>
<th>Combined shear, tension and bending ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( 1.1 ) = 0.18</td>
<td>( 5.1 ) = 0.69</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( 2.1 ) = 2.66</td>
<td>( 6.1 ) = 4.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( 3.1 ) = 0.41</td>
<td>( 7.1 ) = 10.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ul t</td>
<td>( 4.1 ) = 3.39</td>
<td></td>
<td>( 8.1 ) = 0.41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode

\( MS_{\text{bolt\_FS}} := \text{min}(MS_{\text{FS}}) \)
\( MS_{\text{bolt\_FS}} = 0.18 \)

\( MS_{\text{min\_ID}} = 710008002 \) Element Identification (710008) and Bolt Number (2) for Minimum Margin
\( MS_{\text{min\_LC}} = 5031 \) Load Case Number for Minimum Margin
\( MS_{\text{min\_P}} = 3529.9 \) Applied Tensile Load for Minimum Margin
\( MS_{\text{min\_V}} = 1100.3 \) Applied Shear Load for Minimum Margin
\( MS_{\text{min\_M}} = 0 \) Applied Bending Moment for Minimum Margin

Failure Mode FS = "Joint Separation"
Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 2

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, NAS1956C30 (180 ksi), 0.375-24 UNFJ fasteners, holding the Vertex Bracket to the PAS platform. The drawing number for the Vertex Bracket Installation is SGG39135873.

Size	thread/in

\[
bolt2 := \begin{bmatrix} 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \end{bmatrix}
\]

\[s := 1.0 \text{ rows(bolt2)}\]

\[N2s := \text{bolt2}_{s.2} \cdot \frac{1}{\text{in}}\]

\[D2s := \text{bolt2}_{s.1} \text{in}\]

**Tensile Area of bolt**

\[At2s := \beta \left( \frac{D2s - 0.9743 \cdot \frac{1}{N2s}}{2} \right)^2\]

**Shear Area of bolt**

\[As2s := \beta \left( \frac{D2s - 1.299038 \cdot \frac{1}{N2s}}{2} \right)^2\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.75</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2.75</td>
<td>-1.25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2.75</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note Bolt 2 is removed from the bolt pattern.*
Location of applied forces and moments

\[ \begin{align*}
    x_{\text{force}2} &:= 0.0 \text{in} \\
    y_{\text{force}2} &:= 0.0 \text{in} \\
    z_{\text{force}2} &:= 0.0 \text{in} \\
    \text{cgload}2 &:= \begin{pmatrix} x_{\text{force}2} \\ y_{\text{force}2} \\ z_{\text{force}2} \end{pmatrix} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{in}
\end{align*} \]

Center of gravity of bolt group

\[ \begin{align*}
    x_{\text{cg}2} &:= \frac{\sum x_{2s}}{\text{rows}(x2)} \quad x_{\text{cg}2} = 0.92 \text{ in} \\
    y_{\text{cg}2} &:= \frac{\sum y_{2s}}{\text{rows}(y2)} \quad y_{\text{cg}2} = 0.42 \text{ in} \\
    z_{\text{cg}2} &:= \frac{\sum z_{2s}}{\text{rows}(z2)} \quad z_{\text{cg}2} = 0.00 \text{ in} \\
    \text{cgbolt}2 &:= \begin{pmatrix} x_{\text{cg}2} \\ y_{\text{cg}2} \\ z_{\text{cg}2} \end{pmatrix} = \begin{pmatrix} 0.92 \\ 0.42 \\ 0.00 \end{pmatrix} \text{ in}
\end{align*} \]

Note Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 2, the x and y directions in the bolt pattern are unsymmetric and have an offset from the center of gravity.

Load Vector

\[ \begin{align*}
    r_{\text{load}2} &:= \text{cgload}2 - \text{cgbolt}2 \\
    r_{\text{load}2} &:= \begin{pmatrix} -0.92 \\ -0.42 \\ 0.00 \end{pmatrix} \text{ in}
\end{align*} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ \begin{align*}
    r_{2s} &:= \sqrt{(x_{2s} - x_{\text{cg}2})^2 + (y_{2s} - y_{\text{cg}2})^2} \\
    r_{2s} &:= \begin{pmatrix} 3.760 \\ 2.014 \\ 2.478 \end{pmatrix} \text{ in}
\end{align*} \]

Reading database file for bolted joint

\[ \begin{align*}
    ID2 &:= 0 \\
    LC2 &:= 0 \\
    M2 &:= 0 \\
    \text{data} &:= \text{READPRN("boltsVertPlatform.txt")} \\
    q &:= 1 \cdot \text{rows(data)} \quad \text{num_bolts2} := \text{rows(bolt2)}
\end{align*} \]
Loads from 2-06 loads model

Shear in X axis
\[ Fx_2q := -data_q \cdot 3 \text{ lbf} \]

Moment about X axis
\[ Mx_2q := -data_q \cdot 6 \text{ in lbf} \]

Shear in Y axis
\[ Fy_2q := -data_q \cdot 4 \text{ lbf} \]

Moment about Y axis
\[ My_2q := -data_q \cdot 7 \text{ in lbf} \]

Axial Load
\[ Fz_2q := -data_q \cdot 5 \text{ lbf} \]

Torsion
\[ Mz_2q := -data_q \cdot 8 \text{ in lbf} \]

Element Identification
\[ ID_2q := data_q \cdot 1 \]

Load Case Number
\[ LC_2q := data_q \cdot 2 \]

Counter for number of bolts in pattern
\[ ID_2q := ID_2q \cdot 1000 + 1 \]

Applied Bending Moment at Bolts
\[ M_2q := 0 \text{ in lbf} \]

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

Note bolt number 2 is not included.

\[ ID_2 := \text{stack}(ID_2, ID_2 + 2, ID_2 + 3) \]

\[ LC_2 := \text{stack}(LC_2, LC_2, LC_2) \]

Moment Distribution

\[ M_{tot2}^{(q)} := \begin{pmatrix} Mx_2q \\ My_2q \\ Mz_2q \end{pmatrix} + f_{load2} \times \begin{pmatrix} Fx_2q \\ Fy_2q \\ Fz_2q \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{x_boltcg2q} := M_{tot21,q} \]

\[ M_{y_boltcg2q} := M_{tot22,q} \]

\[ M_{z_boltcg2q} := M_{tot23,q} \]

Tension on bolts

\[ F_{\text{direct2},q} := \frac{Fz_2q}{\text{num bolts2}} \]

Direct tensile load calculation

\[ F_{mx2,q} := \begin{cases} 0 \text{ lbf} & \text{if } (x_{2s} - x_{cg2}) = 0 \text{ in} \\ \frac{\left[ M_{x_boltcg2q} (y_{2s} - y_{cg2}) \right] At_{2s}}{\sum_s \left( (y_{2s} - y_{cg2})^2 At_{2s} \right)} & \text{otherwise} \end{cases} \]

\[ F_{my2,q} := \begin{cases} 0 \text{ lbf} & \text{if } (x_{2s} - x_{cg2}) = 0 \text{ in} \\ -\frac{\left[ M_{y_boltcg2q} (x_{2s} - x_{cg2}) \right] At_{2s}}{\sum_s \left( (x_{2s} - x_{cg2})^2 At_{2s} \right)} & \text{otherwise} \end{cases} \]

\[ F_{t2,s,q} := F_{\text{direct2},s,q} + F_{mx2,q} + F_{my2,q} \]

Total Tensile load
Shear on bolts

Secondary shear on bolts

\[ Fs_{s,q} := \frac{M_{\text{boltcg2q}} \cdot r_{2s} \cdot As_{2s}}{\sum_s (r_{2s})^2 \cdot (As_{2s})} \]

\[ u_s := \text{atan2}(x_{2s} - x_{cg2}, y_{2s} - y_{cg2}) \]

Shear

\[ S_x := 0 \quad S_y := 0 \]

\[ Sy_{s,q} := \sin\left(\frac{\beta}{2} - u_s\right) \cdot Fs_{s,q} \quad Sx_{s,q} := -\cos\left(\frac{\beta}{2} - u_s\right) \cdot Fs_{s,q} \]

Loads of first case

\[
\begin{align*}
S_x^1 &= \begin{pmatrix} 15.44 \\ 15.44 \\ -30.87 \end{pmatrix} \text{ lbf} \\
S_y^1 &= \begin{pmatrix} 67.92 \\ -33.96 \\ -33.96 \end{pmatrix} \text{ lbf} \\
u_s &= \begin{pmatrix} 167.2 \\ 24.4 \end{pmatrix} \text{ deg} \\
\end{align*}
\]

\[ F_{\text{tot}2s,q} := \sqrt{\left(Sx_{s,q} + \frac{Fx_q}{2}\right)^2 + \left(Sy_{s,q} + \frac{Fy_q}{2}\right)^2} \]

\[ \max(F_{\text{tot}2}) = 1734.47 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.\[ \min(F_{\text{tot}2}) = 10.79 \text{ lbf} \]

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 2 is not included.

\[
P2 := \text{stack}\left(\begin{pmatrix} (Ft_2)^T \end{pmatrix}^1, \begin{pmatrix} (Ft_2)^T \end{pmatrix}^2, \begin{pmatrix} (Ft_2)^T \end{pmatrix}^3 \right)
\]

\[
V2 := \text{stack}\left(\begin{pmatrix} (F_{\text{tot}2})^T \end{pmatrix}^1, \begin{pmatrix} (F_{\text{tot}2})^T \end{pmatrix}^2, \begin{pmatrix} (F_{\text{tot}2})^T \end{pmatrix}^3 \right)
\]

\[
M2 := \text{stack}(M2, M2, M2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{Output2} := \text{augment}\left(\begin{pmatrix} \text{ID2, LC2} \end{pmatrix}^1, \begin{pmatrix} P2 \end{pmatrix}^2, \begin{pmatrix} V2 \end{pmatrix}^3, \begin{pmatrix} M2 \end{pmatrix}^4 \right)
\]

Size of the "Output2" Array \[ \text{rows(Output2)} = 768 \]

(3 bolts x 256 load cases) x 1 joint = 768 rows

\[
\text{WRITEPRN(\"output_vertpas_r5_onorbit_fs3.txt\") := Output2}
\]

Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.
Bolt Fail-safe Results

The array from the text file above is read

\[
data_{fs} := \text{READPRN}("\text{output\_vertpas\_r5\_onorbit\_fs3.txt}\")\quad s := 1 \ldots \text{rows}(data_{fs})
\]

Fail-safe Loads

- Applied tensile load \( P_{FS} := data_{fs,3} \) lbf
- Applied shear load \( V_{FS} := data_{fs,4} \) lbf
- Applied bending moment \( M_{FS} := data_{fs,5} \) in lbf

Fail-safe Factors of Safety

- Ultimate \( SFu_{FS} := 1.0 \)
- Joint Separation \( SFsep_{FS} := 1.0 \)
Bolts from PAS Vertex Bracket to PAS Platform

This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC

**Bolt Fail-safe Load data**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Max Load (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Psep_FS</td>
<td>6857.367</td>
</tr>
<tr>
<td>Pb_FS</td>
<td>11072.1</td>
</tr>
<tr>
<td>P_FS</td>
<td>6857.367</td>
</tr>
<tr>
<td>V_FS</td>
<td>1734.467</td>
</tr>
</tbody>
</table>

**Summary of fail-safe Margins Removing Bolt 2**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Margin Factor</th>
<th>Marginal Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{minFS}^{1.1} = -0.39</td>
<td></td>
</tr>
<tr>
<td>Direct Tension</td>
<td>MS_{minFS}^{2.1} = 0.88</td>
<td></td>
</tr>
<tr>
<td>Total Tension</td>
<td>MS_{minFS}^{3.1} = 0.34</td>
<td></td>
</tr>
<tr>
<td>Direct Thread</td>
<td>MS_{minFS}^{4.1} = 1.26</td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode**

$$MS_{bolt_FS} := \min(\text{MS}_{FS})$$

$$MS_{bolt_FS} = -0.39$$

Failure Mode = "Joint Separation"

(Note: A negative margin of safety for joint separation is acceptable for fail-safe.)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS_{min_ID}</td>
<td>Element Identification (710008) and Bolt Number (4) for Minimum Margin</td>
</tr>
<tr>
<td>MS_{min_LC}</td>
<td>Load Case Number for Minimum Margin</td>
</tr>
<tr>
<td>MS_{min_P}</td>
<td>Applied Tensile Load for Minimum Margin</td>
</tr>
<tr>
<td>MS_{min_V}</td>
<td>Applied Shear Load for Minimum Margin</td>
</tr>
<tr>
<td>MS_{min_M}</td>
<td>Applied Bending Moment for Minimum Margin</td>
</tr>
</tbody>
</table>
Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 1

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, NAS1956C30 (180 ksi), 0.375-24 UNFJ fasteners, holding the Vertex Bracket to the PAS platform. The drawing number for the Vertex Bracket Installation is SGG39135873.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
\text{bolt2} & \quad 0.375 \quad 24 \\
& \quad 0.375 \quad 24 \\
& \quad 0.375 \quad 24 \\
\end{align*}
\]

\[
s := 1 \quad \text{rows(bolt2)}
\]

\[
N_{2s} := \frac{1}{s} \quad \text{pitch of bolt}
\]

\[
D_{2s} := \text{bolt2} \quad \text{in}
\]

\[
\text{bolt diameter}
\]

**Tensile Area of bolt**

\[
A_{t2s} := \beta \left( \frac{D_{2s} - 0.9743 \frac{1}{N_{2s}}}{2} \right)^2
\]

**Shear Area of bolt**

\[
A_{s2s} := \beta \left( \frac{D_{2s} - 1.299038 \frac{1}{N_{2s}}}{2} \right)^2
\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-2.75 in</td>
<td>-1.25 in</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2.75 in</td>
<td>1.25 in</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2.75 in</td>
<td>-1.25 in</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note Bolt 1 is removed from the bolt pattern.*
Location of applied forces and moments

\[ \text{xforce2} := 0.0 \text{in} \quad \text{yforce2} := 0.0 \text{in} \quad \text{zforce2} := 0.0 \text{in} \]

\[ \text{cgload2} := \begin{pmatrix} \text{xforce2} \\ \text{yforce2} \\ \text{zforce2} \end{pmatrix} \quad \text{cgload2} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{in} \]

Center of gravity of bolt group

\[ x_{cg2} := \frac{\sum x_{2s}}{\text{rows}(x2)} \quad x_{cg2} = 0.92 \text{ in} \]
\[ y_{cg2} := \frac{\sum y_{2s}}{\text{rows}(y2)} \quad y_{cg2} = -0.42 \text{ in} \]
\[ z_{cg2} := \frac{\sum z_{2s}}{\text{rows}(z2)} \quad z_{cg2} = 0.00 \text{ in} \]

\[ \text{cgbolt2} := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} \quad \text{cgbolt2} = \begin{pmatrix} 0.92 \\ -0.42 \\ 0.00 \end{pmatrix} \text{in} \]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 1, the x and y directions in the bolt pattern are unsymmetric and have an offset from the center of gravity.

Load Vector

\[ \eta_{load2} := \text{cgload2} - \text{cgbolt2} \]
\[ \eta_{load2} = \begin{pmatrix} -0.92 \\ 0.42 \\ 0.00 \end{pmatrix} \text{in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_{s} := \sqrt{(x_{2s} - x_{cg2})^2 + (y_{2s} - y_{cg2})^2} \]
\[ r_{s} = \begin{pmatrix} 3.760 \\ 2.478 \\ 2.014 \end{pmatrix} \text{in} \]

Reading database file for bolted joint

\[ \text{ID2} := 0 \quad \text{LC2} := 0 \quad \text{M2} := 0 \]
\[ \text{data} := \text{READPRN}("\text{boltsVertPlatform.txt}\") \]
\[ q := 1 \cdot \text{rows(data)} \quad \text{num\_bolts2} := \text{rows(bolt2)} \]
Loads from 2-06 loads model

Shear in X axis \( F_{x2q} := -data_{q,3} \text{ lbf} \)
Shear in Y axis \( F_{y2q} := -data_{q,4} \text{ lbf} \)
Axial Load \( F_{z2q} := -data_{q,5} \text{ lbf} \)
Element Identification \( ID_{2q} := data_{q,1} \)
Load Case Number \( LC_{2q} := data_{q,2} \)
Moment about X axis \( M_{x2q} := -data_{q,6} \text{ in lbf} \)
Moment about Y axis \( M_{y2q} := -data_{q,7} \text{ in lbf} \)
Torsion \( M_{z2q} := -data_{q,8} \text{ in lbf} \)

Applied Bending Moment at Bolts \( M_{2q} := 0 \text{ in lbf} \)

Counter for number of bolts in pattern \( ID_{2q} := ID_{2q} 1000 + 1 \)

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

Note bolt number 1 is not included.

\( ID_{2} := \text{stack}(ID_{2} + 1, ID_{2} + 2, ID_{2} + 3) \)

\( LC_{2} := \text{stack}(LC_{2}, LC_{2}, LC_{2}) \)

Moment Distribution

\( M_{tot2} := \begin{pmatrix} M_{x2q} \\ M_{y2q} \\ M_{z2q} \end{pmatrix} + \eta_{load2} \times \begin{pmatrix} F_{x2q} \\ F_{y2q} \\ F_{z2q} \end{pmatrix} \)

Use the cross-product to determine the additional moments acting on the fasteners.

\( M_{x\_boltcg2q} := M_{tot2,q} \)

\( M_{y\_boltcg2q} := M_{tot2,q} \)

\( M_{z\_boltcg2q} := M_{tot2,q} \)

Tension on bolts

\( F_{direct2s,q} := \frac{F_{z2q}}{\text{num\_bolts2}} \)

Direct tensile load calculation

\( F_{mx2s,q} := \begin{cases} 0 \text{ lbf if } (y_{2s} - yc2) = 0 \text{ in} \\ \sum_s [(y_{2s} - yc2)^2 \text{ At}_{2s}] \text{ At}_{2s} \end{cases} \)

\( F_{my2s,q} := \begin{cases} 0 \text{ lbf if } (x_{2s} - xc2) = 0 \text{ in} \\ \sum_s [(x_{2s} - xc2)^2 \text{ At}_{2s}] \text{ At}_{2s} \end{cases} \)

\( F_{t2s,q} := F_{direct2s,q} + F_{mx2s,q} + F_{my2s,q} \)

Total Tensile load
Shear on bolts

Secondary shear on bolts

\[ Fs_{s,q} := \frac{M_{z_{bolts}} \tan(\theta_q)}{\sqrt{\sum (r_{s})^2 (A_{s})}} \]

\[ u_s := \tan^{-1}(x_{2s} - x_{cg2}, y_{2s} - y_{cg2}) \]

Shear

\[ S_x := 0 \quad S_y := 0 \]

\[ S_{y_{s,q}} := \sin\left(\frac{\beta}{2} - u_s\right) \cdot F_{s_{2,s,q}} \]

\[ S_{x_{s,q}} := -\cos\left(\frac{\beta}{2} - u_s\right) \cdot F_{s_{2,s,q}} \]

Loads of first case

\[ S_x^1 = \begin{pmatrix} -9.19 \\ 18.37 \\ -9.19 \end{pmatrix} \text{ lbf} \quad S_y^1 = \begin{pmatrix} 40.42 \\ -20.21 \\ -20.21 \end{pmatrix} \text{ lbf} \quad u_s = \begin{pmatrix} -167.2 \\ 42.3 \\ -24.4 \end{pmatrix} \text{ deg} \]

\[ F_{stot_{2,s,q}} := \sqrt{\left(S_{x_{s,q}} + \frac{F_{x_{q}}}{2}\right)^2 + \left(S_{y_{s,q}} + \frac{F_{y_{q}}}{2}\right)^2} \]

\[ \min(F_{stot}) = 11.66 \text{ lbf} \quad \max(F_{stot}) = 1766.25 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 1 is not included.

\[ P_2 := \text{stack}\left(\begin{pmatrix} F_2^T \end{pmatrix}, \begin{pmatrix} F_2^T \end{pmatrix}, \begin{pmatrix} F_2^T \end{pmatrix}\right) \]

\[ V_2 := \text{stack}\left(\begin{pmatrix} F_{stot_2}^T \end{pmatrix}, \begin{pmatrix} F_{stot_2}^T \end{pmatrix}, \begin{pmatrix} F_{stot_2}^T \end{pmatrix}\right) \]

\[ M_2 := \text{stack}(M_2, M_2, M_2) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

Output2 := augment\(\left(\begin{pmatrix} ID2, LC2 \\ P_2, V_2, M_2 \end{pmatrix}\right)\)

Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.

Size of the "Output2" Array rows(\(\text{Output2}\)) = 768

(3 bolts x 256 load cases) x 1 joint = 768 rows

\[ \text{WRITEPRN}(\text{"outputVertpas_r5_onorbit_fs4.txt"}) := \text{Output2} \]
**Bolt Fail-safe Results**

The array from the text file above is read

\[
\text{data}_\text{fs} := \text{READPRN("output_vertpas_r5_onorbit_fs4.txt")}
\]

\[s := 1 \ldots \text{rows(data}_\text{fs})\]

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load</td>
<td>(P_\text{FS}<em>s := \text{data}</em>\text{fs}_{s,3})</td>
<td>(\text{lbf})</td>
</tr>
<tr>
<td>Shear load</td>
<td>(V_\text{FS}<em>s := \text{data}</em>\text{fs}_{s,4})</td>
<td>(\text{lbf})</td>
</tr>
<tr>
<td>Bending moment</td>
<td>(M_\text{FS}<em>s := \text{data}</em>\text{fs}_{s,5})</td>
<td>(\text{in lbf})</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>(\text{SFu}_\text{FS} := 1.0)</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>(\text{SFsep}_\text{FS} := 1.0)</td>
</tr>
</tbody>
</table>
Bolt Fail-safe Load data

Joint separation load  \( \max(P_{\text{sep,FS}}) = 3508.267 \text{ lbf} \)  \( \max(P_{\text{FS}}) = 3508.267 \text{ lbf} \)

Max bolt load (ultimate) \( \max(P_{b,FS}) = 10513.9 \text{ lbf} \)  \( \max(V_{FS}) = 1766.25 \text{ lbf} \)

Summary of fail-safe Margins Removing Bolt 1

<table>
<thead>
<tr>
<th></th>
<th>( \text{MS}_{\text{min,FS}} )</th>
<th>( \text{MS}_{\text{min,FS}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( 1.1 )</td>
<td>( 1.1 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( 2.1 )</td>
<td>( 2.1 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( 3.1 )</td>
<td>( 3.1 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( 4.1 )</td>
<td>( 4.1 )</td>
</tr>
<tr>
<td>Total Thread shear Ult</td>
<td>( 5.1 )</td>
<td>( 5.1 )</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>( 6.1 )</td>
<td>( 6.4 )</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( 7.1 )</td>
<td>( 10.0 )</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>( 8.1 )</td>
<td>( 0.41 )</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode

\( \text{MS}_{\text{bolt,FS}} := \min(\text{MS}_{\text{FS}}) \)

\( \text{MS}_{\text{bolt,FS}} = 0.19 \)  \( \text{Failure Mode}_{\text{FS}} = "\text{Joint Separation}" \)

\( \text{MS}_{\text{min,ID}} = 710008004 \)  Element Identification (710008) and Bolt Number (4) for Minimum Margin

\( \text{MS}_{\text{min,LC}} = 5023 \)  Load Case Number for Minimum Margin

\( \text{MS}_{\text{min,P}} = 3508.3 \)  Applied Tensile Load for Minimum Margin

\( \text{MS}_{\text{min,V}} = 1098.9 \)  Applied Shear Load for Minimum Margin

\( \text{MS}_{\text{min,M}} = 0 \)  Applied Bending Moment for Minimum Margin
4.12.6.2 Vertex Bracket to PAS Platform Shear Bolt Analysis
**Section 4.12.6.2  PAS Vertex Bracket to PAS Platform - Shear Bolt**

**CHECK** Shear Bolt (NAS1160-6-30, .375-24 x 2.482L, CRES A286, 160 KSI), Washer (NAS1587-6C, C-Sink, .375 x .078 THK, CRES), Nut (NAS1805-6, .375-24, CRES A286, 180 KSI)

```plaintext
data := READPRN("output_vertpas_r5_onorbit.txt")
s := 1 .. rows(data)

Flange 1: Vertex Bracket
Part number: SG39135813
Material: 7050-T7451, 16.50x10.72x7.92, BMS-7-323C

Flange 2: PAS Platform
Part number: SG39135817
Material: 7050-T7451, 44.82x45.40x2.75, BMS-7-323C
```

**Loads**

```plaintext
ele1 := 710008001  ele2 := 1

Applied tensile load

P :=
for s3 e s
if data_{s3,1} = ele1 \lor data_{s3,1} = ele2
s2 := s2 + 1
P_{s2} := data_{s3,3} \text{ lbf}
P2
```

Applied bending moment

```plaintext
M :=
for s3 e s
if data_{s3,1} = ele1 \lor data_{s3,1} = ele2
s2 := s2 + 1
P_{s2} := data_{s3,5} \text{ in-lbf}
P2
```

4.12.6.2-2  ESCG-4005-05-AMS-0039
 Applied shear load

\[
V := \text{for } s3 \in s \\
\quad \text{if } \text{data}_{s3,1} = \text{ele1 } \lor \text{data}_{s3,1} = \text{ele2} \\
\quad \quad s2 \leftarrow s2 + 1 \\
\quad \quad \text{P2}_{s2} \leftarrow \text{data}_{s3,4} \text{lbf} \\
\quad \text{P2}
\]

\[
\text{ID} := \text{for } s3 \in s \\
\quad \text{if } \text{data}_{s3,1} = \text{ele1 } \lor \text{data}_{s3,1} = \text{ele2} \\
\quad \quad s2 \leftarrow s2 + 1 \\
\quad \quad \text{P2}_{s2} \leftarrow \text{data}_{s3,1} \\
\quad \text{P2}
\]

\[
\text{LC} := \text{for } s3 \in s \\
\quad \text{if } \text{data}_{s3,1} = \text{ele1 } \lor \text{data}_{s3,1} = \text{ele2} \\
\quad \quad s2 \leftarrow s2 + 1 \\
\quad \quad \text{P2}_{s2} \leftarrow \text{data}_{s3,2} \\
\quad \text{P2}
\]

\[
s := \text{1..rows(ID)} \\
\text{rows(ID)} = 256.00 \\
\frac{384}{64.3} = 2.00
\]

**Temperature data**

- **Assembly**
  - Temp\_initial := 70 deg
- **Maximum**
  - Temp\_max := 151 deg
- **Minimum**
  - Temp\_min := -43 deg

**Factors of Safety**

- **Ultimate**
  - SFu := 2.0
- **Yield**
  - SFy := 1.25
- **Joint Separation**
  - SFsep := 1.2
- **Fitting factor**
  - FF := 1.15
**Bolt and Nut Data**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter of bolt</td>
<td>D = 0.375 in</td>
</tr>
<tr>
<td>Reduced dia of shear bolt</td>
<td>Dnew = 0.306 in</td>
</tr>
<tr>
<td>Shear Bolt Shank Diameter</td>
<td>Dshank = 0.425 in</td>
</tr>
<tr>
<td>GRIP Length of Bolt</td>
<td>GRIP = 30.0625 in</td>
</tr>
<tr>
<td>Total length of bolt</td>
<td>L = GRIP + 0.607 in</td>
</tr>
<tr>
<td>Threaded length</td>
<td>Lt = 2.482 in - 1.885 in - 0.083 in</td>
</tr>
<tr>
<td>Bolt head dia. across flats</td>
<td>dw = 0.554 in</td>
</tr>
<tr>
<td>Number of threads/inch</td>
<td>Nt = 24 1 in</td>
</tr>
</tbody>
</table>

**Washer Data**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of washers (2X)</td>
<td>tw = 0.156 in</td>
</tr>
<tr>
<td>Outer Diameter of washer</td>
<td>Dw = 0.687 in</td>
</tr>
<tr>
<td>Inner Diameter of washer</td>
<td>Dwi = 0.378 in</td>
</tr>
</tbody>
</table>

**Flange data**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of flange 1</td>
<td>tf1 = 0.500 in - 0.175 in = 0.325 in</td>
</tr>
<tr>
<td>Thickness of flange 2</td>
<td>tf2 = 2.75 in - 1.25 in = 1.50 in</td>
</tr>
<tr>
<td>Diameter of hole</td>
<td>D_hole = 0.428 in</td>
</tr>
</tbody>
</table>

**Material Property Data**

**Bolt**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature correction factor for bolt strength ultimate</td>
<td>TSu_bolt = 0.96</td>
</tr>
<tr>
<td>Bolt ultimate tensile allowable stress</td>
<td>Ftu_bolt = 160000 psi</td>
</tr>
<tr>
<td>Bolt ultimate shear allowable stress</td>
<td>Fsu_bolt = 0.6 Ftu_bolt</td>
</tr>
<tr>
<td>Bolt yield Tensile allowable stress</td>
<td>Fty_bolt = 120000 psi</td>
</tr>
<tr>
<td>Temperature correction factor for bolt modulus</td>
<td>TE_bolt = 0.96</td>
</tr>
<tr>
<td>Modulus of elasticity of bolt</td>
<td>E_bolt = $(29.1 \times 10^6)$ psi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>Tsy_bolt = 0.96</td>
</tr>
<tr>
<td>Thermal coefficient for bolt</td>
<td>$\beta_{bolt_hot} = 9.1 \times 10^{-6}$ in/in deg</td>
</tr>
<tr>
<td></td>
<td>$\beta_{bolt_cold} = 8.7 \times 10^{-6}$ in/in deg</td>
</tr>
</tbody>
</table>
**Nut**

Temperature correction factor for nut strength

\[ TS_{\text{nut}} := 0.96 \]

Ultimate tensile allowable stress

\[ F_{tu_{\text{nut}}} := 180000 \text{ psi} \]

Ultimate Shear allowable stress:

\[ F_{su_{\text{nut}}} := 0.6 \times F_{tu_{\text{nut}}} \]

Ultimate axial strength of nut

\[ F_{tu_{\text{nut}}} := 16488 \text{ lbf} \]

(180/125 = 1.44, 11450 * 1.44 = 16488, Ref. NAS1291)

**Washer**

Temperature correction factor for washer modulus

\[ T_{E_{\text{washer}}} := 0.96 \]

Modulus of elasticity of washer:

\[ E_{\text{washer}} := \left( 29.1 \times 10^6 \text{ psi} \right) \]

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{F1E} := 0.98 \text{ (modulus)} \]

Temperature correction factor for flange 2

\[ T_{F2E} := 0.98 \]

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange1}} := \left( 10.3 \times 10^6 \text{ psi} \right) \quad E_{\text{flange2}} := \left( 10.3 \times 10^6 \text{ psi} \right) \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \text{ in in deg} \]

\[ \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \text{ in in deg} \]

\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \text{ in in deg} \]

\[ \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ in in deg} \]

**Torque/Preload data**

Maximum torque

\[ T_{\text{max}} := 339 \text{ in-lbf} \]

\[ 59.0\% \text{ of Yield} \]

Minimum torque

\[ T_{\text{min}} := 288 \text{ in-lbf} \]

\[ 85\% \text{ of Max Torque} \]

Torque coefficient

\[ k := 0.15 \]

Loading plane factor

\[ n := 0.5 \]

Preload Uncertainty

\[ u := 0.25 \]
Bolt Load data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.346</td>
<td>Preload due to temperature</td>
<td>712.1 lbf</td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLDmax = 8245.5 lbf</td>
<td></td>
<td>-912.9 lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLDmin = 2550.4 lbf</td>
<td>Uncertainty factor</td>
<td>0.25</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>max(Psep) = 719.935 lbf</td>
<td>Torque coefficient</td>
<td>0.15</td>
</tr>
<tr>
<td>Max. load on the bolt (ultimate)</td>
<td>max(Pb) = 8484.5 lbf</td>
<td>Loading plane factor</td>
<td>0.50</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>max(Pby) = 8394.8 lbf</td>
<td>Thread pullout strength required to develop full strength of bolt</td>
<td>15838.4 lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PAT = 13198.6 lbf</td>
<td>Nut ultimate tensile strength</td>
<td>15828.5 lbf</td>
</tr>
</tbody>
</table>

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_min_1.1 = 2.73</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_min_2.1 = 7.19</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_min_3.1 = 8.82</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_min_4.1 = 0.33</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_min_5.1 = 0.01</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

MSbolt = 0.01

Failure Mode = "Total Tension Yield"

Element Identification (710008) and Bolt Number (1) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
Fail-safe Analysis

Fail-safe Loads

```lisp
(data_fs1 := READPRN("output_vertpas_r5_onorbit_fs1.txt"))
(data_fs2 := READPRN("output_vertpas_r5_onorbit_fs2.txt"))
(data_fs3 := READPRN("output_vertpas_r5_onorbit_fs3.txt"))
(data_fs4 := READPRN("output_vertpas_r5_onorbit_fs4.txt"))

(data_fs := stack(data_fs1, data_fs2, data_fs3, data_fs4))
(rows(data_fs) = 3072.00)
(s := 1 .. rows(data_fs))
(rows(data_fs1) = 768.00)
```

Fail-safe Factors of Safety

| Ultimate | SFu_FS := 1.0 |
| Joint Separation | SFsep_FS := 1.0 |

P_FS :=

```
for s3 ∈ s
  if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
    s2 ← s2 + 1
    P_{s2} ← data_fs_{s3,3} lbf
  P2
```

ID_FS :=

```
for s3 ∈ s
  if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
    s2 ← s2 + 1
    P_{s2} ← data_fs_{s3,1}
  P2
```

LC FS :=

```
for s3 ∈ s
  if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
    s2 ← s2 + 1
    P_{s2} ← data_fs_{s3,2}
  P2
```

M_FS :=

```
for s3 ∈ s
  if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
    s2 ← s2 + 1
    P_{s2} ← data_fs_{s3,5} in lbf
  P2
```

V_FS :=

```
for s3 ∈ s
  if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
    s2 ← s2 + 1
    P_{s2} ← data_fs_{s3,4} lbf
  P2
```

4.12.6.2-7 ESCG-4005-05-AMS-0039
s := 1. rows(ID_FS)

\[
\text{rows(ID_FS)} = \frac{384}{64.3} = 2.00
\]

This file uses the calculations shown in `\escfl02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC\`

**Bolt Fail-safe Load data**

- Joint separation load  \( \text{max(Psep_FS)} = 1253.012 \text{ lbf} \)
- Max. load on the bolt(ultimate)  \( \text{max(Pb_FS)} = 8495 \text{ lbf} \)

**Summary of fail-safe Margins for bolt**

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>\text{MS}_{\text{minFS}} _1 _1 _1</td>
<td>1.14</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>\text{MS}_{\text{minFS}} _2 _1 _1</td>
<td>8.16</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>\text{MS}_{\text{minFS}} _3 _1 _1</td>
<td>0.55</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>\text{MS}_{\text{minFS}} _4 _1 _1</td>
<td>9.99</td>
</tr>
<tr>
<td>Total thread shear Ultimate</td>
<td>\text{MS}_{\text{minFS}} _5 _1 _1</td>
<td>0.86</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>\text{MS}_{\text{minFS}} _6 _1 _1</td>
<td>4.10</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>\text{MS}_{\text{minFS}} _7 _1 _1</td>
<td>10.00</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>\text{MS}_{\text{minFS}} _8 _1 _1</td>
<td>0.55</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode**

\[
\text{MSbolt_FS} := \min(\text{MS_FS})
\]

\[
\text{MSbolt_FS} = 0.55
\]

Failure_Mode_FS = "Combined Shear Tension Bending Ultimate"

- Element Identification (710008) and Bolt Number (1) for Minimum Margin
- Load Case Number for Minimum Margin
- Applied Tensile Load for Minimum Margin
- Applied Shear Load for Minimum Margin
- Applied Bending Moment for Minimum Margin
4.12.7 Aft Brackets to PAS Platform Bolted Interface
Section 4.12.7  Aft Bracket to PAS Platform Bolted Interface

The Aft Bracket to PAS Platform Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12.7.1</td>
<td>Aft Brackets to PAS Platform</td>
</tr>
<tr>
<td>4.12.7.1</td>
<td>Aft Brackets to PAS Platform Fail Safe</td>
</tr>
<tr>
<td>4.12.7.2</td>
<td>Aft Brackets to PAS Platform Shear Bolt Analysis</td>
</tr>
<tr>
<td>4.12.7.2</td>
<td>Aft Brackets to PAS Platform Shear Bolt Analysis - Fail Safe</td>
</tr>
</tbody>
</table>
4.12.7.1 Aft Brackets to PAS Platform
Section 4.12.7.1  PAS Aft Bracket to PAS Platform Bolt Analysis

There are a total of 4 fasteners attaching one end of the aft brackets to the PAS platform. Three fasteners are EWB 0420 (200 KSI), 0.375-24 UNFJ and 1 fastener is NAS1160-6 (shear bolt). The drawing number for the Aft Brackets Installation is SGG39135873.

Bolt Geometry

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
</tbody>
</table>

\[
i := 1 \ldots \text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{i, 2} \times \frac{1}{\text{in}}
\]

pitch of bolt

\[
D_i := \text{bolt}_{i, 1} \times \frac{1}{\text{in}}
\]

bolt diameter

Tensile Area of bolt

\[
A_t := \beta \left( \frac{D_i - 0.9743}{2} \right)^2
\]

Shear Area of bolt

\[
A_s := \beta \left( \frac{D_i - 1.299038}{2} \right)^2
\]
Bolts from PAS Aft Bracket to PAS Platform

Note For local coordinate system 800001, the z axis direction is tension and the x and y axes are the shear directions.

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinates</th>
<th>y coordinates</th>
<th>z coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.5</td>
<td>2.3125</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-1.5</td>
<td>-2.3125</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>2.3125</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>-2.3125</td>
<td>0</td>
</tr>
</tbody>
</table>

**Location of applied forces and moments**

xforce := 0.0in 
yforce := 0.0in 
zforce := 0.0in

cgload := \[
\begin{pmatrix}
\text{xforce} \\
\text{yforce} \\
\text{zforce}
\end{pmatrix}
\] 
cgload = \[
\begin{pmatrix}
0.00 \\
0.00 \\
0.00
\end{pmatrix}
\] in

Center of gravity of bolt group

Note Since the z direction is into the plate the loads are shared equally between the bolts. The x and y axis have a zero offset from the center of gravity.
Load Vector

\[ \mathbf{r}_{\text{load}} := \mathbf{c}_{\text{load}} - \mathbf{c}_{\text{bolt}} \]

\[ \mathbf{r}_{\text{load}} = \begin{bmatrix} 0.00 \\ 0.00 \\ 0.00 \end{bmatrix} \text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_i := \sqrt{(x_i - x_{cg})^2 + (y_i - y_{cg})^2} \]

\[ r = \begin{bmatrix} 2.756 \\ 2.756 \\ 2.756 \\ 2.756 \end{bmatrix} \text{ in} \]

Loads model 2-06 was used to retrieve loads at the bolted interface. MPCs located at the center of the aft brackets were post processed in NASPOST for forces and moments in the \( x \), \( y \), and \( z \) directions. The MPCs are located on RBE elements 710009 and 710010. These loads are read into an array and distributed out to the 4 bolts for each Aft Bracket.

Note This joint was checked for minimum margins of safety for on-orbit, liftoff, abort landing, and berthing load cases.

Reading database file for bolted joint

See Appendix A22 for NASPOST data.

Data := READPRN("boltsAftPlatform.txt")

\( j := 1 \ldots \text{rows(data)} \)

\( \text{num_bolts} := \text{rows(bolt)} \)

Note that "boltsAftPlatform.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files, see Appendix A22.

Element Identification \( ID_j := \text{data}_{j,1} \)

Load Case Number \( LC_j := \text{data}_{j,2} \)

Applied Bending Moment at Bolts \( M_j := \text{data}_{j,6} \text{ in-lbf} \)

Shear in X axis \( F_{x_j} := -\text{data}_{j,3} \text{ lbf} \)

Shear in Y axis \( F_{y_j} := -\text{data}_{j,4} \text{ lbf} \)

Axial Load \( F_{z_j} := -\text{data}_{j,5} \text{ lbf} \)

Moment about X axis \( M_{x_j} := -\text{data}_{j,6} \text{ in-lbf} \)

Moment about Y axis \( M_{y_j} := -\text{data}_{j,7} \text{ in-lbf} \)

Torsion \( M_{z_j} := -\text{data}_{j,8} \text{ in-lbf} \)
Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\[
\text{ID} := \text{stack}([\text{ID}, \text{ID} + 1, \text{ID} + 2, \text{ID} + 3])
\]

\[
\text{LC} := \text{stack}([\text{LC}, \text{LC}, \text{LC}, \text{LC}])
\]

Moment Distribution

\[
M_{\text{tot}} := \begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} + \begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{bolt}c_{j}} := M_{\text{tot}}^{1,j} \\
M_{\text{bolt}c_{g}} := M_{\text{tot}}^{2,j} \\
M_{\text{bolt}c_{j}} := M_{\text{tot}}^{3,j}
\]

Tension on bolts

\[
F_{\text{direct}_{i,j}} := \frac{F_z}{\text{num\_bolts}}
\]

Direct tensile load calculation

\[
F_{mx_{i,j}} := \begin{cases}
0 \text{ lbf} & \text{if } (y_i - y_{cg}) = 0 \\
\frac{M_{\text{bolt}c_{g}}(y_i - y_{cg})A_t}{\sum_i ([y_i - y_{cg}]^2)A_t} & \text{otherwise}
\end{cases}
\]

Tensile due to the moment about X

\[
F_{my_{i,j}} := \begin{cases}
0 \text{ lbf} & \text{if } (x_i - x_{cg}) = 0 \\
\frac{-M_{\text{bolt}c_{g}}(x_i - x_{cg})A_t}{\sum_i ([x_i - x_{cg}]^2)A_t} & \text{otherwise}
\end{cases}
\]

Tensile due to the moment about Y

\[
F_{t_{i,j}} := F_{\text{direct}_{i,j}} + F_{mx_{i,j}} + F_{my_{i,j}}
\]
**Shear on bolts**

Secondary shear on bolts  
\[ F_{s_{i,j}} = \frac{M_{z_{bolts}} c_{j} y_{i} A_{s_{i}}}{\sum_{i} \left( \frac{M_{z_{bolts}} c_{j} y_{i} A_{s_{i}}}{M_{z_{bolts}} c_{j} y_{i} A_{s_{i}}} \right)^2} \]

\[ u_{i} = \tan(\alpha_{i} - x_{c_g}, y_{i} - y_{c_g}) \]

Shear  
\[ S_{y_{i,j}} = \sin\left(\frac{\beta_{i}}{2} - u_{i}\right) F_{s_{i,j}} \]
\[ S_{x_{i,j}} = -\cos\left(\frac{\beta_{i}}{2} - u_{i}\right) F_{s_{i,j}} \]

\[ u = \begin{pmatrix} 123 \\ -123 \\ 57 \\ -57 \end{pmatrix} \text{ deg} \]

Loads of first case  
\[
\begin{align*}
S_{x} &= \begin{pmatrix} -522.98 \\ 522.98 \\ -522.98 \\ 522.98 \end{pmatrix} \text{ lbf} \\
S_{y} &= \begin{pmatrix} -339.23 \\ 339.23 \end{pmatrix} \text{ lbf} \\
F_{sot_{i,j}} &= \sqrt{\left( \frac{S_{x_{i,j}} + F_{x_{j}}}{2} \right)^2 + \left( \frac{S_{y_{i,j}} + F_{y_{j}}}{2} \right)^2} \\
\end{align*}
\]

\[ \text{max}(F_{sot}) = 1378.67 \text{ lbf} \]

\[ \text{min}(F_{sot}) = 1.38 \text{ lbf} \]

Assume that Fx and Fy are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[ P := \text{stack}\left( \begin{pmatrix} F_{x_{1}} \\ F_{x_{2}} \\ F_{x_{3}} \\ F_{x_{4}} \end{pmatrix}, \begin{pmatrix} F_{x_{1}} \\ F_{x_{2}} \\ F_{x_{3}} \\ F_{x_{4}} \end{pmatrix}, \begin{pmatrix} F_{x_{1}} \\ F_{x_{2}} \\ F_{x_{3}} \\ F_{x_{4}} \end{pmatrix}, \begin{pmatrix} F_{x_{1}} \\ F_{x_{2}} \\ F_{x_{3}} \\ F_{x_{4}} \end{pmatrix} \right) \]

\[ V := \text{stack}\left( \begin{pmatrix} F_{sot_{1}} \\ F_{sot_{2}} \\ F_{sot_{3}} \end{pmatrix}, \begin{pmatrix} F_{sot_{1}} \\ F_{sot_{2}} \\ F_{sot_{3}} \end{pmatrix}, \begin{pmatrix} F_{sot_{1}} \\ F_{sot_{2}} \\ F_{sot_{3}} \end{pmatrix}, \begin{pmatrix} F_{sot_{1}} \\ F_{sot_{2}} \\ F_{sot_{3}} \end{pmatrix} \right) \]

\[ M := \text{stack}(M, M, M, M) \]

The "Output" file outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

\[ \text{Output} := \text{augment}(\text{ID, LC, P, V, M}) \]

Note Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.

Size of the "Output" Array  
\[ \text{rows(Output)} = 2048 \]

(4 bolts x 256 load cases) x 2 joint = 2048 rows

\[ \text{WRITEPRN}("output_aftbrkpas_r5_onorbit.txt") := \text{Output} \]
CHECK Bolts (EWB0420-6-30 bolts 0.375-24UNJF-3A, Material-A-286), Nut (NAS1805-6), Washer (NAS1587-6C)

Data:
```
data := READPRN("output_aftbrkpas_r5_onorbit.txt")
```

**Loads**
- Applied tensile load: $P_s := \text{data}_{s.3}$ lbf
- Applied shear load: $V_s := \text{data}_{s.4}$ lbf
- Applied bending moment: $M_s := \text{data}_{s.5}$ in lbf

**Factors of Safety**
- Ultimate: $SF_u := 2.0$
- Yield: $SF_y := 1.25$
- Joint Separation: $SF_{sep} := 1.2$
- Fitting factor: $FF := 1.15$

**Temperature data**
- Assembly: Temp\_initial := 70 deg
- Maximum: Temp\_max := 151 deg
- Minimum: Temp\_min := -43 deg

**Bolt and Nut Data**
- Nominal diameter of bolt: $D := 0.375$ in
- Total length of bolt: $L := 2.532$ in
- Threaded length: $Lt := 0.657$ in

Number of threads/\(\text{inch}\): $N_t := 24.1$ in
Height of nut: $H := 0.375$ in

(If bolt is fully threaded, input $Lt = L$)

This file uses the calculations shown in `\escfl02\211_mathcad\8307_bolts\thread_data.mcd`

**Washer Data**
- Thickness of washers: $tw := 0.156$ in
- Outer Diameter of washer: $D_w := 0.687$ in
- Inner Diameter of washer: $D_{wi} := 0.378$ in
- Bolt head dia. across flats: $d_w := 0.644$ in

**Flange data**
- Thickness of flange 1: $tf_1 := .350$ in
- Thickness of flange 2: $tf_2 := 1.5$ in
- Diameter of hole: $D_{\text{hole}} := 0.428$ in

Note: If there is no washer, $tw, Dw$, and $D_{wi}$ should be zero.
Bolts from PAS Aft Bracket to PAS Platform

*Material Property Data*

**Bolt**

Temperature correction factor bolt strength \( \text{TS}_\text{u,bolt} := 0.96 \)

Bolt ultimate tensile allowable stress \( \text{Ftu}_\text{bolt} := 200000 \text{ psi} \)

Bolt ultimate shear allowable stress \( \text{Fsu}_\text{bolt} := 0.6 \times \text{Ftu}_\text{bolt} \)

Bolt yield Tensile allowable stress \( \text{Fty}_\text{bolt} := 180000 \text{ psi} \)

Temperature correction factor for bolt modulus \( \text{TE}_\text{bolt} := 0.96 \)

Modulus of elasticity of bolt \( E_\text{bolt} := \left( 29.1 \times 10^6 \right) \text{ psi} \)

Yield \( \text{TS}_\text{y,bolt} := 0.96 \)

**Nut**

Temperature correction factor for nut strength \( \text{TS}_\text{nut} := 0.96 \)

Ultimate tensile allowable stress \( \text{Ftu}_\text{nut} := 180000 \text{ psi} \)

Ultimate Shear allowable stress \( \text{Fsu}_\text{nut} := 0.6 \times \text{Ftu}_\text{nut} \)

Ultimate axial strength of nut \( \text{Ptu}_\text{nut} := 16488 \text{ lbf} \) (180/125=1.44, 11450*1.44=16488, Ref.NAS1291)

**Washer**

Temperature correction factor for washer modulus \( \text{TE}_\text{washer} := .96 \)

Modulus of elasticity of washer \( E_\text{washer} := \left( 29.1 \times 10^6 \right) \text{ psi} \)

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( \text{TF1E} := .98 \) (modulus)

Temperature correction factor for flange 2 \( \text{TF2E} := .98 \)

Modulus of elasticity for the parts in the joint \( E_\text{flange1} := \left( 10.3 \times 10^6 \right) \text{ psi} \)

\( E_\text{flange2} := \left( 10.3 \times 10^6 \right) \text{ psi} \)

Coefficient of thermal expansion for flanges \( _\text{flange1,hot} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in}} \frac{\text{deg}}{\text{deg}} \)

\( _\text{flange2,hot} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in}} \frac{\text{deg}}{\text{deg}} \)

\( _\text{flange1,cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in}} \frac{\text{deg}}{\text{deg}} \)

\( _\text{flange2,cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in}} \frac{\text{deg}}{\text{deg}} \)

**Torque/Preload data**

Maximum torque (65% of yield) \( T_{\text{max}} := 578 \text{ in-lbf} \)

Loading plane factor \( n := 0.5 \)

Minimum torque (95% of max. torque) \( T_{\text{min}} := 549 \text{ in-lbf} \)

Preload Uncertainty \( \varepsilon := 0.25 \)

Torque coefficient \( k := 0.15 \)

Bolts from PAS Aft Bracket to PAS Platform

This file uses the calculations shown in \\escfil02\2111_mathcad\8307_bolts\multi_bolt_stiffness_nut_RevC

**Bolt Load data**

- **Bolt/joint stiffness factor**
  - $y = 0.287$
- **Max preload**
  - $P_{L,\text{max}} = 13441$ lbf
- **Min preload**
  - $P_{L,\text{min}} = 5913$ lbf
- **Joint separation load**
  - $P_{\text{sep}} = 4356$ lbf
- **Max bolt load (ultimate)**
  - $P_{\text{b,ult}} = 14641$ lbf
- **Max bolt load (yield)**
  - $P_{\text{by,ult}} = 14191$ lbf
- **Bolt tensile ult strength**
  - $P_{\text{At}} = 15828$ lbf

- **Temperature Preload**
  - $P_{\text{th, pos}} = 596.6$ lbf
- **Uncertainty factor**
  - $= 0.25$
- **Torque coefficient**
  - $k = 0.15$
- **Loading plane factor**
  - $n = 0.50$
- **Thread pullout strength required to develop full strength of bolt**
  - $P_{\text{As}} = 19798$ lbf
- **Nut tensile ult strength**
  - $P_{\text{tu, nut}} = 15828$ lbf

**Summary of Margins for bolt**

- **Joint separation**
  - $M_{\text{S, min}}_{1.1} = 0.38$
- **Direct Tension Ultimate**
  - $M_{\text{S, min}}_{2.1} = 0.90$
- **Direct Tension Yield**
  - $M_{\text{S, min}}_{3.1} = 1.85$
- **Total Tension Ultimate**
  - $M_{\text{S, min}}_{4.1} = 0.08$
- **Total Tension Yield**
  - $M_{\text{S, min}}_{5.1} = 0.05$

Length check = *Bolt length is sufficient*

**Determination of the smallest margin of safety for the bolt, and the failure mode**

$M_{\text{S,bolt}} = \min(M_{\text{S}})$

- $M_{\text{S,bolt}} = 0.05$
- Minimum Margin of Safety
- Failure Mode = *Total Tension Yield*

$M_{\text{S,min}}_{1.1} = 71009003$
- Element Identification (710009) and Bolt Number (3) for Minimum Margin

$M_{\text{S,min}}_{2.1} = 5056$
- Load Case Number for Minimum Margin

$M_{\text{S,min}}_{3.1} = 3630$
- Applied Tensile Load for Minimum Margin

$M_{\text{S,min}}_{4.1} = 874.1$
- Applied Shear Load for Minimum Margin

$M_{\text{S,min}}_{5.1} = 0$
- Applied Bending Moment for Minimum Margin

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Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 4

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, EWBR0420 0.375-24 UNFJ fasteners, holding the aft bracket to the PAS platform. The drawing number for the Aft Brackets Installation is SGG39135873.

\[
\begin{array}{cc}
\text{bolt2 :=} & \begin{bmatrix}
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
\end{bmatrix} \\
\end{array}
\]

\[s := 1..\text{rows(bolt2)}\]

\[N2_s := \text{bolt2}_{s,2} \frac{1}{\text{in}}\]  \hspace{1cm} \text{pitch of bolt}

\[D2_s := \text{bolt2}_{s,1} \text{in}\]  \hspace{1cm} \text{bolt diameter}

**Tensile Area of bolt**

\[A_{t2_s} := \beta \left( \frac{D2_s - 0.9743 \frac{1}{N2_s}}{2} \right)^2\]

**Shear Area of bolt**

\[A_{s2_s} := \beta \left( \frac{D2_s - 1.299038 \frac{1}{N2_s}}{2} \right)^2\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.5</td>
<td>2.312</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-1.5</td>
<td>-2.312</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>2.312</td>
<td>0</td>
</tr>
</tbody>
</table>

Note Bolt 4 is removed from the bolt pattern.
Location of applied forces and moments

\[ x_{\text{force}2} := 0.0 \text{in} \quad y_{\text{force}2} := 0.0 \text{in} \quad z_{\text{force}2} := 0.0 \text{in} \]

\[ \text{cgload}_2 := \begin{pmatrix} x_{\text{force}2} \\ y_{\text{force}2} \\ z_{\text{force}2} \end{pmatrix} \quad \text{cgload}_2 = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{in} \]

Center of gravity of bolt group

\[ x_{\text{cg}2} := \frac{\sum_{s} x_{2s}}{\text{rows}(x2)} \quad x_{\text{cg}2} = -0.50 \text{ in} \]

\[ y_{\text{cg}2} := \frac{\sum_{s} y_{2s}}{\text{rows}(y2)} \quad y_{\text{cg}2} = 0.7707 \text{ in} \]

\[ z_{\text{cg}2} := \frac{\sum_{s} z_{2s}}{\text{rows}(z2)} \quad z_{\text{cg}2} = 0.00 \text{ in} \]

\[ \text{cg}_{\text{bolt2}} := \begin{pmatrix} x_{\text{cg}2} \\ y_{\text{cg}2} \\ z_{\text{cg}2} \end{pmatrix} \quad \text{cg}_{\text{bolt2}} = \begin{pmatrix} -0.50 \\ 0.77 \\ 0.00 \end{pmatrix} \text{in} \]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 4, the x and y directions in the bolt pattern are unsymmetric and have a offset from the center of gravity.

Load Vector

\[ \text{r}_{\text{load2}} := \text{cgload}_2 - \text{cg}_{\text{bolt2}} \quad \text{r}_{\text{load2}} = \begin{pmatrix} 0.50 \\ -0.77 \\ 0.00 \end{pmatrix} \text{in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_{2s} := \sqrt{(x_{2s} - x_{\text{cg}2})^2 + (y_{2s} - y_{\text{cg}2})^2} \]

\[ r_{2s} = \begin{pmatrix} 1.837 \\ 3.241 \\ 2.525 \end{pmatrix} \text{in} \]

Reading database file for bolted joint

\[ \text{data} := \text{READPRN}("\text{boltsAftPlatform.txt}") \]

\[ \text{q} := 1 \cdot \text{rows(data)} \quad \text{num}_\text{bolts2} := \text{rows(bolt2)} \]
Bolts from PAS Aft Bracket to PAS Platform

**Loads from 2-06 loads model**

- **Shear in X axis**
  \[ F_{x,q} = -data_{q,3} \text{ lbf} \]
  \[ M_{x,q} = -data_{q,6} \text{ in-lbf} \]
- **Shear in Y axis**
  \[ F_{y,q} = -data_{q,4} \text{ lbf} \]
  \[ M_{y,q} = -data_{q,7} \text{ in-lbf} \]
- **Axial Load**
  \[ F_{z,q} = -data_{q,5} \text{ lbf} \]
  \[ M_{z,q} = -data_{q,8} \text{ in-lbf} \]
- **Element Identification**
  \[ ID_{2,q} = -data_{q,1} \]
  \[ ID_{2} = ID_{2,q} \text{ 1000 + 1} \text{ Counter for number of bolts in pattern} \]
- **Load Case Number**
  \[ LC_{2,q} = -data_{q,2} \]
  \[ M_{2,q} = 0 \text{ in-lbf} \]

**Format of Output File**

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

**Note bolt number 4 is not included.**

- \[ ID_{2} = \text{stack}(ID_{2}, ID_{2} + 1, ID_{2} + 2) \]
- \[ LC_{2} = \text{stack}(LC_{2}, LC_{2}, LC_{2}) \]

**Moment Distribution**

\[ M_{tot}^{(q)} := \begin{pmatrix} M_{x_{q}} \\ M_{y_{q}} \\ M_{z_{q}} \end{pmatrix} + \eta_{load2} \times \begin{pmatrix} F_{x_{q}} \\ F_{y_{q}} \\ F_{z_{q}} \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

- \[ M_{x_{bolts2,q}} := M_{tot}^{(1),q} \]
- \[ M_{y_{bolts2,q}} := M_{tot}^{(2),q} \]
- \[ M_{z_{bolts2,q}} := M_{tot}^{(3),q} \]

**Tension on bolts**

\[ F_{direct2,q} := \frac{F_{z_{q}}}{\text{num_bolts2}} \text{ Direct tensile load calculation} \]

\[ F_{m_{x_{q}}} := \begin{cases} 0 \text{ lbf if } (y_{2s} - y_{cg2}) = 0 \text{ in} \\ \left| \frac{M_{x_{bolts2,q}} (y_{2s} - y_{cg2})}{\sum_{s} (y_{2s} - y_{cg2})^2 \text{ At}_{2s}} \right| \end{cases} \]

\[ F_{m_{y_{q}}} := \begin{cases} 0 \text{ lbf if } (x_{2s} - x_{cg2}) = 0 \text{ in} \\ \left| -\frac{M_{y_{bolts2,q}} (x_{2s} - x_{cg2})}{\sum_{s} (x_{2s} - x_{cg2})^2 \text{ At}_{2s}} \right| \end{cases} \]

\[ F_{t_{q}} := F_{direct2,q} + F_{m_{x_{q}}} + F_{m_{y_{q}}} \text{ Total Tensile load} \]

\[ \text{atan2}(\theta, \phi) \]

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Shear on bolts

Secondary shear on bolts
\[ Fs_{2s,q} := \frac{M_{z,boltcg2q} r_{2s} As_{2s}}{\sum_s \left( r_{2s}^2 \cdot (As_{2s}) \right)} \]

\[ u_s := \text{atan2}(x_{2s} - x_{cg2}, y_{2s} - y_{cg2}) \]

Shear
\[ S_x := 0 \quad S_y := 0 \]

\[ S_{y,q} := \sin\left(\frac{\beta}{2} - u_s\right) \quad S_{x,q} := -\cos\left(\frac{\beta}{2} - u_s\right) \]

Loads of first case
\[ S_y \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} -293.43 \\ -293.43 \end{bmatrix} \text{ lbf} \]
\[ S_x \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 904.54 \\ -452.27 \end{bmatrix} \text{ lbf} \]
\[ F_{tot2s,q} := \sqrt{\left( S_{x,q} + \frac{F_{yq}}{2} \right)^2 + \left( S_{y,q} + \frac{F_{xq}}{2} \right)^2} \]

\[ \text{max}(F_{tot2}) = 1697.45 \text{ lbf} \]
\[ \text{min}(F_{tot2}) = 4.02 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 4 is not included.

\[ P2 := \text{stack}\left( \begin{bmatrix} \text{Ft}_2^T \end{bmatrix}, \begin{bmatrix} \text{Ft}_2^T \end{bmatrix}, \begin{bmatrix} \text{Ft}_2^T \end{bmatrix} \right) \]

\[ V2 := \text{stack}\left( \begin{bmatrix} \text{Fstot}_2^T \end{bmatrix}, \begin{bmatrix} \text{Fstot}_2^T \end{bmatrix}, \begin{bmatrix} \text{Fstot}_2^T \end{bmatrix} \right) \]

\[ M2 := \text{stack}(\text{M2}, \text{M2}, \text{M2}) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[ \text{Output2} := \text{augment}(\text{ID2, LC2, P2, V2, M2}) \text{ lbf in lbf} \]

Size of the "Output2" Array
\[ \text{rows(\text{Output2})} = 1536 \]

(3 bolts x 256 load cases) x 2 joint = 1536 rows

\[ \text{WRITEPRN('output_aftbrkpas_r5_onorbit_fs1.txt')} := \text{Output2} \]
Bolt Fail-safe Results

The array from the text file above is read

```plaintext
data_fs := READPRN("output_aftbrkpas_r5_onorbit_fs1.txt")
s := 1..rows(data_fs)
```

**Fail-safe Loads**

- Applied tensile load
  - \( P_{FS} := data_{fs,s,3} \) lbf
  - \( ID_{FS} := data_{fs,s,1} \)
- Applied shear load
  - \( V_{FS} := data_{fs,s,4} \) lbf
  - \( LC_{FS} := data_{fs,s,2} \)
- Applied bending moment
  - \( M_{FS} := data_{fs,s,5} \) in-lbf

**Fail-safe Factors of Safety**

- Ultimate
  - \( SF_{u,FS} := 1.0 \)
- Joint Separation
  - \( SF_{sep,FS} := 1.0 \)
This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC

**Bolt Fail-safe Load data**

Joint separation load \( \max(P_{\text{sep, FS}}) = \mathbf{5951.263} \text{ lbf} \)  
Max bolt load (ultimate) \( \max(P_{\text{b, FS}}) = \mathbf{14424.6} \text{ lbf} \)

**Summary of fail-safe Margins Removing Bolt 4**

| Joint separation | MS_minFS(1) = 0.01 | Total Thread shear Ult | MS_minFS(5) = 0.37 |
| Direct Tension Ultimate | MS_minFS(2) = 1.31 | Shear Ultimate | MS_minFS(6) = 5.52 |
| Total Tension Ultimate | MS_minFS(3) = 0.10 | Bending Ultimate | MS_minFS(7) = 10.00 |
| Direct Thread shear Ultimate | MS_minFS(4) = 1.89 | Combined shear, tension and bending ultimate | MS_minFS(8) = 0.10 |

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode**

\[
\text{MSbolt}_{\text{FS}} := \min(\text{MS}_{\text{FS}}) \\
\text{MSbolt}_{\text{FS}} = \mathbf{0.01} \\
\text{Failure Mode}_{\text{FS}} = "\text{Joint Separation}" \\
\text{MS}_{\text{min ID}} = 710009003 \quad \text{Element Identification (710009) and Bolt Number (3) for Minimum Margin} \\
\text{MS}_{\text{min LC}} = 5056 \quad \text{Load Case Number for Minimum Margin} \\
\text{MS}_{\text{min P}} = 5951.3 \quad \text{Applied Tensile Load for Minimum Margin} \\
\text{MS}_{\text{min V}} = 735.2 \quad \text{Applied Shear Load for Minimum Margin} \\
\text{MS}_{\text{min M}} = 0 \quad \text{Applied Bending Moment for Minimum Margin}
\]
Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 3

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, EWB0420 0.375-24 UNFJ fasteners, holding the aft bracket to the PAS platform. The drawing number for the Aft Brackets Installation is SGG39135873.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
bolt2 := & \quad \begin{bmatrix} 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \end{bmatrix} \\
s := & \quad \text{rows(bolt2)} \\
N_{2s} := & \quad \frac{s}{2} \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt} \\
D_{2s} := & \quad \frac{s}{2} \cdot \frac{1}{\text{in}} \quad \text{bolt diameter}
\end{align*}
\]

**Tensile Area of bolt**

\[
At_{2s} := \beta \left( \frac{D_{2s} - 0.9743 \cdot \frac{1}{N_{2s}}}{2} \right)^2
\]

**Shear Area of bolt**

\[
As_{2s} := \beta \left( \frac{D_{2s} - 1.299038 \cdot \frac{1}{N_{2s}}}{2} \right)^2
\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.5 \text{in}</td>
<td>2.312 \text{in}</td>
<td>0 \text{in}</td>
</tr>
<tr>
<td>2</td>
<td>-1.5 \text{in}</td>
<td>-2.312 \text{in}</td>
<td>0 \text{in}</td>
</tr>
<tr>
<td>4</td>
<td>1.5 \text{in}</td>
<td></td>
<td>0 \text{in}</td>
</tr>
</tbody>
</table>

Note Bolt 3 is removed from the bolt pattern.
Location of applied forces and moments

\[
\begin{align*}
x_{\text{force}2} &:= 0.0 \text{in} \\
y_{\text{force}2} &:= 0.0 \text{in} \\
z_{\text{force}2} &:= 0.0 \text{in}
\end{align*}
\]

\[
\begin{align*}
c_{\text{gload}2} &:= \begin{bmatrix} x_{\text{force}2} \\ y_{\text{force}2} \\ z_{\text{force}2} \end{bmatrix} \\
c_{\text{gload}2} &= \begin{bmatrix} 0.00 \\ 0.00 \\ 0.00 \end{bmatrix} \text{in}
\end{align*}
\]

Center of gravity of bolt group

\[
\begin{align*}
x_{\text{cg}2} &:= \frac{\sum x_{2s}}{\text{rows}(x2)} \\
y_{\text{cg}2} &:= \frac{\sum y_{2s}}{\text{rows}(y2)} \\
z_{\text{cg}2} &:= \frac{\sum z_{2s}}{\text{rows}(z2)}
\end{align*}
\]

\[
\begin{align*}
x_{\text{cg}2} &= -0.50 \text{ in} \\
y_{\text{cg}2} &= -0.77 \text{ in} \\
z_{\text{cg}2} &= 0.00 \text{ in}
\end{align*}
\]

\[
\begin{align*}
c_{\text{gbolt}2} &:= \begin{bmatrix} x_{\text{cg}2} \\ y_{\text{cg}2} \\ z_{\text{cg}2} \end{bmatrix} \\
c_{\text{gbolt}2} &= \begin{bmatrix} -0.50 \\ -0.77 \\ 0.00 \end{bmatrix} \text{in}
\end{align*}
\]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 3, the x and y directions in the bolt pattern are unsymmetric and have an offset from the center of gravity.

Load Vector

\[
\begin{align*}
r_{\text{load}2} &:= c_{\text{gload}2} - c_{\text{gbolt}2}
\end{align*}
\]

\[
\begin{align*}
r_{\text{load}2} &= \begin{bmatrix} 0.50 \\ 0.77 \\ 0.00 \end{bmatrix} \text{in}
\end{align*}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\begin{align*}
r_{2s} &:= \sqrt{(x_{2s} - x_{\text{cg}2})^2 + (y_{2s} - y_{\text{cg}2})^2}
\end{align*}
\]

\[
\begin{align*}
r_{2s} &= \begin{bmatrix} 3.241 \\ 1.837 \\ 2.525 \end{bmatrix} \text{in}
\end{align*}
\]

Reading database file for bolted joint

\[
\begin{align*}
\text{ID2} &:= 0 \\
\text{LC2} &:= 0 \\
\text{M2} &:= 0 \\
\text{data} &:= \text{READPRN\text{("boltsAftPlatform.txt")}}
\end{align*}
\]

\[
\begin{align*}
\text{q} &:= 1 \cdot \text{rows(data)} \\
\text{num_bolts2} &:= \text{rows(bolt2)}
\end{align*}
\]

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Bolts from PAS Aft Bracket to PAS Platform

**Loads from 2-06 loads model**

- **Shear in X axis**: \( F_{x2q} = - \text{data}_q \) lbf
  - Moment about X axis: \( M_{x2q} = \text{data}_q \) in lbf
- **Shear in Y axis**: \( F_{y2q} = - \text{data}_q \) lbf
  - Moment about Y axis: \( M_{y2q} = \text{data}_q \) in lbf
- **Axial Load**: \( F_{z2q} = - \text{data}_q \) lbf
  - Torsion: \( M_{z2q} = \text{data}_q \) in lbf
- **Element Identification**: \( ID_2q = \text{data}_q \)
  - \( ID_2q := ID_2q \, 1000 + 1 \) Counter for number of bolts in pattern
- **Load Case Number**: \( LC_2q = \text{data}_q \)
  - Applied Bending Moment at Bolts: \( M_2q := 0 \) in lbf

**Format of Output File**

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

**Note bolt number 3 is not included.**

\[ \text{ID2} := \text{stack}([\text{ID2}, \text{ID2} + 1, \text{ID2} + 3]) \]

\[ \text{LC2} := \text{stack}([\text{LC2}, \text{LC2}, \text{LC2}]) \]

**Moment Distribution**

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{bolt}} := \begin{bmatrix}
M_{x2q} & My_{2q} & Fx_{2q} \\
My_{2q} & Mz_{2q} & Fy_{2q} \\
Fx_{2q} & Fy_{2q} & Mz_{2q}
\end{bmatrix}
\]

**Tension on bolts**

**Ft2**,q := \( \frac{F_{z2q}}{\text{num_bolts}_2} \)

Direct tensile load calculation

**Fmx2**,q := \( 0 \) lbf if \((y2s - ycg2) = 0\) in

\[
\left( \sum_s \left[ (y2s - ycg2)^2 \right] At2s \right)
\]

**Fmy2**,q := \( 0 \) lbf if \((x2s - xcg2) = 0\) in

\[
\left( \sum_s \left[ (x2s - xcg2)^2 \right] At2s \right)
\]
Shear on bolts

Secondary shear on bolts

\[ F_{s2s, q} := \frac{M_{z, boltcg2q} - r_{2s} \cdot A_{s2s}}{\sum_s (r_{2s})^2 \cdot (A_{s2s})} \]

\[ u_s := \tan(2(x_{2s} - x_{cg2}, y_{2s} - y_{cg2})) \]

Shear

\[ S_x := 0 \]
\[ S_y := 0 \]

\[ S_{ys, q} := \sin\left(\frac{\beta}{2} - u_s\right) F_{s2s, q} \]
\[ S_{xs, q} := -\cos\left(\frac{\beta}{2} - u_s\right) F_{s2s, q} \]

Loads of first case

\[
\begin{align*}
S_x \begin{bmatrix} 1 \end{bmatrix} &= \begin{bmatrix} -1001.90 \\ 500.95 \\ 500.95 \end{bmatrix} \text{ lbf} \\
S_y \begin{bmatrix} 1 \end{bmatrix} &= \begin{bmatrix} -325.01 \\ -325.01 \\ 650.02 \end{bmatrix} \text{ lbf}
\end{align*}
\]

\[ F_{\text{tot2s, q}} := \sqrt{(S_{xs, q} + \frac{F_{xq}}{2})^2 + (S_{ys, q} + \frac{F_{yq}}{2})^2} \]

\[ \max(F_{\text{tot2s}}) = 1764.29 \text{ lbf} \]
\[ \min(F_{\text{tot2s}}) = 1.94 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (\( P_2 \)), applied shear load (\( V_2 \)), and applied moment (\( M_2 \)) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 3 is not included.

\[ P_2 := \text{stack}(F_{t2}^T \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, F_{t2}^T \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}) \]
\[ V_2 := \text{stack}(F_{\text{tot2}}^T \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, F_{\text{tot2}}^T \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, F_{\text{tot2}}^T \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}) \]
\[ M_2 := \text{stack}(M_2, M_2, M_2) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (\( P_2 \)), applied shear on the bolt (\( V_2 \)), and applied moment on the bolt (\( M_2 \)). See the output array example above. The array is written to a text file.

\[ \text{Output2 := augment(ID2, LC2, P2, V2, M2, lbf, lbf, in lbf)} \]

Size of the "Output2" Array

\[ \text{rows(Output2) = 1536} \]

(3 bolts x 256 load cases) x 2 joint = 1536 rows

\[ \text{WRITEPRN("output_aftbrkpas_r5_onorbit_fs2.txt") := Output2} \]
Bolt Fail-safe Results

The array from the text file above is read

```plaintext
data_fs := READPRN("output_aftbrkpas_r5_onorbit_fs2.txt")
```

```
s := 1 .. rows(data_fs)
```

Fail-safe Loads

- Applied tensile load
  \[ P_{FS} := data_{fs,s,3} \text{ lbf} \]
  \[ ID_{FS} := data_{fs,s,1} \]

- Applied shear load
  \[ V_{FS} := data_{fs,s,4} \text{ lbf} \]
  \[ LC_{FS} := data_{fs,s,2} \]

- Applied bending moment
  \[ M_{FS} := data_{fs,s,5} \text{ in lbf} \]

Fail-safe Factors of Safety

- Ultimate
  \[ SFu_{FS} := 1.0 \]

- Joint Separation
  \[ SFsep_{FS} := 1.0 \]
Bolts from PAS Aft Bracket to PAS Platform

This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC Fail-Safe Stiffness File

**Bolt Fail-safe Load data**

- Joint separation load: \( \max(P_{sep\_FS}) = 4872.074 \text{ lbf} \)
- Max bolt load (ult): \( \max(Pb\_FS) = 14246.2 \text{ lbf} \)

**Summary of fail-safe Margins Removing Bolt 3**

| & MS_minFS 1.1 = 0.23 & MS_minFS 3.1 = 0.11 & MS_minFS 4.1 = 2.53 | MS_minFS 5.1 = 0.39 & MS_minFS 6.1 = 5.27 & MS_minFS 7.1 = 10.00 | MS_minFS 8.1 = 0.11 |
|---|---|---|---|---|---|---|
| Joint separation & Total Thread shear Ult & Shear Ultimate & Bending Ultimate & Combined shear, tension and bending ultimate |
| Direct Tension Ultimate & 1.83 & |
| Total Tension Ultimate & 0.11 & |
| Direct Thread shear Ult & 2.53 & |

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode**

- \( MS_{bolt\_FS} := \min(\text{MS\_FS}) \)
- \( MS_{bolt\_FS} = 0.11 \)
- Failure_mode_FS = "Combined Shear Tension Bending Ultimate"

- \( MS_{min\_ID} = 710010001 \)
- \( MS_{min\_LC} = 5060 \)
- \( MS_{min\_P} = 4872.1 \)
- \( MS_{min\_V} = 1525.1 \)
- \( MS_{min\_M} = 0 \)
Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 2

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, EW0420 0.375-24 UNFJ fasteners, holding the aft bracket to the PAS platform. The drawing number for the Aft Brackets Installation is SGG39135873.

\[
\begin{align*}
\text{size thread/in} \\
\text{bolt2 := } & \begin{bmatrix} 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \end{bmatrix} \\
\end{align*}
\]

s := 1..rows(bolt2)

\[
N2_s := \text{bolt2}_{s,2} \frac{1}{\text{in}}
\]
pitch of bolt

\[
D2_s := \text{bolt2}_{s,1} \text{ in}
\]
bolt diameter

**Tensile Area of bolt**

\[
\beta \left( \frac{D2_s - 0.9743 \frac{1}{N2_s}}{2} \right)^2
\]

**Shear Area of bolt**

\[
\beta \left( \frac{D2_s - 1.299038 \frac{1}{N2_s}}{2} \right)^2
\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.5</td>
<td>2.312</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>2.312</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>-2.312</td>
<td>0</td>
</tr>
</tbody>
</table>

Note Bolt 2 is removed from the bolt pattern.
Location of applied forces and moments

\[
x_{\text{force2}} := 0.0 \text{in} \\
y_{\text{force2}} := 0.0 \text{in} \\
z_{\text{force2}} := 0.0 \text{in}
\]
\[
c_{\text{load2}} := \begin{bmatrix} x_{\text{force2}} \\ y_{\text{force2}} \\ z_{\text{force2}} \end{bmatrix} \\
c_{\text{load2}} = \begin{bmatrix} 0.00 \\ 0.00 \\ 0.00 \end{bmatrix} \text{in}
\]

Center of gravity of bolt group

\[
x_{\text{cg2}} := \frac{\sum x_{2s}}{\text{rows}(x2)} \\
y_{\text{cg2}} := \frac{\sum y_{2s}}{\text{rows}(y2)} \\
z_{\text{cg2}} := \frac{\sum z_{2s}}{\text{rows}(z2)}
\]
\[
x_{\text{cg2}} = 0.50 \text{in} \\
y_{\text{cg2}} = 0.77 \text{in} \\
z_{\text{cg2}} = 0.00 \text{in}
\]
\[
c_{\text{gbolt2}} := \begin{bmatrix} x_{\text{cg2}} \\ y_{\text{cg2}} \\ z_{\text{cg2}} \end{bmatrix} \\
c_{\text{gbolt2}} = \begin{bmatrix} 0.50 \\ 0.77 \\ 0.00 \end{bmatrix} \text{in}
\]

Note Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 2, the x and y directions in the bolt pattern are unsymmetric and have a offset from the center of gravity.

Load Vector

\[
r_{\text{load2}} := c_{\text{load2}} - c_{\text{gbolt2}} \\
r_{\text{load2}} = \begin{bmatrix} -0.50 \\ -0.77 \\ 0.00 \end{bmatrix} \text{in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_{2s} = \sqrt{(x_{2s} - x_{\text{cg2}})^2 + (y_{2s} - y_{\text{cg2}})^2}
\]
\[
r_{2s} = 2.525 \text{in}
\]

Reading database file for bolted joint

\[
\text{ID2} := 0 \\
\text{LC2} := 0 \\
\text{M2} := 0
\]
\[
data := \text{READPRN( "boltsAftPlatform.txt" )}
\]
\[
q := 1 \ldots \text{rows}(data) \\
\text{num_bolts2} := \text{rows}(\text{bolt2})
\]
Loads from 2-06 loads model

Shear in X axis

\[ F_{x2q} := -d_{aq.3} \text{ lbf} \]

Moment about X axis

\[ M_{x2q} := -d_{aq.6} \text{ in lbf} \]

Shear in Y axis

\[ F_{y2q} := -d_{aq.4} \text{ lbf} \]

Moment about Y axis

\[ M_{y2q} := -d_{aq.7} \text{ in lbf} \]

Axial Load

\[ F_{z2q} := -d_{aq.5} \text{ lbf} \]

Torsion

\[ M_{z2q} := -d_{aq.8} \text{ in lbf} \]

Element Identification

\[ ID_{2q} := d_{aq.1} \]

\[ ID_{2q} := ID_{2q} \text{ 1000 + 1} \]

Counter for number of bolts in pattern

Load Case Number

\[ LC_{2q} := d_{aq.2} \]

Applied Bending Moment at Bolts

\[ M_{2q} := 0 \text{ in lbf} \]

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

**Note bolt number 2 is not included.**

\[ ID2 := \text{stack}(ID2, ID2 + 2, ID2 + 3) \]

\[ LC2 := \text{stack}(LC2, LC2, LC2) \]

Moment Distribution

\[
M_{tot2}^{(q)} := \begin{pmatrix}
M_{x2q} \\
M_{y2q} \\
M_{z2q}
\end{pmatrix} + n_{load2} \times \begin{pmatrix}
F_{x2q} \\
F_{y2q} \\
F_{z2q}
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{x\_boltcg2q} := M_{tot2}^{(1)q} \]

\[ M_{y\_boltcg2q} := M_{tot2}^{(2)q} \]

\[ M_{z\_boltcg2q} := M_{tot2}^{(3)q} \]

Tension on bolts

\[ F_{t\_direct2s,q} := \frac{F_{z2q}}{\text{num\_bolts2}} \]

Direct tensile load calculation

\[
F_{mx2,q} := \begin{cases} 
0 \text{ lbf} & \text{if } (y_{2s} - y_{cg2}) = 0 \text{ in} \\
\frac{[M_{x\_boltcg2q}(y_{2s} - y_{cg2})] A_{t2s}}{\sum_s (y_{2s} - y_{cg2})^2 A_{t2s}} & \text{otherwise}
\end{cases}
\]

\[
F_{my2,q} := \begin{cases} 
0 \text{ lbf} & \text{if } (x_{2s} - x_{cg2}) = 0 \text{ in} \\
-\frac{[M_{y\_boltcg2q}(x_{2s} - x_{cg2})] A_{t2s}}{\sum_s (x_{2s} - x_{cg2})^2 A_{t2s}} & \text{otherwise}
\end{cases}
\]

\[ F_{t2,q} := F_{t\_direct2s,q} + F_{mx2,q} + F_{my2,q} \]

Total Tensile load
Shear on bolts

Secondary shear on bolts

\[ F_{s_2, q} := \frac{M_{\text{boltc}q} r_{2s} A_{s_2}}{\sum_s \left( r_{2s}^2 \cdot A_{s_2} \right)} \]

\[ u_s := \text{atan2} \left( x_{2s} - x_{cg2}, y_{2s} - y_{cg2} \right) \]

Shear

\[ S_x := 0 \quad S_y := 0 \]

\[ S_{y, q} := \sin \left( \frac{\beta}{2} - u_s \right) \cdot F_{s_2, q} \]

\[ S_{x, q} := -\cos \left( \frac{\beta}{2} - u_s \right) \cdot F_{s_2, q} \]

Loads of first case

\[
\begin{align*}
S_x &= \begin{pmatrix} -545.11 \\ -545.11 \\ 1090.22 \end{pmatrix} \text{ lbf} \\
S_y &= \begin{pmatrix} -707.33 \\ 353.66 \\ 353.66 \end{pmatrix} \text{ lbf}
\end{align*}
\]

\[ F_{\text{stot}, q} := \sqrt{\left( S_{x, q} + \frac{F_{xq}}{2} \right)^2 + \left( S_{y, q} + \frac{F_{yq}}{2} \right)^2} \]

\[ \text{max}(F_{\text{stot}}) = 1716.41 \text{ lbf} \]

\[ \text{min}(F_{\text{stot}}) = 3.85 \text{ lbf} \]

Assume that \( F_x \) and \( F_y \) are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 2 is not included.

\[ P2 := \text{stack} \left[ \left( \text{Ft}^2 \right)^{1}, \left( \text{Ft}^2 \right)^{2}, \left( \text{Ft}^2 \right)^{3} \right] \]

\[ V2 := \text{stack} \left[ \left( F_{\text{stot}} \right)^{1}, \left( F_{\text{stot}} \right)^{2}, \left( F_{\text{stot}} \right)^{3} \right] \]

\[ M2 := \text{stack}(M2, M2, M2) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[ \text{Output2} := \text{augment} \left( \text{ID2, LC2, P2, V2, M2} \right) \text{ lbf, lbf, lbf} \]

Size of the "Output2" Array

\[ \text{rows(Output2)} = 1536 \]

(3 bolts x 256 load cases) x 2 joint = 1536 rows

Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.

\[ \text{WRITEPRN} \left( \text{"output_aftbrkpas_r5_onorbit_fs3.txt"} \right) := \text{Output2} \]
Bolt Fail-safe Results

The array from the text file above is read

\[
data_{fs} := \text{READPRN}("\text{output_aftbrkpas}\_r5\_onorbit\_fs3\.txt")
\]
\[
s := 1..\text{rows}(data_{fs})
\]

**Fail-safe Loads**

- Applied tensile load
  \[
P_{FSs} := data_{fs}_{s.3} \text{ lbf}
  \]
  \[
  ID_{FSs} := data_{fs}_{s.1}
  \]

- Applied shear load
  \[
  V_{FSs} := data_{fs}_{s.4} \text{ lb}
  \]
  \[
  LC_{FSs} := data_{fs}_{s.2}
  \]

- Applied bending moment
  \[
  M_{FSs} := data_{fs}_{s.5} \text{ in lb}
  \]

**Fail-safe Factors of Safety**

- Ultimate
  \[
  SFu_{FS} := 1.0
  \]

- Joint Separation
  \[
  SFsep_{FS} := 1.0
  \]
This file uses the calculations shown in \escfl02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC

**Bolt Fail-safe Load data**

Joint separation load

\[ \text{max}(P_{sep\_FS}) = 5941.62 \text{ lbf} \]

Max bolt load (ultimate)

\[ \text{max}(P_{b\_FS}) = 14423 \text{ lbf} \]

\[ \text{max}(V_{FS}) = 1716.415 \text{ lbf} \]

**Summary of fail-safe Margins Removing Bolt 2**

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>( MS_{\text{minFS}} )</th>
<th>Total Thread shear Ult</th>
<th>( MS_{\text{minFS}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>( 2.1 )</td>
<td>Shear Ultimate</td>
<td>( 6.1 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( 3.1 )</td>
<td>Bending Ultimate</td>
<td>( 7.1 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( 4.1 )</td>
<td>Combined shear, tension and bending ultimate</td>
<td>( 8.1 )</td>
</tr>
</tbody>
</table>

### Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode

\[ MS_{\text{bolt\_FS}} := \min(MS_{\text{FS}}) \]

\[ MS_{\text{bolt\_FS}} = 0.01 \]

**Failure Mode FS = "Joint Separation"**

- **MS_min_ID = 710010001**: Element Identification (710010) and Bolt Number (1) for Minimum Margin
- **MS_min_LC = 5060**: Load Case Number for Minimum Margin
- **MS_min_P = 5941.6**: Applied Tensile Load for Minimum Margin
- **MS_min_V = 724.9**: Applied Shear Load for Minimum Margin
- **MS_min_M = 0**: Applied Bending Moment for Minimum Margin
Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform Removing Bolt 1

Fail-safe analysis is done by removing one bolt at a time and the analysis is repeated 4 times. There are now 3, EWBO420 0.375-24 UNFJ fasteners, holding the aft bracket to the PAS platform. The drawing number for the Aft Brackets Installation is SGG39135873.

<table>
<thead>
<tr>
<th>Size</th>
<th>Thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>2</td>
</tr>
</tbody>
</table>

\[
s := \text{rows(bolt2)}
\]

\[
N_{2s} := \text{bolt2} \cdot \frac{1}{\text{in}}
\]

\[
D_{2s} := \text{bolt2} \cdot \frac{1}{\text{in}}
\]

**Tensile Area of Bolt**

\[
A_{t2s} := \beta \left( \frac{D_{2s} - 0.9743 \cdot \frac{1}{\text{in}}}{2} \right)^2
\]

**Shear Area of Bolt**

\[
A_{s2s} := \beta \left( \frac{D_{2s} - 1.299038 \cdot \frac{1}{\text{in}}}{2} \right)^2
\]

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x coordinate</th>
<th>y coordinate</th>
<th>z coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.5</td>
<td>-2.312</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>2.312</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-1.5</td>
<td>2.312</td>
<td>0</td>
</tr>
</tbody>
</table>

Note Bolt 1 is removed from the bolt pattern.
**Location of applied forces and moments**

\[
x_{\text{force}2} := 0.0 \text{ in} \\
y_{\text{force}2} := 0.0 \text{ in} \\
z_{\text{force}2} := 0.0 \text{ in}
\]

\[
c_{\text{gload}2} = \begin{bmatrix} x_{\text{force}2} \\ y_{\text{force}2} \\ z_{\text{force}2} \end{bmatrix} \\
c_{\text{gload}2} = \begin{bmatrix} 0.00 \\ 0.00 \\ 0.00 \end{bmatrix} \text{ in}
\]

**Center of gravity of bolt group**

\[
x_{\text{cg}2} := \frac{\sum x_{2s}}{\text{rows}(x2)} \\
y_{\text{cg}2} := \frac{\sum y_{2s}}{\text{rows}(y2)} \\
z_{\text{cg}2} := \frac{\sum z_{2s}}{\text{rows}(z2)}
\]

\[
x_{\text{cg}2} = 0.50 \text{ in} \\
y_{\text{cg}2} = -0.77 \text{ in} \\
z_{\text{cg}2} = 0.00 \text{ in}
\]

\[
c_{\text{gbolt}2} = \begin{bmatrix} x_{\text{cg}2} \\ y_{\text{cg}2} \\ z_{\text{cg}2} \end{bmatrix} \\
c_{\text{gbolt}2} = \begin{bmatrix} 0.50 \\ -0.77 \\ 0.00 \end{bmatrix} \text{ in}
\]

Note: Since the z direction is into the plate, the loads are shared equally between the bolts. However, due to a failure in bolt 1, the x and y directions in the bolt pattern are unsymmetric and have a offset from the center of gravity.

**Load Vector**

\[
\mathbf{n}_{\text{load}2} := c_{\text{gload}2} - c_{\text{gbolt}2} \\
\mathbf{n}_{\text{load}2} = \begin{bmatrix} -0.50 \\ 0.77 \\ 0.00 \end{bmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_{2s} := \sqrt{(x_{2s} - x_{\text{cg}2})^2 + (y_{2s} - y_{\text{cg}2})^2}
\]

\[
r_{2s} = \begin{bmatrix} 2.525 \\ 3.241 \\ 1.837 \end{bmatrix} \text{ in}
\]

**Reading database file for bolted joint**

\[
\text{data} := \text{READPRN("boltsAftPlatform.txt")}
\]

\[
q := 1 \text{ . rows(data)} \\
\text{num_bolts2} := \text{rows(bolt2)}
\]
Loads from 2-06 loads model

Shear in X axis  \( F_{x, q} = -q \times A \) lbf

Shear in Y axis  \( F_{y, q} = -q \times A \) lbf

Axial Load  \( F_{z, q} = -q \times A \) lbf

Element Identification  \( ID_{2, q} = \text{data}_q, 1 \)

Load Case Number  \( LC_{2, q} = \text{data}_q, 2 \)

Moment about X axis  \( M_{x, q} = -q \times A \) in lbf

Moment about Y axis  \( M_{y, q} = -q \times A \) in lbf

Torsion  \( M_{z, q} = -q \times A \) in lbf

Counter for number of bolts in pattern

Format of Output File
The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation.

Note bolt number 1 is not included.

\( \text{ID2} := \text{stack}(\text{ID2} + 1, \text{ID2} + 2, \text{ID2} + 3) \)

\( \text{LC2} := \text{stack}(	ext{LC2}, \text{LC2}, \text{LC2}) \)

Moment Distribution

\[ M_{tot2}^{(q)} = \left( \begin{array}{c} M_{x, 2, q} \\ M_{y, 2, q} \\ M_{z, 2, q} \end{array} \right) + \eta_{load2} \times \left( \begin{array}{c} F_{x, 2, q} \\ F_{y, 2, q} \\ F_{z, 2, q} \end{array} \right) \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{x, boltcg2, q} = M_{tot2, 1, q} \]

\[ M_{y, boltcg2, q} = M_{tot2, 2, q} \]

\[ M_{z, boltcg2, q} = M_{tot2, 3, q} \]

Tension on bolts

\[ F_{direct2, s, q} := \frac{F_{z, 2, q}}{\text{num_bolts2}} \]

Direct tensile load calculation

\[ F_{mx, 2, s, q} := \begin{cases} 0 \text{ lbf} & \text{if } (y_{2s} - y_{cg2}) = 0 \text{ in} \\ \left( F_{x, boltcg2, q} (y_{2s} - y_{cg2}) \right) \frac{At_{2s}}{2} & \text{otherwise} \end{cases} \]

\[ F_{my, 2, s, q} := \begin{cases} 0 \text{ lbf} & \text{if } (x_{2s} - x_{cg2}) = 0 \text{ in} \\ -\left( F_{y, boltcg2, q} (x_{2s} - x_{cg2}) \right) \frac{At_{2s}}{2} & \text{otherwise} \end{cases} \]

\[ F_{t, 2, s, q} := F_{direct2, s, q} + F_{mx, 2, s, q} + F_{my, 2, s, q} \]

Total Tensile load
Shear on bolts

Secondary shear on bolts
\[ Fs_{s,q} := \frac{M_{z\_boltcg2q} \cdot r_{s} \cdot A_{s}}{2} \sum_{s} \left( r_{s} \right)^{2} \left( A_{s} \right) \]

\[ u_{s} := \text{atan2}(x_{2s} - x_{cg2}, y_{2s} - y_{cg2}) \]

Shear
\[ Sx := 0 \]
\[ Sy := 0 \]

\[ S_{y,s,q} := \sin \left( \frac{\beta}{2} - u_{s} \right) \cdot Fs_{s,q} \]
\[ S_{x,s,q} := -\cos \left( \frac{\beta}{2} - u_{s} \right) \cdot Fs_{s,q} \]

Loads of first case
\[ S_{x} \left( ^{1} \right) = \begin{bmatrix} 593.79 \\ -1187.58 \\ 593.79 \end{bmatrix} \text{ lbf} \]
\[ S_{y} \left( ^{1} \right) = \begin{bmatrix} -770.49 \\ 385.24 \\ 385.24 \end{bmatrix} \text{ lbf} \]

\[ F_{s\_tot2,s,q} := \sqrt{\left( S_{x,s,q} + \frac{F_{xq}}{2} \right)^{2} + \left( S_{y,s,q} + \frac{F_{yq}}{2} \right)^{2}} \]

\[ u_{s} = \begin{bmatrix} -142.4 \cdot \text{deg} \\ 72 \\ -57 \end{bmatrix} \]

Assume that \( F_{x} \) and \( F_{y} \) are shared by only 2 bolts. \( \min(F_{s\_tot2}) = 0.36 \text{ lbf} \)

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below.

Note there are only 3 bolts, since bolt number 1 is not included.

\[ P_{2} := \text{stack}(P_{2}) \left( ^{1} \right), P_{2} \left( ^{2} \right), P_{2} \left( ^{3} \right) \]

\[ V_{2} := \text{stack}(V_{2}) \left( ^{1} \right), V_{2} \left( ^{2} \right), V_{2} \left( ^{3} \right) \]

\[ M_{2} := \text{stack}(M_{2}, M_{2}, M_{2}) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[ \text{Output2} := \text{augment}(ID2, LC2, P_{2}, V_{2}, M_{2}) \]

Note Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.

Size of the "Output2" Array \( \text{rows(Output2)} = 1536 \)

(3 bolts x 256 load cases) x 2 joint = 1536 rows

\[ \text{WRITEPRN}("output_aftbrkpas_r5_onorbit_fs4.txt") := \text{Output2} \]
Bolt Fail-safe Results

The array from the text file above is read

```plaintext
data_fs := READPRN("output_aftbrkpas_r5_onorbit_fs4.txt")
```

s := 1 .. rows(data_fs)

**Fail-safe Loads**

- Applied tensile load
  
  P_FS := data_fs.s,3 lbf

- Applied shear load
  
  V_FS := data_fs.s,4 lbf

- Applied bending moment
  
  M_FS := data_fs.s,5 in lbf

**Fail-safe Factors of Safety**

- Ultimate
  
  SFu_FS := 1.0

- Joint Separation
  
  SFsep_FS := 1.0
Bolt Fail-safe Load data

Joint separation load \( \max(P_{sep\_FS}) = 4876.276 \text{ lbf} \) \( \max(P\_FS) = 4876.276 \text{ lbf} \)

Max bolt load (ultimate) \( \max(P_{b\_FS}) = 14246.9 \text{ lbf} \) \( \max(V\_FS) = 1739.85 \text{ lbf} \)

Summary of fail-safe Margins Removing Bolt 1

<table>
<thead>
<tr>
<th></th>
<th>MS_minFS</th>
<th>Total Thread shear Ult</th>
<th>MS_minFS</th>
<th>Shear Ultimate</th>
<th>MS_minFS</th>
<th>Bending Ultimate</th>
<th>MS_minFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1.1</td>
<td>0.23</td>
<td>5.1</td>
<td>0.39</td>
<td>6.1</td>
<td>5.36</td>
<td>7.1</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>2.1</td>
<td>1.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>3.1</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>4.1</td>
<td>2.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode

\[ MS_{bolt\_FS} := \min(MS_{FS}) \]

\[ MS_{bolt\_FS} = 0.11 \]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

\[ MS_{min\_ID} = 710009003 \]

Element Identification (710009) and Bolt Number (3) for Minimum Margin

\[ MS_{min\_LC} = 5056 \]

Load Case Number for Minimum Margin

\[ MS_{min\_P} = 4876.3 \]

Applied Tensile Load for Minimum Margin

\[ MS_{min\_V} = 1546.5 \]

Applied Shear Load for Minimum Margin

\[ MS_{min\_M} = 0 \]

Applied Bending Moment for Minimum Margin
4.12.7.2 Aft Brackets to PAS Platform Shear Bolt Analysis
Section 4.12.7.2  
PAS Aft Brackets to PAS Platform - Shear Bolt

CHECK Shear Bolt (NAS1160-6-30, .375-24 x 2.482L, CRES A286, 160 KSI), Washer (NAS1587-6C, C-Sink, .375 x .078 THK, CRES), Nut (NAS1805-6, .375-24, CRES A286, 180 KSI)

Flange 1: Aft Brackets  
Part number: SDG39135814  
Material: 7050-T7451, 14.556x12.052x7.501, BMS-7-323C

Flange 2: PAS Platform  
Part number: SDG39135817  
Material: 7050-T7451, 44.82x45.40x2.75, BMS-7-323C

Loads

ele1 := 710009002  
ele2 := 710010004

Applied tensile load

\[
P := \begin{cases} 
\text{for } s3 \in s & \\
\text{if } \text{data}_{s3,1} = \text{ele1} \lor \text{data}_{s3,1} = \text{ele2} & \\
& s2 \leftarrow s2 + 1 \\
& P_{s2} \leftarrow \text{data}_{s3,3} \text{ lbf} \\
& P2 \\
\end{cases}
\]

Applied bending moment

\[
M := \begin{cases} 
\text{for } s3 \in s & \\
\text{if } \text{data}_{s3,1} = \text{ele1} \lor \text{data}_{s3,1} = \text{ele2} & \\
& s2 \leftarrow s2 + 1 \\
& P_{s2} \leftarrow \text{data}_{s3,5} \text{ in lbf} \\
& P2 \\
\end{cases}
\]

Applied shear load

\[
V := \begin{cases} 
\text{for } s3 \in s & \\
\text{if } \text{data}_{s3,1} = \text{ele1} \lor \text{data}_{s3,1} = \text{ele2} & \\
& s2 \leftarrow s2 + 1 \\
& P_{s2} \leftarrow \text{data}_{s3,4} \text{ lbf} \\
& P2 \\
\end{cases}
\]
Shear Bolt from PAS Aft Brackets to PAS Platform

\[
\begin{align*}
\text{ID} & := \text{for } s_3 \in s \\
& \quad \text{if } \text{data}_{s_3, 1} = \text{ele1} \lor \text{data}_{s_3, 1} = \text{ele2} \\
& \quad \quad s_2 \leftarrow s_2 + 1 \\
& \quad \quad P_{2s_2} \leftarrow \text{data}_{s_3, 1} \\
& \quad \quad P_2 \\
\text{LC} & := \text{for } s_3 \in s \\
& \quad \text{if } \text{data}_{s_3, 1} = \text{ele1} \lor \text{data}_{s_3, 1} = \text{ele2} \\
& \quad \quad s_2 \leftarrow s_2 + 1 \\
& \quad \quad P_{2s_2} \leftarrow \text{data}_{s_3, 2} \\
& \quad \quad P_2 \\
& s := 1..\text{rows(ID)} \\
& \text{rows(ID)} = 512.00 \quad \frac{384}{64.3} = 2.00
\end{align*}
\]

**Temperature data**
- Assembly: \(\text{Temp}_{\text{initial}} := 70\ \text{deg}\)
- Maximum: \(\text{Temp}_{\text{max}} := 151\ \text{deg}\)
- Minimum: \(\text{Temp}_{\text{min}} := -43\ \text{deg}\)

**Factors of Safety**
- Ultimate: \(\text{SFu} := 2.0\)
- Joint Separation: \(\text{SFsep} := 1.2\)
- Yield: \(\text{SFy} := 1.25\)
- Fitting factor: \(\text{FF} := 1.15\)
Bolt and Nut Data

Nominal diameter of bolt $D := .375$ in
Reduced dia of shear bolt $D_{new} := 0.306$ in
Shear Bolt Shank Diameter $D_{shank} := 0.425$ in
GRIP Length of Bolt $GRIP := (30)(0.0625)$ in
Total length of bolt $L := GRIP + 0.607$ in
Threaded length $L_t := 2.482$ in $- 1.885$ in $- 0.083$ in
Bolt head dia. across flats $d_w := 0.554$ in (used only if there is no washer)

Number of threads/inch $N_t := 24$ $\frac{1}{2}$ in

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Washer Data

Thickness of washers (2X) $t_w := 0.156$ in
Outer Diameter of washer $D_{w} := 0.687$ in
Inner Diameter of washer $D_{wi} := 0.378$ in

Note: If there is no washer $t_w$, $D_w$ and $D_{wi}$ should be zero

Flange data

Thickness of flange 1 $t_{f1} := 0.750$ in $- 0.400$ in (Height minus depth of recess)
Thickness of flange 2 $t_{f2} := 2.75$ in $- 1.25$ in
Diameter of hole $D_{hole} := 0.428$ in

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate $T_{Su} := 0.96$
Bolt ultimate tensile allowable stress $F_{tu} := 160000$ psi
Bolt ultimate shear allowable stress $F_{su} := 0.6 \cdot F_{tu}$
Bolt yield Tensile allowable stress $F_{ty} := 120000$ psi
Temperature correction factor for bolt modulus $T_{E} := 0.96$
Modulus of elasticity of bolt $E_{bolt} := (29.1 \cdot 10^6)$ psi
Yield $T_{Sy} := 0.96$

Thermal coefficient for bolt

$\beta_{bolt\_hot} := 9.1 \cdot 10^{-6}$ in in deg
$\beta_{bolt\_cold} := 8.7 \cdot 10^{-6}$ in in deg
Nut

Temperature correction factor for nut strength

\[ T_{S\_nut} = 0.96 \]

Ultimate tensile allowable stress

\[ P_{tu\_nut} = 180000 \text{ psi} \]

Ultimate Shear allowable stress:

\[ P_{su\_nut} = 0.6 \times P_{tu\_nut} \]

Ultimate axial strength of nut

\[ P_{tu\_nut} = 16488 \text{ lbf} \]

Washer

Temperature correction factor for washer modulus

\[ T_{E\_washer} = 0.96 \]

Modulus of elasticity of washer:

\[ E_{\_washer} = (29.1 \times 10^6 \text{ psi}) \]

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1\_E} = 0.98 \text{ (modulus)} \]

Temperature correction factor for flange 2

\[ T_{f2\_E} = 0.98 \]

Modulus of elasticity for the parts in the joint

\[ E_{\_flange1} = (10.3 \times 10^6 \text{ psi}) \quad E_{\_flange2} = (10.3 \times 10^6 \text{ psi}) \]

Coefficient of thermal expansion for flanges

\[ \beta_{\_flange1\_hot} = 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \quad \beta_{\_flange2\_hot} = 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

\[ \beta_{\_flange1\_cold} = 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \quad \beta_{\_flange2\_cold} = 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

Torque/Preload data

Maximum torque

\[ T_{max} = 342 \text{ in-lbf} \]

59% of Yield

Loading plane factor

\[ n = 0.5 \]

Minimum torque

\[ T_{min} = 291 \text{ in-lbf} \]

85% of Max

Preload Uncertainty

\[ u = 0.25 \]

Torque coefficient

\[ k = 0.15 \]
Bolt Load data

Bolt/joint stiffness factor $ = 0.343$  
Max. preload $PLD_{max} = 8311.2$ lbf  
Min. preload $PLD_{min} = 2588.2$ lbf  
Joint separation load $\max(P_{sep}) = 376.427$ lbf  
Max. load on the bolt (ultimate) $\max(P_b) = 8434.8$ lbf  
Max. load on the bolt (yield) $\max(P_{by}) = 8388.5$ lbf  
Bolt ultimate tensile strength $PA_t = 13198.6$ lbf

Preload due to temperature $P_{th \_ pos} = 711.2$ lbf  
Uncertainty factor $u = 0.25$  
Torque coefficient $k = 0.15$  
Loading plane factor $n = 0.50$  
Thread pullout strength required to develop full strength of bolt $P_{As} = 15838.4$ lbf  
Nut ultimate tensile strength $P_{tu \_ nut} = 15828.5$ lbf

Summary of Margins for bolt:

Length_check = "Bolt length is sufficient"

<table>
<thead>
<tr>
<th>Type</th>
<th>MS_min 1.1</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>6.22</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>14.66</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>17.79</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.34</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.01</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MS_min</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>20.95</td>
</tr>
<tr>
<td>7.1</td>
<td>0.88</td>
</tr>
<tr>
<td>8.1</td>
<td>2.98</td>
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<tr>
<td>9.1</td>
<td>1000</td>
</tr>
<tr>
<td>10.1</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} := \min(\text{MS})$

$MS_{bolt} = 0.01$  
Failure Mode = "Total Tension Yield"

$MS_{min \_ ID} = 710010004$  
Element Identification (710010) and Bolt Number (4) for Minimum Margin  
$MS_{min \_ LC} = 6053$  
Load Case Number for Minimum Margin  
$MS_{min \_ P} = 313.7$  
Applied Tensile Load for Minimum Margin  
$MS_{min \_ V} = 208.7$  
Applied Shear Load for Minimum Margin  
$MS_{min \_ M} = 0$  
Applied Bending Moment for Minimum Margin
Fail-safe Analysis

Fail-safe Loads

data_fs1 := READPRN("output_aftbrkpas_r5_onorbit_fs1.txt")
data_fs2 := READPRN("output_aftbrkpas_r5_onorbit_fs2.txt")
data_fs3 := READPRN("output_aftbrkpas_r5_onorbit_fs3.txt")
data_fs4 := READPRN("output_aftbrkpas_r5_onorbit_fs4.txt")

data_fs := stack(data_fs1, data_fs2, data_fs3, data_fs4)  rows(data_fs) = 6144.00
s := 1.  rows(data_fs)  rows(data_fs1) = 1536.00

Fail-safe Factors of Safety

Ultimate
SFu_FS := 1.0

Joint Separation
SFsep_FS := 1.0

ele1 := 710009002  ele2 := 710010004

P_FS :=
  for s3 ∈ s
    if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
      s2 ← s2 + 1
      P2s2 ← data_fs_{s3,3} lbf
    P2

ID_FS :=
  for s3 ∈ s
    if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
      s2 ← s2 + 1
      P2s2 ← data_fs_{s3,1}
    P2

LC_FS :=
  for s3 ∈ s
    if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
      s2 ← s2 + 1
      P2s2 ← data_fs_{s3,2}
    P2

M_FS :=
  for s3 ∈ s
    if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
      s2 ← s2 + 1
      P2s2 ← data_fs_{s3,5} in lbf
    P2

V_FS :=
  for s3 ∈ s
    if data_fs_{s3,1} = ele1 ∨ data_fs_{s3,1} = ele2
      s2 ← s2 + 1
      P2s2 ← data_fs_{s3,4} lbf
    P2
s := 1..rows(ID FS)

\[
\text{rows}(ID\ FS) = \frac{384}{64.3} = 2.00
\]

This file uses the calculations shown in `\escfi02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC`

**Bolt Fail-safe Load data**

Joint separation load \( \max(\text{Psep\_FS}) = 565.699 \text{ lbf} \)
Max. load on the bolt(ultimate) \( \max(\text{Pb\_FS}) = 8422.7 \text{ lbf} \)

**Summary of fail-safe Margins for bolt**

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Margin _FS</th>
<th>Total Thread shear Ultimate</th>
<th>Shear Ultimate</th>
<th>Bending Ultimate</th>
<th>Combined shear, tension and bending ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_minFS 1.1</td>
<td>3.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_minFS 2.1</td>
<td>19.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_minFS 3.1</td>
<td>0.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_minFS 4.1</td>
<td>23.35</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode**

\[
\text{MSbolt\_FS} := \min(\text{MS\_FS})
\]

\[
\text{MSbolt\_FS} = 0.57
\]

Failure Mode _FS = "Combined Shear Tension Bending Ultimate"

<table>
<thead>
<tr>
<th>Identification</th>
<th>Load Case Number</th>
<th>Applied Load</th>
<th>Load Case Number for Minimum Margin</th>
<th>Applied Load for Minimum Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>710010004</td>
<td>6055</td>
<td>565.7</td>
<td>258.4</td>
<td>0</td>
</tr>
</tbody>
</table>

Element Identification (710010) and Bolt Number (4) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
4.12.8  BCS Avionics Bracket to PAS Platform Bolt Analysis
4.12.8  BCS Avionics Bracket to PAS Platform Bolt Analysis

The maximum camera weight:

\[ \text{camera} = 25 \text{- lb} \]

The maximum load factor for lift off/landing:

\[ \text{factor} = 5.9 \]

\[ \text{acc} := \text{factor} \times 32.174 \left( \frac{\text{ft}}{\text{sec}^2} \right) \]

\[ \text{cameraforce} := \text{acc-camera} \]

\[ \text{cameraforce} = 147.5 \text{- lbf} \]

\[ \text{length} := 9.75 \text{- in} \]  (conservative)

\[ \text{moment} := \text{length-cameraforce} \]

\[ \text{moment} = 1438.1 \text{- in-lbf} \]
Use bolt pattern on one bracket only. Very conservative

\[
\begin{align*}
F_{\text{ten}} & := \frac{\text{camerforce}}{4} + \frac{\text{moment}}{\text{min\_couple\_dis}} \\
F_{\text{shear}} & := \frac{\text{camerforce}}{4} \\
\text{Ften} & = 612.1 \text{ lbf} \\
\text{Fshear} & = 36.9 \text{ lbf}
\end{align*}
\]

\[P := \text{Ften} \quad \text{Applied tensile load}\]

\[V := \text{Fshear} \quad \text{Applied shear load}\]
CHECK BOLTS (NAS1351N4-10 bolts 0.250-28UNRF-3A, Material-A-286), Insert MS21209F415L, Washer NAS1149E0432R

Flange 1: BCS Avionics Bracket
Part number: SDG39135822
Material: 7075-T7351

Flange 2: PAS Platform
Part number: SDG39135817
Material: 7050-T7451

Loads - on-orbit loads
Applied tensile load \( P = 612.1 \text{ lbf} \)
Applied shear load \( V = 36.9 \text{ lbf} \)
Applied bending moment \( M := 0 \text{ in-lbf} \)

Factors of Safety
Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)
Assembly
Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)
Maximum
Temperature data (Ref. Appendix C2)
Minimum

Bolt and Insert Data
Nominal diameter of bolt \( D := 0.250 \text{ in} \)
Number of threads/inch \( N_t := 28 \frac{1}{in} \)
Total length of bolt \( L := .625 \text{ in} \)
Length of insert \( L_{ins} := 0.375 \text{ in} \)
Threaded length \( L_t := 0.625 \text{ in} \)
Min. external diameter of insert \( F_{min} := 0.306 \text{ in} \)
Depth of recess for insert \( l_r := 0.02 \text{ in} \)
(If bolt is fully threaded, input \( L_t = L \))

Washer Data
Thickness of washer \( tw := 0.032 \text{ in} \)
Outer Diameter of washer \( D_w := .500 \text{ in} \)
Inner Diameter of washer \( D_{wi} := 0.265 \text{ in} \)
Bolt head dia. across flats \( d_w := 0.365 \text{ in} \)

Flange data
Thickness of flange 1 (Ref. SDG39135822) \( t_f1 := .180 \text{ in} \)
Thickness of flange 2 (Ref. SDG39135817) \( t_f2 := .375 \text{ in} \) (insert length)
Diameter of hole \( D_{hole} := 0.291 \text{ in} \)

This file uses the calculations shown in \escfil02\2i11\mathcad\8307_bolts\thread_data.mcd

Tue Feb 15 10:38:17 AM 2005

ESCG-4005-05-AMS-0039
Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

\[ T_{Su_{-}bolt} := 0.97 \quad \text{yield} \quad T_{Sy_{-}bolt} := 0.97 \]

Bolt ultimate tensile allowable stress
\( F_{tu_{-}bolt} := 160000 \text{-psi} \)

Bolt ultimate shear allowable stress
\( F_{su_{-}bolt} := 0.6 \times F_{tu_{-}bolt} \)

Bolt yield tensile allowable
\( F_{ty_{-}bolt} := 120000 \text{-psi} \)

Temperature correction factor for bolt modulus
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))
\[ T_{E_{-}bolt} := 0.98 \quad \text{in} \quad \beta_{bolt_{-}hot} := 9.1 \times 10^{-6} \quad \text{deg} \]

Modulus of elasticity of bolt
\( E_{-}bolt := \left\{ 29.1 \times 10^6 \text{-psi} \right\} \)
(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

Thermal coefficient for bolt:
(Ref. MIL-HDBK-5J, fig. 6.
\[ \beta_{bolt_{-}cold} := 8.7 \times 10^{-6} \quad \text{deg} \]

Insert
Temperature correction factor for insert strength
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)
\[ T_{S_{-}ins} := 0.98 \]

Ultimate tensile allowable stress
\( F_{tu_{-}ins} := 150000 \text{-psi} \)

Ultimate shear allowable stress
\( F_{su_{-}ins} := 0.6 \times F_{tu_{-}ins} \)

Washer
Temperature correction factor for washer modulus
\( T_{E_{-}w_\text{asher}} := 0.98 \quad \text{(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)} \)

Modulus of elasticity of washer
\( E_{-}w_\text{asher} := \left\{ 29.1 \times 10^6 \text{-psi} \right\} \quad \text{(Ref. MIL-HDBK-5J, table 6.2.1.0(b))} \)

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners,
Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4)
\[ T_{11E} := 0.98 \quad \text{(modulus)} \quad T_{12s} := 0.94 \quad \text{(strength)} \]

Temperature correction factor for flange 2
(Ref. Appendix C9)
\[ T_{21E} := 0.98 \quad \text{(modulus)} \quad T_{22s} := 0.94 \quad \text{(strength)} \]

Modulus of elasticity of the parts in the joint
\[ E_{-}flange_{1} := \left\{ 10.3 \times 10^6 \text{-psi} \right\} \quad E_{-}flange_{2} := \left\{ 10.3 \times 10^6 \text{-psi} \right\} \]

Coefficient of thermal expansion for flanges
(Ref. MIL-HDBK-5J, fig. 3.7.6.0 and Appendix C9)
\[ \beta_{flange_{1\_}hot} := 12.8 \times 10^{-6} \quad \text{in} \quad \beta_{flange_{2\_}hot} := 12.6 \times 10^{-6} \quad \text{in} \quad \text{deg} \]
\[ \beta_{flange_{1\_}cold} := 12.1 \times 10^{-6} \quad \text{in} \quad \beta_{flange_{2\_}cold} := 11.9 \times 10^{-6} \quad \text{in} \quad \text{deg} \]

Torque/Preload data
(Ref. SDG39135815)

Maximum torque
\( T_{max} := 97.3 \text{-in-lbf} \)

Minimum torque
\( T_{min} := 82.7 \text{-in-lbf} \)

Torque coefficient:
\( k := 0.15 \)

Loading plane factor:
\( n := 0.5 \)

Preload Uncertainty:
\( u := 0.25 \)
### Bolt Load data

- **Bolt/joint stiffness factor**: $0.31
- **Preload due to temperature**: $P_{\text{thr\_pos}} = 274.5\text{-lbf}$
- **Max. preload**: $P_{\text{LDMax}} = 3517.8\text{-lbf}$
- **Min. preload**: $P_{\text{LDMin}} = 1187.7\text{-lbf}$
- **Joint separation load**: $P_{\text{sep}} = 734.549\text{-lbf}$
- **Max. load on the bolt (ultimate)**: $P_b = 3736.3\text{-lbf}$
- **Max. load on the bolt (yield)**: $P_{\text{by}} = 3654.4\text{-lbf}$
- **Bolt ultimate tensile strength**: $P_{\text{At}} = 5475.9\text{-lbf}$

**Uncertainty factor**: $u = 0.25$
**Torque coefficient**: $k = 0.15$
**Loading plane factor**: $n = 0.5$

**Thread shear pullout load of bolt or insert**: $P_{\text{ths}} = 12348.8\text{-lbf}$
**Thread shear pullout load in parent metal**: $P_{\text{ppths}} = 7455.1\text{-lbf}$

**Length check**: "Bolt length is sufficient"

### Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>$MS_1$</th>
<th>$MS_2$</th>
<th>$MS_3$</th>
<th>$MS_4$</th>
<th>$MS_5$</th>
<th>$MS_6$</th>
<th>$MS_7$</th>
<th>$MS_8$</th>
<th>$MS_9$</th>
<th>$MS_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>0.664</td>
<td>2.89</td>
<td>3.67</td>
<td>0.47</td>
<td>0.124</td>
<td>4.3</td>
<td>1</td>
<td>34.75</td>
<td>10</td>
<td>0.466</td>
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<td>Direct Tension Ultimate</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Bending Ultimate</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

$$MS_{\text{bolt}} := \min(\text{MS})$$

$$MS_{\text{bolt}} = 0.124 \quad \text{Failure\_Mode} = \text{"Total Tension Yield"}$$
4.12.9  Vertex Bracket to Lower USS-02 Bolted Interface
Section 4.12.9  Vertex Bracket to Lower USS-02 Bolted Interface

The Vertex Bracket to Lower USS-02 Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12.9.1</td>
<td>Vertex Bracket to Lower USS-02 Assembly</td>
</tr>
<tr>
<td>4.12.9.1</td>
<td>Vertex Bracket to Lower USS-02 Assembly Fail Safe</td>
</tr>
</tbody>
</table>
4.12.9.1 Vertex Bracket to Lower USS-02 Assembly
Section 4.12.9.1   PAS Vertex Bracket to Lower USS-02 Bolt Analysis

The AMS-02 assembly consists of one Vertex Bracket with two bolted interfaces that attach to the Lower USS-02. There are a total of 4 fasteners attaching the Vertex Bracket to the Lower USS. The fasteners are NAS1956 (180 KSI), 0.375-24 UNFJ.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
bolt & \quad (0.375 \quad 24) \quad (0.375 \quad 24) \\
i & : = 1 \quad \text{rows(bolt)} \\
N_i & : = \text{bolt}, \quad \frac{1}{i.2} \quad \text{pitch of bolt} \\
D_i & : = \text{bolt}, \quad 1 \quad \text{in} \quad \text{bolt diameter} \\
A_t & : = \beta \left( \frac{D_i - 0.9743}{N_i} \right)^2 \quad \text{Tensile Area of bolt} \\
A_s & : = \beta \left( \frac{D_i - 1.299038}{N_i} \right)^2 \quad \text{Shear Area of bolt}
\end{align*}
\]

- NAS1956C76H  | BOLT, HEX-HEAD .375-24 UNJF-3A X 5.328L
- NAS1587-6C    | WASHER, C-SINK .375 X .078THK
- SDG39137839-001 | VERTEX BRACKET SHIM
- SDG39137837-001 | VERTEX BUSHING A
- SDG39137838-001 | VERTEX BUSHING B
- SDG39137839-001 | VERTEX BRACKET SHIM
- NAS1587-6C    | WASHER, C-SINK .375 X .078THK
- NAS1805-6     | NUT, SELF-LOCKING .375-24 UNJF-3B
Bolts from Vertex Bracket to Lower USS-02

Vertex Bracket to Lower USS Assembly

Aft and Vertex Brackets, MPC Nodes, and Definition/Output Coordinate System 0
Nodes 1515 and 1516 are in Definition Coordinate System 0. Loads are from MPC Forces at Nodes 1515 and 1516 in the Output Coordinate System 0. Analysis is also done in Global Coordinate System 0.

Note: x direction is tension. The y and z are shear.

**Bolt Pattern**

Bolt no. | x coordinate | y coordinate | z co-coordinate |
---|---|---|---|
1 | 0.0 | -1.75 | 0.0 |
2 | 0.0 | 1.75 | 0.0 |

**Location of applied forces and moments**

\[
\begin{align*}
\text{xforce} &= 0.0 \text{in} \\
\text{yforce} &= 0.0 \text{in} \\
\text{zforce} &= 0.0 \text{in}
\end{align*}
\]

\[
\begin{align*}
\text{cgload} &= \begin{pmatrix} \text{xforce} \\ \text{yforce} \\ \text{zforce} \end{pmatrix} \\
\text{cgload} &= \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{in}
\end{align*}
\]

**Center of gravity of bolt group**

\[
\begin{align*}
\text{xcg} &= \frac{\sum x_i}{\text{rows}(x)} \quad \text{xcg} = 0.00 \text{ in} \\
\text{ycg} &= \frac{\sum y_i}{\text{rows}(y)} \quad \text{ycg} = 0.00 \text{ in} \\
\text{zcg} &= \frac{\sum z_i}{\text{rows}(z)} \quad \text{zcg} = 0.00 \text{ in}
\end{align*}
\]

\[
\begin{pmatrix}
\text{cg}_{\text{bolt}} \\
\text{ycg} \\
\text{zcg}
\end{pmatrix} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{in}
\]

Note: Since the x direction is into the plate the loads are shared equally between the bolts. The bolt pattern is symmetric about the y-axis and z-axis with a zero offset from the center of gravity.

**Load Vector**

\[
\begin{align*}
\text{r}_{\text{load}} &= \text{cgload} - \text{cg}_{\text{bolt}} \\
\text{r}_{\text{load}} &= \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \text{in}
\end{align*}
\]

**Distance from CG of Bolts to Individual Bolts for shear calculations**

\[
r = \sqrt{(z_i - \text{zcg})^2 + (y_i - \text{ycg})^2} \\
r = \begin{pmatrix} 1.750 \\ 1.750 \end{pmatrix} \text{in}
\]
Loads model 2-06 was used to retrieve loads at the bolted interface. MPCs located at the center of the vertex brackets were post processed in NASPOST for forces and moments in the x, y, and z directions. The MPCs are located on RBE elements 1515 and 1516. These loads are read into an array and distributed out to the 2 bolts for each attachment on the vertex bracket.

**Note:** This joint was checked for minimum margins of safety for on-orbit, liftoff, abort landing and berthing load cases.

**Reading database file for bolted joint**

```plaintext
data := READPRN("boltsVertUSS.txt")
num_bolts := rows(bolt)
j := 1..rows(data)
```

**Note:** "boltsVertUSS.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files, see Appendix A22.

**Loads**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Load</td>
<td>$F_x := -\text{data}_{j,3}$ lbf</td>
</tr>
<tr>
<td>Shear in Y axis</td>
<td>$F_y := -\text{data}_{j,4}$ lbf</td>
</tr>
<tr>
<td>Shear in Z axis</td>
<td>$F_z := -\text{data}_{j,5}$ lbf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load Case Number</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>$\text{ID}<em>{j} := \text{data}</em>{j,1}$</td>
</tr>
<tr>
<td>LC</td>
<td>$\text{LC}<em>{j} := \text{data}</em>{j,2}$</td>
</tr>
</tbody>
</table>

**Format of Output File**

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

```plaintext
ID := stack(ID, ID + 1)  
LC := stack(LC, LC)
```

**Moment Distribution**

```plaintext
M_{tot} := \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} + \text{load} \times \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}
```

Use the cross-product to determine the additional moments acting on the fasteners.

```plaintext
M_{x,boltcgj} := M_{tot1,j}  
M_{y,boltcgj} := M_{tot2,j}  
M_{z,boltcgj} := M_{tot3,j}
```
Bolts from Vertex Bracket to Lower USS-02

**Tension in bolts**

\[
F_{t\text{direct}, i, j} := \frac{F_{zj}}{\text{num\_bolts}} \quad \text{and} \quad F_{mz, i, j} := \begin{cases} 0 \text{ lbf} & \text{if } (y_i - y_{cg}) = 0 \text{ in} \\ -\left[\frac{M_{\text{boltcg}} (y_i - y_{cg}) A_{tj}}{\sum_i (y_i - y_{cg})^2 A_{tj}}\right] \end{cases}
\]

\[F_{t, i, j} := |F_{t\text{direct}, i, j}| + |F_{mz, i, j}| \quad \text{Total Tensile load}
\]

**Shear on bolts**

Distance from cg of bolt to shear plane is +2" this causes a shear force due to a moment about y.

\[Z \text{ component shear Loads} \quad F_{z\text{total}, i, j} := \frac{F_{zj}}{\text{num\_bolts}} + \frac{M_{\text{boltcg}} (y_i - y_{cg}) A_{s\text{j}}}{\sum_i (y_i - y_{cg})^2 A_{s\text{j}}} + \frac{(M_{\text{boltcg}} 2\text{in}) A_{s\text{j}}}{\sum_i (2\text{in})^2 A_{s\text{j}}}
\]

\[F_{stot, i, j} := \sqrt{\left(\frac{F_{z\text{total}, i, j}}{\text{num\_bolts}}\right)^2 + \left(\frac{F_{yj}}{\text{num\_bolts}}\right)^2} \quad \text{Total shear load}
\]

**Note:** Each bolt has 2 shear planes. Therefore, the total shear load is divided by 2.

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P := \text{stack}\left[\left(\begin{array}{c} F_{zj} \\ (F_{xj})^T \end{array}\right), \left(\begin{array}{c} F_{yj} \\ (F_{yj})^T \end{array}\right)\right] \quad V := \text{stack}\left[\left(\begin{array}{c} F_{z\text{total}, i, j} \\ (F_{z\text{total}, i, j})^T \end{array}\right), \left(\begin{array}{c} F_{y\text{total}, i, j} \\ (F_{y\text{total}, i, j})^T \end{array}\right)\right] \quad M := \text{stack}(M, M)
\]

The "Output" file below outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). See the output array example below. The array is then written to a text file.

Output := augment\left[\begin{array}{cccc} P \text{lbf} & V \text{lbf} & M \text{lbf} \text{in}\text{lbf} \end{array}\right] \quad \text{Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.}

Size of the "Output" Array: rows(Output) = 1024

(2 bolts x 256 load cases) x 2 joints = 1024 rows

\[
\text{WRITEPRN(}"\text{output}_\text{vertiwuss}_r5.txt"\text{)} := \text{Output}
\]
CHECK Bolts (NAS1956C76H 0.375-24 x 5.328L, A286, 180 KSI Tensile, 108 KSI Shear), Washer (NAS1587-6C, CRES), Nut (NAS1805-6, CRES 180 KSI)
Vertex Bushing A (SDG39137837, A286 Stainless, 1.50 DIA x 2.438 LG, AMS 5737)
Vertex Bushing B (SDG39137838, A286 Stainless, 1.50 DIA x 2.406 LG, AMS 5737)
Vertex Bracket Shim (SDG39137839, Shim Stock, AL ALY, 3.0 x 1.5 x .033, AMS-DTL-22499/1)

Note loads must be sorted by case such that the first line is for grid 1515 and the second grid is for the grid 1516.

```
data := READPRN("output_vertlwuss_r5.txt")
s := 1., rows(data) rows(data) = 1024.00
```

Flange 1: Vertex Bracket
Part number: SEG39135813
Material: 7050-T7451, 16.5x10.72x7.92, BMS-7-323C

Flange 2: Lower USS-02
Part number: SDG39135758
Material: 7075-T73511, 46.92 x 4 x 4, ASTM-B221

**Loads**
- Applied tensile load \( P_s := \text{data}_{s,3} \text{ lbf} \)
- Applied shear load \( V_s := \text{data}_{s,4} \text{ lbf} \)
- Applied bending moment \( M_s := \text{data}_{s,5} \text{ in-lbf} \)

**Factors of Safety**
- Ultimate \( SFu := 2.0 \text{ Yield SFy := 1.25} \)
- Joint Separation \( SFsep := 1.2 \text{ Fitting factor FF := 1.15} \)

**Temperature Data**
- Assembly \( \text{Temp}_\text{initial} := 70 \text{ deg} \)
- Maximum \( \text{Temp}_\text{max} := 139 \text{ deg} \)
- Minimum \( \text{Temp}_\text{min} := -37 \text{ deg} \)
Bolt and Nut Data

Nominal diameter of bolt \( D := \text{0.375 in} \)  
Number of threads/inch \( Nt := 24 \frac{1}{8} \text{ in} \)  
Total length of bolt \( L := \text{5.328 in} \)  
Height of nut \( H := \text{0.375 in} \)  
Threaded length \( L_t := \text{0.578 in} \)  
(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \( \text{\\escfl02\\2111\\mathcad\\8307\\bolts\\thread\_data.mcd} \)

Washer Data

Thickness of washers \( tw := \text{0.156 in} \)  
Outer Diameter of washer \( D_w := \text{0.687 in} \)  
Inner Diameter of washer \( D_{wi} := \text{0.378 in} \)  
Bolt head dia. across flats \( dw := \text{0.553 in} \)

Flange data

Thickness of flange 1 \( t_f := \text{0.50 in} \)  
Thickness of flange 2 \( t_f := \text{0.50 in} \)  
Diameter of hole \( D_{hole} := \text{0.409 in} \)  
(used only if there is no washer)

Bushing Data

Thickness of A286 Stainless Steel bushing \( t_b := \text{4.124 in} \)  
Outer Diameter of A286 Stainless Steel bushing \( D_{bo} := \text{0.950 in} \)  
Inner Diameter of A286 Stainless Steel bushing \( D_{bi} := \text{0.409 in} \)

Material Property Data

Bolt

Temperature correction factor bolt strength ult  
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1) \( TS_{u\_bolt} := \text{0.98} \) Yield \( TS_{y\_bolt} := \text{0.98} \)

Bolt Ult tensile allowable stress \( F_{tu\_bolt} := \text{180000 psi} \)  
(Ref. NAS1956)  
Bolt Ult shear allowable stress \( F_{su\_bolt} := \text{0.6 Ftu\_bolt = 108000 psi} \)  
Bolt yield Tensile allowable stress \( F_{ty\_bolt} := \text{132353 psi} \)  
(Ref. Appendix C10)  
Temperature correction factor for bolt modulus \( TE_{bolt} := \text{0.98} \)  
(Ref. MIL-HDBK-5J, fig. 6.2.1.1.4(a))  
Modulus of elasticity of bolt \( E_{bolt} := \text{29.1 \times 10^6 psi} \)
Thermal coefficient for bolt
(Ref. MIL-HDBK-5J, fig. 6.2.1.0)

\[ u_{bolt\_hot} = 9.1 \times 10^{-6} \text{ in in deg} \]
\[ u_{bolt\_cold} = 8.7 \times 10^{-6} \text{ in deg} \]

**Nut**

Temperature correction factor for nut strength
\[ TS_{\text{nut}} = .98 \]

Ult tensile allowable stress
\[ F_{tu\_\text{nut}} = 180000 \text{ psi} \]

Ult Shear allowable stress:
\[ F_{su\_\text{nut}} = 0.6 \]

Ult axial strength of nut
\[ P_{tu\_\text{nut}} = 16488 \text{ lbf} \]

(Ratio 180 KSI/125 KSI = 1.44, 11450 * 1.44 = 16488, Ref. NAS1291)

**Washer**

Temperature correction factor for washer modulus
\[ TE_{\text{washer}} = .98 \]

Modulus of elasticity of washer:
\[ E_{\text{washer}} = 29.1 \times 10^6 \text{ psi} \]

(Ref. MIL-HDBK-5J, fig. 6.2.1.1.1)

(Ref. MIL-HDBK-5J, table 6.2.1.0(b))

**Bushing**

Temperature correction factor for bushing modulus
\[ TE_{\text{bushing}} = .98 \]

Modulus of elasticity of bushing:
\[ E_{\text{bushing}} = 29.1 \times 10^6 \text{ psi} \]

(Ref. MIL-HDBK-5J, fig. 5.4.1.1.1)

(Ref. MIL-HDBK-5J, table 5.4.1.0(c1))

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T1E_{1} = .98 \] (modulus)

Temperature correction factor for flange 2
\[ T2E_{2} = .98 \] (modulus)

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} = (10.6 \times 10^6 \text{ psi}) \]
\[ E_{\text{flange2}} = (10.7 \times 10^6 \text{ psi}) \]

(Ref. MIL-HDBK-5J, fig. 3.7.6.1.4 and Appendix C9)

(Ref. MIL-HDBK-5J, table 3.7.4.0(b1))
## Coefficient of thermal expansion for flanges
(Ref. MIL-HDBK-5J, table 3.7.4.0(b1) and Appendix C3)

<table>
<thead>
<tr>
<th>Flange</th>
<th>Coefficient</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>u_flange1_hot</td>
<td>$12.7 \times 10^{-6}$</td>
<td>in/in deg</td>
</tr>
<tr>
<td>u_flange1_cold</td>
<td>$12.1 \times 10^{-6}$</td>
<td>in/in deg</td>
</tr>
<tr>
<td>u_flange2_hot</td>
<td>$12.5 \times 10^{-6}$</td>
<td>in/in deg</td>
</tr>
<tr>
<td>u_flange2_cold</td>
<td>$12.1 \times 10^{-6}$</td>
<td>in/in deg</td>
</tr>
</tbody>
</table>

## Torque/Preload data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum torque (66.4% of yield)</td>
<td>$T_{\text{max}} = 425$ in lbf</td>
</tr>
<tr>
<td>Minimum torque (95% of max. torque)</td>
<td>$T_{\text{min}} = 404$ in lbf</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>$k = 0.15$</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>$n = 0.5$</td>
</tr>
<tr>
<td>Preload Uncertainty</td>
<td>$\pm 0.25$</td>
</tr>
</tbody>
</table>

This collapsed section includes the strength calculations as in the bolt template.

### Joint load factor
The joint load factor ($f$) is specified by Ref. 1 as:

$$ f = \frac{k_b}{K_b + K_j} $$

where $K_b$ is the stiffness of the bolt and $K_j$ the stiffness of the joint. Ref. 1, does not give a method for calculating these stiffnesses. $K_b$ and $K_j$ will be calculated using a cylindrical stiffness method.

$$ k_{\text{bolt}} = \frac{A_d \cdot A_t \cdot E_{\text{bolt}}}{A_d \cdot A_t + A_d \cdot A_l d} $$

(Ref. 2, page 461)

This gives the washer area as:

$$ A_{\text{washer}} = \beta \frac{D_w^2 - D_{wl}^2}{4} $$

This gives the Vertex Bracket (flange 1) area as:

$$ A_{f1} = \beta \frac{D_{bo}^2 - D_{bi}^2}{4} $$

This gives the A286 stainless steel bushing area as:

$$ A_{\text{bushing}} = \beta \frac{D_{bo}^2 - D_{bi}^2}{4} $$

This gives the Lower USS (flange 2) area as:

$$ A_{f2} = \beta \frac{D_{bo}^2 - D_{bi}^2}{4} $$
The stiffness for each of the members is then given by treating each one as a cylinder:

\[
k_{\text{washer}} := \begin{cases} 
0.0 \frac{\text{lbf}}{\text{in}} & \text{if } tw = 0.0 \\
\frac{A_{\text{washer}}E_{\text{washer}}}{tw} & \text{otherwise}
\end{cases}
\]

\[
k_{\text{flange}1} := \frac{A_{f1}E_{\text{flange}1}}{tf1} \quad k_{\text{bushing}} := \frac{A_{\text{bushing}}E_{\text{bushing}}}{tb}
\]

\[
k_{\text{flange}2} := \frac{A_{f2}E_{\text{flange}2}}{tf2}
\]

The joint stiffness will be

\[
K_j := \begin{cases} 
\frac{1}{k_{\text{flange}1} + \frac{1}{k_{\text{bushing}}} + \frac{1}{k_{\text{flange}2}}} & \text{if } tw = 0 \\
\frac{1}{k_{\text{flange}1} + \frac{1}{k_{\text{bushing}}} + \frac{1}{k_{\text{flange}2}} + \frac{1}{k_{\text{washer}}}} & \text{otherwise}
\end{cases}
\]

The joint load factor will then be:

\[
= \frac{k_{\text{bolt}}}{K_j + k_{\text{bolt}}}
\]

stiffness of joint

\[
K_{\text{therm}} := \frac{k_{\text{bolt}}K_j}{k_{\text{bolt}} + K_j}
\]

**Calculation of Preload on the Bolt**

Increase in preload due to increase in temperature

\[
P_{\text{thr} - 1} := \left[ (tf1) \cdot (\text{Temp}_{\text{max}} - \text{Temp}_{\text{initial}}) \cdot (u_{\text{flange1\_hot}} - u_{\text{bolt\_hot}}) \ldots \right] K_{\text{therm}} \\
+ \left[ (tf2) \cdot (\text{Temp}_{\text{max}} - \text{Temp}_{\text{initial}}) \cdot (u_{\text{flange2\_hot}} - u_{\text{bolt\_hot}}) \ldots \right] \\
+ \left[ (tb) \cdot (\text{Temp}_{\text{max}} - \text{Temp}_{\text{initial}}) \cdot (u_{\text{bushing\_hot}} - u_{\text{bolt\_hot}}) \right]
\]
Decrease in preload due to reduction in temperature:

\[
P_{thr, 2} := \left[ (t_1) \left( Temp_{min} - Temp_{initial} \right) \left( u_{flange1\_cold} - u_{bolt\_cold} \right) + (t_2) \left( Temp_{min} - Temp_{initial} \right) \left( u_{flange2\_cold} - u_{bolt\_cold} \right) + \left[ (t_b) \left( Temp_{min} - Temp_{initial} \right) \left( u_{bushing\_cold} - u_{bolt\_cold} \right) \right] \right] \cdot K_{therm}
\]

This collapsed section includes the rest of the calculations for the bolt template.

**Bolt Load data**

<table>
<thead>
<tr>
<th>Bolt/joint stiffness factor</th>
<th>0.913</th>
<th>Preload due to temperature</th>
<th>Pthr_pos = 504.2 lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. preload</td>
<td>PLDmax = 9949 lbf</td>
<td>Pthr_neg = -759.5 lbf</td>
<td></td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLDmin = 4155 lbf</td>
<td>Uncertainty factor = 0.25</td>
<td></td>
</tr>
<tr>
<td>Joint separation load</td>
<td>max(Psep) = 844.8 lbf</td>
<td>Torque coefficient k = 0.15</td>
<td></td>
</tr>
<tr>
<td>Max. load on the bolt(Ult)</td>
<td>max(Pb) = 10688 lbf</td>
<td>Loading plane factor n = 0.50</td>
<td></td>
</tr>
<tr>
<td>Max. load on the bolt(yield)</td>
<td>max(Pby) = 10411 lbf</td>
<td>Thread pullout strength required to develop full strength of bolt PAs = 18189 lbf</td>
<td></td>
</tr>
<tr>
<td>Bolt Ult tensile strength</td>
<td>PAT = 15158 lbf</td>
<td>Nut Ult tensile strength Ptu_nut = 16158 lbf</td>
<td></td>
</tr>
</tbody>
</table>

**Length_check = "Bolt length is sufficient"**

**Summary of Margins for bolt**

| Joint separation | MS_min_1_1 = 6.87 Direct Thread shear Ult | MS_min_6.1 = 10.23 |
| Direct Tension Ult | MS_min_2_1 = 8.4 Total Thread shear Ult | MS_min_7.1 = 0.70 |
| Direct Tension Yield | MS_min_3_1 = 10.0 Shear Ult | MS_min_8.1 = 6.18 |
| Total Tension Ult | MS_min_4_1 = 0.42 Bending Ult | MS_min_9.1 = 1000 |
| Total Tension Yield | MS_min_5_1 = 0.07 Combined shear, tension and bending Ult | MS_min_10.1 = 0.42 |

**Determination of the smallest margin of safety for the bolt, and the failure mode**

\[
MS_{bolt} := \min(MS)
\]

MS_min_ID = 1516000001 Node Identification (1516) and Bolt Number (1) for Minimum Margin

Bolts from Vertex Bracket to Lower USS-02

MS_min_LC = 5006
MS_min_P = 704
MS_min_V = 418.8
MS_min_M = 0

Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin

Bolt Fail-Safe Analysis for Vertex Bracket to Lower USS-02

Since bolt number 1516 (bolt 2) has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. For fail safe the pattern is assumed to include all 4 bolts and not two separate patterns of two bolts each. There are now 3, NAS1956C 0.375-24 UNFJ fasteners, holding the vertex bracket to the Lower USS-02. The drawing number for the Vertex and Aft Bracket Installation is SDG39135873. The below figure shows the fastener removed as fastener number 3.

size thread/in

```
<table>
<thead>
<tr>
<th></th>
<th>.375</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>bolt2 :=</td>
<td>.375</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>.375</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>.375</td>
<td>24</td>
</tr>
</tbody>
</table>

s := 1..rows(bolt2)

N2s := bolt2.s,2 1 in
pitch of bolt

D2s := bolt2.s,1 in
bolt diameter

At2s := \( \beta \left( \frac{D2s - 0.9743}{N2s} \right)^2 \)
Tensile Area of bolt

As2s := \( \beta \left( \frac{D2s - 1.299038}{N2s} \right)^2 \)
Shear Area of bolt

Bolt no. x coordinate y coordinate z coordinate
Bolts from Vertex Bracket to Lower USS-02

1. There are 4 bolts. One was removed. The distances for the y direction is + 5.5" half the distance from the cg of the bolt pattern to the bolts.

2. Location of applied forces and moments

   Two loads are recovered and combined into a single load for this analysis. The loads are at the positions 1515 and 1516 shown above. The first grid is 1515. This node is located using cgload2 where the distances are listed x,y,z going down the array. The second is shown as cgload3.

   \[
   \text{cgload2} := \begin{pmatrix} 0.0 \text{in} \\ -5.5 \text{in} \\ 0.0 \text{in} \end{pmatrix} \quad \text{cgload3} := \begin{pmatrix} 0.0 \text{in} \\ 5.5 \text{in} \\ 0.0 \text{in} \end{pmatrix}
   \]

3. Center of gravity of bolt group

   \[
   x_{cg2} := \frac{\sum x_2s}{\text{rows}(x2)} \quad x_{cg2} = 0.00 \text{ in} \quad y_{cg2} := \frac{\sum y_2s}{\text{rows}(y2)} \quad y_{cg2} = -1.25 \text{ in} \quad z_{cg2} := \frac{\sum z_2s}{\text{rows}(z2)} \quad z_{cg2} = 0.00 \text{ in}
   \]

   \[
   c_{gbolt2} := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} \quad c_{gbolt2} := \begin{pmatrix} 0.00 \\ -1.25 \\ 0.00 \end{pmatrix} \text{ in}
   \]

4. Load Vector

   Two load vectors are computed, r2load2 is for node 1515 and r2load3 is for 1516.

   \[
   r_{load2} := \text{cgload2} - c_{gbolt2} \quad r_{load2} := \begin{pmatrix} 0.00 \\ -4.25 \\ 0.00 \end{pmatrix} \text{ in}
   \]

   \[
   r_{load3} := \text{cgload3} - c_{gbolt2} \quad r_{load3} := \begin{pmatrix} 0.00 \\ 6.75 \\ 0.00 \end{pmatrix} \text{ in}
   \]
Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r_2 = \sqrt{(z_2 - z_{cg2})^2 + (y_2 - y_{cg2})^2} \]

\[ \begin{bmatrix} 6.000 \\ 2.500 \\ 8.500 \end{bmatrix} \text{ in} \]

Reading database file for bolted joint

```plaintext
data := READPRN("boltsVertUSS.txt")
q := 1..rows(data) num_bolts2 := rows(bolt2)
```

Loads from Vertex loads model, launch case

Note that the element direction is such that compression is positive. This template is derived such that compression is negative. The template is adjusted in the read statements to change the loads to match the template with compression negative.

Axial Load

\[ Fx_{2q} := -data_{q,3} \text{ lbf} \quad \text{Torsion} \]

\[ Mx_{2q} := -data_{q,6} \text{ in-lbf} \]

Shear in Y axis

\[ Fy_{2q} := -data_{q,4} \text{ lbf} \quad \text{Moment about Y axis} \]

\[ My_{2q} := -data_{q,7} \text{ in-lbf} \]

Shear in Z axis

\[ Fz_{2q} := -data_{q,5} \text{ lbf} \quad \text{Moment about Z axis} \]

\[ Mz_{2q} := -data_{q,8} \text{ in-lbf} \]

Element Identification

\[ ID2_q := data_{q,1} \]

Load Case Number

\[ LC2_q := data_{q,2} \]

Applied Bending Moment at Bolts

\[ M2_q := 0 \text{ in-lbf} \]

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 3 is not included.

```
"error" if ID2_1 ≠ 1515 = "ok" This checks that the data is in the correct order result should be "ok"
"error" if ID2_2 ≠ 1516
"ok" otherwise
```
\[ q := 1 \cdot \frac{\text{rows(data)}}{2} \quad \text{set the counter} \]

**Moment Distribution**

The data has two lines of data for each load case. The first case is for grid 1515 and the second is for 1516. The for loop combines the two lines of data and calculates the Moments due to the offset distance for all loadcases. This is the reason the data must be sorted with the data sorted by load case.

Use the cross-product to determine the additional moments acting on the fasteners.

\[
\begin{align*}
M_t & := \left[ \begin{array}{l}
cc \leftarrow 1 \\
\text{for } \ w_w \in 1 .. \frac{\text{rows(data)}}{2} \\
M_t^{(ww)} \leftarrow \left( \frac{M_x^{2,cc}}{M_y^{2,cc}} \right) + f_{\text{load}2} \times \left( \frac{F_x^{2,cc}}{F_y^{2,cc}} \right) + \left( \frac{M_x^{2,cc+1}}{M_y^{2,cc+1}} \right) + f_{\text{load}3} \times \left( \frac{F_x^{2,cc+1}}{F_y^{2,cc+1}} \right) \\
cc \leftarrow cc + 2 \\
M_t
\end{array} \right]
\end{align*}
\]

\[
\begin{align*}
M_{x,\text{bolt}cg2,q} & := M_t^{1,q} \\
M_{y,\text{bolt}cg2,q} & := M_t^{2,q} \\
M_{z,\text{bolt}cg2,q} & := M_t^{3,q}
\end{align*}
\]

\[
\begin{align*}
F_{xt} & := \left[ \begin{array}{l}
cc \leftarrow 1 \\
\text{for } \ w_w \in 1 .. \frac{\text{rows(data)}}{2} \\
F_{xt}^{ww} \leftarrow F_x^{2,cc} + F_x^{2,cc+1} \\
cc \leftarrow cc + 2 \\
F_{xt}
\end{array} \right]
\end{align*}
\]

\[
\begin{align*}
F_{yt} & := \left[ \begin{array}{l}
cc \leftarrow 1 \\
\text{for } \ w_w \in 1 .. \frac{\text{rows(data)}}{2} \\
F_{yt}^{ww} \leftarrow F_y^{2,cc} + F_y^{2,cc+1} \\
cc \leftarrow cc + 2 \\
F_{yt}
\end{array} \right]
\end{align*}
\]
Fzt := \[ c_c \leftarrow 1 \]
\[ \text{for } w \in 1 \ldots \text{rows(data)} \]
\[ Fzt_{ww} \leftarrow Fz_{2c} + Fz_{c2c} \]
\[ c_c \leftarrow c_c + 2 \]
\[ Fzt \]

Cases := \[ c_c \leftarrow 1 \]
\[ \text{for } w \in 1 \ldots \text{rows(data)} \]
\[ \text{Cases}_{ww} \leftarrow L2_{c2c} \]
\[ c_c \leftarrow c_c + 2 \]

ID2 := \[ \text{for } w \in 1 \ldots \text{rows(data)} \]
\[ ID2_{ww} \leftarrow 1 \]
\[ ID2 \]

Tension on bolts

\[ F_{t,direct2,q} := \frac{F_{xt,q}}{\text{num_bolts2}} \]

Direct tensile load calculation

\[ F_{m2,q} := \begin{cases} 0 \text{ lbf if } (x_{2q} - x_{cg}) = 0 \text{ in} \\ \frac{M_{z,bolts2q} (x_{2q} - x_{cg}) A_{t2q}}{\sum_s (x_{2s} - x_{cg})^2 A_{t2s}} \end{cases} \]

\[ F_{t2,q} := \left| F_{t,direct2,q} \right| + \left| F_{m2,q} \right| \]

Total Tensile load

Shear on bolts

Distance from cg of bolt to shear plane is +_2" this causes a shear force due to a moment about y.

\[ Z \text{ component shear Loads} \]
\[ F_{total2,q} := \frac{F_{zt,q}}{\text{num_bolts2}} + \frac{M_{x,bolts2q} (y_{2q} - y_{cg2}) A_{s}}{\sum_s (y_{2s} - y_{cg2})^2 A_{s}} + \frac{M_{y,bolts2q} 2 \text{ in} A_s}{\sum_s (2 \text{ in})^2 A_s} \]

Total shear load
\[ F_{tot2,q} := \sqrt{\left( F_{total2,q} \right)^2 + \left( \frac{F_{ts}}{\text{num_bolts2}} \right)^2} \]

Note: Each bolt has 2 shear planes. Therefore, the total shear load is divided by 2.

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and
applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below. Notice how there is only 3 bolts, since bolt number 3 is not included.

Since bolt moment is zero, set it to that.

\[ M_{3q} := 0 \text{ in lbf} \]

\[ M3 := \text{stack}(M3, M3, M3) \]

\[ V2 := \text{stack}
\begin{bmatrix}
(F_{\text{stot}2})^T \left[ \begin{array}{c}
1 \\
2 \\
3
\end{array} \right]
\end{bmatrix}
\]

\[ P2 := \text{stack}
\begin{bmatrix}
(F_{t2})^T \left[ \begin{array}{c}
1 \\
2 \\
3
\end{array} \right]
\end{bmatrix}
\]

Set ID's and cases for the new data sets.

\[ \text{Cases} := \text{stack}(\text{Cases}, \text{Cases}, \text{Cases}) \]

\[ \text{ID2} := \text{stack}(\text{ID2}, \text{ID2} + 1, \text{ID2} + 3) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[ \text{Output2} := \text{augment}(\text{ID2, Cases, P2, V2, M3}, \text{lb}, \text{lb}, \text{in lbf}) \]

Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.

Size of the "Output2" Array: \[ \text{rows(Output2)} = 768 \]

(3 bolt x 256 load cases) x 1 joints = 768 load cases

\[ \text{WRITEPRN("output_veriwuss_r5_fs.txt") := Output2} \]
Bolt Fail-safe Results

The array from the text file above is read:

```plaintext
data_fs := Output2
s := 1..rows(data_fs)
```

### Fail-safe Loads

- **Applied tensile load**
  \[ P_{FS_s} := \text{data}_s \text{,}_3 \text{lbf} \]
- **Applied shear load**
  \[ V_{FS_s} := \text{data}_s \text{,}_4 \text{lbf} \]
- **Applied bending moment**
  \[ M_{FS_s} := \text{data}_s \text{,}_5 \text{in-lbf} \]

### Fail-safe Factors of Safety

- **Joint Separation**
  \[ SF_{sep} := 1.0 \]
- **Ult**
  \[ SF_{u} := 1.0 \]

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC`

**Bolt Fail-safe Load data**

- **Joint separation load**
  \[ \text{max}(P_{sep} \text{,}_FS) = 810.333 \text{ lbf} \]
  \[ \text{max}(P_{FS}) = 810.333 \text{ lbf} \]
- **Max. load on the bolt(Ult)**
  \[ \text{max}(P_{b} \text{,}_FS) = 10374.3 \text{ lbf} \]
  \[ \text{max}(V_{FS}) = 890.524 \text{ lbf} \]

### Summary of fail-safe Margins for bolt

- **Joint separation**
  \[ MS_{\text{min}FS} = 7.21 \]
- **Direct Tension Ult**
  \[ MS_{\text{min}FS} = 15.27 \]
- **Total Tension Ult**
  \[ MS_{\text{min}FS} = 0.46 \]
- **Direct Thread shear Ult**
  \[ MS_{\text{min}FS} = 18.52 \]
- **Total Thread shear Ult**
  \[ MS_{\text{min}FS} = 0.75 \]
- **Shear Ult**
  \[ MS_{\text{min}FS} = 10.41 \]
- **Bending Ult**
  \[ MS_{\text{min}FS} = 1000 \]
- **Combined shear, tension and bending Ult**
  \[ MS_{\text{min}FS} = 0.46 \]

### Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode

- **MSbolt_FS := min(MS_{FS})**
  \[ MS_{FS} = 0.46 \]
  **Failure Mode_FS = "Combined Shear Tension Bending Ultimate"**

- **MS_{FSmin-ID} = 4**
  Element Identification (1516) and Bolt Number (4) for Minimum Margin
- **MS_{FSmin-LC} = 5031**
  Load Case Number for Minimum Margin
- **MS_{FSmin-P} = 810.3**
  Applied Tensile Load for Minimum Margin
- **MS_{FSmin-V} = 852.3**
  Applied Shear Load for Minimum Margin
- **MS_{FSmin-M} = 0**
  Applied Bending Moment for Minimum Margin
Bushing Analysis

Factors of safety

FSu = 2.0 (Ult)  
FSy = 1.25 (yield)

Material properties - A-286

Tensile allowable, Ult and yield

Ftu = 140000 psi  
Fty = 95000 psi

Shear allowable

Fsu = .6 Ftu  
Fsu = 84000 psi

Temperature Correction Factors

+ At 151°F for On-orbit condition:

- Ult:

  \[ y_u = 0.97 \]

- Yield:

  \[ y_Y = 0.97 \]

Ftua = y_u Ftu  
Ftua = 135800 psi

Ftya = y_Y Fty  
Ftya = 92150 psi

Fsua = y_u Fsu  
Fsua = 81480 psi
Section Properties: Cross section is a circular tube.

Thick portion of bushing:
\[ \text{Id1} := 0.409 \text{ in} \]
Outer Diameter
\[ \text{Od1} := 0.950 \text{ in} \]
Thickness
\[ t1 := \frac{\text{Od1} - \text{Id1}}{2} \]
\[ t1 = 0.27 \text{ in} \]

Thin portion of bushing:
\[ t2 := \frac{t1}{2} \]
\[ t2 = 0.14 \text{ in} \]
Outer Diameter
\[ \text{Od2} := 0.950 \text{ in} \]
Inner Diameter
\[ \text{Id2} := \text{Od2} - t2 \cdot 2 \]
\[ \text{Id2} = 0.68 \text{ in} \]
Area:
\[ \text{Area} := \beta \left( \frac{\text{Od2}^2 - \text{Id2}^2}{4} \right) \]
\[ \text{Area} = 0.35 \text{ in}^2 \]
Thread Shear Area:
\[ \text{Ast} := \beta \frac{\text{Dt} \cdot \text{Lst}}{2} \]
\[ \text{Ast} = 0.63 \text{ in}^2 \]
Distance from centroid to outer fiber:
\[ c := \frac{\text{Od2}}{2} \]
\[ c = 0.48 \text{ in} \]
Moments of inertia about centroid:
\[ \text{Iy} := \frac{\beta \left(\text{Od2}^4 - \text{Id2}^4\right)}{64} \]
\[ \text{Iy} = 0.0295 \text{ in}^4 \]
\[ \text{Iz} := \text{Iy} \]
Torsional constant:
\[ \text{Jx} := \frac{\beta \left(\text{Od2}^4 - \text{Id2}^4\right)}{32} \]
\[ \text{Jx} = 0.059 \text{ in}^4 \]

Loads
Bushiong Thread Shear Strength:
\[ \text{Ptu} := \text{Ftu Apst} \]
\[ \text{Ptu} = 87579.7 \text{ lbf} \]
Compressive Load in Bushing:
\[ \text{Pc} := \max(\text{Pb}) \]
\[ \text{Pc} = 10688.2 \text{ lbf} \]
Applied load + Preload
Applied Shear Load:
\[ (\text{Minimum Margin of Safety from Bolt Analysis above}) \]
\[ \text{Sc} := \max(\nu) \]
\[ \text{Sc} = 708.2 \text{ lbf} \]
**Stresses on cross section**

Normal is direct axial (compression):

\[
t = \frac{P_c}{A} \quad \text{, } t = 30874 \text{ psi}
\]

Shear due to transverse loading

\[
\varepsilon_v := \frac{S_c}{A} \quad \text{max(} \varepsilon_v \text{) = 2046 psi}
\]

Principal Stresses:

\[
p_1 := \frac{1}{2} \left[ \frac{1}{2} t + \left( \frac{1}{2} t + \varepsilon_v^2 \right)^{\frac{1}{2}} \right] \quad \text{, } p_1 = 31009 \text{ psi}
\]

\[
p_2 := \frac{1}{2} \left[ \frac{1}{2} t - \left( \frac{1}{2} t + \varepsilon_v^2 \right)^{\frac{1}{2}} \right] \quad \text{, } p_2 = -135 \text{ psi}
\]

Maximum principal stress is:

\[
\max := \begin{cases} p_1 & \text{if } |p_1| \geq |p_2| \\ p_2 & \text{otherwise} \end{cases}
\]

Von Mises Stress:

\[
\sigma_m := \sqrt{\frac{1}{2} (p_1^2 + p_2^2 - p_1 - p_2)} \quad \text{, } \sigma_m = 31077 \text{ psi}
\]

**Margins of safety**

Ult

\[
MS_u := \left( \frac{F_{tu}}{FSU} \right) - 1 \quad \text{MSu} = 1.20
\]

Ult, shear

\[
MSsu := \left( \frac{F_{sua}}{FSU \cdot \varepsilon_v} \right) - 1 \quad \text{MSsu} = 18.92
\]

Yield (using Von Mises)

\[
MSy := \left( \frac{F_{tya}}{FSy \cdot \sigma_m} \right) - 1 \quad \text{MSy} = 1.37
\]

Ult, thread shear

\[
MSstu := \left( \frac{P_{tu}}{Pc} \right) - 1 \quad \text{MSstu} = 7.19
\]
Buckling Analysis Scenario

Additional Material Properties for Steel A-286

Compressive modulus \( E_c := 29100000 \) psi  
Total Length \( L := 4.0 \) in  
(Ref. MIL-HDBK-5J, Table 6.2.1.0(b))

Both ends Pinned Condition

Critical Load \( P_{cr1} := \frac{\beta^2 E_c I_y}{L^2} \) \( P_{cr1} = 529844.9 \) lbf

Both ends Fixed Condition

Critical Load \( P_{cr2} := \frac{\beta^2 E_c I_y 4}{L^2} \) \( P_{cr2} = 2119379.7 \) lbf

Compressive Load in Bushing: \( P_c := \max(P_b) \) \( P_c = 10688.2 \) lbf

Margin of Safety

\( \frac{P_{cr1}}{FS_u \cdot P_c} - 1 \) \( M_{sub} = 23.79 \)
4.12.10 Aft Bracket to Lower USS-02 Bolted Interface
Section 4.12.10  Aft Bracket to Lower USS-02 Bolted Interface

The Aft Bracket to Lower USS-02 Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>4.12.10.1</th>
<th>Aft Brackets to Lower USS-02 Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12.10.1</td>
<td>Aft Brackets to Lower USS-02 Assembly Fail Safe</td>
</tr>
</tbody>
</table>
4.12.10.1 Aft Brackets to Lower USS-02 Assembly
Section 4.12.10.1 PAS Aft Bracket to Lower USS-02 Bolt Analysis

There are a total of 6 fasteners attaching one end of the Aft brackets to the Lower USS-02. The fasteners are NAS1956C14 180 KSI, 0.375-24 UNIF-3A x 1.453L. The drawing number for the AMS-02 Assembly is SGG39135873.

**Bolt Geometry**

<table>
<thead>
<tr>
<th>size</th>
<th>thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
</tbody>
</table>

\[
i := 1.. \text{rows(bolt)} \quad \# \text{ of bolts}
\]

\[
N_i := \text{bolt}_{i,2} \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{i,1} \text{in} \quad \text{bolt diameter}
\]

**Tensile Area of bolt**

\[
A_{t_i} := \beta \left( \frac{D_i - 0.9743}{2} \frac{1}{N_i} \right)^2
\]

**Shear Area of bolt**

\[
A_{s_i} := \beta \left( \frac{D_i - 1.299038}{2} \frac{1}{N_i} \right)^2
\]
Recovering MFC forces from Node 1570 for RBE2 609511.

Recovering MPC forces from Node 1571 for RBE2 709511.

Note: z direction is tension, x & y directions are shear.

**Bolt Pattern**

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.125</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-2.125</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-2.125</td>
<td>-1.25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2.125</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2.125</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>2.125</td>
<td>-1.25</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: Assume our coordinate system origin is located at the CG of the bolt pattern.

**Location of applied forces and moments**

\[
\begin{align*}
xforce &= 0.0 \text{ in} \\
yforce &= 0.0 \text{ in} \\
zforce &= 3.0 \text{ in}
\end{align*}
\]

\[
\begin{align*}
cgload &= \begin{pmatrix} xforce \\ yforce \\ zforce \end{pmatrix} \\
cgload &= \begin{pmatrix} 0.00 \\ 0.00 \\ 3.00 \end{pmatrix} \text{ in}
\end{align*}
\]

Note: The independent node of the RBE2, where the MPC forces are recovered, is located 3 inches above the CG of the bolt pattern.

The locations are put into an array.
Coordinates of the Center of Gravity of the Bolt Pattern

(Necessary if analysis coordinate system origin is not at the CG of the bolt pattern)

\[
\begin{align*}
x_{cg} := & \frac{\sum x_i}{\text{rows}(x)} \quad x_{cg} = 0.00 \text{ in} \\
y_{cg} := & \frac{\sum y_i}{\text{rows}(y)} \quad y_{cg} = 0.00 \text{ in} \\
z_{cg} := & \frac{\sum z_i}{\text{rows}(z)} \quad z_{cg} = 0.00 \text{ in}
\end{align*}
\]

\[
c_{gbolt} := \begin{pmatrix}
x_{cg} \\
y_{cg} \\
z_{cg}
\end{pmatrix} = \begin{pmatrix}
0.00 \\
0.00 \\
0.00
\end{pmatrix} \text{ in}
\]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. The x and y axis have a zero offset from the center of gravity.

Load Vector

\[
r_{load} := c_{gbolt} - c_{gbolt}
\]

\[
r_{load} := \begin{pmatrix}
0.00 \\
0.00 \\
3.00
\end{pmatrix} \text{ in}
\]

Distance (RMS) from CG of Bolts to Each Individual Bolts for shear calculations

\[
r_i := \sqrt{(x_i - x_{cg})^2 + (y_i - y_{cg})^2} \quad r = \begin{pmatrix}
2.465 \\
2.125 \\
2.465 \\
2.465 \\
2.125 \\
2.465
\end{pmatrix} \text{ in}
\]

Loads model 2-06 was used to retrieve loads at the bolted interface. MPCs located at the center of the aft brackets were post processed in NASPOST for forces and moments in the x, y, and z directions. The MPCs are located on RBE elements 1570 and 1571. These loads are read into an array and distributed out to the 6 bolts for each aft bracket.

Note This joint was checked for minimum margins of safety for on-orbit, liftoff, abort landing, and berthing load cases.

Reading database file for bolted joint

\[
data := \text{REAPRNT("boltsAftUSS.txt")}
\]

\[
j := 1..\text{rows(data)} \quad \# \text{ of load cases}
\]

\[
\text{num_bolts} := \text{rows(bolt)}
\]
Bolts from PAS Aft Bracket to Lower USS-02

Element Identification

\[ ID_j := \text{data}_j.1 \quad \text{ID}_j := \text{ID}_j \times 1000 + 1 \quad \text{Counter for number of bolts in pattern} \]

Load Case Number

\[ LC_j := \text{data}_j.2 \]

Applied Bending Moment at Bolts

\[ M_j := 0 \text{ in-lbf} \]

Shear in X axis

\[ F_{x_j} := -\text{data}_j.3 \text{ lbf} \]

Moment about X axis

\[ M_{x_j} := -\text{data}_j.6 \text{ in-lbf} \]

Shear in Y axis

\[ F_{y_j} := -\text{data}_j.4 \text{ lbf} \]

Moment about Y axis

\[ M_{y_j} := -\text{data}_j.7 \text{ in-lbf} \]

Axial Load

\[ F_{z_j} := -\text{data}_j.5 \text{ lbf} \]

Torsion

\[ M_{z_j} := -\text{data}_j.8 \text{ in-lbf} \]

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\[ \text{ID} := \text{stack}(\text{ID}, \text{ID} + 1, \text{ID} + 2, \text{ID} + 3, \text{ID} + 4, \text{ID} + 5) \quad \# \text{ of items in "ID" equals the number of bolts} \]

\[ \text{LC} := \text{stack}(\text{LC}, \text{LC}, \text{LC}, \text{LC}, \text{LC}) \]

Moment Distribution at CG of Bolt Pattern for Each Load Case

\[ M_{\text{tot}}(j) := \left[ \begin{array}{c} M_{x_j} \\ M_{y_j} \\ M_{z_j} \end{array} \right] + r_{\text{load}} \times \left[ \begin{array}{c} F_{x_j} \\ F_{y_j} \\ F_{z_j} \end{array} \right] \]

Use the cross-product to determine the moments acting at the CG of the bolt pattern.

\[ \text{Mx}_\text{boltcg}_j := M_{\text{tot}1.j} \quad \text{My}_\text{boltcg}_j := M_{\text{tot}2.j} \quad \text{Mz}_\text{boltcg}_j := M_{\text{tot}3.j} \]

Tension on bolts

\[ F_{\text{direct}i,j} := \frac{F_{z_j}}{\text{num_bolts}} \quad \text{Direct tensile load calculation} \]

\[ F_{\text{tx}_j} := 0 \text{ lbf if } (y_i - yc) = 0 \text{ in} \]

\[ \frac{\text{Mx}_\text{boltcg}_j (y_i - yc)}{\sum_i (y_i - yc)^2} \cdot At_i \]

\[ \text{Tensile due to the moment about X} \]

\[ F_{\text{ty}_j} := 0 \text{ lbf if } (x_i - xc) = 0 \text{ in} \]

\[ -\text{My}_\text{boltcg}_j (x_i - xc) \cdot At_i \]

\[ \text{Tensile due to the moment about Y} \]
**Shear on bolts**  
Secondary shear on bolts

\[ F_{S_i,j} := \frac{M_{z, \text{boltc}_{ij}} \eta_i A_s}{\sum_i \left( \eta_i^2 \left( A_s \right) \right)} \]

\[ u_i := \text{atan2} (x_i - x_{cg}, y_i - y_{cg}) \]

\[ S_{Yi,j} := \sin \left( \frac{\beta - u_i}{2} \right) F_{S_i,j} \quad S_{Xi,j} := -\cos \left( \frac{\beta - u_i}{2} \right) F_{S_i,j} \]

Loads of first case

\[
S_x(1) = \begin{pmatrix}
-64.33 \\
-0.00 \\
64.33 \\
-64.33 \\
-0.00 \\
64.33 \\
\end{pmatrix} \quad \text{lb}f \\
S_y(1) = \begin{pmatrix}
-109.36 \\
-109.36 \\
-109.36 \\
109.36 \\
109.36 \\
109.36 \\
\end{pmatrix} \quad \text{lb}f
\]

\[ F_{\text{stot},ij} := \sqrt{\left( S_{xi,j} + \frac{F_{xj}}{2} \right)^2 + \left( S_{yi,j} + \frac{F_{yj}}{2} \right)^2} \quad \max(F_{\text{stot}}) = 1187.95 \text{lb}f \quad \min(F_{\text{stot}}) = 3.21 \text{lb}f \]

**Assume that Fx and Fy are shared by only 2 bolts.**

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[ P := \text{stack} \left( \left( \text{F}_{i}^T \right)^\text{1} , \left( \text{F}_{i}^T \right)^\text{2} , \left( \text{F}_{i}^T \right)^\text{3} , \left( \text{F}_{i}^T \right)^\text{4} , \left( \text{F}_{i}^T \right)^\text{5} , \left( \text{F}_{i}^T \right)^\text{6} \right) \]

\[ V := \text{stack} \left( \left( \text{Fstot}_{i}^T \right)^\text{1} , \left( \text{Fstot}_{i}^T \right)^\text{2} , \left( \text{Fstot}_{i}^T \right)^\text{3} , \left( \text{Fstot}_{i}^T \right)^\text{4} , \left( \text{Fstot}_{i}^T \right)^\text{5} , \left( \text{Fstot}_{i}^T \right)^\text{6} \right) \]

\[ M := \text{stack}(M, M, M, M, M) \]

The "Output" file outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

\[ \text{Output} := \text{augment}(\text{ID}, \text{LC}, \frac{P}{\text{lb}f}, \frac{V}{\text{lb}f}, \frac{M}{\text{in} \cdot \text{lb}f}) \]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \( \text{rows(Output)} = 3072 \)

(6 bolts x 256 load cases) x 2 joints = 3072 rows

```
WRITEPRN("output_aftbrkuss_r5_onorbit.txt") := Output
```

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CHECK Bolts (NAS1956C14 0.375-24 UNJF-3A x 1.453L, A-286)
Washer (NAS1587-6C .375 x .078 THK, C-Sink, CRES)
Insert (MS51831CA204L .375-24 Key-Locked CRES A286 140 KSI)

Factors of Safety

| Ultimate | SFu := 2.0 | Yield | SFy := 1.25 |
| Joint Separation | SFsep := 1.2 | Fitting factor | FF := 1.15 |

Temperature data

| Assembly | Temp_initial := 70 deg |
| Maximum | Temp_max := 151 deg |
| Minimum | Temp_min := -46 deg |

Bolt and Insert Data

| Nominal diameter of bolt | D := 0.375 in |
| Total length of bolt | L := 1.453 in |
| Threaded length | Lt := 0.578 in |

Note: If bolt is fully threaded, input Lt = L

(Washer Data)

| Thickness of washers | tw := 0.078 in |
| Outer Diameter of washer | Dw := 0.687 in |
| Inner Diameter of washer | Dwi := 0.378 in |
| Bolt head dia. across flats | dw := 0.553 in |

(Flange data)

| Thickness of flange 1 | tf1 := 0.750 in |
| Thickness of flange 2 | tf2 := 0.50 in |
| Diameter of hole | D_hole := 0.428 in |

Note: If there is no washer tw, Dw and Dwi should be zero
Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate. \( T_{Su\_bolt} = 0.96 \)
Bolt ultimate tensile allowable stress \( F_{tu\_bolt} = 180000 \text{ psi} \)
Bolt ultimate shear allowable stress \( F_{su\_bolt} = 0.6 \times F_{tu\_bolt} \)
Bolt yield Tensile allowable stress \( F_{ty\_bolt} = 132353 \text{ psi} \)
Temperature correction factor for bolt modulus \( T_{E\_bolt} = 0.96 \)
Modulus of elasticity of bolt \( E_{\_bolt} := (29.1 \times 10^6 \text{ psi}) \)
Thermal coefficient for bolt
\( \_bolt\_hot := 9.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
\( \_bolt\_cold := 8.5 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)

Insert
Temperature correction factor for insert strength \( T_{S\_ins} := 0.96 \)
Ultimate tensile allowable stress \( F_{tu\_ins} := 140000 \text{ psi} \)
Ultimate shear allowable stress \( F_{su\_ins} := 0.6 \times F_{tu\_ins} \)

Washer
Temperature correction factor for washer modulus \( T_{E\_washer} := 0.96 \)
Modulus of elasticity of washer:
\( E_{\_washer} := (29.1 \times 10^6 \text{ psi}) \)

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners,
Modulus of elasticity of these members, and diameters of the bolt and the washer.
Temperature correction factor for flange 1 \( T_{f1E} := 0.98 \) (modulus)
Temperature correction factor for flange 2 \( T_{f2E} := 0.98 \)
Modulus of elasticity for the parts in the joint
\( E_{\_flange1} := (10.3 \times 10^6 \text{ psi}) \)
\( E_{\_flange2} := (10.3 \times 10^6 \text{ psi}) \)
Coefficient of thermal expansion for flanges
\( \_flange1\_hot := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
\( \_flange1\_cold := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
\( \_flange2\_hot := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
\( \_flange2\_cold := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)

Torque/Preload data
Maximum torque (61.3% of yield) \( T_{max} := 392 \text{ in-lbf} \)
Minimum torque (95% of max. torque) \( T_{min} := 373 \text{ in-lbf} \)
Torque coefficient \( k := 0.15 \)
Loading plane factor \( n := 0.5 \)
Preload Uncertainty \( = := 0.25 \)
This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC

Bolt Load data

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>( y = 0.351 )</td>
<td>Preload due to temperature</td>
</tr>
<tr>
<td>Max. preload</td>
<td>( P_{LDMAX} = 9367.4 \text{ lbf} )</td>
<td></td>
</tr>
<tr>
<td>Min. preload</td>
<td>( P_{LDMin} = 3623.3 \text{ lbf} )</td>
<td>Uncertainty factor</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>( P_{max(Psep)} = 2788.1 \text{ lbf} )</td>
<td>Torque coefficient</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
<td>( P_{max(Pb)} = 10304.8 \text{ lbf} )</td>
<td>Loading plane factor</td>
</tr>
<tr>
<td>Max. load on the bolt(yield)</td>
<td>( P_{max(Pby)} = 9953.3 \text{ lbf} )</td>
<td>Thread shear pullout load of bolt or insert</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>( P_{AT} = 14848.5 \text{ lbf} )</td>
<td>Thread shear pullout load in parent metal</td>
</tr>
</tbody>
</table>

Length check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Component</th>
<th>Min Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{min}^{1.1} = 0.37</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{min}^{2.1} = 1.78</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_{min}^{3.1} = 2.27</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{min}^{4.1} = 0.44</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_{min}^{5.1} = 0.10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{min}^{6.1} = 1.88</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS_{min}^{7.1} = 0.49</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS_{min}^{8.1} = 2.07</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS_{min}^{9.1} = 10.00</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_{min}^{10.1} = 0.39</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ MS_{bolt} := \min(MS) \]

\[ MS_{bolt} = 0.10 \]  
Minimum Margin of Safety

Failure Mode = "Total Tension Yield"

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS_{min,ID}</td>
<td>1570001</td>
</tr>
<tr>
<td>MS_{min,LC}</td>
<td>5014</td>
</tr>
<tr>
<td>MS_{min,P}</td>
<td>2323.4</td>
</tr>
<tr>
<td>MS_{min,V}</td>
<td>1044.7</td>
</tr>
<tr>
<td>MS_{min,M}</td>
<td>0</td>
</tr>
</tbody>
</table>

Element Identification (1570) and Bolt Number (1) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin

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Bolt Fail-Safe Analysis for Aft Bracket to PAS Platform

Since bolt number 1 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 5, NAS1956C14 0.375-24 UNJF-3A fasteners, holding the Aft Bracket to the Lower USS-02. The drawing number for the AMS-02 Assembly is SGG39135873.

\[
\begin{array}{|c|c|}
\hline
\text{size} & \text{thread/in} \\
\hline
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
\hline
\end{array}
\]

\[
bolt2 :=
\]

\[
s := 1 \cdot \text{rows(bolt2)}
\]

\[
N_{2s} := \text{bolt2}_{s,2} \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_{2s} := \text{bolt2}_{s,1} \cdot \text{in} \quad \text{bolt diameter}
\]

**Tensile Area of bolt**

\[
At_{2s} := \beta \left( \frac{D_{2s} - 0.9743 \frac{1}{N_{2s}}}{2} \right)^2
\]

**Shear Area of bolt**

\[
As_{2s} := \beta \left( \frac{D_{2s} - 1.299038 \frac{1}{N_{2s}}}{2} \right)^2
\]

Bolt no. \quad x co-ord \quad y co-ord \quad z co-ord

\[
\begin{bmatrix}
2 \\
3 \\
4 \\
5 \\
6 \\
\end{bmatrix} = \begin{bmatrix}
-2.125 \\
-2.125 \\
2.125 \\
2.125 \\
2.125 \\
\end{bmatrix} \cdot \text{in} \\
\begin{bmatrix}
0.0 \\
-1.25 \\
1.25 \\
0.0 \\
-1.25 \\
\end{bmatrix} \cdot \text{in} \\
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix} \cdot \text{in}
\]

\[
x2 := \begin{bmatrix}
2 \\
3 \\
4 \\
5 \\
6 \\
\end{bmatrix} = \begin{bmatrix}
2.125 \\
-2.125 \\
2.125 \\
2.125 \\
2.125 \\
\end{bmatrix} \cdot \text{in}
\]

\[
y2 := \begin{bmatrix}
0.0 \\
-1.25 \\
1.25 \\
0.0 \\
-1.25 \\
\end{bmatrix} \cdot \text{in}
\]

\[
z2 := \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix} \cdot \text{in}
\]

*Note Bolt 4 is removed from the bolt pattern.*
Location of applied forces and moments

\[
x_{force2} := 0.0 \text{ in} \quad y_{force2} := 0.0 \text{ in} \quad z_{force2} := 3.0 \text{ in}
\]

\[
cgload2 := \begin{pmatrix} x_{force2} \\ y_{force2} \\ z_{force2} \end{pmatrix} \quad cgload2 = \begin{pmatrix} 0.00 \\ 0.00 \\ 3.00 \end{pmatrix} \text{ in}
\]

Center of gravity of bolt group

\[
x_{cg} := \frac{\sum x_{2s}}{\text{rows}(x2)} \quad x_{cg2} := 0.43 \text{ in} \quad y_{cg} := \frac{\sum y_{2s}}{\text{rows}(y2)} \quad y_{cg2} := -0.25 \text{ in} \quad z_{cg} := \frac{\sum z_{2s}}{\text{rows}(z2)} \quad z_{cg2} := 0.00 \text{ in}
\]

\[
cgbolt2 := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} \quad cgbolt2 = \begin{pmatrix} 0.43 \\ -0.25 \\ 0.00 \end{pmatrix} \text{ in}
\]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 6, the x and y directions in the bolt pattern are unsymmetric and have a offset from the center of gravity.

Load Vector

\[
\tau_{load2} := cgload2 - cgbolt2 \quad \tau_{load2} = \begin{pmatrix} -0.43 \\ 0.25 \\ 3.00 \end{pmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_{2s} := \sqrt{(x_{2s} - x_{cg2})^2 + (y_{2s} - y_{cg2})^2}
\]

\[
\begin{array}{c}
r_{2s} = 2.562 \\
2.739 \\
2.267 \\
1.718 \\
1.972
\end{array}
\]

Reading database file for bolted joint

\[
data := \text{READPRN}("boltsAftUSS.txt")
\]

\[
q := 1 \text{ .. rows(data)} \quad \text{num_bolts2} := \text{rows(bolt2)}
\]
Bolts from PAS Aft Bracket to Lower USS-02

Loads from 2-06 loads model

Shear in X axis  \( Fx_{2q} := \text{data}_q \times 3 \) lbf  
Moment about X axis  \( Mx_{2q} := \text{data}_q \times 6 \) in lbf

Shear in Y axis  \( Fy_{2q} := \text{data}_q \times 4 \) lbf  
Moment about Y axis  \( My_{2q} := \text{data}_q \times 7 \) in lbf

Axial Load  \( Fz_{2q} := \text{data}_q \times 5 \) lbf  
Torsion  \( Mz_{2q} := \text{data}_q \times 8 \) in lbf

Element Identification  \( ID_{2q} := \text{data}_q \times 1 \)  
ID2q := ID2q 1000 + 1  
Counter for number of bolts in pattern

Load Case Number  \( LC_{2q} := \text{data}_q \times 2 \)

Applied Bending Moment at Bolts  \( M2_{q} := 0 \) in lbf

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. **Note number 1 is not included.**

\[
ID2 := \text{stack}(ID2 + 1, ID2 + 2, ID2 + 3, ID2 + 4, ID2 + 5)
\]

\[
LC2 := \text{stack}(LC2, LC2, LC2, LC2, LC2)
\]

Moment Distribution

\[
M_{tot2}^{(q)} := \left( \begin{array}{c}
Mx_{2q} \\
My_{2q} \\
Mz_{2q}
\end{array} \right) + \eta_{load2} \times \left( \begin{array}{c}
Fx_{2q} \\
Fy_{2q} \\
Fz_{2q}
\end{array} \right)
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{\text{boltcg2q}} := M_{\text{tot21,q}}  \\
My_{\text{boltcg2q}} := M_{\text{tot22,q}}  \\
Mz_{\text{boltcg2q}} := M_{\text{tot23,q}}
\]

Tension on bolts

\[
F_{\text{direct2s,q}} := \frac{Fz_{2q}}{\text{num_bolts2}}
\]

Direct tensile load calculation

\[
F_{mx_{2s,q}} := \begin{cases} 
0 \text{ lbf} & \text{if } (y_{2s} - ycg2) = 0 \text{ in} \\
\left[ \left( M_{\text{boltcg2q}} (y_{2s} - ycg2) \right) \times At_{2s} \right] & \text{if } (x_{2s} - xcg2) \neq 0 \text{ in} \\
\sum_s \left[ (y_{2s} - ycg2) \times At_{2s} \right] & \text{if } (x_{2s} - xcg2) = 0 \text{ in}
\end{cases}
\]

\[
F_{my_{2s,q}} := \begin{cases} 
0 \text{ lbf} & \text{if } (x_{2s} - xcg2) = 0 \text{ in} \\
\left[ \left( M_{\text{boltcg2q}} (x_{2s} - xcg2) \right) \times At_{2s} \right] & \text{if } (x_{2s} - xcg2) \neq 0 \text{ in} \\
\sum_s \left[ (x_{2s} - xcg2) \times At_{2s} \right] & \text{if } (x_{2s} - xcg2) = 0 \text{ in}
\end{cases}
\]

\[
F_{t2s,q} := F_{\text{direct2s,q}} + F_{mx_{2s,q}} + F_{my_{2s,q}}
\]

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Bolts from PAS Aft Bracket to Lower USS-02

Shear on bolts

Secondary shear on bolts

\[ F_{s_2,q} := \frac{M_{z_{bolts}} r_{2_s} A_{s_2}}{\left( r_{2_s}^2 \right) \left( A_{s_2} \right)} \]

\[ u_s := \text{atan2}(x_{2_s} - xc_{g2}, y_{2_s} - yc_{g2}) \]

Shear

\[ S_x := 0 \]
\[ S_y := 0 \]

Loads of first case

\[
\begin{bmatrix}
-23.69 \\
94.74 \\
-142.12 \\
-23.69 \\
94.74
\end{bmatrix}
\]

\[
\begin{bmatrix}
-241.60 \\
-241.60 \\
161.06 \\
161.06 \\
161.06
\end{bmatrix}
\]

\[ u_s = 174.4 \text{ deg} \]
\[ -158.6 \]
\[ 41.4 \]
\[ 8.4 \]
\[ -30.5 \]

\[ F_{s_{tot},q} := \sqrt{\left( S_{x,q} + \frac{F_{x,q}}{2} \right)^2 + \left( S_{y,q} + \frac{F_{y,q}}{2} \right)^2} \]

\[ \max(F_{s_{tot}}) = 1276.47 \text{ lbf} \]
\[ \min(F_{s_{tot}}) = 3.44 \text{ lbf} \]

Assume that Fx and Fy are shared by only 2 bolts.

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output2" file below. Note there are only 5 bolts, since bolt number 1 is not included.

\[ P2 := \text{stack}\left( F_{t_2} \right)^1, \left( F_{t_2} \right)^2, \left( F_{t_2} \right)^3, \left( F_{t_2} \right)^4, \left( F_{t_2} \right)^5 \]

\[ V2 := \text{stack}\left( F_{stot} \right)^1, \left( F_{stot} \right)^2, \left( F_{stot} \right)^3, \left( F_{stot} \right)^4, \left( F_{stot} \right)^5 \]

\[ M2 := \text{stack}(M_2, M_2, M_2, M_2, M_2) \]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), Load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

Output2 := augment\left( ID2, LC2, \frac{P2}{\text{lbf}}, \frac{V2}{\text{lbf}}, \frac{M2}{\text{in lbf}} \right)

(Note: Since the ID2 and LC2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: rows(Output2) = 2560

(5 bolts x 256 load cases) x 2 joint = 2560 load cases

WRITEPRN("output_aftbrkuss_r5_onorbit_fs.txt") := Output2

Bolt Fail-safe Results

The array from the text file above is read:

\[ \text{data_fs} := \text{READPRN}("output_aftbrkuss_r5_onorbit_fs.txt") \]

\[ s := 1 \text{ . rows(data_fs)} \]
Bolts from PAS Aft Bracket to Lower USS-02

**Fail-safe Loads**

- Applied tensile load: \( P_{FS} := \text{data\textsubscript{fs}} \_s \_3 \text{ lbf} \)
- Applied shear load: \( V_{FS} := \text{data\textsubscript{fs}} \_s \_4 \text{ lbf} \)
- Applied bending moment: \( M_{FS} := \text{data\textsubscript{fs}} \_s \_5 \text{ in-lbf} \)

**Fail-safe Factors of Safety**

- Ultimate: \( SF_{u\_FS} := 1.0 \)
- Joint Separation: \( SF_{sep\_FS} := 1.0 \)

This file uses the calculations shown in \( \text{\textbackslash escfil02\textbackslash 2i11_mathcad\textbackslash 8307\_bolts\textbackslash multi\_bolt\_stiffness\_insert\_FS\_RevC} \)

**Bolt Fail-safe Load data**

- Joint separation load: \( \max(P_{sep\_FS}) = 3570.172 \text{ lbf} \)
- Max. load on the bolt (ultimate): \( \max(P_{b\_FS}) = 10087.6 \text{ lbf} \)

**Summary of fail-safe Margins for bolt:**

- Joint separation: \( MS_{min\_FS} \_s \_1 := 0.07 \)
- Direct Tension Ultimate: \( MS_{min\_FS} \_s \_2 := 2.62 \)
- Total Tension Ultimate: \( MS_{min\_FS} \_s \_3 := 0.47 \)
- Direct Thread shear Ultimate: \( MS_{min\_FS} \_s \_4 := 2.75 \)
- Total Thread shear Ultimate: \( MS_{min\_FS} \_s \_5 := 0.52 \)
- Shear Ultimate: \( MS_{min\_FS} \_s \_6 := 4.71 \)
- Bending Ultimate: \( MS_{min\_FS} \_s \_7 := 10 \)
- Combined shear, tension and bending ultimate: \( MS_{min\_FS} \_s \_8 := 0.47 \)

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

- \( MS_{bolt\_FS} := \min(\text{MS\_FS}) \)
- \( MS_{bolt\_FS} = 0.07 \)
- Failure Mode\_FS = "Joint Separation"

- \( MS_{min\_ID} = 1571004 \) Element Identification (1571) and Bolt Number (4) for Minimum Margin
- \( MS_{min\_LC} = 5016 \) Load Case Number for Minimum Margin
- \( MS_{min\_P} = 3570.2 \) Applied Tensile Load for Minimum Margin
- \( MS_{min\_V} = 570.9 \) Applied Shear Load for Minimum Margin
- \( MS_{min\_M} = 0 \) Applied Bending Moment for Minimum Margin
4.13 PAS Nonstructural Items
4.13 PAS Nonstructural Items

4.13.1 Keyway Hardware, SDG39135827

This hardware, made of 15-5 PH, is used to keep the capture bar retained when the bar is manually removed from the active capture claw. There is no significant loading.

4.13.2 Handle Retainer Bracket, SDG39135823

Material is 7075-T7351 Plate. The capture bar handle rides in the groove of this bar, keeping it upright until the capture bar is removed. There is no significant loading.
4.13.3 Cover Assembly, SDG39135829

Material is 7075-T3751 plate. This covers the bridge beam and contains the EVA extension. Given that the only loads it will see are liftoff/landing, and the thickness of the part, it is acceptable by engineering judgment.

4.13.4 EVA Extension, SDG39135830

Material is A286 steel. Used by the EVA astronaut to drive the release mechanism wedge backward, forcing the capture bar down to release it from the capture claw. The only loading is the low torque used by the EVA tool. Acceptable by engineering judgment.
4.13.5 Release Screw Plate Assembly, SDG39135831

Material is 7075-T3751. Surface for the Lock Mechanism to rest against. As part of the EVA release system, it sees minor loads from liftoff/landing. Acceptable by engineering judgment.

4.13.6 Lock Mechanism Base, SDG39135834

Material is 15-5PH. This is part of the mechanism to prevent the EVA release screw from turning on its own. No significant loading given strength of the part so it is acceptable by engineering judgment.
4.13.7  Lock Mechanism Retractor, SDG39135835

Material is A286 steel. Another part of the mechanism to prevent the EVA release screw from turning on its own. No significant loading given strength of the part so it is acceptable by engineering judgment.

4.13.8  Handle Pin, SDG39135855

Material is A286 steel. Used to hold the handle in the Handle Retainer bracket, in order to keep the Handle upright until the capture bar is removed. No significant loading, so it is acceptable by engineering judgment.

4.13.9  Handle Bushing, SDG39135852

Material is aluminum bronze. Bushing to allow the capture bar handle to rotate upward so the EVA astronaut may remove the capture bar. No significant loading, so acceptable by engineering judgment.
4.13.10  Bushings, SDG39135842

Material is Aluminum Bronze. Bushings used for EVA release mechanism (-003) and Capture bar housing (-001). No significant loading so acceptable by engineering judgment.

4.13.11  Wedge Release Screw, SDG39135843

Material is A286. Used to move the release wedge back and forth. Driven by the EVA extension. Only loading is low torque caused the EVA tool so part is acceptable by engineering judgment.
4.13.12 Bearing Housing Cover, SDG39135846

Material is 15-5PH. Cover to keep spherical bearing retained in the bearing housing. No loading, so acceptable by engineering judgment.

4.13.13 Limit Screws, SDG39135847

Material is A286 steel. –001 and –003 are limit screws used to prevent the release wedge from moving too far. –006 parts are shoulder screws used to hold the release mechanism housing to the bridge beam. None of these screws see significant loading, so they are acceptable by engineering judgment.
4.13.14  **Release Screw Cover, SDG39135848**

Material is 7075-T3751. Surface for the wedge release screw to ride in. As part of the EVA release system, it sees minor loads from liftoff/landing. Acceptable by engineering judgment.

4.13.15  **Housing Assembly, Release Mechanism, SDG39135838**

Material is 7075-T7351. Housing in which the release wedge sits. It is mounted to the bridge beam using shoulder bolts. This cross section is closed once the EVA extension is mounted to the top lip. This results in a very robust cross section compared to the Bridge Beam, which is a ‘hat’ section. Therefore, it is acceptable by comparison to the Bridge beam margins.
4.13.16  Slip Plate, SDG39135839

Material is 15-5PH. This plate mounts to the inside bottom of the Release Housing. It provides a low friction surface for the Release Wedge to slide along. It is acceptable by engineering judgment.

4.13.17  Wedge, SDG39135840

Material is 15-5 PH. Wedge slides along the inside of the Release housing. The Bearing Housing is held to its upper surface using a wedge screw. When the wedge is pulled using the EVA extension screw, the bearing housing is lowered, resulting in the capture bar being lowered and release from the capture claw. Primary loading is block compression cause by the 6430 lbf capture bar loading. Given the size of the wedge, it is acceptable by engineering judgment.
4.13.18 Wedge Components, SDG39135841

Material is 15-5 PH. –001 is the wedge washer that allows the bearing housing to ride along the wedge’s surface. –003 is a washer between the nut on the threaded end of the bearing housing and the wedge washer. Parts are acceptable by engineering judgment.

4.13.19 Locating Pins, SDG39135857

Material is A286 (-001, -003) and 6061-T6 (-005). –001 and –003 are locating pins used in the PAS Platform Base assembly. –005 is a shim used in mounting the guidepins to the base. Acceptable by engineering judgment.
4.13.20  Guide Pin Shim, SDG39135856

Material is aluminum shim stock. Used in assembly of the PAS platform base assembly. Acceptable by engineering judgment.

4.13.21  Scuff Plates, SDG39135819

Material is 7075-T7351. The only loading is an on-orbit kick load. Given the thickness of the cross section the plates are acceptable by engineering judgment.

4.13.22  Capture Bar Retainer Brackets, SDG39135820

Material is 15-5PH. Brackets mount to the underside of the PAS platform. They are used to keep the capture bar aligned perpendicular to its axis. Since the primary capture bar load is vertical, there is no significant loading and the parts are acceptable by engineering judgment.
5.0 Strength Assessment for AMS-02 STS and ISS Integration Hardware
5.1 UMA Bracket
5.2 PVGF Bracket
### Margins of Safety

#### Table 5.2-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135860</td>
<td>PVGF Bracket</td>
<td>AL ALY 7075-T7351</td>
<td>SSRMS Interface Loads</td>
<td>Ultimate</td>
<td>0.082 (u)</td>
<td>5.2-13</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
3. u = ultimate
Factors of Safety

The hardware is designed with a yield factor of 1.25 and an ultimate factor of 2.0 against limit loads.

Description of Structure

Figure 5.2-1 below shows the locations of the PVGF brackets on the Upper USS-02. The brackets were machined out of 7075-T7351 Aluminum Alloy plate. The PVGF bracket bolts to the Upper USS-02 and the other side of PVGF bracket is used to bolt the PVGF.

Figure 5.2-1 : Location of PVGF Brackets on Upper USS-02
**Description of Model**

A FE model was built for the PVGF bracket hardware using FEMAP.

1. The part was modeled as CQUAD4, CTRIA3, CBAR, and CHEXA elements.
2. The bolt holes are represented with SPC’s with DOF’s 1, 2, and 3.
3. The mass of the PVGF is represented by a mass element in the model. The interface between the PVGF and PVGF bracket is represented by a RBE3 rigid element with DOF’s 1 thru 6 at the reference grid point. The grid points at the bolt locations have DOF’s 1, 2, and 3.
4. A RBE2 with DOF’s 1, 2, and 3 were used to distribute the load at the bolt hole locations.

![Figure 5.2-2: FEMAP Model of PVGF Bracket](image)
MSC/NASTRAN v.2005 was used as a solver for analyzing the math model of the PVGF bracket. Stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in the PVGF Bracket. SPC forces were recovered at the bolt locations.

Table below shows detail of model inputs.

**Table 5.2-2: Inputs of Finite Element Model of PVGF Bracket**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>PROP</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVGF Bracket</td>
<td>2 – 19991</td>
<td>1 – 15696</td>
<td>1-25</td>
<td>1 – 7050-T7451</td>
</tr>
</tbody>
</table>

**Model Checks**

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)***
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.005845E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>9.328232E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.199028E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>4.664418E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.223564E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.255611E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)***
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.370248E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>5.856691E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.228968E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>4.493716E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.203667E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.631400E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)***
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.370248E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>5.856691E-09</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.228968E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>4.493716E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.203667E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.631400E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>
A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 5.2-3: Eigenvalue Summary of PVGF Bracket

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIAN</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-2.018E-05</td>
<td>4.492E-03</td>
<td>7.149E-04</td>
<td>1.000E+00</td>
<td>-2.018E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.096E-05</td>
<td>3.310E-03</td>
<td>5.269E-04</td>
<td>1.000E+00</td>
<td>-1.096E-05</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-1.334E-06</td>
<td>1.155E-03</td>
<td>1.838E-04</td>
<td>1.000E+00</td>
<td>-1.334E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>5.492E-07</td>
<td>7.411E-04</td>
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<td>1.000E+00</td>
<td>5.492E-07</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.349E-06</td>
<td>1.162E-03</td>
<td>1.849E-04</td>
<td>1.000E+00</td>
<td>1.349E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>8.586E-06</td>
<td>2.930E-03</td>
<td>4.663E-04</td>
<td>1.000E+00</td>
<td>8.586E-06</td>
</tr>
<tr>
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<td>7</td>
<td>1.050E+07</td>
<td>3.241E+03</td>
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<td>1.050E+07</td>
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<tr>
<td>8</td>
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<td>1.000E+00</td>
<td>9.495E+07</td>
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<tr>
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<td>9</td>
<td>1.525E+08</td>
<td>1.235E+04</td>
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<td>1.000E+00</td>
<td>1.525E+08</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.728E+08</td>
<td>1.315E+04</td>
<td>2.092E+03</td>
<td>1.000E+00</td>
<td>1.728E+08</td>
</tr>
</tbody>
</table>

Additionally, the mass of the FEM (.1896942*g = 73.22 lb) matches closely the mass of the actual hardware (PVGF bracket plus PVGF = 72.3 lb).
Material and Temperature

The PVGF bracket is made of 7075-T7351 Aluminum Alloy. Material properties of 7075-T7351 are taken from MMPDS-01. The temperature extremes for the PVGF bracket are -65 °F to 225 °F.

Analysis

The critical stresses for the PVGF bracket are compared to the ultimate and yield strength of 7075-T7351 Aluminum Alloy. The PVGF bracket was analyzed for liftoff/landing loads, 125 lb kickload, and SSRMS/PVGF interface loads. All margins of safety are positive.
CHECK OF PVGF BRACKET

Material Properties : 7075-T7351 AL ALY  \quad (Ref. MMPDS-01, Table 3.7.6.0(b₂))

\[ F_{tu} := 63000 \text{ psi} \]
\[ F_{ty} := 52000 \text{ psi} \]
\[ F_{su} := 39000 \text{ psi} \]

Factors of Safety, \quad F_{Su} := 2.0 \quad F_{Sy} := 1.25

Temperature reduction factors,

+ At 225°F: (For PVGF, the temperature extremes are -65°F to 225°F; These temperature reduction factors are conservative for lift-off/landing conditions)

- Ultimate: \quad \beta_{u1} := 0.87 \quad \text{(Ref. MMPDS-01, Figure 3.7.6.1.1(c))}

- Yield: \quad \beta_{y1} := 0.89 \quad \text{(Ref. MMPDS-01, Figure 3.7.6.1.1(d))}

Allowable stresses:

\[ F_{tu1,a} := \beta_{u1} \cdot F_{tu} \]
\[ F_{tu1,a} = 54810 \text{ psi} \]

\[ F_{ty1,a} := \beta_{y1} \cdot F_{ty} \]
\[ F_{ty1,a} = 46280 \text{ psi} \]

\[ F_{su1,a} := \beta_{u1} \cdot F_{su} \]
\[ F_{su1,a} = 33930 \text{ psi} \]
Applying Simplified Design Loads from AMS-02 SVP (Table 4-4) for Liftoff and Landing Loads

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from 24 load cases. The launch/landing design limit load factors for small secondary structures were used in this analysis. Using Table 4-4 from document JSC 28792, a load factor of 40g was obtained (since the mass of the PVGF bracket is less than 20 lb). This load factor was applied in all three axis, with a load factor of 25% of the primary load applied to the remaining two orthogonal axes, simultaneously. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>X-axis Load Factor</th>
<th>Y-axis Load Factor</th>
<th>Z-axis Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>40</td>
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<tr>
<td>1002</td>
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</tr>
<tr>
<td>1024</td>
<td>-10</td>
<td>-10</td>
<td>-40</td>
</tr>
</tbody>
</table>

\[ u_{uu,max} := 9500.57 \text{ psi} \quad \text{LC# 1016, ELEM# 14983 (Maximum Principal Stress)} \]

\{appendix}{A24}{28}\right)

\[ u_{uy,max} := 9444.71 \text{ psi} \quad \text{LC# 1014, ELEM# 15132 (Maximum Von-Mises Stress)} \]

\appendix\{A24}{36}\right)

\[ u_{us,max} := 5290.69 \text{ psi} \quad \text{LC# 1009; ELEM# 15131 (Maximum Shear Stress)} \]

\{appendix}{A24}{44}\right)
Margins of Safety,

\[
\begin{align*}
MS_{u1} := & \frac{F_{u1,a}}{FS_{u}u_{u1,\text{max}}} - 1 & MS_{u1} = 1.885 \\
MS_{y1} := & \frac{F_{y1,a}}{FS_{y}u_{y1,\text{max}}} - 1 & MS_{y1} = 2.92 \\
MS_{s1} := & \frac{F_{s1,a}}{FS_{s}u_{s1,\text{max}}} - 1 & MS_{s1} = 2.21
\end{align*}
\]
Applying 125 lb Kickload

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from the 125 lb kickload cases. The kickload was applied on the side of the PVGF bracket since it was the largest unsupported area in the bracket. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Node Where Load is Applied</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>4001</td>
<td>6660</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4002</td>
<td>6660</td>
<td>0</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>4003</td>
<td>6660</td>
<td>0</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>4004</td>
<td>7007</td>
<td>-125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4005</td>
<td>7007</td>
<td>0</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>4006</td>
<td>7007</td>
<td>0</td>
<td>0</td>
<td>125</td>
</tr>
</tbody>
</table>

\[ u_{uu1,max} := 2053.12 \text{ psi} \quad \text{LC# 4001, ELEM# 5433} \]  
(See Appendix A24, p.A24-76)

\[ u_{uy1,max} := 1863.63 \text{ psi} \quad \text{LC# 4001, ELEM# 5433} \]  
(Maximum Von-Mises Stress)

\[ u_{us1,max} := 1026.56 \text{ psi} \quad \text{LC# 4001; ELEM# 5433} \]  
(Maximum Shear Stress)

Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{FS_u \cdot u_{uu1,max}} - 1 \]

\[ MS_{u1} = 12.348 \]

\[ MS_{y1} := \frac{F_{y1,a}}{FS_y \cdot u_{uy1,max}} - 1 \]

\[ MS_{y1} = 18.87 \]

\[ MS_{s1} := \frac{F_{s1,a}}{FS_s \cdot u_{us1,max}} - 1 \]

\[ MS_{s1} = 15.53 \]
Applying PVGF Structural Interface Loads from SSP 42004, Part 1, Revision H (Section N3.2.1.3)

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from the 36 load cases generated using the loads given in section N3.2.1.3 of document SSP 42004. The following table shows the loads given in document SSP 42004.

<table>
<thead>
<tr>
<th>Torsion Moment</th>
<th>Bending Moment</th>
<th>Shear Force</th>
<th>Axial Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in-lb)</td>
<td>(in-lb)</td>
<td>(lb)</td>
<td>(lb)</td>
</tr>
<tr>
<td>27360</td>
<td>27360</td>
<td>225</td>
<td>225</td>
</tr>
</tbody>
</table>

One moment and one force can be applied simultaneously. The forces and moments are valid for any direction. Therefore, the following 36 load cases were generated. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Force Applied</th>
<th>Moment Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>5001</td>
<td>225</td>
<td>27360</td>
</tr>
<tr>
<td>5002</td>
<td>-225</td>
<td>27360</td>
</tr>
<tr>
<td>5003</td>
<td>225</td>
<td>-27360</td>
</tr>
<tr>
<td>5004</td>
<td>-225</td>
<td>-27360</td>
</tr>
<tr>
<td>5005</td>
<td>225</td>
<td>27360</td>
</tr>
<tr>
<td>5006</td>
<td>-225</td>
<td>27360</td>
</tr>
<tr>
<td>5007</td>
<td>225</td>
<td>-27360</td>
</tr>
<tr>
<td>5008</td>
<td>-225</td>
<td>-27360</td>
</tr>
<tr>
<td>5009</td>
<td>225</td>
<td>27360</td>
</tr>
<tr>
<td>5010</td>
<td>-225</td>
<td>27360</td>
</tr>
<tr>
<td>5011</td>
<td>225</td>
<td>-27360</td>
</tr>
<tr>
<td>5012</td>
<td>-225</td>
<td>-27360</td>
</tr>
<tr>
<td>5013</td>
<td>225</td>
<td>27360</td>
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<tr>
<td>5014</td>
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<td>27360</td>
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<td>5015</td>
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<td>5016</td>
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<td>5017</td>
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<td>27360</td>
</tr>
<tr>
<td>5018</td>
<td>-225</td>
<td>27360</td>
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<tr>
<td>5019</td>
<td>225</td>
<td>-27360</td>
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<tr>
<td>5020</td>
<td>-225</td>
<td>-27360</td>
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<tr>
<td>5021</td>
<td>225</td>
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<tr>
<td>5022</td>
<td>-225</td>
<td>27360</td>
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<td>5023</td>
<td>225</td>
<td>-27360</td>
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<tr>
<td>5024</td>
<td>-225</td>
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<tr>
<td>5025</td>
<td>225</td>
<td>27360</td>
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<td>5026</td>
<td>-225</td>
<td>27360</td>
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<tr>
<td>5027</td>
<td>225</td>
<td>-27360</td>
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<td>5028</td>
<td>-225</td>
<td>-27360</td>
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<td>5029</td>
<td>225</td>
<td>27360</td>
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<tr>
<td>5030</td>
<td>-225</td>
<td>27360</td>
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<tr>
<td>5031</td>
<td>225</td>
<td>-27360</td>
</tr>
<tr>
<td>5032</td>
<td>-225</td>
<td>-27360</td>
</tr>
<tr>
<td>5033</td>
<td>225</td>
<td>27360</td>
</tr>
<tr>
<td>5034</td>
<td>-225</td>
<td>27360</td>
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<td>225</td>
<td>-27360</td>
</tr>
<tr>
<td>5036</td>
<td>-225</td>
<td>-27360</td>
</tr>
</tbody>
</table>
AMS-02 PVGF Bracket

\[ u_{uu, \text{max}} := 25324.11 \text{ psi} \quad \text{(Maximum Principal Stress)} \]
\[ \text{LC# 5024, ELEM# 14951} \]
\[ \text{(See Appendix A24, p.A24-123)} \]

\[ u_{uy, \text{max}} := 23959.87 \text{ psi} \quad \text{(Maximum Von-Mises Stress)} \]
\[ \text{LC# 5024, ELEM# 14951} \]
\[ \text{(See Appendix A24, p.A24-131)} \]

\[ u_{us, \text{max}} := 12662.06 \text{ psi} \quad \text{(Maximum Shear Stress)} \]
\[ \text{LC# 5024; ELEM# 14951} \]
\[ \text{(see Appendix A24, p.A24-139)} \]

Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{FS_{u1}u_{uu,\text{max}}} - 1 \quad \text{MS}_{u1} = 0.082 \]

\[ MS_{y1} := \frac{F_{y1,a}}{FS_{y1}u_{uy,\text{max}}} - 1 \quad \text{MS}_{y1} = 0.55 \]

\[ MS_{s1} := \frac{F_{s1,a}}{FS_{s1}u_{us,\text{max}}} - 1 \quad \text{MS}_{s1} = 0.34 \]
Figure 5.2-3: Stress Contour Plot of Minimum Principal Stress

Figure 5.2-4: Stress Contour Plot of Von Mises Stress
Figure 5.2-5: Stress Contour Plot of Max. Shear Stress
5.3 Intentionally Left Blank
<table>
<thead>
<tr>
<th>Pre pared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G. Reyes</td>
<td>07/20/08</td>
<td>Sec5-3.mcd</td>
</tr>
<tr>
<td>Checked By</td>
<td>C. Bala</td>
<td></td>
<td>Drawing No.</td>
</tr>
<tr>
<td>Title</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Intentionally Left Blank**
5.4 FRGF Bracket
# Margins of Safety

## Table 5.4-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135861</td>
<td>FRGF Bracket</td>
<td>AL ALY 7050-T7451</td>
<td>SRMS Induced Loads</td>
<td>Ultimate</td>
<td>0.498 (u)</td>
<td>5.4-12</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Applied liftoff/landing loads, kickload, and SRMS induced loads.
3. $u = \text{ultimate}$
Factors of Safety

The hardware is designed with a yield factor of 1.25 and an ultimate factor of 2.0 against limit loads.

Description of Structure

Figure 5.4-1 below shows the locations of the FRGF brackets on the Upper USS-02. The brackets were machined out of 7050-T7451 Aluminum Alloy plate. The FRGF bracket bolts to the Upper USS-02 and the other side of FRGF bracket is used to bolt the FRGF.

Figure 5.4-1 : Location of FRGF Brackets on Upper USS-02
Description of Model

A FEM model was built for the FRGF bracket hardware using FEMAP.

1. The part was modeled as CQUAD4 and CTRIA3 elements.
2. The bolt holes are represented with SPC’s with DOF’s 1, 2, 3, 4, 5, & 6.
3. The mass of the FRGF is represented by a mass element in the model. The interface between the FRGF and FRGF bracket is represented by a RBE2 rigid element with DOF’s 3.

Figure 5.4-2: FEMAP Model of FRGF Bracket

MSC/NASTRAN v.2005 was used as a solver for analyzing the math model of the FRGF bracket. Plate stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in the FRGF Bracket. SPC forces were recovered at the bolt locations.
Table below shows detail of model inputs.

**Table 5.4-2: Inputs of Finite Element Model of FRGF Bracket**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>PROP</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRGF Bracket</td>
<td>1001 – 11212</td>
<td>1197 – 20001</td>
<td>1-7</td>
<td>1-2 – 7050-T7451</td>
</tr>
</tbody>
</table>

**Model Checks**

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02  
DIRECTION        STRAIN ENERGY        PASS/FAIL  
---------        -------------        ---------  
1               6.666596E-08          PASS  
2               1.009539E-07          PASS  
3               2.652087E-08          PASS  
4               4.962349E-07          PASS  
5               1.509545E-06          PASS  
6               1.158535E-06          PASS

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02  
DIRECTION        STRAIN ENERGY        PASS/FAIL  
---------        -------------        ---------  
1               6.985634E-08          PASS  
2               1.037590E-07          PASS  
3               2.662869E-08          PASS  
4               5.719806E-07          PASS  
5               1.525227E-06          PASS  
6               1.224789E-06          PASS

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02  
DIRECTION        STRAIN ENERGY        PASS/FAIL  
---------        -------------        ---------  
1               6.985634E-08          PASS  
2               1.037590E-07          PASS  
3               2.662869E-08          PASS  
4               5.719806E-07          PASS  
5               1.525227E-06          PASS  
6               1.224789E-06          PASS
A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 5.4-3: Eigenvalue Summary of FRGF Bracket

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-5.575E-06</td>
<td>2.361E-03</td>
<td>3.758E-04</td>
<td>1.000E+00</td>
<td>-5.575E-06</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-2.022E-06</td>
<td>1.422E-03</td>
<td>2.263E-04</td>
<td>1.000E+00</td>
<td>-2.022E-06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>5.104E-07</td>
<td>7.144E-04</td>
<td>1.137E-04</td>
<td>1.000E+00</td>
<td>5.104E-07</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1.289E-06</td>
<td>1.135E-03</td>
<td>1.807E-04</td>
<td>1.000E+00</td>
<td>1.289E-06</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.085E-05</td>
<td>3.293E-03</td>
<td>5.242E-04</td>
<td>1.000E+00</td>
<td>1.085E-05</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1.697E-05</td>
<td>4.120E-03</td>
<td>6.557E-04</td>
<td>1.000E+00</td>
<td>1.697E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>5.869E+07</td>
<td>7.661E+03</td>
<td>1.219E+03</td>
<td>1.000E+00</td>
<td>5.869E+07</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>9.386E+07</td>
<td>9.688E+03</td>
<td>1.542E+03</td>
<td>1.000E+00</td>
<td>9.386E+07</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1.390E+08</td>
<td>1.179E+04</td>
<td>1.876E+03</td>
<td>1.000E+00</td>
<td>1.390E+08</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.425E+08</td>
<td>1.194E+04</td>
<td>1.900E+03</td>
<td>1.000E+00</td>
<td>1.425E+08</td>
</tr>
</tbody>
</table>

Additionally, the mass of the FEM (.0975603*g = 37.7 lb) matches closely the mass of the actual hardware (37.3 lb).
Material and Temperature

The FRGF bracket is made of 7050-T7451 Aluminum Alloy. Material properties of 7050-T7451 are taken from MMPDS-01. The temperature extremes for the FRGF bracket are -75 °F to 260 °F.

Analysis

The critical stresses for the FRGF bracket are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy. The FRGF bracket was analyzed for liftoff/landing loads, 125 lb kickload, and SRMS induced loads. All margins of safety are positive.
CHECK OF FRGF BRACKET

Material Properties: 7050-T7451 AL ALY  
(Ref. MMPDS-01, Table 3.7.4.0(b), or BMS 7-323C)

\[ F_{u} := 66000 \text{ psi} \]
\[ F_{y} := 57000 \text{ psi} \]
\[ F_{s} := 43000 \text{ psi} \]

Factors of Safety,  
\[ F_{S_u} := 2.0 \]
\[ F_{S_y} := 1.25 \]

Temperature reduction factors,

+ At 260°F: (For FRGF, the temperature extremes are -75°F to 260°F)

- Ultimate:  \[ \beta_{u} := 0.78 \]  
  (Ref. MMPDS-01, Figure 3.7.4.2.1)

- Yield:  \[ \beta_{y} := 0.86 \]  
  (Ref. MMPDS-01, Figure 3.7.4.2.1)

Allowable stresses:

\[ F_{u1.a} := \beta_{u} \cdot F_{u} \]
\[ F_{u1.a} = 51480 \text{ psi} \]

\[ F_{y1.a} := \beta_{y} \cdot F_{y} \]
\[ F_{y1.a} = 49020 \text{ psi} \]

\[ F_{s1.a} := \beta_{s} \cdot F_{s} \]
\[ F_{s1.a} = 33540 \text{ psi} \]
Applying Simplified Design Loads from AMS-02 SVP (Table 4-4) for Liftoff and Landing Loads

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from 24 load cases. The launch/landing design limit load factors for small secondary structures were used in this analysis. Using Table 4-4 from document JSC 28792, a load factor of 40g was obtained (since the mass of the FRGF bracket is less than 20 lb). This load factor was applied in all three axis, with a load factor of 25% of the primary load applied to the remaining two orthogonal axes, simultaneously. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>X-axis Load Factor</th>
<th>Y-axis Load Factor</th>
<th>Z-axis Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>40</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1002</td>
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</tr>
<tr>
<td>1003</td>
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<tr>
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</tr>
</tbody>
</table>

\( u_{uu,\text{max}} := 8912.17 \text{ psi} \)  \( \text{LC# 1016, ELEM# 5742} \)  \( \text{(Maximum Principal Stress)} \)
(See Appendix A23, p.A23-9)

\( u_{uy,\text{max}} := 7897.83 \text{ psi} \)  \( \text{LC# 1016, ELEM# 5742} \)  \( \text{(Maximum Von-Mises Stress)} \)
(See Appendix A23, p.A23-12)

\( u_{us,\text{max}} := 4456.09 \text{ psi} \)  \( \text{LC# 1016; ELEM# 5742} \)  \( \text{(Maximum Shear Stress)} \)
(see Appendix A23, p.A23-14)
Margins of Safety,

\[ MS_{u1} := \frac{F_{u1.a}}{FS_u u_{uu,max}} - 1 \quad MS_{u1} = 1.888 \]

\[ MS_{y1} := \frac{F_{y1.a}}{FS_y u_{uy,max}} - 1 \quad MS_{y1} = 3.97 \]

\[ MS_{s1} := \frac{F_{s1.a}}{FS_u u_{us,max}} - 1 \quad MS_{s1} = 2.76 \]
Applying 125 lb Kickload

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from the 125 lb kickload cases. The kickload was applied on the side of the FRGF bracket since it was the largest unsupported area in the bracket. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Node Where Load is Applied</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>4001</td>
<td>3313</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4002</td>
<td>3313</td>
<td>0</td>
<td>-125</td>
<td>0</td>
</tr>
<tr>
<td>4003</td>
<td>3313</td>
<td>0</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>4004</td>
<td>2997</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4005</td>
<td>2997</td>
<td>0</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>4006</td>
<td>2997</td>
<td>0</td>
<td>0</td>
<td>125</td>
</tr>
</tbody>
</table>

\[ u_{ul1,max} = 3288.38 \text{ psi} \quad \text{LC# 4005, ELEM# 7082} \quad \text{(Maximum Principal Stress)} \]

(See Appendix A23, p.A23-22)

\[ u_{yly1,max} = 2917.95 \text{ psi} \quad \text{LC# 4005, ELEM# 7082} \quad \text{(Maximum Von-Mises Stress)} \]

(See Appendix A23, p.A23-24)

\[ u_{sly1,max} = 1644.19 \text{ psi} \quad \text{LC# 4005; ELEM# 7082} \quad \text{(Maximum Shear Stress)} \]

(see Appendix A23, p.A23-26)

Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{FS_{u} \cdot u_{ul1,max}} - 1 \quad MS_{u1} = 6.828 \]

\[ MS_{y1} := \frac{F_{y1,a}}{FS_{y} \cdot u_{yly1,max}} - 1 \quad MS_{y1} = 12.44 \]

\[ MS_{s1} := \frac{F_{s1,a}}{FS_{u} \cdot u_{sly1,max}} - 1 \quad MS_{s1} = 9.20 \]
Applying SRMS Induced Loads from NSTS-21000-IDD-ISS (Section 14.4.5.1.4.1)

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from 2 load cases. The design loads given in section 14.4.5.1.4.1 of document NSTS-21000-IDD-ISS were used in this analysis. NASPOST V.2.1 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Torsion Moment (in-lb)</th>
<th>Bending Moment (in-lb)</th>
<th>Shear Force (lb)</th>
<th>Axial Force (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5001</td>
<td>8400</td>
<td>10800</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>5002</td>
<td>5400</td>
<td>14400</td>
<td>150</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ \begin{align*}
u_{uu2, max} & := 17187.36 \text{ psi} & L\# 5002, ELEM\# 5742 & \text{(Maximum Principal Stress)} \\
& & (See Appendix A23, p.A23-34)
\end{align*} \]

\[ \begin{align*}
u_{uy2, max} & := 15334.17 \text{ psi} & L\# 5002, ELEM\# 5742 & \text{(Maximum Von-Mises Stress)} \\
& & (See Appendix A23, p.A23-36)
\end{align*} \]

\[ \begin{align*}
u_{us2, max} & := 8593.68 \text{ psi} & L\# 5002; ELEM\# 5742 & \text{(Maximum Shear Stress)} \\
& & (see Appendix A23, p.A23-38)
\end{align*} \]

Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{FS_{u} \cdot u_{uu2, max}} - 1 \quad \text{MS}_{u1} = 0.498 \]

\[ MS_{y1} := \frac{F_{ly1,a}}{FS_{y} \cdot u_{uy2, max}} - 1 \quad \text{MS}_{y1} = 1.56 \]

\[ MS_{s1} := \frac{F_{su1,a}}{FS_{u} \cdot u_{us2, max}} - 1 \quad \text{MS}_{s1} = 0.95 \]
Figure 5.4-3: Stress Contour Plot of Minimum Principal Stress

Figure 5.4-4: Stress Contour Plot of Von Mises Stress
Figure 5.4-5: Stress Contour Plot of Max. Shear Stress
5.5 ROEU Assembly
Section 5.5  ROEU Assembly

The ROEU Assembly Analysis is performed in the following report sections. These sections include analysis of the ROEU Assembly and the fastener analysis.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
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<td>ROEU Clevis Assembly Bending Analysis</td>
</tr>
<tr>
<td>5.11.6.1</td>
<td>ROEU Arm Flange to Sill Joint</td>
</tr>
<tr>
<td>5.11.6.1</td>
<td>ROEU Arm Flange to Sill Joint (Fail-Safe)</td>
</tr>
<tr>
<td>5.11.6.2</td>
<td>ROEU Bearing Failure Analysis</td>
</tr>
<tr>
<td>5.11.6.3</td>
<td>ROEU PDA Bracket, Pin, and Lug Analysis</td>
</tr>
<tr>
<td>5.11.6.4</td>
<td>ROEU Assembly Harness Bracket and Bolt Analysis</td>
</tr>
</tbody>
</table>
5.5.1 ROEU Clevis Assembly Bending Analysis
Section 5.5.1 ROEU/USS Interface
Foldable ROEU Clevis Assembly Bending Analysis
Part no.: SEG39137677

The following provides bending analysis at various cross sections of the ROEU Clevis Assembly. Stresses were determined at cross sections ranging from 2.4 in. to 6.29 in. from the clevis flange. Dimensions were obtained from drawing number SEG39137676.

[Image: View of ROEU Assembly SEG39137677]

Note: Unless otherwise stated, "Ref. MMPDS" refers to MMPDS-01
Location of the Centroid of the Fastener Group

cg of bolt pattern located 0.117 in. right and 1.345 in. above the lower left corner of the clevis.
Material properties of the SDG39137676 - 001 ROEU Clevis -11.99 x 8.61 x 4.60
7050-T7451, BMS-7-323C:

Tensile allowable, ultimate ST: \( F_{tu} := 67000 \text{ psi} \)  
Yield ST: \( F_{ty} := 57000 \text{ psi} \)  
Shear allowable: \( F_{su} := 43000 \text{ psi} \)

Factors of safety: \( F_{Su} := 2.0 \) (ultimate) \( F_{Sy} := 1.25 \) (yield)

Location of Applied Forces and Moments

The loads information was obtained from the loads group. The load cases are comprised of launch and abort landing load cases. Loads model 2-06 was used to retrieve loads. The data recovered are the MPC forces for node 9900, which represents the end of the CBUSH connected to the beam. These loads are recovered in the global coordinate system at the center of gravity of the bolt pattern. The origin of the local coordinate system is at the centroid of the cross section. Post processing was performed in NASPOST for forces and moments in the global x, y, and z directions. These loads are read into an array and transferred to the center of gravity of the minimum cross section of the ROEU clevis flange. This requires a 180 degree counterclockwise rotation.

Position Vector - \( rvec \) \((x_G, y_G, z_G)\) represents the components of the position vector measured from the centroid of the various cross sections of the clevis to the cg of the bolt pattern on the ROEU clevis flange. See drawing no. SEG39137676 for dimensions.
Reading NASPOST file for loads

data := READPRN("Input_forces_ROEU_uss_3_6_07.txt")

i := 1..rows(data)    rows(data) = 128    cols(data) = 8

* Note: the "Input_forces_ROEU_uss_3_6_07.txt" data file was generated from the NASPOST result (.LIS file) by removing all words and comments. This file is archived along with the other analysis files.

Loads From 2-06 Loads Model, Launch, and Abort Landing Case

Element Identification  IDi := datai,1

Load Case Number  LCi := datai,2

Axial Load  Fxi := datai,3·lbf

Shear in Y axis  Fyi := datai,4·lbf

Shear in Z axis  Fzi := datai,5·lbf

Torsion  Mxi := datai,6·in·lbf

Moment about Y axis  Myi := datai,7·in·lbf

Moment about Z axis  Mzi := datai,8·in·lbf

Rotation of Coordinate System of Loads For Alignment With Coordinate System at Centroid of Cross Section

The loads are recovered in the global coordinate system at the cg of the bolt pattern. The forces and moments are transformed to the local coordinate system at the centroid of the clevis cross sections by a 180 degree ccw rotation about the global Z axis.

\[
\beta := 180 \text{ deg} \\
F_{\text{transform}} := \begin{pmatrix}
\cos(\beta) & -\sin(\beta) & 0 \\
\sin(\beta) & \cos(\beta) & 0 \\
0 & 0 & 1
\end{pmatrix} \\
F_{\text{transform}} = \begin{pmatrix}
-1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Flocal := (augment(Fx, Fy, Fz))·Ftransform

Fx := Flocal\(^{(1)}\)  Fy := Flocal\(^{(2)}\)  Fz := Flocal\(^{(3)}\)

Mlocal := (augment(Mx, My, Mz))·Ftransform

Mx := Mlocal\(^{(1)}\)  My := Mlocal\(^{(2)}\)  Mz := Mlocal\(^{(3)}\)
Section Properties: The properties of this clevis cross section are valid from a distance of 2.50 in. to 4.50 in. from the clevis flange. The cross section is an I-beam shape. All dimensions were obtained from drawing no. SEG39137676. The properties of the cross section were obtained from Excel data (see attached).

At 2.5 inches from the clevis flange:

**Area of cross section:** Area := \(3.875\text{-in}^2\)  \quad Area25 := Area  

**Distance from centroid to outer fiber:**

\[
\begin{align*}
\text{cz25} & := \begin{pmatrix} -1.57 \\ -1.57 \\ 1.43 \\ 1.43 \end{pmatrix}\text{-in} \\
\text{cy25} & := \begin{pmatrix} -1.0075 \\ 1.0075 \\ 1.0075 \\ -1.0075 \end{pmatrix}\text{-in} \\
\text{points} & := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \end{pmatrix}
\end{align*}
\]

**Moments of inertia about centroid:**

\[
\begin{align*}
\text{Iy25} & := 3.9271\text{-in}^4 \\
\text{Iz25} & := 0.9201\text{-in}^4 \\
\text{s} & := 1.\text{rows(points)}
\end{align*}
\]

**Centroid of bolt pattern in local coordinates:**

\[
\text{cgglobal} := \begin{pmatrix} -2.5 \\ -0.909 \\ -0.225 \end{pmatrix}\text{-in}
\]

\[5.5.1-6\] ESCG-4005-05-AMS-0039
rcs represents the origin of the local coordinate system, Xcg, Ycg, Zcg located at the centroid of the cross section.

\[
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

\[
\begin{bmatrix}
-2.5 \\
-0.89 \\
-0.225
\end{bmatrix}
\]

\[
M_{x_{cs}} := M_{tot,1,i} \\
M_{y_{cs}} := M_{tot,2,i} \\
M_{z_{cs}} := M_{tot,3,i}
\]

\[
T := M_{x_{cs}}
\]

t_1 := 0.50\text{ in} \quad t_2 := 0.775\text{ in} \quad t_3 := 0.75\text{ in} \quad b_1 := 2.015\text{ in} \quad b_2 := 1.75\text{ in} \quad b_3 := 2.015\text{ in}

### Stresses on cross section:

**Normal** is direct axial plus bending:

\[
u_{1,s} := \frac{F_{x_i}}{\text{Area}_{25}} + \frac{M_{x_{cs} \cdot cz_{25}}}{I_{y_{25}}} - \frac{M_{z_{cs} \cdot cy_{25}}}{I_{z_{25}}}
\]

max(\(u\)) = 4046 psi

min(\(u\)) = -4234 psi

**Shear due to transverse loading**

\[
v_{1,s} := \sqrt{\left(\frac{F_{y_i}}{\text{Area}}\right)^2 + \left(\frac{F_{z_i}}{\text{Area}}\right)^2}
\]

max(\(v\)) = 145 psi

**Shear due to torsion:**

The torsional shear stress will be largest in the thickest element of the cross section.

\[
c := \frac{b_2}{t_2}
\]

Ref: Bruhn, Table A6.1

\[
T_{1,t} := \frac{t_1}{b_1 t_1^3 + b_2 t_2^3 + b_3 t_3^3}
\]

Ref: Bruhn, p.A6.4

max(\(T\)) = 369 psi

**Combined shear:**

\[
i,s := v_{1,s} + t_i
\]

\[
\text{max( } = 369 \text{ psi} \quad \text{max( ) = 448 psi}
\]
Foldable ROEU Clevis Assembly Beam Analysis

Principal Stresses:

\[ u_{1p_{1,s}} := \frac{u_{i,s}}{2} + \left[ \frac{\left( \frac{u_{i,s}}{2} \right)^2 + \left( \frac{i_s}{s} \right)^2}{2} \right]^{\frac{1}{2}} \]

\[ \max(u_{1p}) = 4066 \text{ psi} \]

\[ u_{2p_{1,s}} := \frac{u_{i,s}}{2} - \left[ \frac{\left( \frac{u_{i,s}}{2} \right)^2 + \left( \frac{i_s}{s} \right)^2}{2} \right]^{\frac{1}{2}} \]

\[ \min(u_{2p}) = -4253 \text{ psi} \]

Maximum principal stress is:

\[ \max_{i,s} := \begin{cases} u_{1p_{1,s}} & \text{if } \left| u_{1p_{1,s}} \right| \geq \left| u_{2p_{1,s}} \right| \\ u_{2p_{1,s}} & \text{otherwise} \end{cases} \]

\[ \max(\max_{i,s}) = 4253 \text{ psi} \]

Von-Mises Stress:

\[ \text{vm}_{i,s} := \sqrt{\left( u_{1p_{1,s}} \right)^2 + \left( u_{2p_{1,s}} \right)^2 - u_{1p_{1,s}} \cdot u_{2p_{1,s}}} \]

\[ \max(\text{vm}_{i,s}) = 4262 \text{ psi} \]

Maximum shear:

\[ \max_{i,s} := \frac{1}{4} \left( \frac{u_{i,s}}{2} \right)^2 + \left( \frac{i_s}{s} \right)^2 \]

\[ \max(\max_{i,s}) = 2136 \text{ psi} \]

Margins of safety:

Ultimate:

\[ \text{MS}_{i,s} := \frac{F_{su}}{F_{tu} \cdot \max_{i,s}} - 1 \text{ if } \max_{i,s} \neq 0 \text{ psi} \]

\[ 10000 \text{ otherwise} \]

\[ \min(\text{MS}_{i,s}) = 6.88 \]

Ultimate, shear:

\[ \text{MSu}_{i,s} := \left( \frac{F_{su}}{F_{tu} \cdot \text{vm}_{i,s}} \right)^{-1} - 1 \text{ if } \text{vm} \neq 0 \text{ psi} \]

\[ 10000 \text{ otherwise} \]

\[ \min(\text{MSu}_{i,s}) = 9.07 \]

Yield (using von-Mises):

\[ \text{MSy}_{i,s} := \left( \frac{F_{ty}}{F_{sy} \cdot \text{vm}_{i,s}} \right)^{-1} - 1 \text{ if } \text{vm} \neq 0 \text{ psi} \]

\[ 10000 \text{ otherwise} \]

\[ \min(\text{MSy}_{i,s}) = 9.7 \]
Element ID, LC and Forces/Moments for Minimum Margin Cases

For each load case four margins of safety were determined for ultimate, shear, and yield. To display the minimum margin of safety for all load cases, the minimum margin of safety for each load case must be determined initially.

Place the minimum margin of safety for each load case in matrices MSu, MSsu, and MSy in each row of MSminu, MSminsu, and MSminy, respectively, forming a single column.

\[
\begin{align*}
MSminu_i & := \min\left((MSu)^T\right) \\
MSminsu_i & := \min\left((MSsu)^T\right) \\
MSminy_i & := \min\left((MSy)^T\right)
\end{align*}
\]

Create output file, Output2, of Element ID, Load Case, Forces and Moments corresponding to the minimum margins of safety.

\[
\text{Output2} := \text{augment}\left(\text{ID, LC, } \frac{Fx}{\text{lbf}}, \frac{Fy}{\text{lbf}}, \frac{Fz}{\text{lbf}}, \frac{Mx}{\text{in-lbf}}, \frac{My}{\text{in-lbf}}, \frac{Mz}{\text{in-lbf}}, MSminu, MSminsu, MSminy\right)
\]

Rearrange the rows of Output2 until the columns containing the margins of safety are in ascending order. Transpose the result and select the first column. Transposing the result a second time places the output in row order.

\[
\text{MS}_m := \text{augment}\left(\text{csort(Output2, 9)}^T\right)^\langle 1 \rangle, \left(\text{csort(Output2, 10)}^T\right)^\langle 1 \rangle, \left(\text{csort(Output2, 11)}^T\right)^\langle 1 \rangle^T
\]

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>MSminu</th>
<th>MSminsu</th>
<th>MSminy</th>
</tr>
</thead>
</table>

\[
\begin{align*}
\text{MS}_m_{ID} & := \text{MS}_m_{1,1} \\
\text{MS}_m_{LC} & := \text{MS}_m_{1,2} \\
\text{MS}_m_{Fx} & := \text{MS}_m_{1,3} \\
\text{MS}_m_{My} & := \text{MS}_m_{1,7} \\
\text{MS}_m_{Fz} & := \text{MS}_m_{1,5} \\
\text{MS}_m_{Mz} & := \text{MS}_m_{1,8} \\
\text{MS}_m_{T} & := \text{MS}_m_{1,6}
\end{align*}
\]
Identifying Element ID Number, Load Case Number, and Loads for Minimum Margins of Safety Determined on Page 5.5.1-8.

\[
\text{MS\_min\_ID} = 9900 \quad \text{Element Identification for Minimum Margin}
\]
\[
\text{MS\_min\_LC} = 2048 \quad \text{Load Case Number for Minimum Margin}
\]
\[
\text{MS\_min\_Fx} = 98.75288 \quad \text{Axial Load}
\]
\[
\text{MS\_min\_Fy} = -115.072 \quad \text{Shear in Y axis}
\]
\[
\text{MS\_min\_Fz} = -551.5204 \quad \text{Shear in Z axis}
\]
\[
\text{MS\_min\_T} = -732.7131 \quad \text{Torsion}
\]
\[
\text{MS\_min\_My} = 8097.33 \quad \text{Moment about Y axis}
\]
\[
\text{MS\_min\_Mz} = -1820.659 \quad \text{Moment about Z axis}
\]

**Cross Section at 4.50 in. From the Clevis Flange**

The properties of this cross section are the same as at a distance of 2.50 in. from the clevis flange. Only the position vector is different.

Position Vector - \( \mathbf{r}_{\text{vec2}} \), represents the components of the position vector measured from the centroid of the cross section of the ROEU clevis at 4.5 inches from the clevis flange to the point of application of the forces and moments at the cg of the bolt pattern.

At 4.50 inches from the clevis flange:

\( \mathbf{r}_{\text{cs2}} \) represents the origin of the local coordinate system, \( X_{\text{cg}}, Y_{\text{cg}}, Z_{\text{cg}} \) located at the centroid of the cross section.

\[
\text{Centroid of bolt pattern in local coordinates:} \quad \mathbf{c}_{\text{global}} := \begin{pmatrix} -4.5 \\ -0.89 \\ -0.225 \end{pmatrix} \text{ in}
\]
\[
\mathbf{r}_{\text{cs2}} := \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{r}_{\text{vec2}} := \mathbf{c}_{\text{global}} - \mathbf{r}_{\text{cs2}} \quad \mathbf{r}_{\text{vec2}} := \begin{pmatrix} -4.5 \\ -0.89 \\ -0.225 \end{pmatrix} \text{ in}
\]
**Moment Distribution**

\[
M_{\text{tot}}^{(i)} := \begin{pmatrix} M_{x_i} \\ M_{y_i} \\ M_{z_i} \end{pmatrix} + r_{\text{vec}2} \times \begin{pmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{pmatrix}
\]

\[
M_{x_{cs2}} := M_{\text{tot}1, i}, \quad M_{y_{cs2}} := M_{\text{tot}2, i}, \quad M_{z_{cs2}} := M_{\text{tot}3, i}
\]

**Section Properties:** The cross section properties are determined at a distance of 4.50 in. from the clevis flange. All dimensions were obtained from drawing no. SEG39137676. The properties of the cross section were obtained from Excel data (see attached).
Distance from centroid to outer fiber:

\[
\begin{align*}
\text{cz45} & := \begin{pmatrix} -1.57 \\ -1.57 \\ 1.43 \\ 1.43 \end{pmatrix} \text{ in} \\
\text{cy45} & := \begin{pmatrix} -1.0075 \\ 1.0075 \\ 1.0075 \\ -1.0075 \end{pmatrix} \text{ in} \\
\text{points} & := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \end{pmatrix}
\end{align*}
\]

Area:

\[
\text{Area45} := 3.875 \text{ in}^2
\]

Moments of inertia about centroid:

\[
\begin{align*}
\text{Iy45} & := 3.9271 \text{ in}^4 \\
\text{Iz45} & := 0.9201 \text{ in}^4 \\
\end{align*}
\]

\[
s := 1..\text{rows(points)}
\]

\[
\begin{align*}
t_1 & := 0.50 \text{ in} \\
t_2 & := 0.775 \text{ in} \\
t_3 & := 0.75 \text{ in} \\
b_1 & := 2.015 \text{ in} \\
b_2 & := 1.75 \text{ in} \\
b_3 & := 2.015 \text{ in}
\end{align*}
\]

\[
T := \text{Mx}\_\text{cs2}
\]

**Stresses on cross section:**

Normal is direct axial plus bending:

\[
u_{i,s} := \frac{F_{x_i}}{\text{Area45}} + \frac{\text{My}\_\text{cs2}_i \cdot \text{cz45}_i}{\text{Iy45}_i} - \frac{\text{Mz}\_\text{cs2}_i \cdot \text{cy45}_i}{\text{Iz45}_i}
\]

\[
\begin{align*}
\text{max}(u2) & = 3393 \text{ psi} \\
\text{min}(u2) & = -3541 \text{ psi}
\end{align*}
\]

Shear due to transverse loading:

\[
\nu_{i,s} := \left( \frac{F_{y_i}}{\text{Area}} \right)^2 + \left( \frac{F_{z_i}}{\text{Area}} \right)^2
\]

\[
\text{max}(\nu) = 145 \text{ psi}
\]

Shear due to torsion:

The torsional shear stress will be largest in the thickest element of the cross section.

\[
\begin{align*}
\tau_{\text{min}} & := .246 \\
\tau_{\text{max}} & := .258 \\
\beta_{\text{min}} & := 2.00 \\
\beta_{\text{max}} & := 2.50 \\
\beta & := \frac{b_2}{t_2}
\end{align*}
\]

\[
\tau_i := \frac{\beta - \beta_{\text{min}}}{\beta_{\text{max}} - \beta_{\text{min}}} \left( \tau_{\text{max}} - \tau_{\text{min}} \right) + \tau_{\text{min}} = 0.252 \\
\text{Ref: Bruhn, Table A6.1}
\]

\[
\tau_i := \frac{T \cdot t_2}{b_1^3 t_1^3 + b_2^3 t_2^3 + b_3^3 t_3^3}
\]

\[
\text{Ref: Bruhn, p.A6.4} \\
\text{max}(\tau) = 368.631 \text{ psi}
\]

5.5.1-12
ESCG-4005-05-AMS-0039
Combined shear:

\[ i_s := v_i + \frac{t_i}{2} \quad \max(t) = 369 \text{ psi} \quad \max() = 448 \text{ psi} \]

Principal Stresses:

\[ u_{1p_i,s} := \frac{u_{2, i_s}^2}{2} + \left( \frac{u_{2, i_s}^2}{2} \right)^2 \quad \max(u_{1p}) = 3416 \text{ psi} \]

\[ u_{2p_i,s} := \frac{u_{2, i_s}^2}{2} - \left( \frac{u_{2, i_s}^2}{2} \right)^2 \quad \min(u_{2p}) = -3564 \text{ psi} \]

Maximum principal stress is:

\[ u_{\max, i_s} := \begin{cases} u_{1p, i_s}, & \text{if } |u_{1p, i_s}| \geq |u_{2p, i_s}| \\ u_{2p, i_s}, & \text{otherwise} \end{cases} \quad \max(u_{\max}) = 3564 \text{ psi} \]

Von-Mises Stress:

\[ u_{vm, i_s} := \sqrt{\left( u_{1p, i_s} \right)^2 + \left( u_{2p, i_s} \right)^2 - u_{1p, i_s} \cdot u_{2p, i_s}} \quad \max(u_{vm}) = 3575 \text{ psi} \]

Maximum shear:

\[ \max_{i_s} := \sqrt{\frac{1}{4} \left( \frac{u_{2, i_s}^2}{2} \right)^2 \quad \max(\max) = 1793 \text{ psi} \]

Margins of safety:

Ultimate

\[ MS_{1, i_s} := \begin{cases} \frac{Fu}{FS_{\max, i_s}} - 1, & \text{if } u_{\max, i_s} \neq 0 \text{-psi} \\ 10000, & \text{otherwise} \end{cases} \quad \min(MS_u) = 8.4 \]

Ultimate, shear

\[ MS_{u, i_s} := \begin{cases} \frac{FS}{FS_{\max, i_s}} - 1, & \text{if } \max_{i_s} \neq 0 \text{-psi} \\ 10000, & \text{otherwise} \end{cases} \quad \min(MS_{u, i_s}) = 10.99 \]
Yield (using von-Mises)

\[ MS_{y,i,s} := \begin{cases} \frac{F_{ty}}{F_{Sy} \cdot uvm_{i,s}} - 1 & \text{if } uvm_{i,s} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]

\[ \min (MS_y) = 11.76 \]

Element ID, LC and Forces/Moments for Minimum Margin Cases

For each load case four margins of safety were determined for ultimate, shear, and yield. To display the minimum margin of safety for all load cases, the minimum margin of safety for each load case must be determined initially.

Place the minimum margin of safety for each load case in matrix MSu, MSsu, and MSy in each row of MSminu, MSminsu, and MSminy, respectively, forming a single column.

\[ MS_{minu,i} := \min \left( \left( MS_u^T \right)^{<i>} \right) \]

\[ MS_{minsu,i} := \min \left( \left( MS_{su}^T \right)^{<i>} \right) \]

\[ MS_{miny,i} := \min \left( \left( MS_y^T \right)^{<i>} \right) \]

Create output file, Output2, of Element ID, Load Case, Forces and Moments corresponding to the minimum margins of safety.

\[ \text{Output2} := \text{augment} \left( \text{ID, LC, } \frac{Fx}{\text{lbf}}, \frac{Fy}{\text{lbf}}, \frac{Fz}{\text{lbf}}, \frac{My}{\text{in-lbf}}, \frac{Mx}{\text{in-lbf}}, \frac{Mz}{\text{in-lbf}}, \text{MSminu, MSminsu, MSminy} \right) \]

Rearrange the rows of Output2 until the columns containing the margins of safety are in ascending order. Transpose the result and select the first column. Transposing the result a second time places the output in row order.

\[ \text{MS_min} := \text{augment} \left( \left( \text{csort(Output2, 9)}^T \right)^{<i>}, \left( \text{csort(Output2, 10)}^T \right)^{<i>}, \left( \text{csort(Output2, 11)}^T \right)^{<i>} \right)^T \]

\[ \begin{array}{cccccccccc}
\text{ID} & \text{LC} & Fx & Fy & Fz & Mx & My & Mz & \text{minu} & \text{minsu} & \text{miny} \\
\end{array} \]

\[ \begin{array}{cccc}
\text{MS_min_ID} := \text{MS_min}_{1,1} & \text{MS_min_Fy} := \text{MS_min}_{1,4} & \text{MS_min_My} := \text{MS_min}_{1,7} \\
\text{MS_min_LC} := \text{MS_min}_{1,2} & \text{MS_min_Fz} := \text{MS_min}_{1,5} & \text{MS_min_Mz} := \text{MS_min}_{1,8} \\
\text{MS_min_Fx} := \text{MS_min}_{1,3} & \text{MS_min_T} := \text{MS_min}_{1,6} \\
\end{array} \]
Identifying Element ID Number, Load Case Number, and Loads for Minimum Margins of Safety Determined on pages 5.5.1-13 and 14.

ML_min_ID = 9900  Element Identification for Minimum Margin
ML_min_LC = 2048  Load Case Number for Minimum Margin
ML_min_Fx = 98.75288  Axial Load
ML_min_Fy = -115.072  Shear in Y axis
ML_min_Fz = -551.5204  Shear in Z axis
ML_min_T = -732.7131  Torsion
ML_min_My = 8097.33  Moment about Y axis
ML_min_Mz = -1820.659  Moment about Z axis
Clevis Cross Section at 4.51 in. From the Clevis Flange

Section Properties: The cross section at this location is uniquely shaped. The properties of this cross section are valid from a distance of 4.51 in. to 5.70 in. from the clevis flange and will be used to determine the bending stress in this range. The cross section will subsequently be treated as an I-beam to determine the properties used in the torsional shear stress calculation. All dimensions were obtained from drawing no. SEG39137676. The properties of the cross section were obtained from Excel data (see attached).

Properties for the unique shape:

Distance from centroid to outer fiber:

\[
\begin{align*}
  \text{cz451} & := \begin{pmatrix} -1.392 \\ -1.392 \\ 1.608 \\ 1.608 \end{pmatrix} \text{in} \\
  \text{cy451} & := \begin{pmatrix} -1.0075 \\ 1.0075 \\ 1.0075 \\ -1.0075 \end{pmatrix} \text{in} \\
  \text{points} & := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \end{pmatrix}
\end{align*}
\]

Moments of inertia about centroid:

\[
\begin{align*}
  \text{Iy451} & := 3.1033 \text{in}^4 \\
  \text{Iz451} & := 0.8765 \text{in}^4 \\
  s & := 1.. \text{rows(points)}
\end{align*}
\]

Position Vector - rvec3, represents vector components measured from the centroid of the cross section of the ROEU clevis at 4.51 inches from the clevis flange to the point of application of the forces and moments at the cg of the bolt pattern. The properties of this cross section are valid from 4.51 in. to 5.70 in. from the clevis flange. See drawing no. SEG39137676 for dimensions.
At 4.51 inches from the clevis flange:

cia3 represents the origin of the local coordinate system, Xcg, Ycg, Zcg located at the centroid of the cross section.

Centroid of bolt pattern in local coordinates:

\[
\begin{align*}
\text{cgglobal} &= \begin{pmatrix} -4.51 \\ -0.890 \\ -0.047 \end{pmatrix} \text{ in} \\
\text{r}_{cs3} &= \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}
\end{align*}
\]

\[
\text{r}_{vec3} := \text{cgglobal} - \text{r}_{cs3}
\]

\[
\text{r}_{vec3} = \begin{pmatrix} -4.51 \\ -0.89 \\ -0.047 \end{pmatrix} \text{ in}
\]

**Moment Distribution**

rvec3 is used to determine the moment at the centroid of the cross section.

\[
\begin{align*}
\text{Total Moment:} \\
M_{\text{tot}}^{(i)} &= \begin{pmatrix} Mx_i \\ My_i \\ Mz_i \end{pmatrix} + \text{r}_{vec3} \times \begin{pmatrix} Fx_i \\ Fy_i \\ Fz_i \end{pmatrix} \\
M_{x,cs3,1}^{(i)} &= M_{\text{tot},1}^{(i)} \\
M_{y,cs3,1}^{(i)} &= M_{\text{tot},2}^{(i)} \\
M_{z,cs3,1}^{(i)} &= M_{\text{tot},3}^{(i)}
\end{align*}
\]

**Stresses on cross section:**

Normal is direct axial plus bending:

\[
\begin{align*}
\text{max}(u_3) &= 4329 \text{ psi} \\
\text{min}(u_3) &= -3880 \text{ psi}
\end{align*}
\]
Cross Section Treated as I - Beam:

Properties for the I - Beam:

Moments of inertia about centroid of I - beam:

\[ I_y := 2.0103 \text{ in}^4 \]
\[ I_z := 0.5792 \text{ in}^4 \]
\[ s := 1 \text{ . rows (points)} \]

\[ T := M_x_{cs3} \]
\[ t_1 := 0.25 \text{ in} \]
\[ t_2 := 0.50 \text{ in} \]
\[ t_3 := 0.775 \text{ in} \]
\[ b_1 := 2.015 \text{ in} \]
\[ b_2 := 2.015 \text{ in} \]
\[ b_3 := 1.75 \text{ in} \]

Stresses on cross section:

Shear due to transverse loading:

\[ \nu_{i,s} := \sqrt{\left( \frac{F_{y_1}}{\text{Area451Ibm}} \right)^2 + \left( \frac{F_{z_1}}{\text{Area451Ibm}} \right)^2} \]
\[ \text{max( } \nu \text{ )} = 196 \text{ psi} \]

Shear due to torsion:

The torsional shear stress will be largest in the thickest element of the cross section.

\[ \nu_{\text{tors}} := \frac{b_3}{t_3} \]
\[ \nu_{\text{tmax}} := \nu_{\text{tmax}} \]
\[ \nu_{\text{tmin}} := \nu_{\text{tmin}} \]
\[ \nu := \nu_{\text{tmin}} + \frac{(\nu_{\text{tmax}} - \nu_{\text{tmin}})}{\nu_{\text{tmax}} - \nu_{\text{tmin}}} \]
\[ \nu = 0.252 \]

Ref: Bruhn, Table A6.1
Ref: Bruhn, p.A6.4

\[
t_i := \frac{T_i \cdot t_3}{b_1 \cdot t_1^3 + b_2 \cdot t_2^3 + b_3 \cdot t_3^3}
\]

\(\max(t) = 676 \text{ psi}\)

Combined shear:
\[
i_{i,s} := \frac{v_i}{i} + \frac{t_i}{i}
\]

\(\max(i_{i,s}) = 782 \text{ psi}\)

Principal Stresses:
\[
u_{1p_{i,s}} := \frac{u_{3_{i,s}}}{2} + \left(\frac{u_{3_{i,s}}}{2}\right)^2 + \left(\frac{i_{i,s}}{2}\right)^2
\]

\(\max(u_{1p}) = 4385 \text{ psi}\)

\[
u_{2p_{i,s}} := \frac{u_{3_{i,s}}}{2} - \left(\frac{u_{3_{i,s}}}{2}\right)^2 + \left(\frac{i_{i,s}}{2}\right)^2
\]

\(\min(u_{2p}) = -3942 \text{ psi}\)

Maximum principal stress is:
\[
\max_{i,s} := \begin{cases} u_{1p_{i,s}} & \text{if } u_{1p_{i,s}} \geq u_{2p_{i,s}} \\ u_{2p_{i,s}} & \text{otherwise} \end{cases}
\]

\(\max(\max_{i,s}) = 4385 \text{ psi}\)

Von-Mises Stress:
\[
u_{vm_{i,s}} := \sqrt{(u_{1p_{i,s}})^2 + (u_{2p_{i,s}})^2 - u_{1p_{i,s}} \cdot u_{2p_{i,s}}}
\]

\(\max(\nu_{vm}) = 4413 \text{ psi}\)

Maximum shear:
\[
\max_{i,s} := \sqrt{\frac{1}{4} \left(\frac{u_{3_{i,s}}}{2} + \left(\frac{i_{i,s}}{2}\right)^2\right)^2}
\]

\(\max(\max_{i,s}) = 2221 \text{ psi}\)

Margins of safety:

Ultimate
\[
\text{MSu}_{i,s} := \begin{cases} \frac{\text{Ftu}}{\text{FSu} \cdot \max_{i,s}} - 1 & \text{if } \max_{i,s} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \\
\end{cases}
\]

\(\min(\text{MSu}) = 6.64\)
Element ID, LC and Forces/Moments for Minimum Margin Cases

For each load case four margins of safety were determined for ultimate, shear, and yield. To display the minimum margin of safety for all load cases, the minimum margin of safety for each load case must be determined initially.

Place the minimum margin of safety for each load case in matrix MSu, MSsu, and MSy in each row of MSminu, MSminsu, and MSminy, respectively, forming a single column.

\[ \text{MSmin}_{i} := \min \left( \left( \text{MSu}_{i} \right)^T \right) \]

\[ \text{MSmin}_{isu} := \min \left( \left( \text{MSsu}_{i} \right)^T \right) \]

\[ \text{MSmin}_{isy} := \min \left( \left( \text{MSy}_{i} \right)^T \right) \]

Create output file, Output2, of Element ID, Load Case, Forces and Moments corresponding to the minimum margins of safety.

\[ \text{Output2} := \text{augment} \left( \text{ID}, \text{LC}, \frac{\text{Fx}}{\text{lbf}}, \frac{\text{Fy}}{\text{lbf}}, \frac{\text{Fz}}{\text{in-lbf}}, \frac{\text{Mx}}{\text{in-lbf}}, \frac{\text{My}}{\text{in-lbf}}, \frac{\text{Mz}}{\text{in-lbf}}, \text{MSminu}, \text{MSminsu}, \text{MSminy} \right) \]

Rearrange the rows of Output2 until the columns containing the margins of safety are in ascending order. Transpose the result and select the first column. Transposing the result a second time places the output in row order.

\[ \text{MS}_{\text{min}} := \text{augment} \left( \left( \text{csort(Output2, 9)} \right)^T \right)^{(1)}, \left( \text{csort(Output2, 10)} \right)^T, \left( \text{csort(Output2, 11)} \right)^T \]

\[
\begin{array}{ccccccccc}
\text{ID} & \text{LC} & \text{Fx} & \text{Fy} & \text{Fz} & \text{Mx} & \text{My} & \text{Mz} & \text{minu} & \text{minsu} & \text{miny} \\
\end{array}
\]
Identifying Element ID Number, Load Case Number, and Loads for Minimum Margins of Safety Determined on Pages 5.5.1-19 and 20.

MS_min_ID = 9900  
Element Identification for Minimum Margin

MS_min_LC = 2048  
Load Case Number for Minimum Margin

MS_min_Fx = 98.75288  
Axial Load

MS_min_Fy = −115.072  
Shear in Y axis

MS_min_Fz = −551.5204  
Shear in Z axis

MS_min_T = −732.7131  
Torsion

MS_min_My = 8097.33  
Moment about Y axis

MS_min_Mz = −1820.659  
Moment about Z axis
Cross Section at 5.70 in. From the Clevis Flange

The properties of this cross section are the same as at a distance of 4.51 in. from the clevis flange. Only the position vector is different.

Position Vector - rvec4, represents vector components measured from the centroid of the cross section of the ROEU clevis at 5.70 inches from the clevis flange to the point of application of the forces and moments at the cg of the bolt pattern.

Properties for the unique shape:

Area: \( \text{Area570} := 3.3675 \text{ in}^2 \)

Distance from centroid to outer fiber:

\[
\begin{align*}
\text{cz570} & := \begin{pmatrix} -1.392 \\ -1.392 \\ 1.608 \\ 1.608 \end{pmatrix} \text{ in} \\
\text{cy570} & := \begin{pmatrix} -1.0075 \\ 1.0075 \\ 1.0075 \\ -1.0075 \end{pmatrix} \text{ in}
\end{align*}
\]

Moments of inertia about centroid:

\[
\begin{align*}
\text{Iy570} & := 3.1033 \text{ in}^4 \\
\text{Iz570} & := 0.8765 \text{ in}^4 \\
\end{align*}
\]

At 5.70 inches from the clevis flange:

\( \text{rcs4} \) represents the origin of the local coordinate system, \( X_{cg}, Y_{cg}, Z_{cg} \) located at the centroid of the cross section.

Centroid of bolt pattern in local coordinates:

\[
\begin{align*}
\text{cgglobal} & := \begin{pmatrix} -5.70 \\ -0.890 \\ -0.047 \end{pmatrix} \text{ in} \\
\text{r}_{cs4} & := \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}
\end{align*}
\]

\[
\text{r}_{vec4} := \text{cgglobal} - \text{r}_{cs4}
\]

\[
\text{r}_{vec4} = \begin{pmatrix} -5.7 \\ -0.89 \\ -0.047 \end{pmatrix} \text{ in}
\]

Moment Distribution

rvec4 is used to determine the moment at the centroid of the cross section.
\[
M_{tot} := \begin{pmatrix} M_{x_i} \\ M_{y_i} \\ M_{z_i} \end{pmatrix} + r_{vec4} \times \begin{pmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{pmatrix}
\]

\[
M_{x_{cs4},i} := M_{tot,1,i} \quad M_{y_{cs4},i} := M_{tot,2,i} \quad M_{z_{cs4},i} := M_{tot,3,i}
\]

**Stresses on cross section:**

Normal is direct axial plus bending:

\[
u_{i,s} := \frac{F_{x_i}}{Area_{570}} + \frac{M_{y_{cs4},i} c_{z570}}{I_{y570}} - \frac{M_{z_{cs4},i} c_{y570}}{I_{z570}}
\]

\[\max(u_4) = 3832 \text{ psi}\]

\[\min(u_4) = -3428 \text{ psi}\]

**Cross Section Treated as I - Beam:**

**Properties for the I - Beam:**

\[\text{Area: } \quad Area_{570 \text{ lbm}} := 2.8675 \text{ in}^2\]

Moments of inertia about centroid of I - beam:

\[I_y := 2.0103 \text{ in}^4 \quad I_z := 0.5792 \text{ in}^4 \quad s := 1..\text{rows(points)}\]

\[t_1 := 0.25 \text{ in} \quad t_2 := 0.50 \text{ in} \quad t_3 := 0.775 \text{ in} \quad b_1 := 2.015 \text{ in} \quad b_2 := 2.015 \text{ in} \quad b_3 := 1.75 \text{ in}\]

\[T := M_{x_{cs4}}\]

**Stresses on cross section:**

Shear due to transverse loading:

\[\nu_{i,s} := \sqrt{\left(\frac{F_{y_i}}{Area_{570 \text{ lbm}}}\right)^2 + \left(\frac{F_{z_i}}{Area_{570 \text{ lbm}}}\right)^2} \quad \max(\nu) = 196 \text{ psi}\]

Shear due to torsion:

The torsional shear stress will be largest in the thickest element of the cross section.

*Ref: Bruhn, Table A6.1*

\[\beta_{min} := 0.246 \quad \beta_{max} := 0.258 \quad \beta_{t_{min}} := 2.00 \quad \beta_{t_{max}} := 2.50 \quad \beta := \frac{b_3}{t_3}\]
\[ e := \frac{bt - b_{\text{min}}}{b_{\text{max}} - b_{\text{min}}} \left( e_{\text{max}} - e_{\text{min}} \right) \quad e = 0.252 \]

\[ t_i := \frac{T_i \cdot t_3}{(b_1 \cdot t_1^3 + b_2 \cdot t_2^3 + b_3 \cdot t_3^3)} \]

Combined shear:
\[ i, s := v_i, s + t_i \]
\[ \text{max}( ) = 782 \text{ psi} \]

Principal Stresses:
\[ u_{1p, i, s} := \frac{u_4, i, s}{2} + \left( \frac{u_4, i, s}{2} \right)^2 + \left( i, s \right)^2 \]
\[ \text{max}(u_{1p}) = 3895 \text{ psi} \]
\[ u_{2p, i, s} := \frac{u_4, i, s}{2} - \left( \frac{u_4, i, s}{2} \right)^2 + \left( i, s \right)^2 \]
\[ \text{min}(u_{2p}) = -3499 \text{ psi} \]

Maximum principal stress is:
\[ \text{umax}_{i, s} := \begin{cases} u_{1p, i, s} & \text{if } u_{1p, i, s} \geq u_{2p, i, s} \\ u_{2p, i, s} & \text{otherwise} \end{cases} \]
\[ \text{max}(\text{umax}) = 3895 \text{ psi} \]

Von-Mises Stress:
\[ \text{uv}_1, s := \sqrt{u_{1p, i, s}^2 + u_{2p, i, s}^2 - u_{1p, i, s} \cdot u_{2p, i, s}} \]
\[ \text{max}(\text{uv}_1) = 3926 \text{ psi} \]

Maximum shear:
\[ \text{max}_{i, s} := \sqrt{\frac{1}{4} \left( u_4, i, s \right)^2 + \left( i, s \right)^2} \]
\[ \text{max}(\text{max}) = 1979 \text{ psi} \]

Margins of safety:
\[ \text{Ultimate} \]
\[ \text{MSu}_{i, s} := \begin{cases} \frac{\text{Ftu}}{\text{FSu} \cdot \text{umax}_{i, s}} - 1 & \text{if } \text{umax}_{i, s} \neq 0 \text{ psi} \\ 10000 & \text{otherwise} \end{cases} \]
\[ \text{min}(\text{MSu}) = 7.6 \]
**Element ID, LC and Forces/Moments for Minimum Margin Cases**

For each load case four margins of safety were determined for ultimate, shear, and yield. To display the minimum margin of safety for all load cases, the minimum margin of safety for each load case must be determined initially.

Place the minimum margin of safety for each load case in matrix MSu, MSsu, and MSy in each row of MSminu, MSminsu, and MSminy, respectively, forming a single column.

\[
\text{MSminu}_i := \min \left( (\text{MSu}^T)^{\dagger} \right) \\
\text{MSminsu}_i := \min \left( (\text{MSsu}^T)^{\dagger} \right) \\
\text{MSminy}_i := \min \left( (\text{MSy}^T)^{\dagger} \right)
\]

Create output file, Output2, of Element ID, Load Case, Forces and Moments corresponding to the minimum margins of safety.

\[
\text{Output2} := \text{augment} \left\{ \text{ID}, \text{LC}, \frac{\text{Fx}}{\text{lbf}}, \frac{\text{Fy}}{\text{lbf}}, \frac{\text{Fz}}{\text{lbf}}, \frac{\text{Mx}}{\text{in-lbf}}, \frac{\text{My}}{\text{in-lbf}}, \frac{\text{Mz}}{\text{in-lbf}}, \text{MSminu}, \text{MSminsu}, \text{MSminy} \right\}
\]

Rearrange the rows of Output2 until the columns containing the margins of safety are in ascending order. Transpose the result and select the first column. Transposing the result a second time places the output in row order.

\[
\text{MS}_{\text{min}} := \text{augment} \left[ (\text{csort(Output2, 9)}^T)^{\dagger}, (\text{csort(Output2, 10)}^T)^{\dagger}, (\text{csort(Output2, 11)}^T)^{\dagger} \right]^T
\]

<table>
<thead>
<tr>
<th>ID</th>
<th>LC</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>minu</th>
<th>minsu</th>
<th>miny</th>
</tr>
</thead>
<tbody>
<tr>
<td>9900</td>
<td>2048</td>
<td>98.753</td>
<td>-115.072</td>
<td>-551.52</td>
<td>-732.713</td>
<td>8097.33</td>
<td>-1820.659</td>
<td>7.602</td>
<td>9.865</td>
<td>10.613</td>
</tr>
</tbody>
</table>

\[
\text{MS}_{\text{min}} = \begin{bmatrix} 9900 & 2048 & 98.753 & -115.072 & -551.52 & -732.713 & 8097.33 & -1820.659 & 7.602 & 9.865 & 10.613 \\
\end{bmatrix}
\]
Identifying Element ID Number, Load Case Number, and Loads for Minimum Margins of Safety Determined on Pages 5.5.1-24 and 25.

\[
\begin{align*}
MS_{\text{min\_ID}} & := MS_{\text{min}}_{1,1} \\
MS_{\text{min\_LC}} & := MS_{\text{min}}_{1,2} \\
MS_{\text{min\_Fx}} & := MS_{\text{min}}_{1,3} \\
MS_{\text{min\_Fy}} & := MS_{\text{min}}_{1,4} \\
MS_{\text{min\_Fz}} & := MS_{\text{min}}_{1,5} \\
MS_{\text{min\_T}} & := MS_{\text{min}}_{1,6} \\
MS_{\text{min\_My}} & := MS_{\text{min}}_{1,7} \\
MS_{\text{min\_Mz}} & := MS_{\text{min}}_{1,8} \\
\end{align*}
\]

Cross Section at 5.71 in. to 6.29 in. From the Clevis Flange

**Section Properties:** The cross section is rectangular with a 1.015 in. x .50 in. area removed. The properties of this clevis cross section are valid from a distance of 5.71 in. to 6.29 in. from the clevis flange and will be used to determine the bending stress in this range. The cross section will be treated as a rectangle to determine the properties used in the torsional shear stress calculation. All dimensions were obtained from drawing no. SEG39137676. The properties of the cross section were obtained from Excel data (see attached).
Moments of inertia about centroid:

\[ I_{y571} := 3.6575 \text{ in}^4 \quad I_{z571} := 2.0018 \text{ in}^4 \quad s := 1 \text{ rows(points)} \]

Position Vector - \( r_{vec5} \), represents the components of the position vector measured from the centroid of the cross section of the ROEU clevis at 5.71 inches from the clevis flange to the point of application of the forces and moments at the cg of the bolt pattern.

Cross section at 5.71 inches from the clevis flange:

\( rcs5 \) represents the origin of the local coordinate system, \( X_{cg}, Y_{cg}, Z_{cg} \) located at the centroid of the cross section.

Centroid of bolt pattern in local coordinates:

\[
\begin{bmatrix}
-5.71 \\
-0.890 \\
-0.040
\end{bmatrix} \text{ in} \quad r_{cs5} := \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad r_{vec5} := cgglobal - r_{cs5}
\]

**Moment Distribution**

\( r_{vec5} \) is used to determine the moment at the centroid of the cross section.
Total Moment:
\[
M_{\text{tot}} := \begin{pmatrix}
M_{x_i} \\
M_{y_i} \\
M_{z_i}
\end{pmatrix} + r_{vec5} \times \begin{pmatrix}
F_{x_i} \\
F_{y_i} \\
F_{z_i}
\end{pmatrix}
\]
\[
r_{vec5} = \begin{pmatrix}
-5.71 \\
-0.89 \\
-0.04
\end{pmatrix} \text{ in}
\]

\[
M_{x\_cs5,1} := M_{\text{tot}1,1} \quad M_{y\_cs5,1} := M_{\text{tot}2,1} \quad M_{z\_cs5,1} := M_{\text{tot}3,1}
\]

Bending Stress on Cross Section:

Normal is direct axial plus bending:
\[
u_{i,s}^5 := \frac{F_{x_i}}{\text{Area}571} + \frac{M_{y\_cs5,1} \cdot cz571_s}{Iy571} - \frac{M_{z\_cs5,1} \cdot cy571_s}{Iz571}
\]

Stresses on cross section:
max(\(u^5\)) = 2742 psi
min(\(u^5\)) = -2396 psi

Shear due to transverse loading
\[
v_{i,s} := \sqrt{\left(\frac{F_{y_i}}{\text{Area}571}\right)^2 + \left(\frac{F_{z_i}}{\text{Area}571}\right)^2}
\]

Shear due to torsion:
\[
a := \frac{3.00}{2} \text{ in} \quad b := \frac{2.015}{2} \text{ in} \quad a = 1.5 \text{ in} \quad b = 1.008 \text{ in}
\]

\[
t_i := 3 \cdot \frac{T_i}{8 \cdot a \cdot b^2} \left[1 + 0.6095 \frac{b}{a} + 0.8865 \left(\frac{b}{a}\right)^2 - 1.8023 \left(\frac{b}{a}\right)^3 + 0.9100 \left(\frac{b}{a}\right)^4\right]
\]

(combined shear):
\[
(\text{Roark's, 7th Ed., Case 4, p. 401})
\]

\[
(\text{Roark's, 7th Ed., Case 4, p. 401})
\]

Combined shear:
max(\(t\)) = 86 psi

Principal Stresses:
max(\(u_{1p}\)) = 2742 psi
min(\(u_{2p}\)) = -2396 psi
Maximum principal stress is:

\[
\text{u}_{1,s}^{\text{max}} := \begin{cases} 
    |\text{u}_{1,s}^{1p}| & \text{if } |\text{u}_{1,s}^{1p}| \geq |\text{u}_{2,s}^{2p}| \\
    |\text{u}_{2,s}^{2p}| & \text{otherwise}
\end{cases}
\]

\[\text{max(u}_{1,s}^{\text{max}}) = 2742 \text{ psi}\]

Von-Mises Stress:

\[
\text{u}_{1,s}^{vM} := \sqrt{\left(\text{u}_{1,s}^{1p}\right)^2 + \left(\text{u}_{2,s}^{2p}\right)^2} - \text{u}_{1,s}^{1p} \cdot \text{u}_{2,s}^{2p}
\]

\[\text{max(u}_{1,s}^{vM}) = 2742 \text{ psi}\]

Maximum shear:

\[
\text{max}_{1,s} := \frac{1}{4} \left(\text{u}_{5,s}^{1p}\right)^2 + \left(\frac{\text{u}_{1,s}^{1p} - \text{u}_{2,s}^{2p}}{2}\right)^2
\]

\[\text{max( max) = 1371 psi}\]

Margins of safety:

Ultimate

\[
\text{MS}_{1,s}^{\text{U}} := \frac{\text{F}_{\text{tu}}}{\text{FS}_{\text{u}} \cdot \text{u}_{1,s}^{\text{max}}} \begin{cases} 
    1 & \text{if } \text{u}_{1,s}^{\text{max}} \neq 0 \text{ psi} \\
    10000 & \text{otherwise}
\end{cases}
\]

\[\text{min(\text{MS}_{1,s}^{\text{U}}}) = 11.22\]

Ultimate, shear

\[
\text{MS}_{1,s}^{\text{SU}} := \left(\frac{\text{F}_{\text{su}}}{\text{FS}_{\text{u}} \cdot \text{max}_{1,s}^{\text{u}}}\right) - 1 \begin{cases} 
    1 & \text{if } \text{max}_{1,s}^{\text{u}} \neq 0 \text{ psi} \\
    10000 & \text{otherwise}
\end{cases}
\]

\[\text{min(\text{MS}_{1,s}^{\text{SU}}}) = 14.68\]

Yield (using von-Mises)

\[
\text{MS}_{1,s}^{\text{Y}} := \left(\frac{\text{F}_{\text{ty}}}{\text{FS}_{\text{y}} \cdot \text{u}_{1,s}^{vM}}\right) - 1 \begin{cases} 
    1 & \text{if } \text{u}_{1,s}^{vM} \neq 0 \text{ psi} \\
    10000 & \text{otherwise}
\end{cases}
\]

\[\text{min(\text{MS}_{1,s}^{\text{Y}}}) = 15.63\]

Element ID, LC and Forces/Moments for Minimum Margin Cases

Element ID, LC and Forces/Moments for Minimum Margin Cases

For each load case four margins of safety were determined for ultimate, shear, and yield. To display the minimum margin of safety for all load cases, the minimum margin of safety for each load case must be determined initially.

Place the minimum margin of safety for each load case in matrix MSu, MSsu, and MSy in each row of MSminu, MSminsu, and MSminy, respectively, forming a single column.

\[
\text{MS}_{1}^{\text{minu}} := \min\left(\left(\text{MS}_{1}^{\text{U}}\right)^{\text{T}}\right) \quad \text{MS}_{1}^{\text{minsu}} := \min\left(\left(\text{MS}_{1}^{\text{SU}}\right)^{\text{T}}\right) \quad \text{MS}_{1}^{\text{miny}} := \min\left(\left(\text{MS}_{1}^{\text{Y}}\right)^{\text{T}}\right)
\]

5.5.1-29

ESCG-4005-05-AMS-0039
Create output file, Output2, of Element ID, Load Case, Forces and Moments corresponding to the minimum margins of safety.

\[
\text{Output2} := \text{augment}\left[ \begin{array}{cccccccccc}
\text{ID, LC, Fx, Fy, Fz, Mx, My, Mz, MSminu, MSminsu, MSminy} \\
\text{lbf, lbf, lbf, in-lbf, in-lbf, in-lbf} \end{array} \right]
\]

Rearrange the rows of Output2 until the columns containing the margins of safety are in ascending order. Transpose the result and select the first column. Transposing the result a second time places the output in row order.

\[
\text{MS_min} := \text{augment}\left[ \begin{array}{cccccccccc}
\text{csort(Output2, 9)}^T & (1) & \text{csort(Output2, 10)}^T & (1) & \text{csort(Output2, 11)}^T & (1)^T \\
\text{ID, LC, Fx, Fy, Fz, Mx, My, Mz, minu, minsu, miny} \end{array} \right]
\]

Identifying Element ID Number, Load Case Number, and Loads for Minimum Margins of Safety Determined on Page 5.5.1-29.

\[
\begin{array}{cccccccccccc}
\text{ID} & \text{LC} & \text{Fx} & \text{Fy} & \text{Fz} & \text{Mx} & \text{My} & \text{Mz} & \text{minu} & \text{minsu} & \text{miny} \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{MS_min_ID} := \text{MS_min}_{1,1} & \text{MS_min_Fx} := \text{MS_min}_{1,3} & \text{MS_min_My} := \text{MS_min}_{1,7} \\
\text{MS_min_LC} := \text{MS_min}_{1,2} & \text{MS_min_Fy} := \text{MS_min}_{1,4} & \text{MS_min_Mz} := \text{MS_min}_{1,8} \\
\text{MS_min_Fz} := \text{MS_min}_{1,5} & \text{MS_min_T} := \text{MS_min}_{1,6} \\
\end{array}
\]

\[
\begin{array}{llll}
\text{MS_min_ID} = 9900 & \text{Element Identification for Minimum Margin} \\
\text{MS_min_LC} = 2048 & \text{Load Case Number for Minimum Margin} \\
\text{MS_min_Fx} = 98.75288 & \text{Axial Load} \\
\text{MS_min_Fy} = -115.072 & \text{Shear in Y axis} \\
\text{MS_min_Fz} = -551.5204 & \text{Shear in Z axis} \\
\text{MS_min_T} = -732.7131 & \text{Torsion} \\
\text{MS_min_My} = 8097.33 & \text{Moment about Y axis} \\
\text{MS_min_Mz} = -1820.659 & \text{Moment about Z axis} \\
\end{array}
\]
**Cross Section at 6.29 in. From the Clevis Flange**

The properties of this cross section are the same as at a distance of 5.71 in. from the clevis flange. Only the position vector is different.

Position Vector - `rvec6`, represents the components of the position vector measured from the centroid of the cross section of the ROEU clevis at 6.29 inches from the clevis flange to the point of application of the forces and moments at the cg of the bolt pattern.

Properties for the rectangular shape:

Area: \( \text{Area629} := 5.5375 \text{in}^2 \)

Distance from centroid to outer fiber:

\[
\begin{align*}
\text{cz629} & := \begin{pmatrix} -1.3854 \\ -1.3854 \\ 1.6146 \\ 1.6146 \end{pmatrix} \text{in} \\
\text{cy629} & := \begin{pmatrix} 1.0075 \\ 1.0075 \\ -1.0075 \end{pmatrix} \text{in} \\
\text{points} & := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \end{pmatrix}
\end{align*}
\]

Moments of inertia about centroid:

\( \text{Iy629} := 3.6575 \text{in}^4 \quad \text{Iz629} := 2.0018 \text{in}^4 \quad s := 1 \ldots \text{rows(points)} \)

Centroid of bolt pattern in local coordinates:

\[
\begin{align*}
\text{cgglobal} & := \begin{pmatrix} -6.29 \\ -0.890 \\ -0.040 \end{pmatrix} \text{in} \\
\text{r}_\text{cs6} & := \begin{pmatrix} 0 \\ 0 \end{pmatrix} \\
\text{rvec6} & := \text{cgglobal} - \text{r}_\text{cs6}
\end{align*}
\]

**Moment Distribution**

`rvec6` is used to determine the moment at the centroid of the cross section.

Total Moment:

\[
\begin{align*}
M_{\text{tot}}^{(i)} & := \begin{pmatrix} M_{x_i} \\ M_{y_i} \\ M_{z_i} \end{pmatrix} + r_{\text{vec6}} \times \begin{pmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{pmatrix} \\
M_{x_{\text{cs6}}} & := M_{\text{tot1}}^{(i)} \\
M_{y_{\text{cs6}}} & := M_{\text{tot2}}^{(i)} \\
M_{z_{\text{cs6}}} & := M_{\text{tot3}}^{(i)}
\end{align*}
\]

\[
\begin{align*}
\text{rvec6} & = \begin{pmatrix} -6.29 \\ -0.89 \\ -0.04 \end{pmatrix} \text{in}
\end{align*}
\]
Bending Stress on cross section:

Normal is direct axial plus bending: \( u_{6|s} = \frac{F_x}{\text{Area629}} + \frac{M_{y_{cs6}} \cdot c_{z629}}{I_{y629}} - \frac{M_{z_{cs6}} \cdot c_{y629}}{I_{z629}} \)

Stresses on cross section:

Shear due to transverse loading

\( v_{i,s} := \sqrt{\left( \frac{F_y}{\text{Area629}} \right)^2 + \left( \frac{F_z}{\text{Area629}} \right)^2} \)

Shear due to torsion:

\[
T_i := 3\frac{t_i}{8\cdot a \cdot b^2} \left[ 1 + 0.6095 \frac{b}{a} + 0.8865 \left( \frac{b}{a} \right)^2 - 1.8023 \left( \frac{b}{a} \right)^3 + 0.9100 \left( \frac{b}{a} \right)^4 \right]
\]

Combined shear:

\( v_{i,s} := v_{i,s} + t_i \)

Principal Stresses:

\( u_{1p|s} := \frac{u_{6|s}}{2} + \left[ \left( \frac{u_{6|s}}{2} \right)^2 + \left( \frac{v_{i,s}}{2} \right)^2 \right]^{\frac{1}{2}} \)

\( u_{2p|s} := \frac{u_{6|s}}{2} - \left[ \left( \frac{u_{6|s}}{2} \right)^2 + \left( \frac{v_{i,s}}{2} \right)^2 \right]^{\frac{1}{2}} \)

Maximum principal stress is:

\( u_{\text{max}|s} := \begin{cases} u_{1p|s} & \text{if } |u_{1p|s}| \geq |u_{2p|s}| \\ u_{2p|s} & \text{otherwise} \end{cases} \)

Von-Mises Stress:

\( u_{\text{vm}|s} := \sqrt{u_{1p|s}^2 + u_{2p|s}^2 - u_{1p|s} \cdot u_{2p|s}} \)

\[
\text{max}(u_{\text{vm}}) = 2567 \text{ psi}
\]
Maximimum shear: 
\[
\max_{i,s} = \sqrt{\frac{1}{4} (u6_{i,s})^2 + (i_{i,s})^2}
\]
\[
\text{max( max) } = 1284 \text{ psi}
\]

Margins of safety:

Ultimate
\[
\text{MSu}_{i,s} := \frac{\text{Ftu}}{\text{FSu} \cdot \text{umax}_{i,s}} - 1 \quad \text{if } \text{umax}_{i,s} \neq 0\text{-psi}
\]
\[
\text{min(MSu)} = 12.05
\]

Ultimate, shear
\[
\text{MSsu}_{i,s} := \left(\frac{\text{Fsu}}{\text{FSu} \cdot \text{max}_{i,s}}\right) - 1 \quad \text{if } \text{max}_{i,s} \neq 0\text{-psi}
\]
\[
\text{min(MSsu)} = 15.75
\]

Yield (using von-Mises)
\[
\text{MSy}_{i,s} := \left(\frac{\text{Fty}}{\text{FSy} \cdot \text{uvm}_{i,s}}\right) - 1 \quad \text{if } \text{uvm}_{i,s} \neq 0\text{-psi}
\]
\[
\text{min(MSy)} = 16.76
\]

Element ID, LC and Forces/Moments for Minimum Margin Cases

For each load case four margins of safety were determined for ultimate, shear, and yield. To display the minimum margin of safety for all load cases, the minimum margin of safety for each load case must be determined initially.

Place the minimum margin of safety for each load case in matrix MSu, MSsu, and MSy in each row of MSminu, MSminsu, and MSminy, respectively, forming a single column.

\[
\text{MSminu}_i := \min\left(\left(\text{MSu}^T\right)^\dagger\right)
\]
\[
\text{MSminsu}_i := \min\left(\left(\text{MSsu}^T\right)^\dagger\right)
\]
\[
\text{MSminy}_i := \min\left(\left(\text{MSy}^T\right)^\dagger\right)
\]

Create output file, Output2, of Element ID, Load Case, Forces and Moments corresponding to the minimum margins of safety.

\[
\text{Output2} := \text{augment} \left(\text{ID}, \text{LC}, \frac{\text{Fx}}{\text{lbf}}, \frac{\text{Fy}}{\text{lbf}}, \frac{\text{Fz}}{\text{lbf}}, \frac{\text{Mx}}{\text{in-lbf}}, \frac{\text{My}}{\text{in-lbf}}, \frac{\text{Mz}}{\text{in-lbf}}, \text{MSminu}, \text{MSminsu}, \text{MSminy}\right)
\]

Rearrange the rows of Output2 until the columns containing the margins of safety are in ascending order. Transpose the result and select the first column. Transposing the result a second time places the output in row order.

\[
\text{MS_min} := \text{augment} \left(\left(csort(Output2, 9)^T\right)^\dagger, \left(csort(Output2, 10)^T\right)^\dagger, \left(csort(Output2, 11)^T\right)^\dagger\right)^T
\]

5.5.1-33 ESCG-4005-05-AMS-0039
Identifying Element ID Number, Load Case Number, and Loads for Minimum Margins of Safety
Determined on Page 5.5.1-33.

\[
\begin{bmatrix}
\text{ID} & \text{LC} & \text{Fx} & \text{Fy} & \text{Fz} & \text{Mx} & \text{My} & \text{Mz} & \text{minu} & \text{minsu} & \text{miny} \\
9900 & 2048 & 98.753 & -115.072 & -551.52 & -732.713 & 8097.33 & -1820.659 & 12.05 & 15.75 & 16.763 \\
9900 & 2048 & 98.753 & -115.072 & -551.52 & -732.713 & 8097.33 & -1820.659 & 12.05 & 15.75 & 16.763 \\
9900 & 2048 & 98.753 & -115.072 & -551.52 & -732.713 & 8097.33 & -1820.659 & 12.05 & 15.75 & 16.763
\end{bmatrix}
\]

\[
\begin{align*}
\text{MS_min}\_\text{ID} & := \text{MS_min}^{1,1} \\
\text{MS_min}\_\text{LC} & := \text{MS_min}^{1,2} \\
\text{MS_min}\_\text{Fx} & := \text{MS_min}^{1,3} \\
\text{MS_min}\_\text{Fy} & := \text{MS_min}^{1,4} \\
\text{MS_min}\_\text{Fz} & := \text{MS_min}^{1,5} \\
\text{MS_min}\_\text{T} & := \text{MS_min}^{1,6} \\
\text{MS_min}\_\text{My} & := \text{MS_min}^{1,7} \\
\text{MS_min}\_\text{Mz} & := \text{MS_min}^{1,8}
\end{align*}
\]
### Summary

The following table depicts the analysis results.

<table>
<thead>
<tr>
<th>Part Name / Drawing No.</th>
<th>Material &amp; Heat Treatment</th>
<th>Distance From Clevis Flange(in.)</th>
<th>Margin of Safety, M.S.</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clevis SDG39137676</td>
<td>7050-T7451</td>
<td>2.5</td>
<td>6.88</td>
<td>5.5.1-8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>8.4</td>
<td>5.5.1-13,14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.51</td>
<td>6.64</td>
<td>5.5.1-19,20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.7</td>
<td>7.60</td>
<td>5.5.1-24,25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.71</td>
<td>11.22</td>
<td>5.5.1-29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.29</td>
<td>12.05</td>
<td>5.5.1-33</td>
</tr>
</tbody>
</table>

Based on the margins of safety in the above table, the critical cross section has a margin of safety of 6.64 ultimate and is located a distance of 4.51 inches from the clevis flange.
5.6 Intentionally Left Blank
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
<th>Date</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G. Reyes</td>
<td>07/20/08</td>
<td>Sec5-6.mcd</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Checked By</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Bala</td>
<td>AMS-02</td>
</tr>
</tbody>
</table>
5.7 Intentionally Left Blank
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<tr>
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<th>Name</th>
<th>Date</th>
<th>File Name</th>
<th>Checked By</th>
<th>Drawing No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G. Reyes</td>
<td>07/20/08</td>
<td>Sec5-7.mcd</td>
<td>C. Bala</td>
<td></td>
</tr>
</tbody>
</table>

**Title**

AMS-02

**Intentionally Left Blank**
5.8 Scuff Plate
Margins of Safety

Table 5.8-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135867</td>
<td>Scuff Plate, USS-02 Assembly</td>
<td>AL ALY 7050-T7451</td>
<td>Impact (Note 3)</td>
<td>Principal Stress</td>
<td>0.449 (u)</td>
<td>5.8-12</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield
2. $u = \text{ultimate}$
3. Critical load condition is impact, due to maximum contact velocity of 0.11 ft/sec (Ref. Appendix C14-1)

References:
1. Formulas for Stress, Strain, and Structural Matrices, by Walter D. Pilkey
Factors of Safety

The Scuff Plates are designed with a yield factor of 1.25 and an ultimate factor of 2.0 against the equivalent static load, as calculated on page 5.8-9 (see also Analysis Approach on page 5.8-8).

Description of Structure

Figure 5.8-1 below shows the locations of the Scuff Plates on USS-02 Assembly.
Figure 5.8-1: Location of Scuff Plates on USS-02 Assembly

Figure 5.8-2 below shows the configuration of the Scuff Plate.

Figure 5.8-2: Configuration of Scuff Plate
Description of Model

A FEM model was built of the Scuff Plate hardware using FEMAP.

1. The Scuff Plate was mainly modeled as CQUAD4 and CTRIA3 plate elements.
2. At the bolt holes, RBE2 rigid elements with DOF’s 1-6 are represented.
3. The model was then constrained with DOF’s 1-3 at six bolt location.
4. Eight load cases were applied. Each case included a 125-lb load distributed on several nodes. Critical locations were selected by engineering judgment.
5. MSC/NASTRAN v.2005 was used as a solver for analyzing the complete math model of the Scuff Plate. The static solution was run.

Figure 5.8-3 FEMAP Model of Scuff Plate
6. Plate stresses and SPC forces were recovered.

7. NASPOST was used to sort out the maximum of Principal, Von-Mises, and Shear stresses (see Appendix A18).

The Table below shows detail of model inputs.

**Table 5.8-2 – Inputs of Finite Element Model of Scuff Plates**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>ELEM #</th>
<th>TYPE</th>
<th>COLOR</th>
<th>PROP</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scuff Plate</td>
<td>11,001 - 17,304</td>
<td>plate</td>
<td>124</td>
<td>1</td>
<td>TK.37706 1 - 7050-T7451</td>
</tr>
<tr>
<td></td>
<td>10,001 - 10,084</td>
<td>@ RBE</td>
<td></td>
<td>1</td>
<td>TK.37706 1 - 7050-T7451</td>
</tr>
<tr>
<td></td>
<td>20,001 - 20,006</td>
<td>RBE</td>
<td>49</td>
<td></td>
<td>1 - 7050-T7451</td>
</tr>
<tr>
<td></td>
<td>20,101 - 20,258</td>
<td>bar</td>
<td>49</td>
<td>2</td>
<td>dummy</td>
</tr>
</tbody>
</table>

The 6 attachment bolts are modeled as SPC at nodes 10,001 to 10,006.

**Model Checks**

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.50000E-02  
DIRECTION STRAIN ENERGY PASS/FAIL  
------- -----------------  
1 5.106904E-08 PASS  
2 1.143951E-08 PASS  
3 1.467737E-08 PASS  
4 5.528508E-06 PASS  
5 1.375455E-06 PASS  
6 1.417476E-07 PASS
### USER INFORMATION MESSAGE 7570 (GPWG1D)

**RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:**

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.441881E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.582691E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.910115E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.450374E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.857942E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.417501E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

### USER INFORMATION MESSAGE 7570 (GPWG1D)

**RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:**

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<thead>
<tr>
<th>DIRECTION</th>
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<td>4.441881E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.582691E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.910115E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>5.450374E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.857942E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.417501E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

### USER INFORMATION MESSAGE 7570 (GPWG1D)

**RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET) FOLLOW:**

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<thead>
<tr>
<th>DIRECTION</th>
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<tbody>
<tr>
<td>1</td>
<td>4.441881E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.582691E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
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<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.857942E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.417501E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>
A further check is done for the rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 5.8-3: Eigenvalue Summary of Scuff Plate

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRATION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.43E-05</td>
<td>3.78E-03</td>
<td>6.02E-04</td>
<td>1.00E+00</td>
<td>-1.43E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.20E-05</td>
<td>3.47E-03</td>
<td>5.52E-04</td>
<td>1.00E+00</td>
<td>-1.20E-05</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-4.98E-06</td>
<td>2.23E-03</td>
<td>3.55E-04</td>
<td>1.00E+00</td>
<td>-4.98E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>-3.98E-06</td>
<td>1.99E-03</td>
<td>3.17E-04</td>
<td>1.00E+00</td>
<td>-3.98E-06</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>4.33E-06</td>
<td>2.08E-03</td>
<td>3.31E-04</td>
<td>1.00E+00</td>
<td>4.33E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1.14E-05</td>
<td>3.38E-03</td>
<td>5.38E-04</td>
<td>1.00E+00</td>
<td>1.14E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>9.08E+05</td>
<td>9.53E+02</td>
<td>1.52E+02</td>
<td>1.00E+00</td>
<td>9.08E+05</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1.09E+06</td>
<td>1.04E+03</td>
<td>1.66E+02</td>
<td>1.00E+00</td>
<td>1.09E+06</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>4.94E+06</td>
<td>2.22E+03</td>
<td>3.54E+02</td>
<td>1.00E+00</td>
<td>4.94E+06</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>5.78E+06</td>
<td>2.40E+03</td>
<td>3.83E+02</td>
<td>1.00E+00</td>
<td>5.78E+06</td>
</tr>
</tbody>
</table>

Material and Temperature

The Scuff Plates are made from 7050-T7451 Aluminum Alloy. Material properties are taken from Boeing Material Specification, BMS 7-323C, and MIL-HDBK-5H (see page 5.8-10). Temperature limits are -47°F to 150°F, as defined in Appendix C2.

Analysis Approach

The Scuff Plates are designed to withstand an impact associated with a payload mass of 15,000 lb, moving at a maximum contact velocity of 0.11 foot per second (see Appendix C14-1). The approach used to calculate the equivalent static loads and stresses is as per Ref. 1, pages 458 and 459.

Eight different critical impact locations are considered, which are selected by engineering judgment. In each case, a 125-lb load is applied distributed over several nodes. The recovered stresses are scaled by a factor proportional to the stiffness coefficients, as predicted by the FEM (see detail analysis starting on page 5.8-9).

The critical stresses for the Scuff Plate are compared to the ultimate and yield strength of 7050-T7451 Aluminum Alloy, corrected for the maximum temperature of 150°F. All Margins of Safety are positive.
DETAIL ANALYSIS

Load applied in FEMAP: \( F := 125 \text{ lbf} \)

Eight different load cases are considered selected by engineering judgment, as shown in the Figures:

- Case 1 - See Figure 5.8-4
- Case 5 - See Figure 5.8-8
- Case 2 - See Figure 5.8-5
- Case 6 - See Figure 5.8-9
- Case 3 - See Figure 5.8-6
- Case 7 - See Figure 5.8-10
- Case 4 - See Figure 5.8-7
- Case 8 - See Figure 5.8-11

Recovered displacements from FEM at the eight selected locations where the loads are applied - see Appendix A18, page 6:

\[
\beta := \begin{pmatrix}
0.03518277 \\
0.08391396 \\
0.05281544 \\
0.1182711 \\
0.003485398 \\
0.03611127 \\
0.005072352 \\
0.05173062
\end{pmatrix} \text{ in} \quad k := \frac{F}{\beta} \quad k = \begin{pmatrix}
3553 \\
1490 \\
2367 \\
1057 \\
35864 \\
3462 \\
24643 \\
2416
\end{pmatrix} \frac{\text{lbf}}{\text{in}}
\]

AMS mass: \( \text{mass} := 15000 \text{ lb} \)

Impact velocity: \( v := 0.11 \text{ ft/sec} \) See Appendix C14

Equivalent static loads:

\[
\text{Pequ} := \sqrt{k \cdot \text{mass} \cdot v^2} \quad \text{Pequ} = \begin{pmatrix}
490 \\
318 \\
400 \\
267 \\
1558 \\
484 \\
1292 \\
404
\end{pmatrix} \text{lbf}
\]

From Ref. 1, pages 458 & 459
Scale factors:

\[
\text{factor} := \frac{\text{P}_{\text{equ}}}{F}
\]

\[
\begin{bmatrix}
3.923341 \\
2.540411 \\
3.202142 \\
2.139842 \\
12.465075 \\
3.872574 \\
10.332761 \\
3.235543
\end{bmatrix}
\]

Material properties: 7050-T7451 Aluminum Alloy, BMS 7-323C, or AMS 4050

From Boeing Material Specification, BMS 7-323C, Table 1 & MIL-HDBK-5H, Table 3.7.3.0(b1) for thickness of 3.00 inch to 4.00 inch

\[\text{F}_{\text{tu}} := 68000\text{psi}\]

\[\text{F}_{\text{ty}} := 57000\text{psi}\]

\[\text{F}_{\text{su}} := 43000\text{psi}\]

\[\text{f}_{\text{tu}} := 0.91\]

\[\text{f}_{\text{ty}} := 0.97\]

Temperature correction factors for 150 deg F, from MIL-HDBK-5H, Figure 3.7.3.2.1

\[\text{F}_{\text{tu}} := \text{f}_{\text{tu}} \cdot \text{F}_{\text{tu}}\]

\[\text{F}_{\text{ty}} := \text{f}_{\text{ty}} \cdot \text{F}_{\text{ty}}\]

\[\text{F}_{\text{su}} := \text{f}_{\text{tu}} \cdot \text{F}_{\text{su}}\]

Factors of Safety:

\[\text{F}_{\text{Su}} := 2.0\]

\[\text{F}_{\text{Sy}} := 1.25\]

NASPOST results for the applied load of 125-lb (see Appendix A18):

\[
\begin{bmatrix}
2857.669 \\
7245.839 \\
3855.998 \\
8272.945 \\
532.4983 \\
5515.129 \\
731.6878 \\
6323.05
\end{bmatrix}
\]

\[
\begin{bmatrix}
2800.524 \\
6942.232 \\
3815.599 \\
7923.911 \\
483.2235 \\
5278.989 \\
705.6795 \\
6080.801
\end{bmatrix}
\]

\[
\begin{bmatrix}
1428.834 \\
3622.919 \\
1927.999 \\
4136.472 \\
266.2491 \\
2757.565 \\
365.8439 \\
3161.525
\end{bmatrix}
\]

\[i := 1..8\]
New stresses including the scale factors:

\[ \text{maxPrin}_i := \text{factor}_i \cdot \text{maxU}_i \]
\[ \text{maxPrin} = \begin{pmatrix} 11212 \\ 18407 \\ 12347 \\ 17703 \\ 6638 \\ 21358 \\ 7560 \\ 20459 \end{pmatrix} \text{ psi} \]

See Figures Pages 5.8-13 to 20

\[ \text{maxYield}_i := \text{factor}_i \cdot \text{maxY}_i \]
\[ \text{maxYield} = \begin{pmatrix} 10987 \\ 17636 \\ 12218 \\ 16956 \\ 6023 \\ 20443 \\ 7292 \\ 19675 \end{pmatrix} \text{ psi} \]

See Figures Pages 5.8-21 to 28

\[ \text{maxShear}_i := \text{factor}_i \cdot \text{maxS}_i \]
\[ \text{maxShear} = \begin{pmatrix} 5606 \\ 9204 \\ 6174 \\ 8851 \\ 3319 \\ 10679 \\ 3780 \\ 10229 \end{pmatrix} \text{ psi} \]

Margins of Safety:

\[ \text{MSu}_i := \frac{\text{Ptu}}{\text{FSu} \cdot \text{maxPrin}_i} - 1 \]
\[ \text{MSu} = \begin{pmatrix} 1.76 \\ 0.681 \\ 1.506 \\ 0.748 \\ 3.661 \\ 0.449 \\ 3.092 \\ 0.512 \end{pmatrix} \]
AMS-02 SCUFF PLATE

\[
\begin{align*}
MS_y_i & := \frac{F_{ty}}{F_{sy,maxYield,i}} - 1 \\
MS_y & = 3.026 \\
& \begin{cases}
1.508 \\
2.62 \\
1.609 \\
6.343 \\
1.164 \\
5.066 \\
1.248
\end{cases}
\end{align*}
\]

\[
\begin{align*}
MS_s_i & := \frac{F_{su}}{F_{su,maxShear,i}} - 1 \\
MS_s & = 2.49 \\
& \begin{cases}
1.126 \\
2.169 \\
1.21 \\
4.895 \\
0.832 \\
4.176 \\
0.913
\end{cases}
\end{align*}
\]

\[
\begin{align*}
MS_u & := \min(MS_u) \\
& MS_u = 0.449 \\
& \text{Ultimate - using principal - Load Case 6, Figure 5.8-9}
\end{align*}
\]

\[
\begin{align*}
MS_y & := \min(MS_y) \\
& MS_y = 1.164 \\
& \text{Yield - using Von-Mises - Load Case 6, Figure 5.8-9}
\end{align*}
\]

\[
\begin{align*}
MS_s & := \min(MS_s) \\
& MS_s = 0.832 \\
& \text{Shear - using shear - Load Case 6, Figure 5.8-9}
\end{align*}
\]
Output Set: LINEAR COMBINATION
Contour Plane Top Major Stress

Figure 5.8-5
Figure 5.8-14
5.9 EVA Connector Panel Assembly
Margins of Safety

Table 5.9-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEG39136085</td>
<td>EVA Connector Panel</td>
<td>AL ALY 6061-T651</td>
<td>Kickload</td>
<td>Ultimate</td>
<td>0.162 (u)</td>
<td>5.9-14</td>
</tr>
</tbody>
</table>

Table 5.9-2: Fasteners Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1351N3-10</td>
<td>Fasteners connecting Connector Panel Assembly to Lower USS-02 Tube Assembly</td>
<td>A286</td>
<td>Total Tension Yield</td>
<td>0.1 (y)</td>
<td>5.9-31</td>
</tr>
</tbody>
</table>

Table 5.9-3: Fail-Safe Fastener Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1351N3-10</td>
<td>Fasteners connecting Connector Panel Assembly to Lower USS-02 Tube Assembly</td>
<td>A286</td>
<td>Total Thread Shear Ultimate (Flange)</td>
<td>0.19 (u)</td>
<td>5.9-32</td>
</tr>
</tbody>
</table>

Notes:

1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Applied liftoff/landing loads and 125 lb kickload.
3. u = ultimate; y = yield
Factors of Safety

The hardware is designed with a yield factor of 1.25 and an ultimate factor of 2.0 against limit loads.

Description of Structure

Figure 5.9-1 below shows the locations of the EVA Connector Panel on the Lower USS-02. The panel is machined out of 6061-T651 Aluminum Alloy plate. The EVA Connector Panel bolts to the Lower USS-02.

![EVA Connector Panel](image)

**Figure 5.9-1 : Location of EVA Connector Panel on Lower USS-02**
*(Note: Figure does not show cover plates)*

Description of Model

A FE model was built for the EVA Connector Panel hardware using FEMAP.

1. The part was modeled as CQUAD4, CTRIA3, and CBAR elements.
2. The bolt holes are represented with SPC’s with DOF’s 1, 2, and 3.
MSC/NASTRAN v.2005 was used as a solver for analyzing the math model of the EVA Connector Panel. Stresses were recovered and sorted to find the maximum of Principal, Von-Mises, and Shear in the EVA Connector Panel. SPC forces were recovered at the bolt locations.

Table below shows detail of model inputs.

Table 5.9-4: Inputs of Finite Element Model of EVA Connector Panel

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NODE #</th>
<th>ELEM #</th>
<th>PROP</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA Connector Panel</td>
<td>4 – 36027</td>
<td>1 – 34352</td>
<td>1, 3-6</td>
<td>Al 6061-T651</td>
</tr>
</tbody>
</table>
Model Checks

Rigid body checks were performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>4.415551E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.130938E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.568448E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.886341E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.821504E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.460552E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
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<th>DIRECTION</th>
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<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.460552E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
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<th>PASS/FAIL</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.130938E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.568448E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.886341E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.821504E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.460552E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 1.000000E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4.415551E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.130938E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.568448E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.886341E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.821504E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.460552E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>
A further check is that of rigid body modes. The first 10 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 5.9-5: Eigenvalue Summary of EVA Connector Panel

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-2.169E-04</td>
<td>1.473E-02</td>
<td>2.344E-03</td>
<td>1.000E+00</td>
<td>-2.169E-04</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.946E-05</td>
<td>4.411E-03</td>
<td>7.021E-04</td>
<td>1.000E+00</td>
<td>-1.946E-05</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1.231E-05</td>
<td>3.508E-03</td>
<td>5.584E-04</td>
<td>1.000E+00</td>
<td>1.231E-05</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>6.259E-05</td>
<td>7.911E-03</td>
<td>1.259E-03</td>
<td>1.000E+00</td>
<td>6.259E-05</td>
</tr>
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Additionally, the mass of the FEM (.017483*g = 6.75 lb) matches closely the mass of the actual hardware (EVA Connector Panel without electrical components = 6.8 lb).

Material and Temperature

The EVA Connector Panel is made of 6061-T651 Aluminum Alloy. Material properties of 6061-T651 are taken from MMPDS-01. The temperature extremes for the EVA Connector Panel are -40°F to 175°F.

Analysis

The critical stresses for the EVA Connector Panel are compared to the ultimate and yield strength of 6061-T651 Aluminum Alloy. The EVA Connector Panel was analyzed for liftoff/landing loads and 125 lb kickloads. Analysis for the fasteners used to assemble the EVA Connector Panel and attach to the Lower USS-02 was also performed. All margins of safety are positive.
CHECK OF EVA CONNECTOR PANEL

Material Properties : 6061-T651 AL ALY  
(Ref. MMPDS-01, Table 3.6.2.0(b2))

\[
\begin{align*}
F_{tu} &:= 40000 \text{ psi} \\
F_{ty} &:= 35000 \text{ psi} \\
F_{su} &:= 27000 \text{ psi}
\end{align*}
\]

Factors of Safety, \(FS_u := 2.0\) \(FS_y := 1.25\)

Temperature reduction factors,

+ At 175°F: (For EVA Connector Panel, the temperature extremes are -40°F to 175°F; These temperature reduction factors are conservative for lift-off/landing conditions)

- Ultimate: \(\beta_{u1} := 0.93\)  
  (Ref. MMPDS-01, Figure 3.6.2.2.1(a))

- Yield: \(\beta_{y1} := 0.94\)  
  (Ref. MMPDS-01, Figure 3.6.2.2.1(b))

Allowable stresses:

\[
\begin{align*}
F_{tu1.a} &:= \beta_{u1} \cdot F_{tu} \\
F_{tu1.a} &= 37200 \text{ psi} \\
F_{ty1.a} &:= \beta_{y1} \cdot F_{ty} \\
F_{ty1.a} &= 32900 \text{ psi} \\
F_{su1.a} &:= \beta_{u1} \cdot F_{su} \\
F_{su1.a} &= 25110 \text{ psi}
\end{align*}
\]
NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the following elements located at the bolt holes were omitted from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.

<table>
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<th>Omitted Elements From NASPOST Sort for Kickload Analysis</th>
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The following figures show the location of the omitted elements.
Applying Simplified Design Loads from AMS-02 SVP (Table 4-4) for Liftoff and Landing Loads

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from 24 load cases. The launch/landing design limit load factors for small secondary structures were used in this analysis. Using Table 4-4 from document JSC 28792, a load factor of 40g was obtained (since the mass of the EVA connector panel is less than 20 lb). This load factor was applied in all three axis, with a load factor of 25% of the primary load applied to the remaining two orthogonal axes, simultaneously. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases.

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\[ \text{The principal stresses for elements listed above were omitted.} \]

\[ \text{u_{max} = 11793 \text{ psi}} \]

\( \text{LC# 1015, ELEM# 26574 (Maximum Principal Stress)} \)

(See Appendix A26, p.A26-9)
The Von-Mises stresses for elements 25522, 26558, 25525, 25523, 25524, 26888, 26717, 25518 and 26648 were omitted.

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</table>

\[ u_{uy,max} := 14202.15 \text{ psi} \] \( LC\# \ 1014, \ ELEM\# \ 26948 \) (Maximum Von-Mises Stress)
(See Appendix A26, p.A26-9)

The shear stresses for elements 25522, 26558, 25525, 25523, 25524, 26888, 26717, and 26648 were omitted.

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>MAX-SHEAR-TOP</th>
<th>MAX-SHEAR-BOT</th>
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</table>

\[ u_{us,max} := 7955.55 \text{ psi} \] \( LC\# \ 1015; \ ELEM\# \ 26560 \) (Maximum Shear Stress)
(see Appendix A26, p.A26-10)
Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{F_{S_u'u_{uu,max}}} - 1 \quad MS_{u1} = 0.577 \]

\[ MS_{y1} := \frac{F_{y1,a}}{F_{S_y'u_{uy,max}}} - 1 \quad MS_{y1} = 0.85 \]

\[ MS_{s1} := \frac{F_{s1,a}}{F_{S_u'u_{us,max}}} - 1 \quad MS_{s1} = 0.58 \]
Applying 125 lb Kickload

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from the 125 lb kickload cases. The kickload was applied at different locations of the EVA Connector Panel. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Node Where Load is Applied</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
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<tbody>
<tr>
<td>4001</td>
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</table>
The principal, Von-Mises, and shear stresses for elements 25522, 26558, 25525, 25523, 25524, and 26648 were omitted.

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>MAX-PRIN-TOP</th>
<th>MIN-PRIN-TOP</th>
<th>MAX-PRIN-BOT</th>
<th>MIN-PRIN-BOT</th>
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<tr>
<td>25522</td>
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</tbody>
</table>

$u_{uu1,max} := 16004.91$-psi

$LC# \ 4004, ELEM# \ 26560$ (Maximum Principal Stress)

(See Appendix A26, p.A26-22)

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>VON-MISES-TOP</th>
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<td>14719.56</td>
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</table>

$u_{uy1,max} := 14719.56$-psi

$LC# \ 4001, ELEM# \ 11691$ (Maximum Von-Mises Stress)

(See Appendix A26, p.A26-23)

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>MAX-SHEAR-TOP</th>
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<th>MAXABS-SHR</th>
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</table>

$u_{us1,max} := 8002.46$-psi

$LC# \ 4004; ELEM# \ 26560$ (Maximum Shear Stress)

(see Appendix A26, p.A26-24)

Margins of Safety,

$$MS_{u1} := \frac{F_{uu1,a}}{F_u u_{uu1,max}} - 1 \quad MS_{u1} = 0.162$$

$$MS_{y1} := \frac{F_{uy1,a}}{F_u u_{uy1,max}} - 1 \quad MS_{y1} = 0.79$$

$$MS_{s1} := \frac{F_{us1,a}}{F_u u_{us1,max}} - 1 \quad MS_{s1} = 0.57$$
Bolt Analysis

CHECK BOLTS (NAS8103U9 0.19"-32 x 0.56 L Material-A-286), Nut Plate: MS21076L3N, Washer NAS1149E0332R

There is a total of 4 fasteners attaching the end plate to the Connector Panel Assembly and the loads are shared equally between the 4 fasteners.

Area of plate $A := 39.701 \text{ in}^2$

Thickness of plate $t := 0.125 \text{ in}$

Volume of plate $v := A \cdot t = 4.963 \text{ in}^3$

Density of material 6061 $\beta := 0.098 \frac{\text{lbf}}{\text{in}^3}$

Weight of plate $w := v \cdot \beta = 0.486 \text{ lbf}$

Using 40 g in the axial direction and 10 g in the transverse directions

Total tension load $P_{tot} := 40 \cdot w = 19.453 \text{ lbf}$

Total shear load in the transverse directions $S1 := 10 \cdot w = 4.863 \text{ lbf}$

Resultant shear load $S_{tot} := \sqrt{S1^2 + S2^2}$

$S_{tot} = 6.878 \text{ lbf}$

Tension load per bolt $P := \frac{P_{tot}}{4} = 4.9 \text{ lbf}$

Shear load per bolt $V := \frac{S_{tot}}{4} = 1.7 \text{ lbf}$
AMS-02 EVA Connector Panel

CHECK BOLTS (NAS8103U9 0.19"-32 x 0.56 L Material-A-286), Nut Plate: MS21076L3N, Washer NAS1149E0332R

<table>
<thead>
<tr>
<th>Flange_1 := &quot;End Plate&quot;</th>
<th>Part number: SDG39136088</th>
<th>Material: Al Aly 6061-T651</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_2 := &quot;Connector Panel Assy&quot;</td>
<td>Part number: SDG39136086</td>
<td>Material: Al Aly 6061-T651</td>
</tr>
</tbody>
</table>

Minimum edge distance of flange one: edge1 := .287-in

flange two: edge2 := .547-in

Loads

- Applied tensile load \( P := 4.9 \text{lbf} \)
- Applied shear load \( V := 1.7 \text{lbf} \)
- Applied bending moment \( M := 0.0 \text{in-lbf} \)

Factors of Safety

- Ultimate \( SF_u := 2.0 \)
- Yield \( SF_y := 1.25 \)
- Joint Separation \( SF_{sep} := 1.2 \)
- Fitting factor \( FF := 1.15 \)

Temperature data

- Assembly \( Temp_{initial} := 70 \text{deg} \)
- Maximum \( Temp_{max} := 175 \text{deg} \)
- Minimum \( Temp_{min} := -40 \text{deg} \)

Bolt Data

- Nominal diameter of bolt \( D := .190 \text{in} \)
- Shank diameter of bolt \( D_{shank} := .190 \text{in} \)
- Total length of bolt \( L := 0.56 \text{in} \)
- Threaded length \( L_t := 0.56 \text{in} \)
- Bolt head dia. across flats \( d_w := 0.357 \text{in} \)
- Bolt head height \( b_h := .122 \text{in} \)

Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

If bolt is fully threaded, input \( L_t = L \)

(dia of pressure boss if it exists, otherwise dia of head)

(head height is 0 if bolt is flat head)

Note: Figure is for reference only, Not to scale, and actual joint made differ

Washer may be on nut side, head side, or both

Note, these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative
Thread data lookup table is hidden

This file uses the data shown in `\escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd`

Temperature correction factor for bolt strength ultimate:  \( TSu_{\text{bolt}} := 0.97 \)  
Yield  \( TSy_{\text{bolt}} := 0.97 \)  
Bolt ultimate tensile allowable stress ultimate:  \( Ftu_{\text{bolt}} := 160000 \text{ psi} \)  
Yield  \( Fty_{\text{bolt}} := 120000 \text{ psi} \)  
Bolt ultimate shear allowable stress  \( Fsu_{\text{bolt}} := 0.6 \times Ftu_{\text{bolt}} \) 

Temperature correction factor for bolt modulus  \( TE_{\text{bolt}} := 0.98 \)  
Modulus of elasticity of bolt  \( E_{\text{bolt}} := (29.1 \times 10^6 \text{ psi}) \%\)

Thermal coefficients for bolt  
\[
\begin{align*}
&u_{\text{bolt\_hot}} := 9.15 \times 10^{-6} \frac{\text{in}}{\text{in \ deg}} \\
&u_{\text{bolt\_cold}} := 8.7 \times 10^{-6} \frac{\text{in}}{\text{in \ deg}}
\end{align*}
\]

Washer Data

Thickness of washers: head  \( twh := 0.032 \text{ in} \)  
these are total washer thickness, if there are more than one  
nut  \( twn := 0.0 \text{ in} \)  

Diameter of washer under head, Outer:  \( Dwoh := 0.438 \text{ in} \)  
Inner:  \( Dwih := 0.203 \text{ in} \)  

Diameter of washer under nut, Outer:  \( Dwon := 0.0 \text{ in} \)  
Inner:  \( Dwin := 0.0 \text{ in} \)  

\textbf{Note: If there are no washer tw's, Dw's and Dwi's should be zero}

Modulus of elasticity, head:  \( E_{\text{washerh}} := (29.1 \times 10^6 \text{ psi}) \%\)  
Temperature correction factor for modulus, head:  \( TE_{\text{washerh}} := 0.98 \)  

Modulus of elasticity, nut:  \( E_{\text{washern}} := (29.1 \times 10^6 \text{ psi}) \%\)  
Temperature correction factor for modulus, nut:  \( TE_{\text{washern}} := 0.0 \)

Nut Data

Height of nut  \( H := 0.25 \text{ in} \)  
Nut dia. across flats  \( Dn := 0.29 \text{ in} \)  

Temperature correction factor for nut strength  \( TS_{\text{nut}} := 0.97 \)  

Ultimate allowable stress, tensile:  \( Ftu_{\text{nut}} := 125000 \text{ psi} \)  
Shear:  \( Fsu_{\text{nut}} := 0.6 \times Ftu_{\text{nut}} \)  

Ultimate axial strength of nut  \( Ptu_{\text{nut}} := 2460 \text{ lbf} \)  
\textit{(Reference MS21076)}
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

Thickness of flange 1: \( t_{f1} := .125 \text{ in} \)  
flange 2: \( t_{f2} := .125 \text{ in} \)

Diameter of thru hole \( D_{\text{hole}} := 0.240 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint

\[ E_{\text{flange}1} := (10.1 \times 10^6 \text{ psi}) \]  
\[ E_{\text{flange}2} := (10.1 \times 10^6 \text{ psi}) \]

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.99 \)  
flange 2: \( T_{f2E} := 0.99 \)

Coefficient of thermal expansion for flanges

\[ u_{\text{flange}1\_hot} := 12.9 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]  
\[ u_{\text{flange}2\_hot} := 12.9 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

\[ u_{\text{flange}1\_cold} := 12.25 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]  
\[ u_{\text{flange}2\_cold} := 12.25 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data

Maximum torque \( T_{\text{max}} := 41 \text{ in-lbf} \)
Minimum torque \( T_{\text{min}} := 34 \text{ in-lbf} \)

Joint is lubed/dry Preload Uncertainty \( \leq 0.25 \)
Torque coefficient \( k := 0.15 \)

Stiffness and Margin calculations are hidden

\[ \text{This file uses the calculations shown in } \text{ Escfi02\2111\mathcad\8307\bolts\Rev_D\bolt\stiffness\nut.mcd} \]

Bolt Load data

Bolt/joint stiffness factor \( \nu = 0.332 \)  
Preload due to temperature \( P_{\text{thr\_pos}} = 80.5 \text{ lbf} \)  
\( P_{\text{thr\_neg}} = -79.869 \text{ lbf} \)
Max. preload \( P_{\text{LDMax}} = 1879 \text{ lbf} \)
Min. preload \( P_{\text{LDMin}} = 725 \text{ lbf} \)
Nom. preload \( P_{\text{LDMnom}} = 1439 \text{ lbf} \)
Preload to yield ratio(nom.) \( P_{\text{LDratio}} = 0.642 \)
Preload due to temperature \( P_{\text{thr\_pos}} = 80.5 \text{ lbf} \)  
\( P_{\text{thr\_neg}} = -79.869 \text{ lbf} \)
Max. preload \( P_{\text{LDMax}} = 1879 \text{ lbf} \)
Min. preload \( P_{\text{LDMin}} = 725 \text{ lbf} \)
Nom. preload \( P_{\text{LDMnom}} = 1439 \text{ lbf} \)
Preload to yield ratio(nom.) \( P_{\text{LDratio}} = 0.642 \)
Joint separation load \( P_{\text{sep}} = 5.88 \text{ lbf} \)
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Component</th>
<th>Calculation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 4.9 \text{lbf}$</td>
<td>$Pb = 1881 \text{lbf}$ (ultimate)</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 1.7 \text{lbf}$</td>
<td>$Pby = 1880 \text{lbf}$ (yield)</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0 \text{in-lbf}$</td>
<td>$Pbapp = 1880 \text{lbf}$ (without factor of safety)</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$PA_{t} = 2987 \text{lbf}$</td>
<td>$VA_{u} = 1633 \text{lbf}$</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>$PA_{s} = 2386 \text{lbf}$</td>
<td>$MA_{u} = 62 \text{in-lbf}$</td>
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<tr>
<td>Nut ultimate tensile strength</td>
<td>$P_{tu_nut} = 2386 \text{lbf}$</td>
<td></td>
</tr>
</tbody>
</table>

General Checks

- `length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"`
- `cone_check = "Joint pressure cone does not extend pass flange edge"`
- `preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"`
- `washer_check = "Washers under head and nut do not extend past flanges"`

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_{1} = 127.53$</td>
<td>Direct Thread shear Ultimate $MS_{6} = 210.73$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_{2} = 264.08$</td>
<td>Total Thread shear Ultimate $MS_{7} = 0.27$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_{3} = 317.09$</td>
<td>Shear Ultimate $MS_{8} = 416.53$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_{4} = 0.59$</td>
<td>Bending Ultimate $MS_{9} = 100$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_{5} = 0.19$</td>
<td>Combined shear, tension and bending ultimate $MS_{10} = 0.59$</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} = 0.19$  Failure Mode = "Total Tension Yield"
Fail-safe Analysis

**Fail-safe Loads**
- Applied tensile load: $P_{FS} := 9.8 \text{ lbf}$
- Applied shear load: $V_{FS} := 3.4 \text{ lbf}$
- Applied bending moment: $M_{FS} := 0.0 \text{ in-lbf}$

**Fail-safe Factors of Safety**
- Ultimate: $SF_{u,FS} := 1.0$
- Joint Separation: $SF_{sep,FS} := 1.0$

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd`

**Bolt Fail-safe Load data**
- Joint separation load: $P_{sep,FS} = 9.8 \text{ lbf}$
- Max. load on the bolt (ultimate): $P_{b,FS} = 1880.6 \text{ lbf}$

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Margin Value</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_{FS} = 76.12$</td>
<td>Total Thread shear Ultimate $MS_{FS} = 0.27$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_{FS} = 264.08$</td>
<td>Shear Ultimate $MS_{FS} = 416.53$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_{FS} = 0.59$</td>
<td>Bending Ultimate $MS_{FS} = 10$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$MS_{FS} = 210.73$</td>
<td>Combined shear, tension and bending ultimate $MS_{FS} = 0.59$</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

$MS_{bolt,FS} = 0.27$  
Failure Mode $FS = \text{"Total Thread Shear Ultimate (Nut)"}$
There is a total of 4 fasteners attaching the connector plate to the Connector Panel Assembly and the loads are shared equally by the 4 fasteners.

Area of plate \( A := 61.79 \text{ in}^2 \)

Thickness of plate \( t := 0.087 \text{ in} \)

Volume of plate \( v := A \times t = 5.376 \text{ in}^3 \)

Density of material 6061 \( \beta := 0.098 \frac{\text{lb}}{\text{in}^3} \)

Weight of plate \( w := v \times \beta = 0.527 \text{ lb} \)

Using 40 g in the axial direction and 10 g in the transverse direction

Total tension load \( P_{\text{tot}} := 40 \times w = 21.073 \text{ lb} \)

Toal shear load in the transverse directions \( S1 := 10 \times w = 5.268 \text{ lb} \quad S2 := S1 \)

Resultant shear load \( S_{\text{tot}} := \sqrt{(S1)^2 + (S2)^2} = 7.45 \text{ lb} \)

Tension load per bolt \( P := \frac{P_{\text{tot}}}{4} = 5.3 \text{ lb} \)

Shear load per bolt \( V := \frac{S_{\text{tot}}}{4} = 1.9 \text{ lb} \)
CHECK BOLTS (NAS8103U9 0.19"-32 x 0.50 L Material-A-286), Insert MS51830CA201L, Washer NAS1149E0332R

Flange_1 := "Connector Plate"
Part number: SDG39136087
Material: Al Aly 6061-T651

Flange_2 := "Connector Panel Assy"
Part number: SDG39136086
Material: Al Aly 6061-T651

Minimum edge distance of flange one: edge1 := .312-in
flange two: edge2 := .312-in

Loads
Applied tensile load  \( P := 5.3 \text{lbf} \)
Applied shear load  \( V := 1.9 \text{lbf} \)
Applied bending moment  \( M := 0.0 \text{in-lbf} \)

Factors of Safety
Ultimate  \( SF_u := 2.0 \)
Yield  \( SF_y := 1.25 \)
Joint Separation  \( SF_{sep} := 1.2 \)
Fitting factor  \( FF := 1.15 \)

Temperature data
Assembly  \( Temp_{initial} := 70 \text{-deg} \)
Maximum  \( Temp_{max} := 175 \text{-deg} \)
Minimum  \( Temp_{min} := -40 \text{-deg} \)

Bolt Data
Nominal diameter of bolt  \( D := .190 \text{-in} \)
Number of threads/inch  \( N_t := 32 \frac{1}{\text{in}} \)
Shank diameter of bolt  \( D_{shank} := .190 \text{-in} \)
Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area
Total length of bolt  \( L := 0.56 \text{-in} \)
Threaded length  \( L_t := 0.56 \text{-in} \)
(If bolt is fully threaded, input \( L_t = L \))
Bolt head dia. across flats  \( d_w := 0.357 \text{-in} \)
(dia of pressure boss if it exists, otherwise dia of head)
Bolt head height  \( b_h := .122 \text{-in} \)
(head height is 0 if bolt is flat head)
Thread data lookup table is hidden

This file uses the data shown in \\escf\i02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength ultimate. \( TS_u_{\text{bolt}} := 0.97 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{tu_{\text{bolt}}} := 160000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 \times F_{tu_{\text{bolt}}} \)

Temperature correction factor for bolt modulus \( TE_{\text{bolt}} := 0.98 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left( 29.1 \times 10^6 \text{ psi} \right) \)

Thermal coefficients for bolt

\[
\begin{align*}
    u_{\text{bolt}}_{\text{hot}} & := 9.15 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \\
    u_{\text{bolt}}_{\text{cold}} & := 8.7 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}}
\end{align*}
\]

Washer Data

Thickness of washers: \( t_{wh} := 0.032 \text{ in} \)

Diameter of washer under head, Outer: \( D_{woh} := 0.438 \text{ in} \)

Diameter of washer under head, Inner: \( D_{wi} := 0.203 \text{ in} \)

Note: If there are no washer tw's, Dw's and Dw'i's should be zero

Modulus of elasticity: \( E_{\text{washerh}} := \left( 29.1 \times 10^6 \text{ psi} \right) \)

Temperature correction factor for modulus, \( TE_{\text{washerh}} := 0.98 \)

Insert Data

Length of insert \( L_{ins} := 0.312 \text{ in} \)

Min. external diameter of insert \( F_{min} := 0.312 \text{ in} \)

Depth of recess for insert \( l_{r} := 0.01 \text{ in} \)

Temperature correction factor for insert strength \( TS_{\text{ins}} := 0.98 \)

Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} := 140000 \text{ psi} \)

Ultimate shear allowable stress \( F_{su_{\text{ins}}} := 0.6 \times F_{tu_{\text{ins}}} \)
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

Thickness of flange 1: $t_{f1} := 0.087\text{ in}$  
flange 2: $t_{f2} := 0.312\text{ in}$  
Diameter of thru hole $D_{\text{hole}} := 0.240\text{ in}$

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint

$E_{\text{flange}1} := (10.1 \cdot 10^6 \text{ psi})$  
$E_{\text{flange}2} := (10.1 \cdot 10^6 \text{ psi})$

Temperature correction factor (modulus) for flange 1: $T_{f1E} := 0.99$  
flange 2: $T_{f2E} := 0.99$

Coefficient of thermal expansion for flanges

$u_{\text{flange}_1\_\text{hot}} := 12.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$  
$u_{\text{flange}_1\_\text{cold}} := 12.25 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$  
$u_{\text{flange}_2\_\text{hot}} := 12.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$  
$u_{\text{flange}_2\_\text{cold}} := 12.25 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$

Shear strength of flange two, with temperature reduction

$F_{su\_f2} := 27000 \text{ psi}$  
$T_{f2s} := 0.99$

Torque/Preload data

Maximum torque $T_{\text{max}} := 41\text{-in-lbf}$  
Minimum torque $T_{\text{min}} := 34\text{-in-lbf}$

Joint is lubed/dry

Preload Uncertainty $:= 0.25$  
Torque coefficient $k := 0.15$  
Loading plane factor $n := 0.5$

Stiffness and Margin calculations are hidden

Bolt Load data

Bolt/joint stiffness factor $= = 0.358$  
Preload due to temperature $P_{\text{thr\_pos}} = 169.5\text{lbf}$

Max. preload $PLD_{\text{max}} = 1968\text{lbf}$  
Min. preload $PLD_{\text{min}} = 637\text{lbf}$

Nom. preload $PLD_{\text{nom}} = 1439\text{lbf}$

Preload to yield ratio(nom.) $PLD_{\text{ratio}} = 0.642$

Joint separation load $P_{\text{sep}} = 6.36\text{lbf}$  
Uncertainty factor $= 0.25$

Torque coefficient $k = 0.15$  
Loading plane factor $n = 0.5$
Bolt Load data (cont.)

Applied Tensile load on the bolt: $P = 5.3 \text{ lbf}$

Max. load on the bolt with preload and Factor of safety:
- (ultimate) $P_b = 1970 \text{ lbf}$
- (yield) $P_{by} = 1969 \text{ lbf}$

Applied shear on the bolt: $V = 1.9 \text{ lbf}$

Max. load on the bolt with preload without factor of safety: $P_{bapp} = 1969 \text{ lbf}$

Applied bending on the bolt: $M = 0 \text{ in-lbf}$

Bolt ultimate tensile strength: $P_{At} = 2987 \text{ lbf}$

Bolt shear strength: $V_{Au} = 1633 \text{ lbf}$

Thread pullout strength: $P_{As} = 4087 \text{ lbf}$

Bolt bending strength: $M_{Au} = 62 \text{ in-lbf}$

General Checks
- length_check = "Bolt length is sufficient and insert fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washer(s) under head do not extend past flange"
- insert_check = "Flange two is thick enough for insert"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>$MS_1$</th>
<th>$MS_2$</th>
<th>$MS_3$</th>
<th>$MS_4$</th>
<th>$MS_5$</th>
<th>$MS_6$</th>
<th>$MS_7$</th>
<th>$MS_8$</th>
<th>$MS_9$</th>
<th>$MS_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>105.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>334.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>244.07</td>
<td></td>
<td></td>
<td>0.52</td>
<td>0.14</td>
<td></td>
<td>1.07</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>293.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>372.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.52</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

$MS_{b} = 0.14$  \hspace{1cm} Failure Mode = "Total Tension Yield"
 Fail-safe Analysis

**Fail-safe Loads**
- Applied tensile load: \( P_{FS} := 10.6 \text{ lbf} \)
- Applied shear load: \( V_{FS} := 3.8 \text{ lbf} \)
- Applied bending moment: \( M_{FS} := 0.0 \text{ in-lbf} \)

**Fail-safe Factors of Safety**
- Ultimate: \( SF_{UL} := 1.0 \)
- Joint Separation: \( SF_{SEP} := 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

**Bolt Fail-safe Load data**
- Joint separation load: \( P_{SEP} = 10.6 \text{ lbf} \)
- Max. load on the bolt (ultimate): \( P_{BOL} = 1970 \text{ lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{FS1} = 62.63 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{FS2} = 244.07 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{FS3} = 0.52 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{FS4} = 334.29 )</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{BOLT_{FS}} = 0.52 \]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"
CHECK BOLTS (NAS1351N3-10 0.19"-32 x 0.625 L Material-A-286), Insert MS21209F1-10L, Washer NAS1149E0332R

There is a total of 8 fasteners attaching the EVA Connector Panel to the Lower USS-02 beam.

**Loads** : Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

loads := READPRN("boltload3.txt")

\[
i := 1, \text{rows}(\text{loads}) = 248 \quad j := 2, \text{cols}(\text{loads}) = 10
\]

ID := \text{loads}\langle 1 \rangle \quad Fx := \text{loads}\langle 3 \rangle \cdot \text{lbf} \quad Fz := \text{loads}\langle 5 \rangle \cdot \text{lbf} \quad My := \text{loads}\langle 7 \rangle \cdot \text{in-lbf}

LC := \text{loads}\langle 2 \rangle \quad Fy := \text{loads}\langle 4 \rangle \cdot \text{lbf} \quad Mx := \text{loads}\langle 6 \rangle \cdot \text{in-lbf} \quad Mz := \text{loads}\langle 8 \rangle \cdot \text{in-lbf}

* Note that "boltload3.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
F_t_i := \left| F_z_i \right| \quad \text{max}(F_t) = 323.43 \text{lbf} \quad \text{Tensile Load}
\]

\[
F_v_i := \sqrt{(Fx_i)^2 + (Fy_i)^2} \quad \text{max}(F_v) = 68.5 \text{lbf} \quad \text{Shear Load}
\]
CHECK BOLTS (NAS1351N3-10 0.19"-32 x 0.625 L Material-A-286), Insert MS21209F1-10L, Washer NAS1149E0332R

Flange_1 := "CONNECTOR PANEL ASSEMBLY"
Part number: SDG39136086
Material: Al Aly 6061-T651

Minimum edge distance of flange one:  edge1 := .625-in
flange two: edge2 := 1.0-in

Loads
Applied tensile load P := 323.43lbf
Applied shear load V := 68.5lbf
Applied bending moment M := 0.0 in-lbf

Factors of Safety
Ultimate SFu := 2.0
Yield SFy := 1.25
Joint Separation SFsep := 1.2
Fitting factor FF := 1.15

Temperature data
Assembly Temp_initial := 70-deg
Maximum Temp_max := 175-deg
Minimum Temp_min := -40deg

Bolt Data
Nominal diameter of bolt D := .190-in
Number of threads/inch Nt := 32 \frac{1}{in}
Shank diameter of bolt D_shank := .184-in
Total length of bolt L := 0.625-in
Threaded length Lt := 0.625-in (If bolt is fully threaded, input Lt = L)
Bolt head dia. across flats dw := 0.303-in (dia of pressure boss if it exists, otherwise dia of head)
Bolt head height bh := .185-in (head height is 0 if bolt is flat head)

Note: Figure is for reference only.
Not to scale, and actual joint may differ
There may or may not be a washer(s)

note, these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative
Temperature correction factor for bolt strength ultimate.

\[
TSu_{\text{bolt}} := 0.97 \\
Yield \\
TSy_{\text{bolt}} := 0.97
\]

Bolt ultimate tensile allowable stress ultimate:

\[
Ftu_{\text{bolt}} := 160000 \text{ psi} \\
Yield \\
Fty_{\text{bolt}} := 120000 \text{ psi}
\]

Bolt ultimate shear allowable stress

\[
Fsu_{\text{bolt}} := 0.6 \times Ftu_{\text{bolt}}
\]

Temperature correction factor for bolt modulus

\[
TE_{\text{bolt}} := 0.98
\]

Modulus of elasticity of bolt

\[
E_{\text{bolt}} := (29.1 \times 10^6 \text{ psi})
\]

Thermal coefficients for bolt

\[
\beta_{\text{bolt}_{-\text{hot}}} := 8.7 \times 10^{-6} \text{ in}^{-1} \text{ in}^{-1} \text{ deg} \\
\beta_{\text{bolt}_{-\text{cold}}} := 9.15 \times 10^{-6} \text{ in}^{-1} \text{ in}^{-1} \text{ deg}
\]

**Washer Data**

Thickness of washers: \( twh := 0.032 \text{ in} \) this is total washer thickness, if there are more than one

Diameter of washer under head, Outer: \( Dwo_{\text{h}} := 0.438 \text{ in} \) Inner: \( Dw_{\text{i}} := 0.203 \text{ in} \)

Note: If there are no washer tw's, Dw's and Dw_i's should be zero

Modulus of elasticity:

\[
E_{\text{washes}} := (29.1 \times 10^6 \text{ psi})
\]

Temperature correction factor for modulus,

\[
TE_{\text{washes}} := 0.98
\]

**Insert Data**

Length of insert

\[
L_{\text{ins}} := 0.190 \text{ in}
\]

Min. external diameter of insert

\[
F_{\text{min}} := 0.236 \text{ in}
\]

Depth of recess for insert

\[
Lr := 0.01 \text{ in}
\]

Temperature correction factor for insert strength

\[
TS_{\text{ins}} := 0.97
\]

Ultimate tensile allowable stress

\[
Ftu_{\text{ins}} := 150000 \text{ psi}
\]

Ultimate shear allowable stress

\[
Fsu_{\text{ins}} := 0.6 \times Ftu_{\text{ins}}
\]
**Flange data**

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

- Thickness of flange 1: \( t_{f1} := .1875 \text{ in} \)  
- Flange 2: \( t_{f2} := .25 \text{ in} \)  
- Diameter of thru hole \( D_{hole} := .236 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors

- Compressive Modulus of elasticity for the parts in the joint \( E_{flange1} := \left(10.1 \cdot 10^6 \text{ psi}\right) \)  
- \( E_{flange2} := \left(10.7 \cdot 10^6 \text{ psi}\right) \)

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.99 \)  
- Flange 2: \( T_{f2E} := 0.98 \)

Coefficient of thermal expansion for flanges

- \( \beta_{flange1\_hot} := 12.9 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)  
- \( \beta_{flange2\_hot} := 12.65 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

- \( \beta_{flange1\_cold} := 12.25 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)  
- \( \beta_{flange2\_cold} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

Shear strength of flange two, with temperature reduction \( F_{su\_f2} := 37000 \text{ psi} \)  
- \( T_{f2s} := 0.98 \)

**Torque/Preload data**

- Maximum torque \( T_{max} := 41 \text{ in-lbf} \)  
- \( (\text{Reference dwg.SGG39135872}) \)

- Minimum torque \( T_{min} := 34 \text{ in-lbf} \)

- Joint is lubed/dry

- Preload Uncertainty \( u := 0.25 \)

- Torque coefficient \( k := 0.15 \)

- Loading plane factor \( n := 0.5 \)

**Stiffness and Margin calculations are hidden**

This file uses calculations shown in \\( \text{escfl02\i11\_mathcad\8307\_bolts\Rev_D\bolt\_insert\_stiffness.mcd} \)

**Bolt Load data**

- Bolt/joint stiffness factor \( = 0.845 \)

- Preload due to temperature
  - \( P_{thr\_pos} = 40.5 \text{ lbf} \)
  - \( P_{thr\_neg} = -31.5 \text{ lbf} \)

- Max. preload \( P_{LDMax} = 1839 \text{ lbf} \)

- Min. preload \( P_{LDMin} = 773 \text{ lbf} \)

- Nom. preload \( P_{LDMnom} = 1439 \text{ lbf} \)

- Preload to yield ratio(nom.) \( P_{LDRatio} = 0.642 \)

- Joint separation load \( P_{sep} = 388.116 \text{ lbf} \)

5.9-30  
ESCG-4005-05-AMS-0039
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>( P = 323.43 \text{lbf} )</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety (ultimate)</td>
<td>( P_b = 2153 \text{lbf} )</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>( V = 68.5 \text{lbf} )</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety (yield)</td>
<td>( P_{by} = 2035 \text{lbf} )</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>( M = 0 \text{in-lbf} )</td>
</tr>
<tr>
<td>Max. load on the bolt with preload without factor of safety</td>
<td>( P_{bapp} = 1996 \text{lbf} )</td>
</tr>
</tbody>
</table>

**Bolt ultimate tensile strength**

- \( P_{At} = 2987 \text{lbf} \)
- \( V_{Au} = 1633 \text{lbf} \)
- \( M_{Au} = 62 \text{in-lbf} \)

**Thread pullout strength**

- \( P_{As} = 2554 \text{lbf} \)

**General Checks**

- length_check = "Bolt length is sufficient and insert fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washer(s) under head do not extend past flange"
- insert_check = "Flange two is thick enough for insert"

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Minimum Margin Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_1 = 2 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_2 = 3.02 )</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>( MS_3 = 3.82 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_4 = 0.39 )</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>( MS_5 = 0.1 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_6 = 2.43 )</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( MS_7 = 0.19 )</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>( MS_8 = 9.36 )</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( MS_9 = 100 )</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>( MS_{10} = 0.39 )</td>
</tr>
</tbody>
</table>

**Smallest margin of safety for the bolt, and the failure mode:**

- \( MS_{bolt} = 0.1 \)
- Failure_Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

Fail-safe Analysis

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Applied load type</th>
<th>Load Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P_{FS} := 646.86-lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V_{FS} := 137.0-lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_{FS} := 0.0-in-lbf</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Safety Factor Type</th>
<th>Factor Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu_{FS} := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep_{FS} := 1.0</td>
</tr>
</tbody>
</table>

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file calculations shown in \escf02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness__FS.mcd

Bolt Fail-safe Load data

<table>
<thead>
<tr>
<th>Load type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation load</td>
<td>P_{sep_{FS}} = 646.86 lbf</td>
</tr>
<tr>
<td>Maximum load on the bol (ultimate)</td>
<td>P_{b_{FS}} = 2153 lbf</td>
</tr>
</tbody>
</table>

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Factor Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{FS_1} = 0.8</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{FS_2} = 3.02</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{FS_3} = 0.39</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{FS_4} = 2.43</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS_{FS_5} = 0.19</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS_{FS_6} = 9.36</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS_{FS_7} = 10</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_{FS_8} = 0.39</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MSbolt_{FS} = 0.19  
Failure Mode_{FS} = "Total Thread Shear Ultimate (Flange)"
5.10 Debris Shield Analysis
Section 5.10 Debris Shield Analysis

The Debris Shield Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>5.10.1</th>
<th>Port Debris Shield Assembly (SEG39137851)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.10.1.1</td>
<td>Port Debris Shield Assembly Bolt Analysis</td>
</tr>
<tr>
<td>5.10.2</td>
<td>Starboard Debris Shield Assembly (SEG39137852)</td>
</tr>
<tr>
<td>5.10.2.1</td>
<td>Starboard Debris Shield Assembly Bolt Analysis</td>
</tr>
<tr>
<td>5.10.3</td>
<td>TRD Gas Ballistic Cover Assembly (SEG39137915)</td>
</tr>
<tr>
<td>5.10.3.1</td>
<td>TRD Gas Ballistic Cover Assembly Bolt Analysis</td>
</tr>
</tbody>
</table>
5.10.1 Port Debris Shield Assembly
### 5.10.1.1 General

**Minimum Margins of Safety**

#### Table 5.10.1.1 Parts Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137847-001</td>
<td>Debris Shield Interface Joint Bracket</td>
<td>AL ALY</td>
<td>Lift Off</td>
<td>Tensile Ultimate</td>
<td>0.008</td>
<td>5.10.1-35</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Debris Shield Mounting Brackets</td>
<td>AL ALY</td>
<td>Lift Off</td>
<td>Tensile Ultimate</td>
<td>0.29</td>
<td>5.10.1-31</td>
</tr>
<tr>
<td>SDG39137849-001</td>
<td>Debris Shield Corner Bracket</td>
<td>AL ALY</td>
<td>Lift Off</td>
<td>Tensile Ultimate</td>
<td>0.75</td>
<td>5.10.1-27</td>
</tr>
<tr>
<td>SDG39137853-001</td>
<td>Port External Bumper Assy</td>
<td>AL ALY</td>
<td>Landing</td>
<td>Tensile Ultimate</td>
<td>0.07</td>
<td>5.10.1-20</td>
</tr>
<tr>
<td>SDG39137858-001</td>
<td>Debris Shield Inner Plate</td>
<td>AL ALY</td>
<td>Lift Off</td>
<td>Tensile Ultimate</td>
<td>0.81</td>
<td>5.10.1-23</td>
</tr>
</tbody>
</table>

#### Table 5.10.1.2 Fastener Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Fastener</th>
<th>Material</th>
<th>MS_{nominal}</th>
<th>Failure Mode</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Lower Vacuum Case</td>
<td>NAS1008-8</td>
<td>A286</td>
<td>.24</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-6</td>
</tr>
<tr>
<td>SDG39135727</td>
<td>Interface Joint to Upper Vacuum Case</td>
<td>NAS1008-8</td>
<td>A286</td>
<td>.23</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-14</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Mounting Bracket to Lower Trunnion Bridge Beam</td>
<td>NAS1351N4-12</td>
<td>A286</td>
<td>.14</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-22</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Mounting Bracket to Sill Joint</td>
<td>NAS1351N4-20</td>
<td>A286</td>
<td>.13</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-30</td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td>External Bumper to Interface Joint</td>
<td>NAS1133E4</td>
<td>A286</td>
<td>.10</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-38</td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4</td>
<td>A286</td>
<td>.10</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-46</td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4</td>
<td>A286</td>
<td>.10</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-54</td>
</tr>
<tr>
<td>SDG39137855-001</td>
<td>Inner Plate to Standoff B</td>
<td>NAS1004-1</td>
<td>A286</td>
<td>.10</td>
<td>Total Tension Yield</td>
<td>5.10.1.1-62</td>
</tr>
<tr>
<td>SDG39137855-001</td>
<td>External Bumper to Standoff B</td>
<td>NAS1004-40</td>
<td>A286</td>
<td>.09</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.1.1-69</td>
</tr>
<tr>
<td>SDG39137849</td>
<td>Corner Bracket to External Bumper</td>
<td>NAS1398DFC4-3</td>
<td>A286</td>
<td>1.97</td>
<td>Tensile Ultimate</td>
<td>5.10.1.1-72</td>
</tr>
</tbody>
</table>

---

5.10.1-2

ESCG-4005-05-AMS-0039
# Table 5.10.1.3 Fastener Fail-Safe Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Fastener</th>
<th>Material</th>
<th>( MS_{\text{fail-safe}} )</th>
<th>Failure Mode</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Lower Vacuum Case</td>
<td>NAS1008-8 .5000-20</td>
<td>A286</td>
<td>.82</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.1.1-7</td>
</tr>
<tr>
<td>SDG39135737</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Upper Vacuum Case</td>
<td>NAS1008-8 .5000-20</td>
<td>A286</td>
<td>.82</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.1.1-15</td>
</tr>
<tr>
<td>SDG39135727</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Mounting Bracket to Lower Trunnion Bridge Beam</td>
<td>NAS1351N4-12 .2500-28</td>
<td>A286</td>
<td>.22</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.1.1-23</td>
</tr>
<tr>
<td>SDG39135735</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137848-003</td>
<td>Mounting Bracket to Sill Joint</td>
<td>NAS1351N4-20 .2500-28</td>
<td>A286</td>
<td>.21</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.1.1-31</td>
</tr>
<tr>
<td>SDG39135730</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td>External Bumper to Interface Joint</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.17</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.1.1-39</td>
</tr>
<tr>
<td>SDG39137848-001</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137853-002</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.17</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.1.1-47</td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137848-003</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.16</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.1.1-55</td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137858-002</td>
<td>Inner Plate to Standoff B</td>
<td>NAS1004-1 .2500-28</td>
<td>A286</td>
<td>.62</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.1.1-63</td>
</tr>
<tr>
<td>SDG39137855-001</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td>External Bumper to Standoff B</td>
<td>NAS1004-40 .2500-28</td>
<td>A286</td>
<td>.09</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.1.1-70</td>
</tr>
<tr>
<td>SDG39137855-001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137849</td>
<td>Corner Bracket to External Bumper</td>
<td>NAS1398DFC4-3 .125 Dia</td>
<td>AL ALY 2017-T4</td>
<td>1.97</td>
<td>Tensile Ultimate</td>
<td>5.10.1.1-73</td>
</tr>
<tr>
<td>SDG39137853-301</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Boundary conditions are at nine AMS-2 bolts distributed as two along the Sill Joint, three along the Lower Trunnion Bridge Beam, two along the Lower Vacuum Case, and two along the Upper Vacuum Case.
3. 64 launch load cases, 64 landing load cases were applied to the DS.
4. Factors of Safety for Fail-Safe analysis are 1.0 for Ultimate and 1.0 for Yield.
5.10.1.2 Introduction

The Port Side Debris Shield (DS) provides shielding for the pressurized vessels on AMS-02 Transition Radiation Detector (TRD) tanks (Xenon, CO2 and Mixing) to prevent catastrophic rupture of these tanks in the event of MMOD impact which would release high-velocity fragments creating a potential hazard for the crew, Space Shuttle, and the International Space Station.

Structural Description

The Port DS (Figure 5.10.1.1 Port Debris Shield Assembly, SEG39137851) consists of two thin aluminum panels sandwiching a ballistic blanket and its supports (Figure 5.10.1.6 Port Debris Shield Mounting Plates Supporting the Ballistic Blanket). The three layers are separated by aluminum standoffs (Figure 5.10.1.5 Transparent View Looking Through the Side of External Bumper at Standoffs). Bolts are used to connect the various panels.

![Figure 5.10.1.1 Port Debris Shield Assembly, SEG39137851](image)

Figure 5.10.1.2 Port Debris Shield with the Unique Support Structure (USS), shows a top view of where the Port DS fits into the USS. While Figure 5.10.1.3 Port Debris Shield with the USS Assembly View, shows an exploded view of the Port DS and some of the tanks it protects.
Figure 5.10.1.2 Port Debris Shield with the Unique Support Structure (USS)

Figure 5.10.1.3 Port Debris Shield with the USS Assembly View

Figure 5.10.1.4 Features of the Port Debris Shield, shows a bottom view of the Port DS with some of the features highlighted.
Figure 5.10.1.4 Features of the Port Debris Shield
The Port DS attaches to the Sill Joint with two fasteners, to the Lower Trunnion Bridge Beam with three fasteners, to the Lower Vacuum Case with two fasteners, and to the Upper Vacuum Case with two fasteners (Figure 5.10.1.7 Port Debris Shield Mounting Brackets).
Load Conditions

An initial assessment of the Shuttle flight loads was made using the secondary structure load factors provided in Table 4-4 of the AMS-02 Structural Verification Plan (JSC-28792, Rev. E). However, these loads are very conservative and the results of the analysis showed that the structural margins were unacceptable. The load factors are provided in Table 5.10.1.4 Launch/Landing Design Limit Load Factors for Small Secondary Structures for reference.

Table 5.10.1.4 Launch/Landing Design Limit Load Factors for Small Secondary Structures

<table>
<thead>
<tr>
<th>Weight (pounds)</th>
<th>Load Factor (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>40</td>
</tr>
<tr>
<td>20-50</td>
<td>31</td>
</tr>
<tr>
<td>50-100</td>
<td>22</td>
</tr>
<tr>
<td>100-200</td>
<td>17</td>
</tr>
<tr>
<td>200-500</td>
<td>13</td>
</tr>
</tbody>
</table>

To reduce the conservatism for the flight loads assessment, the Port DS math model was integrated with the math model of the full AMS-02 payload. The liftoff and landing load factors from the AMS-02 design coupled loads analysis (as specified in Table 5-2 of the AMS-02 SVP) were applied to the integrated math model. These loads are provided in Table 5.10.1.5 Second DCLA Liftoff and Landing Load Factors for reference.
Table 5.10.1.5  Second DCLA Liftoff and Landing Load Factors

<table>
<thead>
<tr>
<th>Event</th>
<th>Nx</th>
<th>Ny</th>
<th>Nz</th>
<th>Rx</th>
<th>Ry</th>
<th>Rz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liftoff</td>
<td>-3.7 / 0.4</td>
<td>-1.4 / 1.6</td>
<td>-1.4 / 1.5</td>
<td>-4.5 / 4.1</td>
<td>-8.4 / 11.0</td>
<td>-3.9 / 4.1</td>
</tr>
<tr>
<td>Abort Landing</td>
<td>-1.2 / 1.3</td>
<td>-0.7 / 0.6</td>
<td>-2.1 / 5.6</td>
<td>-5.2 / 4.7</td>
<td>-10.7 / 13.9</td>
<td>-6.0 / 4.8</td>
</tr>
</tbody>
</table>

A static loads analysis was performed using NASTRAN with 64 subcases representing all combinations of the liftoff load factors and 64 subcases representing all combinations of the landing load factors. Loads and stresses were then recovered from this integrated analysis for the Port DS interface and internal components and used to compute the structural strength margins.

**Factors of Safety**

The hardware is designed with an Ultimate Factor of Safety of 2.0 and a Yield Factor of Safety of 1.25 against limit loads.

**Materials and Temperature**

**Table of Material Allowables**

The materials, and their allowables, used in the Port Debris Shield are shown in Table 5.10.1.6 Material Allowables.

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Allowables</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137847-001</td>
<td>Debris Shield Interface Joint Bracket</td>
<td>AL ALY 7075-T7351 7075-T73</td>
<td>$F_{tu} = 66000$ psi $F_{ty} = 55000$ psi $F_{su} = 39000$ psi</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Debris Shield Mounting Brackets</td>
<td>AL ALY 6061-T651 6061-T651</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
<tr>
<td>SDG39137848-003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137849-001</td>
<td>Debris Shield Corner Bracket</td>
<td>AL ALY 6061-T651 6061-T651</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
<tr>
<td>SDG39137849-002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDG39137849-003</td>
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<td>SDG39137849-004</td>
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</tr>
<tr>
<td>SDG39137853-001</td>
<td>Port External Bumper Assy</td>
<td>AL ALY 7075-T73 7075-T73</td>
<td>$F_{tu} = 67000$ psi $F_{ty} = 55000$ psi $F_{su} = 38000$ psi</td>
</tr>
<tr>
<td>SDG39137858-001</td>
<td>Debris Shield Inner Plate</td>
<td>AL ALY 7075-T73 7075-T73</td>
<td>$F_{tu} = 67000$ psi $F_{ty} = 55000$ psi $F_{su} = 38000$ psi</td>
</tr>
</tbody>
</table>

**Temperature Degradation**

The temperature extremes are -76°F to 140°F.
5.10.1.3 Description of the Port DS Finite Element Model

The FEMAP modeling software was used to generate a finite element model of the Port DS for structural analysis using NASTRAN.

1. The geometry of each part was identified by a CAD model (Parasolid format) that was provided by the design group. This geometry was used as the basis for generating the finite element mesh.
2. The External Bumper, Inner Plate (bumper), Corner Brackets, and Mounting Brackets are modeled using plate elements (CQUAD4 and CTRIA3).
3. The Mounting Bracket to USS and the Mounting Bracket to External Bumper fasteners are represented by CBUSH elements with stiffness values for the three translation directions that represent axial and shear stiffness.
4. The standoffs that provide separation between the External Bumper, Ballistic Blanket, and Inner Plate are modeled with beam (CBAR) elements.
5. The Ballistic Blanket and it’s supports are represented by CMass elements with the total weight of the blanket and it’s supports evenly distributed at the intersections with the Standoffs.
6. The Port DS model is integrated with the USS model.

A summary from NASTRAN of the finite elements comprising the model is provided below.

<table>
<thead>
<tr>
<th>Model Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Grid Points</td>
</tr>
<tr>
<td>Number of CBAR Elements</td>
</tr>
<tr>
<td>Number of CBEAM Elements</td>
</tr>
<tr>
<td>Number of CBUSH Elements</td>
</tr>
<tr>
<td>Number of CHEXA Elements</td>
</tr>
<tr>
<td>Number of CONM2 Elements</td>
</tr>
<tr>
<td>Number of CPENTA Elements</td>
</tr>
<tr>
<td>Number of CQUAD4 Elements</td>
</tr>
<tr>
<td>Number of CROD Elements</td>
</tr>
<tr>
<td>Number of CTETRA Elements</td>
</tr>
<tr>
<td>Number of CTRIA3 Elements</td>
</tr>
<tr>
<td>Number of RBE2 Elements</td>
</tr>
<tr>
<td>Number of RBE3 Elements</td>
</tr>
</tbody>
</table>

Description of the Integrated Port DS and Full Payload Math Model

The 2-06 version of the AMS-02 loads model was used to represent the payload in the integrated model. The Port DS math model described in the preceding sections was connected to the payload model using two rigid elements (RBE2). The independent nodes for the two rigid elements are the nodes on the beam elements representing the Port DS interface with the Upper Trunnion Bridge Beam and the Lower Trunnion Bridge Beam. The dependent nodes of the rigid elements are the Port DS nodes that represent the interface bolt locations. A view of the full payload math model is shown in Figure 5.10.1.8 Finite Element Model of Port DS Integrated with Full Payload.
Constraint and Grounding Checks

Constraint and grounding checks were performed using MSC NASTRAN. The results of these checks are shown below for an unconstrained model. The model passes the checks at all degree-of-freedom set levels with sufficiently low strain energy to indicate that there are no unintended constraints or grounding issues.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 4.703487E-01

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.899828E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.004083E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>4.015733E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>7.521169E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.014671E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.324051E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

SOME POSSIBLE REASONS MAY LEAD TO THE FAILURE:
1. CELASI ELEMENTS CONNECTING TO ONLY ONE GRID POINT;
2. CELASI ELEMENTS CONNECTING TO NON-COINCIDENT POINTS;
3. CELASI ELEMENTS CONNECTING TO NON-COLINEAR DOF;
4. IMPROPERLY DEFINED DMIG MATRICES;
### RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.208936E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.499612E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.474857E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>6.511780E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.893722E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.981926E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Some possible reasons may lead to the failure:
1. Multipoint constraint equations which do not satisfy rigid-body motion;
2. RBE3 elements for which the independent degree-of-freedom cannot describe all possible rigid-body motions.

### RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.208936E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.499612E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.474857E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>6.511780E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.893722E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.981926E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Some possible reasons may lead to the failure:
1. Constraints which prevent rigid-body motion.

### RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET) FOLLOW:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.208936E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.499612E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.474857E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>6.511780E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.893722E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.981926E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

If the model has passed the previous checks for the G-SET and N-SET, then some possible causes are:
1. The model is not intended to be free-free which indicates that the model is properly constrained to ground;
2. The reference grid point (GRID=GID on the GROUNDCHECK command) is located too far from the model's center of gravity. It is recommended that the reference grid point be located as close as possible to the model's center of gravity of the model (see the grid point weight generator output);
3. PARAM, AUTOSPC, YES constrains near-singular degrees-of-freedom. When a finite element model with AUTOSPC fails the A-SET check, it is not evident that grounding has occurred. The use of PARAM, SNORM will not eliminate the spurious failure.

### Modal Check

A modal analysis was performed using NASTRAN to determine the modal frequencies and confirm that the model has appropriate rigid-body modes. A list of the rigid-body modes and elastic modes are provided below.

<table>
<thead>
<tr>
<th>MODE</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2.479914E-07</td>
<td>4.979873E-04</td>
<td>7.925714E-05</td>
<td>1.000000E+00</td>
<td>2.479914E-07</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3.999739E-07</td>
<td>6.324394E-04</td>
<td>1.006551E-04</td>
<td>1.000000E+00</td>
<td>3.999739E-07</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6.368180E-07</td>
<td>7.980088E-04</td>
<td>1.270070E-04</td>
<td>1.000000E+00</td>
<td>6.368180E-07</td>
</tr>
</tbody>
</table>
Mass Properties Check

Since the Port DS was run integrated with the full payload model, a NASTRAN mass properties check would not be useful as the Port DS is a small portion of the total mass of the integrated model. So, using FEMAP, a mass properties check was performed on just the Port DS.

Using FEMAP 9.3.1 > Tools > Mass Properties > Mesh Properties, the Port Debris Shield assembly FEM has a mass of 0.103216 lbf-s²/in or a weight of 39.85 lbf.

Check Mass Properties
51847 Element(s) Selected...

<table>
<thead>
<tr>
<th>Mass</th>
<th>Center of Gravity in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>0.103216  X= 45.7279  Y= 52.01566  Z= 396.1079</td>
</tr>
<tr>
<td>NonStructural</td>
<td>0. X= 0.  Y= 0.  Z= 0.</td>
</tr>
<tr>
<td>Total Mass</td>
<td>0.103216  X= 45.7279  Y= 52.01566  Z= 396.1079</td>
</tr>
</tbody>
</table>

Inertias about CSys 0

<table>
<thead>
<tr>
<th>Inertias about C.G. in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ixx = 16511.53  Ixy= 245.5348  Ixx = 37.5122  Ixy= 0.0284379</td>
</tr>
<tr>
<td>Iyy = 16435.36  Iyz= 2132.587  Iyy = 24.77252  Iyz= 5.942361</td>
</tr>
<tr>
<td>Izz = 508.3945  Izx= 1869.641  Izz = 13.30104  Izx= 0.06955</td>
</tr>
</tbody>
</table>

Total Length (Line Elements only) = 38.31308
Total Area {Area Elements only} = 3416.785
Total Volume {All Elements} = 301.5013

Based on the Unigraphics CAD model, the Port Debris Shield assembly SDG39137851 has a weight of 36.28 lbf, without the soft goods.
5.10.1.4 **Detailed Stress Analysis**

The critical stresses for all components of the Port Debris Shield assembly are compared to the Ultimate and Yield strength of the Aluminum Alloy materials used in the assembly. Analysis of the fasteners used to assemble the Port DS was also performed. All margins of safety are positive.

The minimum Margins of Safety Summary of the parts are shown in Table 5.10.1.1 Parts Minimum Margins of Safety, Table 5.10.1.2 Fastener Minimum Margins of Safety, and Table 5.10.1.3 Fastener Fail-Safe Minimum Margins of Safety.
Intentionally Left Blank
Intentionally Left Blank
CHECK of Debris Shield Port (TRD) - Port External Bumper ASSY, SDG39137853

Allowables

Material Properties

AL ALY, 7075-T73, Sheet, 0.040-0.249, A, AMS-QQ-A-250/12

\[ F_{tu} := 67000 \text{ psi} \]
\[ F_{ty} := 55000 \text{ psi} \]
\[ F_{su} := 38000 \text{ psi} \]

Factors of Safety

\[ FS_u := 2.0 \quad FS_y := 1.25 \]

Temperature Reduction Factors

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: \[ \beta_u := 0.96 \]
  (Ref. MMPDS-03, Figure 3.7.7.1.1.(c))

- Yield: \[ \beta_y := 0.96 \]
  (Ref. MMPDS-03, Figure 3.7.7.1.1.(d))

Allowable Stresses

\[ F_{tug} := \beta_u \cdot F_{tu} \]
\[ F_{tug} = 64320 \text{ psi} \]
\[ F_{tyg} := \beta_y \cdot F_{ty} \]
\[ F_{tyg} = 52800 \text{ psi} \]
\[ F_{sug} := \beta_u \cdot F_{su} \]
\[ F_{sug} = 36480 \text{ psi} \]
Port (TRD) - Port External Bumper ASSY, SDG39137853

Omitted Elements

NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Launch and Landing Cases, the elements at the bolt holes were removed from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.

<table>
<thead>
<tr>
<th>Port - Bumper External - Excluded Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>5025839 thru 5025982</td>
</tr>
<tr>
<td>5041143 thru 5041222</td>
</tr>
<tr>
<td>5043059 thru 5043138</td>
</tr>
<tr>
<td>5047993 thru 5048056</td>
</tr>
<tr>
<td>5052183 thru 5052398</td>
</tr>
<tr>
<td>5052722 thru 5052791</td>
</tr>
<tr>
<td>5052934</td>
</tr>
<tr>
<td>5053136</td>
</tr>
<tr>
<td>5053218</td>
</tr>
<tr>
<td>5053397 thru 5053398</td>
</tr>
<tr>
<td>5053415 thru 5053423</td>
</tr>
<tr>
<td>5053649 thru 5053650</td>
</tr>
<tr>
<td>5055017 thru 5055080</td>
</tr>
<tr>
<td>5056376 thru 5056449</td>
</tr>
<tr>
<td>5057030 thru 5057036</td>
</tr>
<tr>
<td>5057699 thru 5057706</td>
</tr>
<tr>
<td>5057743 thru 5057745</td>
</tr>
<tr>
<td>5058315 thru 5058317</td>
</tr>
<tr>
<td>5058375 thru 5058386</td>
</tr>
<tr>
<td>5058686</td>
</tr>
<tr>
<td>5058704</td>
</tr>
<tr>
<td>5058728</td>
</tr>
<tr>
<td>5059088</td>
</tr>
<tr>
<td>5059122</td>
</tr>
<tr>
<td>5059131</td>
</tr>
<tr>
<td>5059216 thru 5059217</td>
</tr>
<tr>
<td>5059251 thru 5059253</td>
</tr>
<tr>
<td>5059261</td>
</tr>
<tr>
<td>5059804 thru 5059809</td>
</tr>
<tr>
<td>5060036 thru 5060037</td>
</tr>
<tr>
<td>5060068 thru 5060070</td>
</tr>
<tr>
<td>5060303 thru 5060307</td>
</tr>
<tr>
<td>5060586 thru 5060587</td>
</tr>
<tr>
<td>5060851 thru 5060852</td>
</tr>
<tr>
<td>5060988 thru 5060992</td>
</tr>
<tr>
<td>5061006 thru 5061113</td>
</tr>
<tr>
<td>5061388 thru 5061389</td>
</tr>
<tr>
<td>5061613 thru 5061613</td>
</tr>
<tr>
<td>5061659 thru 5061660</td>
</tr>
<tr>
<td>5061689 thru 5061701</td>
</tr>
</tbody>
</table>
Port (TRD) - Port External Bumper ASSY, SDG39137853

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-lo-v5.pch

Maximum Stresses

(See Appendix A28.2.6)

\[ u_{tu} := 24710 \text{ psi} \quad \text{LC# 1030, ELEM# 5052163} \]

(Maximum Principal Stress, p.A28-11)

\[ u_{ty} := 24156 \text{ psi} \quad \text{LC# 1030, ELEM# 5052163} \]

(Maximum Von-Mises Stress, p.A28-11)

\[ u_{su} := 12665 \text{ psi} \quad \text{LC# 1030; ELEM# 5053213} \]

(Maximum Shear Stress, p.A-28-12)

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_{u} \cdot u_{tu}} - 1 \]

\[ MS_{tyg} := \frac{F_{tyg}}{FS_{y} \cdot u_{ty}} - 1 \]

\[ MS_{sug} := \frac{F_{sug}}{FS_{u} \cdot u_{su}} - 1 \]

\[ MS_{tug} = 0.30 \quad \ldots \text{Margin of Safety Tensile Ultimate} \]

\[ MS_{tyg} = 0.75 \quad \ldots \text{Margin of Safety Tensile Yield} \]

\[ MS_{sug} = 0.44 \quad \ldots \text{Margin of Safety Shear Ultimate} \]
Port (TRD) - Port External Bumper ASSY, SDG39137853

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-landing-v5.pch

Maximum Stresses

\[
\sigma_{tu} := 29933 \text{ psi} \quad \text{LC# 2061 ELEM# 5027275} \quad (\text{Maximum Principal Stress, p.A28-10})
\]

\[
\sigma_{ty} := 29489 \text{ psi} \quad \text{LC# 2013 ELEM# 5027330} \quad (\text{Maximum Von-Mises Stress, p.A28-10})
\]

\[
\sigma_{su} := 16263 \text{ psi} \quad \text{LC# 2013 ELEM# 5027330} \quad (\text{Maximum Shear Stress, p.A28-10})
\]

Margins of Safety

\[
\text{MS}_{tu} := \frac{F_{tu}}{F_{Su} \cdot \sigma_{tu}} - 1 \quad \text{MS}_{tu} = 0.07 \quad \ldots \text{Margin of Safety Tensile Ultimate}
\]

\[
\text{MS}_{ty} := \frac{F_{ty}}{F_{Sy} \cdot \sigma_{ty}} - 1 \quad \text{MS}_{ty} = 0.43 \quad \ldots \text{Margin of Safety Tensile Yield}
\]

\[
\text{MS}_{su} := \frac{F_{su}}{F_{Su} \cdot \sigma_{su}} - 1 \quad \text{MS}_{su} = 0.12 \quad \ldots \text{Margin of Safety Shear Ultimate}
\]
Port (TRD) - Debris Shield Inner Plate, SDG39137858-001

**Allowables**

**Material Properties**

\[ F_{tu} := 67000 \text{ psi} \quad \text{(Ref. MMPDS-03, Table 3.7.7.0(b3))} \]
\[ F_{ty} := 55000 \text{ psi} \]
\[ F_{su} := 38000 \text{ psi} \]

**Factors of Safety**

\[ FS_u := 2.0 \quad \text{FS}_y := 1.25 \]

**Temperature Reduction Factors**

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: \[ \beta_u := 0.96 \quad \text{(Ref. MMPDS-03, Figure 3.7.7.1.1.(c))} \]
- Yield: \[ \beta_y := 0.96 \quad \text{(Ref. MMPDS-03, Figure 3.7.7.1.1.(d))} \]

**Allowable Stresses**

\[ F_{tug} := \beta_u \cdot F_{tu} \]

\[ F_{tug} = 64320 \text{ psi} \]

\[ F_{tyg} := \beta_y \cdot F_{ty} \]

\[ F_{tyg} = 52800 \text{ psi} \]

\[ F_{sug} := \beta_u \cdot F_{su} \]

\[ F_{sug} = 36480 \text{ psi} \]
Port (TRD) - Debris Shield Inner Plate, SDG39137858-001

Omitted Elements

NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Launch and Landing Cases, the elements at the bolt holes were removed from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.

Port - Bumper Inner - Excluded Elements
5130875 thru 5131018, 5131135 thru 5131278
Port (TRD) - Debris Shield Inner Plate, SDG39137858-001

**Liftoff Loads**

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-lo-v5.pch

*(See Appendix A28.2.6)*

### Maximum Stresses

- $u_t := 17796$ psi  
  **LC# 1014, ELEM# 5131485**  
  *(Maximum Principal Stress, p.A28-12)*

- $u_y := 17428$ psi  
  **LC# 1014, ELEM# 5131485**  
  *(Maximum Von-Mises Stress, p.A28-12)*

- $u_s := 9025$ psi  
  **LC# 1014, ELEM# 5131485**  
  *(Maximum Shear Stress, p.A28-12)*

### Margins of Safety

- $MS_{tu} := \frac{F_{tu}}{FS_u \times u_t} - 1$  
  **$MS_{tu} = 0.81$**  
  *Margin of Safety Tensile Ultimate*

- $MS_{ty} := \frac{F_{ty}}{FS_y \times u_y} - 1$  
  **$MS_{ty} = 1.42$**  
  *Margin of Safety Tensile Yield*

- $MS_{su} := \frac{F_{su}}{FS_u \times u_s} - 1$  
  **$MS_{su} = 1.02$**  
  *Margin of Safety Shear Ultimate*
Port (TRD) - Debris Shield Inner Plate, SDG39137858-001

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-landing-v5.pch

Maximum Stresses

\( u_{tu} := 12089 \text{ psi} \)

\( LC\# 2014, \ ELEM\#\ 5131485 \) (Maximum Principal Stress, p.A28-10)

\( u_{ty} := 12648 \text{ psi} \)

\( LC\# 2014, \ ELEM\#\ 5131485 \) (Maximum Von-Mises Stress, p.A28-10)

\( u_{su} := 6592 \text{ psi} \)

\( LC\# 2014, \ ELEM\#\ 5131485 \) (Maximum Shear Stress, p.A28-10)

Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{F_{su} \cdot u_{tu}} - 1 \]

\( MS_{tu} = 1.66 \) ... Margin of Safety Tensile Ultimate

\[ MS_{ty} := \frac{F_{ty}}{F_{sy} \cdot u_{ty}} - 1 \]

\( MS_{ty} = 2.34 \) ... Margin of Safety Tensile Yield

\[ MS_{su} := \frac{F_{su}}{F_{su} \cdot u_{su}} - 1 \]

\( MS_{su} = 1.77 \) ... Margin of Safety Shear Ultimate
Port (TRD) - Debris Shield Corner Bracket, SDG39137849

Allowables

Material Properties

AL ALY, 6061-T651, Plate, 0.250-2.000, A, AMS-QQ-A-250/11

\[ F_{tu} := 42000 \text{ psi} \]
\[ F_{ty} := 36000 \text{ psi} \]
\[ F_{su} := 27000 \text{ psi} \]

(Ref. MMPDS-03, Table 3.6.2.0(d))

Factors of Safety

\[ FS_{u} := 2.0 \]
\[ FS_{y} := 1.25 \]

Temperature Reduction Factors

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate:
\[ \beta_{u} := 0.96 \]

(Ref. MMPDS-03, Figure 3.6.2.2.1(a))

- Yield:
\[ \beta_{y} := 0.96 \]

(Ref. MMPDS-03, Figure 3.6.2.2.1(b))

Allowable Stresses

\[ F_{tug} := \beta_{u} \cdot F_{tu} \]
\[ F_{tug} = 40320 \text{ psi} \]

\[ F_{tyg} := \beta_{y} \cdot F_{ty} \]
\[ F_{tyg} = 34560 \text{ psi} \]

\[ F_{sug} := \beta_{u} \cdot F_{su} \]
\[ F_{sug} = 25920 \text{ psi} \]
Port (TRD) - Debris Shield Corner Bracket, SDG39137849

Omitted Elements

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2's, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.

Port - Brackets Corner - Excluded Elements

5000713 thru 5000776, 5000798 thru 5000861, 5001570 thru 5001633
5001662 thru 5001725, 5002442 thru 5002489, 5002514 thru 5002561
5003146 thru 5003209, 5003235 thru 5003298, 5003734 thru 5003797
5003825 thru 5003888, 5006146 thru 5006209, 5006238 thru 5006301
5006994 thru 5007057, 5007081 thru 5007144, 5008169 thru 5008216
5008241 thru 5008288, 5014914 thru 5014977, 5015005 thru 5015068
5015494 thru 5015557, 5015583 thru 5015646
Port (TRD) - Debris Shield Corner Bracket, SDG39137849

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-lo-v5.pch

Maximum Stresses

(See Appendix A28.2.6)

\[ u_{tu} := 11501 \text{ psi} \quad LC#\ 1004,\ ELEM#\ 5002721 \quad (Maximum\ Principal\ Stress,\ p.A28-12) \]

\[ u_{ty} := 11910 \text{ psi} \quad LC#\ 1004,\ ELEM#\ 5002723 \quad (Maximum\ Von-Mises\ Stress,\ p.A28-12) \]

\[ u_{su} := 6213 \text{ psi} \quad LC#\ 1004;\ ELEM#\ 5002723 \quad (Maximum\ Shear\ Stress,\ p.A28-12) \]

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \quad MS_{tug} = 0.75 \quad ...\ Margin\ of\ Safety\ Tensile\ Ultimate \]

\[ MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1 \quad MS_{tyg} = 1.32 \quad ...\ Margin\ of\ Safety\ Tensile\ Yield \]

\[ MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1 \quad MS_{sug} = 1.09 \quad ...\ Margin\ of\ Safety\ Shear\ Ultimate \]
Port (TRD) - Debris Shield Corner Bracket, SDG39137849

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-landing-v5.pch

Maximum Stresses

\[ u_{tu} := 6915 \text{ psi} \quad \text{LC# 2045, ELEM# 5008602} \]  
(Maximum Principal Stress, p.A28-10)

\[ u_{ty} := 7041 \text{ psi} \quad \text{LC# 2045, ELEM# 5000694} \]  
(Maximum Von-Mises Stress, p.A28-11)

\[ u_{su} := 3833 \text{ psi} \quad \text{LC# 2045; ELEM# 5000694} \]  
(Maximum Shear Stress, p.A28-11)

Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{FS_u \cdot u_{tu}} - 1 \]  
\[ MS_{tu} = 1.92 \]  
... Margin of Safety Tensile Ultimate

\[ MS_{ty} := \frac{F_{ty}}{FS_y \cdot u_{ty}} - 1 \]  
\[ MS_{ty} = 2.93 \]  
... Margin of Safety Tensile Yield

\[ MS_{su} := \frac{F_{su}}{FS_u \cdot u_{su}} - 1 \]  
\[ MS_{su} = 2.38 \]  
... Margin of Safety Shear Ultimate
Port (TRD) - Debris Shield Mounting Brackets, SDG39137848

**Allowables**

**Material Properties**

AL ALY 6061-T651, Plate, 0.250-2.000, A, AMS-QQ-A-250/11

\[
\begin{align*}
F_{tu} & := 42000 \text{ psi} \\
F_{ty} & := 36000 \text{ psi} \\
F_{su} & := 27000 \text{ psi}
\end{align*}
\]

(Ref. MMPDS-03, Table 3.6.2.0(b2))

**Factors of Safety**

\[
\begin{align*}
FS_u & := 2.0 \\
FS_y & := 1.25
\end{align*}
\]

**Temperature Reduction Factors**

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: \( \beta_u := 0.96 \)  
  (Ref. MMPDS-03, Figure 3.6.2.2.1(a))

- Yield: \( \beta_y := 0.96 \)  
  (Ref. MMPDS-03, Figure 3.6.2.2.1(b))

**Allowable Stresses**

\[
\begin{align*}
F_{tug} & := \beta_u F_{tu} \\
F_{tug} & = 40320 \text{ psi} \\
F_{tyg} & := \beta_y F_{ty} \\
F_{tyg} & = 34560 \text{ psi} \\
F_{sug} & := \beta_u F_{su} \\
F_{sug} & = 25920 \text{ psi}
\end{align*}
\]
**Port (TRD) - Debris Shield Mounting Brackets, SDG39137848**

**Omitted Elements**

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2's, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.

<table>
<thead>
<tr>
<th>Port - Brackets Mounting and Interface Joint - Excluded Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000094 thru 5000114, 5000130 thru 5000154, 5000179 thru 5000198</td>
</tr>
<tr>
<td>5000200 thru 5000201, 5000405 thru 5000436, 5000465 thru 5000492</td>
</tr>
<tr>
<td>5000509 thru 5000511, 5000548 thru 5000550, 50007830 thru 50007861</td>
</tr>
<tr>
<td>5000787 thru 50007915, 5008111, 5008113 thru 5008114</td>
</tr>
<tr>
<td>50008701 thru 50008732, 5008758 thru 5008786, 5008982</td>
</tr>
<tr>
<td>5000884 thru 5000985, 5009157 thru 5009166, 5009231 thru 5009240</td>
</tr>
<tr>
<td>5009266 thru 5009269, 5009294 thru 5009295, 5009314 thru 5009316</td>
</tr>
<tr>
<td>5009322 thru 5009327, 5009330 thru 5009334, 5009338</td>
</tr>
<tr>
<td>5009341 thru 5009345, 5009504 thru 5009505, 5009517 thru 5009519</td>
</tr>
<tr>
<td>5009562 thru 5009570, 5009590 thru 5009594, 5009930 thru 5009934</td>
</tr>
<tr>
<td>5009941 thru 5009942, 5009945 thru 5009949, 5009951 thru 5009957</td>
</tr>
<tr>
<td>5009972 thru 5009974, 5009977, 5010046 thru 5010051</td>
</tr>
<tr>
<td>5010114 thru 5010115, 5010434 thru 5010443, 5010460</td>
</tr>
<tr>
<td>5010475, 5010483, 5010508 thru 5010517</td>
</tr>
<tr>
<td>5010543 thru 5010546, 5010571 thru 5010572, 5010591 thru 5010593</td>
</tr>
<tr>
<td>5010599 thru 5010604, 5010607 thru 5010611, 5010615</td>
</tr>
<tr>
<td>5010618 thru 5010622, 5010781 thru 5010782, 5010794 thru 5010796</td>
</tr>
<tr>
<td>5010839 thru 5010847, 5010939 thru 5010941, 5011210 thru 5011212</td>
</tr>
<tr>
<td>5011218 thru 5011219, 5011222 thru 5011226, 5011228 thru 5011234</td>
</tr>
<tr>
<td>5011249 thru 5011251, 5011254, 5011323 thru 5011328</td>
</tr>
<tr>
<td>5011391 thru 5011392, 5011563 thru 5011594, 5011597 thru 5011628</td>
</tr>
<tr>
<td>5011873 thru 5011904, 5011907 thru 5011938, 5012133 thru 5012164</td>
</tr>
<tr>
<td>5012167 thru 5012198, 5012990 thru 5013021, 5013136 thru 5013167</td>
</tr>
<tr>
<td>5013282 thru 5013313, 5200000 thru 5200011</td>
</tr>
</tbody>
</table>

5.10.1-30 ESCG-4005-05-AMS-0039
Port (TRD) - Debris Shield Mounting Brackets, SDG39137848

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-lo-v5.pch

Maximum Stresses

(See Appendix A28.2.2)

\[ u_{tu} := 15633 \text{ psi} \quad \text{LC# 1020 ELEM# 5000372} \quad (\text{Maximum Principal Stress, p.A28-6}) \]

\[ u_{ty} := 14735 \text{ psi} \quad \text{LC# 1020 ELEM# 5000413} \quad (\text{Maximum Von-Mises Stress, p.A28-6}) \]

\[ u_{su} := 7817 \text{ psi} \quad \text{LC# 1020 ELEM# 5000372} \quad (\text{Maximum Shear Stress, p.A28-6}) \]

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \quad \text{MS}_{tug} = 0.290 \quad \ldots \text{Margin of Safety Tensile Ultimate} \]

\[ MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1 \quad \text{MS}_{tyg} = 0.88 \quad \ldots \text{Margin of Safety Tensile Yield} \]

\[ MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1 \quad \text{MS}_{sug} = 0.66 \quad \ldots \text{Margin of Safety Shear Ultimate} \]
Port (TRD) - Debris Shield Mounting Brackets, SDG39137848

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-landing-v5.pch

Maximum Stresses

(See Appendix A28.2.1)

\[ u_{tu} := 12342 \text{ psi} \quad \text{LC# 2045 ELEM# 5000420} \quad \text{(Maximum Principal Stress, p.A28-4)} \]

\[ u_{ty} := 12112 \text{ psi} \quad \text{LC# 2045 ELEM# 5000413} \quad \text{(Maximum Von-Mises Stress, p.A28-4)} \]

\[ u_{su} := 6171 \text{ psi} \quad \text{LC# 2045 ELEM# 5000420} \quad \text{(Maximum Shear Stress, p.A28-5)} \]

Margins of Safety

\[ M_{Stu} := \frac{F_{tu}}{F_{S_{tu}}u_{tu}} - 1 \quad \text{MS}_{tu} = 0.63 \quad \text{... Margin of Safety Tensile Ultimate} \]

\[ M_{Sty} := \frac{F_{ty}}{F_{S_{ty}}u_{ty}} - 1 \quad \text{MS}_{ty} = 1.28 \quad \text{... Margin of Safety Tensile Yield} \]

\[ M_{S_{su}} := \frac{F_{su}}{F_{S_{su}}u_{su}} - 1 \quad \text{MS}_{su} = 1.10 \quad \text{... Margin of Safety Shear Ultimate} \]
Port (TRD) - Debris Shield Interface Joint Bracket, SDG39137847

Allowables

Material Properties

AL ALY 7075-T7351, Plate, 1.501-2.000, A, AMS-QQ-A-250/12

\[ F_{tu} := 66000 \text{ psi} \quad \text{(Ref. MMPDS-03, Table 3.7.7.0(b3))} \]

\[ F_{ty} := 55000 \text{ psi} \]

\[ F_{su} := 39000 \text{ psi} \]

Factors of Safety

\[ FS_u := 2.0 \quad FS_y := 1.25 \]

Temperature Reduction Factors

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: \[ \beta_u := 0.96 \quad \text{(Ref. MMPDS-03, Figure 3.7.7.1.1.(c))} \]

- Yield: \[ \beta_y := 0.96 \quad \text{(Ref. MMPDS-03, Figure 3.7.7.1.1.(d))} \]

Allowable Stresses

\[ F_{tug} := \beta_u \cdot F_{tu} \]

\[ F_{tug} = 63360 \text{ psi} \]

\[ F_{tyg} := \beta_y \cdot F_{ty} \]

\[ F_{tyg} = 52800 \text{ psi} \]

\[ F_{sug} := \beta_u \cdot F_{su} \]

\[ F_{sug} = 37440 \text{ psi} \]
Port (TRD) - Debris Shield Interface Joint Bracket, SDG39137847

Omitted Elements

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2’s, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.

Port – Brackets Mounting and Interface Joint – Excluded Elements

Port (TRD) - Debris Shield Interface Joint Bracket, SDG39137847

Omitted Elements

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2’s, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.
Port (TRD) - Debris Shield Interface Joint Bracket, SDG39137847

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-lo-v5.pch

Maximum Stresses

\( \sigma_{tu} := 31423 \text{ psi} \quad \text{LC# 1004 ELEM# 5010484} \)  
\( \text{(Maximum Principal Stress, p.A28-6)} \)

\( \sigma_{ty} := 31017 \text{ psi} \quad \text{LC# 1004 ELEM# 5010484} \)  
\( \text{(Maximum Von-Mises Stress, p.A28-7)} \)

\( \sigma_{su} := 15711 \text{ psi} \quad \text{LC# 1004 ELEM# 5010484} \)  
\( \text{(Maximum Shear Stress, p.A28-7)} \)

Margins of Safety

\begin{align*}
MS_{tu} &:= \frac{F_{tu}}{F_{Su} \cdot \sigma_{tu}} - 1 \quad \text{MS}_{tu} = 0.008 \quad \text{... Margin of Safety Tensile Ultimate} \\
MS_{ty} &:= \frac{F_{ty}}{F_{Sy} \cdot \sigma_{ty}} - 1 \quad \text{MS}_{ty} = 0.36 \quad \text{... Margin of Safety Tensile Yield} \\
MS_{su} &:= \frac{F_{su}}{F_{Su} \cdot \sigma_{su}} - 1 \quad \text{MS}_{su} = 0.19 \quad \text{... Margin of Safety Shear Ultimate}
\end{align*}
Port (TRD) - Debris Shield Interface Joint Bracket, SDG39137847

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: debris-shield-landing-v5.pch

Maximum Stresses

\[ \sigma_{tu} := 31356 \text{ psi} \quad \text{(Maximum Principal Stress, p.A28-5)} \]
\[ \sigma_{ty} := 30944 \text{ psi} \quad \text{(Maximum Von-Mises Stress, p.A28-5)} \]
\[ \sigma_{su} := 15678 \text{ psi} \quad \text{(Maximum Shear Stress, p.A28-5)} \]

Margins of Safety

\[ M_{Stug} := \frac{F_{tu}}{F_{Su} \sigma_{tu}} - 1 \quad \text{MS}_{tu} = 0.01 \quad \text{Margin of Safety Tensile Ultimate} \]
\[ M_{Styg} := \frac{F_{ty}}{F_{Sy} \sigma_{ty}} - 1 \quad \text{MS}_{ty} = 0.37 \quad \text{Margin of Safety Tensile Yield} \]
\[ M_{Ssug} := \frac{F_{su}}{F_{Su} \sigma_{su}} - 1 \quad \text{MS}_{su} = 0.19 \quad \text{Margin of Safety Shear Ultimate} \]
5.10.1.1 Port Debris Shield Assembly Bolt Analysis
Intentionally Left Blank
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Lower Vacuum Case

CHECK

Bolt := "SDG39135892-828, NAS1008-8A, .5000-20, .500 GRIP, CRES A286"
Washer := "NAS1587-8C"
Insert := "MS51831CA206, .500-20, CRES A286, 160 KSI"

Flange_1 := "Tab Angle Bracket"
Part_Number_1 := "SDG39137847"
Material_1 := "AL ALY 6061-T651 Sheet"

Flange_2 := "Lower Vacuum Case"
Part_Number_2 := "SDG39135737"
Material_2 := "AL ALY 7050-T7451"

Loads

Applied tensile load P := 201·lbf
Applied shear load V := 357·lbf
Applied bending moment M := 0·in·lbf

Factors of Safety

Ultimate SFu := 2.0
Yield SFy := 1.25
Assembly

Joint Separation SFsep := 1.2
Fitting factor FF := 1.15
Maximum Temp_initial := 70·deg
Minimum Temp_max := 140·deg
Temp_min := −76·deg

Bolt and Insert Data

Nominal diameter of bolt D := .5·in
Number of threads/inch Nt := 20·
Total length of bolt L := 1.342·in
Length of insert Lins := .688·in
Threaded length Lt := .842·in
Min. external diameter of insert Fmin := .615·in
(If bolt is fully threaded, input Lt = L)
Depth of recess for insert lr := 0.02·in

Washer Data

Thickness of washer tw := .078·in
Outer Diameter of washer Dw := .875·in
Inner Diameter of washer Dwi := .504·in
Bolt head dia. across flats dw := .74·in

Flange data

Thickness of flange 1 tf1 := .38·in
Thickness of flange 2 tf2 := .75·in
Diameter of hole D_hole := .531·in

Note: If there is no washer, tw, Dw, and Dwi should be zero.
Material Property Data

**Bolt**

Temperature correction factor for bolt strength ultimate

\[TS_{\text{bolt}} = 0.96\quad \text{yield} \quad TS_{\text{y bolt}} = 0.96\]

Bolt ultimate tensile allowable stress

\[F_{\text{tu bolt}} = 140000\text{-psi}\]

Bolt ultimate shear allowable stress

\[F_{\text{su bolt}} = 0.6F_{\text{tu bolt}}\]

Bolt yield tensile allowable

\[F_{\text{ty bolt}} = 95000\text{-psi}\]

Temperature correction factor for bolt modulus

\[TE_{\text{bolt}} = 0.98\]

\[\beta_{\text{bolt hot}} = 9.1 \times 10^{-6}\text{ in}\text{in}^{-1}\text{deg}\]

Modulus of elasticity of bolt

\[E_{\text{bolt}} = \left(29.1 \times 10^6\text{ psi}\right)\]

Thermal coefficient for bolt:

\[\beta_{\text{bolt cold}} = 8.5 \times 10^{-6}\text{ in}\text{in}^{-1}\text{deg}\]

**Insert**

Temperature correction factor for insert strength

\[TS_{\text{ins}} = 0.96\]

Ultimate tensile allowable stress

\[F_{\text{tu ins}} = 140000\text{-psi}\]

Ultimate shear allowable stress

\[F_{\text{su ins}} = 0.6F_{\text{tu ins}}\]

**Washer**

Temperature correction factor for washer modulus

\[TE_{\text{washer}} = 1.0\]

Modulus of elasticity of washer

\[E_{\text{washer}} = \left(29.1 \times 10^6\text{ psi}\right)\]

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners,
Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[T_{f1E} = 0.98\text{ (modulus)} \quad T_{f2s} = 0.91\text{ (strength)}\]

Temperature correction factor for flange 2

\[T_{f2E} = 0.98\text{ (modulus)} \quad F_{s2} = 43000\text{-psi}\]

Modulus of elasticity for the parts in the joint

\[E_{\text{flange1}} = \left(10.1 \times 10^6\text{ psi}\right) \quad E_{\text{flange2}} = \left(10.8 \times 10^6\text{ psi}\right)\]

Coefficient of thermal expansion for flanges

\[\beta_{\text{flange1 hot}} = 12.8 \times 10^{-6}\text{ in}\text{in}^{-1}\text{deg}\]

\[\beta_{\text{flange2 hot}} = 12.5 \times 10^{-6}\text{ in}\text{in}^{-1}\text{deg}\]

\[\beta_{\text{flange1 cold}} = 12.1 \times 10^{-6}\text{ in}\text{in}^{-1}\text{deg}\]

\[\beta_{\text{flange2 cold}} = 12.1 \times 10^{-6}\text{ in}\text{in}^{-1}\text{deg}\]

**Torque/Preload data**

Maximum torque

\[T_{max} = 651\text{-in-lbf}\]

Loading plane factor: \(n = 0.5\)

Minimum torque

\[T_{min} = 553\text{-in-lbf}\]

Preload Uncertainty: \(u = 0.25\)

Torque coefficient: \(k = 0.15\)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Lower Vacuum Case

<table>
<thead>
<tr>
<th>Bolt Load data</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.646</td>
<td>Preload due to temperature</td>
<td>Pthr_pos = 586.1 lbf</td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLDmax = 11436.1 lbf</td>
<td>Min. preload</td>
<td>PLDmin = 3731.9 lbf</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>Psep = 241.2 lbf</td>
<td>Torque coefficient</td>
<td>k = 0.15</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
<td>Pb = 11585.4 lbf</td>
<td>Loading plane factor</td>
<td>n = 0.5</td>
</tr>
<tr>
<td>Max. load on the bolt(yield)</td>
<td>Pby = 11529.4 lbf</td>
<td>Thread shear pullout load of bolt or insert</td>
<td>Pths = 51164.1 lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PA_t = 21111.4 lbf</td>
<td>Thread shear pullout load in parent metal</td>
<td>Ppths = 26007.2 lbf</td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_1 = 18.88</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_2 = 44.67</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_3 = 48.58</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_4 = 0.82</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_5 = 0.243</td>
</tr>
</tbody>
</table>

Failure_Mode = "Total Tension Yield"

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

MSbolt = 0.243
Fail-safe Analysis

Fail-safe Loads

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Load Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P_{FS} := 240-lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V_{FS} := 666-lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_{FS} := 0-in-lbf</td>
</tr>
</tbody>
</table>

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Factor Type</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SF_{u} := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SF_{sep} := 1.0</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escfil02\2111\mathcad\8307\bolts\bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

Joint separation load \( P_{sep_{FS}} = 240\text{-lbf} \)
Max. load on the bolt(ultimate) \( P_{b_{FS}} = 11525.2\text{-lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{FS1} = 18.97</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{FS2} = 75.49</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{FS3} = 0.83</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{FS4} = 93.23</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt_{FS}} := \min(MS_{FS}) \]

\[ MS_{bolt_{FS}} = 0.83 \]

Failure Mode = "Combined Shear Tension Bending Ultimate"
Bolt Hole Analysis

Minimum edge distance of flange one $\text{edge}_1 := 0.470\text{-in}$
Minimum edge distance of flange two $\text{edge}_2 := 0.812\text{-in}$
Shank diameter of bolt $D_{\text{shank}} := 0.497\text{-in}$

Recall loads from bolt calculation

Safety Factors
- $SF_u = 2.000$ (Ultimate)
- $SF_y = 1.25$ (Yield)
- $FF = 1.15$ (Fitting Factor)

Input Loads
- $V = 357\text{-lbf}$ (Shear Load)
- $P = 201\text{-lbf}$ (Axial Load)

Bolt calc results
- $P_b = 11585\text{-lbf}$ (Max Bolt Load)

Dimensions
- $L = 1.342\text{-in}$ (Length of Bolt)
- $t_w = 0.078\text{-in}$ (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions

$t_{f_1} := tf_1$  $t_{f_1} = 0.38\text{-in}$ (Entire Thickness of Flange 1)
$t_{f_2} := tf_2$  $t_{f_2} = 0.75\text{-in}$ (Entire Thickness of Flange 2)
$\text{edge}_1 := \text{edge}_1$  $\text{edge}_1 = 0.47\text{-in}$ (Edge Distance for Hole in Plate 1)
$\text{edge}_2 := \text{edge}_2$  $\text{edge}_2 = 0.812\text{-in}$ (Edge Distance for Hole in Plate 2)

$D = 0.5\text{-in}$ (Diameter of Bolt)
$D_{\text{shank}} = 0.497\text{-in}$ (Min. Shank Diameter of Bolt)
$D_{\text{hole}} = 0.531\text{-in}$ (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

$$A_{\text{shrp1}} := \frac{2tf_{1}\left(\text{edge}_{1} - \frac{1}{2}D_{\text{hole}}\right)}{\pi}$$

Allowables for plates that fastener goes through

$F_{su_1} := T_{f1E} = 27\text{-ksi}$  $F_{su_1} = 26.46\text{-ksi}$ (Ultimate Shear Allowable for Plate 1)
$F_{su_2} := T_{f2E} = 43\text{-ksi}$  $F_{su_2} = 42.14\text{-ksi}$ (Ultimate Shear Allowable for Plate 2)
$P_{su} := \left(A_{\text{shrp1}}\times F_{su}\right)$  $P_{su} = \left(\frac{4112}{34544}\right)\text{-lbf}$ (Shear Ultimate Allowable)
**Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert**

**TRD Side - Tab Angle Bracket to Lower Vacuum Case**

**Title**

C. Bala

**Prepared By**

Kent Peters

**Date**

08/21/2008

**Checked By**

C. Bala

**File Name**

DS TRD TabAngle to LVC

**Structural Analysis Section**

**Engineering and Science Contract Group**

**MS for Shear Tear-Out**

\[
MS_{su} := \left( \frac{P_{su}}{V \cdot SF_{u} \cdot FF} - 1 \right)
\]

\[
MS_{bh1} := \min(MS_{su}) \quad MS_{bh1} = 4.008
\]

... **Shear Tear-Out MS**

**Bearing Check**

*Recall bolt hole dimensions*

- \(tf_1 = 0.38\) in
- \(tf_2 = 0.75\) in
- \(edge_1 = 0.47\) in
- \(edge_2 = 0.812\) in

**Typical Bearing Failure**

\[
A_{br} := (tf_{min}(D, D_{shank}) \quad A_{br} = \left( \frac{0.189}{0.373} \right)^2 \quad \text{in}^2
\]

\[
e_{D} := \frac{edge}{D_{hole}} \quad e_{D} = \left( \frac{0.885}{1.529} \right)
\]

**Allowables for plates that fastener goes through**

**Bearing strength at \(e/D = 1.5\)**

- \(Fbru_{151} := TtE \cdot 67\) ksi
- \(Fbru_{151} = 65.66\) ksi
- \(Fbru_{201} := TtE \cdot 88\) ksi
- \(Fbru_{201} = 86.24\) ksi

**Bearing strength at \(e/D = 2.0\)**

- \(Fbru_{152} := TtE \cdot 107\) ksi
- \(Fbru_{152} = 104.86\) ksi
- \(Fbru_{202} := TtE \cdot 140\) ksi
- \(Fbru_{202} = 137.2\) ksi

- \(Fbry_{151} := TtE \cdot 50\) ksi
- \(Fbry_{151} = 49\) ksi
- \(Fbry_{201} := TtE \cdot 58\) ksi
- \(Fbry_{201} = 56.84\) ksi

- \(Fbry_{152} := TtE \cdot 86\) ksi
- \(Fbry_{152} = 84.28\) ksi
- \(Fbry_{202} := TtE \cdot 101\) ksi
- \(Fbry_{202} = 98.98\) ksi
**Modified bearing strength**

\[
F_{bru_1} := \begin{cases}
2.0 & \text{if } e_{D1} > 2.0, \\
2.0 & \text{if } e_{D2} > 2.0, \\
e_{D1} & \text{if } e_{D1} < 2.0, \\
& \text{if } e_{D2} < 2.0
\end{cases} \left( F_{bru_1} - F_{bru_15} \right) \left[ F_{bru_15} (e_{D1} - 0.5) \right]
\]

\[
F_{bru_2} := \begin{cases}
2.0 & \text{if } e_{D1} > 2.0, \\
2.0 & \text{if } e_{D2} > 2.0, \\
e_{D2} & \text{if } e_{D1} < 2.0, \\
& \text{if } e_{D2} < 2.0
\end{cases} \left( F_{bru_2} - F_{bru_20} \right) \left[ F_{bru_20} (e_{D2} - 0.5) \right]
\]

\[
F_{bry_1} := \begin{cases}
1.5 & \text{if } e_{D1} > 2.0, \\
1.5 & \text{if } e_{D2} > 2.0, \\
e_{D1} & \text{if } e_{D1} < 2.0, \\
& \text{if } e_{D2} < 2.0
\end{cases} \left( F_{bry_1} - F_{bry_15} \right) \left[ F_{bry_15} (e_{D1} - 0.5) \right]
\]

\[
F_{bry_2} := \begin{cases}
1.5 & \text{if } e_{D1} > 2.0, \\
1.5 & \text{if } e_{D2} > 2.0, \\
e_{D2} & \text{if } e_{D1} < 2.0, \\
& \text{if } e_{D2} < 2.0
\end{cases} \left( F_{bry_2} - F_{bry_20} \right) \left[ F_{bry_20} (e_{D2} - 0.5) \right]
\]

\[
F_{bru_1} = \begin{pmatrix} 25.287 \\ 106.748 \end{pmatrix} \left( \text{Plate1} \right) \left( \text{Plate2} \right) \quad \text{(Ultimate)}
\]

\[
F_{bry_1} = \begin{pmatrix} 18.871 \\ 85.138 \end{pmatrix} \left( \text{Plate1} \right) \left( \text{Plate2} \right) \quad \text{(Yield)}
\]

\[
P_{bru} := (A_{bru} F_{bru_1})
\]

\[
P_{bru} = \begin{pmatrix} 4776 \\ 39790 \end{pmatrix} \quad \text{lbf} \quad \text{(Bearing Ultimate Allowable)}
\]

\[
P_{bry} := (A_{bry} F_{bry_1})
\]

\[
P_{bry} = \begin{pmatrix} 3564 \\ 31735 \end{pmatrix} \quad \text{lbf} \quad \text{(Bearing Yield Allowable)}
\]

**MS for Bearing Failure**

\[
MS_{bru} := \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1
\]

\[
MS_{bru} = \begin{pmatrix} 4.816 \\ 47.46 \end{pmatrix} \left( \text{Plate1} \right) \left( \text{Plate2} \right)
\]

\[
MS_{bh2} := \min \left( MS_{bru} \right)
\]

\[
MS_{bh2} = 4.816 \quad \text{... Bearing MS based on Ultimate Strength}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Lower Vacuum Case

\[ MS_{by} := \left( \frac{P_{by}}{V \cdot SFy \cdot FF} \right) - 1 \]
\[ MS_{by} = \begin{pmatrix} 5.94 \\ 60.84 \end{pmatrix} \]
\[ MS_{bh3} := \min( MS_{by} ) \]
\[ MS_{bh3} = 5.945 \]

... Bearing MS based on Yield Strength
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Upper Vacuum Case

CHECK

Bolt := "SDG39135892-828, NAS1008-8A, .5000-20, .500 GRIP, CRES A286"
Washer := "NAS1587-8C"
Insert := "MS51831CA206, .500-20, CRES A286, 160 KSI"

Flange_1 := "Tab Angle Bracket"
Part_Number_1 := "SDG39137847"
Material_1 := "AL ALY 6061-T651 Sheet"

Flange_2 := "Upper Vacuum Case"
Part_Number_2 := "SDG39135727"
Material_2 := "AL ALY 7050-T7451"

Loads
Applied tensile load \( P := 201 \text{ lbf} \)
Applied shear load \( V := 357 \text{ lbf} \)
Applied bending moment \( M := 0 \text{ in-lbf} \)

Factors of Safety

| Ultimate | SFu := 2.0 | Yield | SFy := 1.25 | Assembly | Temp_initial := 70-deg |
| Joint Separation | SFsep := 1.2 | Fitting factor | FF := 1.15 | Maximum | Temp_max := 140-deg |
| Minimum | Temp_min := -76-deg |

Bolt and Insert Data

Nominal diameter of bolt \( D := .5 \text{ in} \)
Total length of bolt \( L = 1.342 \text{ in} \)
Threaded length \( Lt = .842 \text{ in} \)
Number of threads/inch \( Nt := 20 \frac{1}{\text{in}} \)
Length of insert \( Lins := .688 \text{ in} \)
Min. external diameter of insert \( Fmin := .615 \text{ in} \)
Depth of recess for insert \( lr := 0.02 \text{ in} \)

(If bolt is fully threaded, input \( Lt = L \))

This file uses the calculations shown in \escfil02\2f11_mathcad\8307_bolts\thread_data.mcd

Washer Data

| Thickness of washer | \( tw := .078 \text{ in} \) |
| Outer Diameter of washer | \( Dw := .875 \text{ in} \) |
| Inner Diameter of washer | \( Dwi := .504 \text{ in} \) |
| Bolt head dia. across flats | \( dw := .741 \text{ in} \) |

Flange data

| Thickness of flange 1 | \( tf1 := .38 \text{ in} \) |
| Thickness of flange 2 | \( tf2 := .75 \text{ in} \) |
| Diameter of hole | \( D_{hole} := .531 \text{ in} \) |

Note: If there is no washer, \( tw, Dw, \) and \( Dwi \) should be zero.

5.10.1.1-11 ESCG-4005-05-AMS-0039
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Upper Vacuum Case

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate
\[ TS_u_{\text{bolt}} := 0.96 \quad \text{yield} \quad TS_y_{\text{bolt}} := 0.96 \]

Bolt ultimate tensile allowable stress
\[ F_{tu_{\text{bolt}}} := 140000 \text{ psi} \]

Bolt ultimate shear allowable stress
\[ F_{su_{\text{bolt}}} := 0.6 \times F_{tu_{\text{bolt}}} \]

Bolt yield tensile allowable
\[ F_{ty_{\text{bolt}}} := 95000 \text{ psi} \]

Temperature correction factor for bolt modulus
\[ TE_{\text{bolt}} := 0.98 \]

Modulus of elasticity of bolt
\[ E_{\text{bolt}} := (29.1 \times 10^6 \text{ psi}) \]

Thermal coefficient for bolt:
\[ \beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{bolt\_cold}} := 8.5 \times 10^{-6} \text{ in/in deg} \]

Insert

Temperature correction factor for insert strength
\[ TS_{\text{ins}} := 0.96 \]

Ultimate tensile allowable stress
\[ F_{tu_{\text{ins}}} := 140000 \text{ psi} \]

Ultimate shear allowable stress
\[ F_{su_{\text{ins}}} := 0.6 \times F_{tu_{\text{ins}}} \]

Washer

Temperature correction factor for washer modulus
\[ TE_{\text{washer}} := 1.0 \]

Modulus of elasticity of washer
\[ E_{\text{washer}} := (29.1 \times 10^6 \text{ psi}) \]

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ tf1E := 0.98 \quad \text{(modulus)} \quad tf2s := 0.91 \quad \text{(strength)} \]

Temperature correction factor for flange 2
\[ tf2E := 0.98 \quad \text{(modulus)} \quad F_{su_{\text{f2}}} := 43000 \text{ psi} \]

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := (10.1 \times 10^6 \text{ psi}) \quad E_{\text{flange2}} := (10.8 \times 10^6 \text{ psi}) \]

Coefficient of thermal expansion for flanges
\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \text{ in/in deg} \quad \beta_{\text{flange2\_hot}} := 12.5 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \quad \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \]

Torque/Preload data

Maximum torque
\[ T_{\text{max}} := 651 \text{ in-lbf} \]

Loading plane factor:
\[ n := 0.5 \]

Minimum torque
\[ T_{\text{min}} := 553 \text{ in-lbf} \]

Preload Uncertainty:
\[ u := 0.25 \]

Torque coefficient:
\[ k := 0.15 \]
Bolt Load data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.646</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td>Pthr_pos = 586.1 lbf</td>
</tr>
<tr>
<td>Max. preload</td>
<td>PLDmax = 11436.1 lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLDmin = 3731.9 lbf</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>Psep = 241.2 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt (ultimate)</td>
<td>Pb = 11585.4 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt (yield)</td>
<td>Pby = 11529.4 lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PAt = 21111.4 lbf</td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS₁ = 18.88</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS₂ = 44.67</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS₃ = 48.58</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS₄ = 0.82</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS₅ = 0.243</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS₆ = 55.26</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS₇ = 1.24</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS₈ = 13.6</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS₉ = 10</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS₁₀ = 0.82</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

MSbolt = 0.243  Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

Fail-safe Loads

- **Applied tensile load**
  
  \[ P_{FS} := 240\text{ lbf} \]

- **Applied shear load**
  
  \[ V_{FS} := 666\text{ lbf} \]

- **Applied bending moment**
  
  \[ M_{FS} := 0\text{ in-lbf} \]

Fail-safe Factors of Safety

- **Ultimate**
  
  \[ SF_{u} := 1.0 \]

- **Joint Separation**
  
  \[ SF_{sep} := 1.0 \]

This file uses the calculations shown in `\\escfil022\i11_mathcad8307_bolts\bolt_stiffness_insert_FS_RevC`

Bolt Fail-safe Load data

- **Joint separation load**
  
  \[ P_{sep_{FS}} = 240\text{ lbf} \]

- **Max. load on the bolt(ultimate)**
  
  \[ P_{b\_FS} = 11525.2\text{ lbf} \]

Summary of fail-safe Margins for bolt:

- **Joint separation**
  
  \[ MS_{FS_1} = 18.97 \]

- **Direct Tension Ultimate**
  
  \[ MS_{FS_2} = 75.49 \]

- **Total Tension Ultimate**
  
  \[ MS_{FS_3} = 0.83 \]

- **Direct Thread shear Ultimate**
  
  \[ MS_{FS_4} = 93.23 \]

Determinations of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt\_FS} := \min(\text{MS}_{FS}) \]

\[ MS_{bolt\_FS} = 0.83 \]

Failure Mode = "Combined Shear Tension Bending Ultimate"
Bolt Hole Analysis

Minimum edge distance of flange one \( \text{edge}_1 := 0.470\text{-in} \)
Minimum edge distance of flange two \( \text{edge}_2 := 0.844\text{-in} \)
Shank diameter of bolt \( D_{\text{shank}} := .4970\text{-in} \)

\[ \text{Recall loads from bolt calculation} \]
Safety Factors
- SF\( u \) = 2.000 (Ultimate)
- SF\( y \) = 1.25 (Yield)
- FF = 1.15 (Fitting Factor)
Input Loads
- \( V \) = 357·lbf (Shear Load)
- \( P \) = 201·lbf (Axial Load)
Bolt calc results
- \( P_b \) = 11585·lbf (Max Bolt Load)

\[ \text{Dimensions} \]
- \( L \) = 1.342·in (Length of Bolt)
- \( t_w \) = 0.078·in (Thickness of Washer)

Shear Tear-Out Check

\[ \text{Recall bolt hole dimensions} \]
- \( t_{f1} := tf1 \), \( t_{f1} = 0.38\text{-in} \) (Entire Thickness of Flange 1)
- \( T_{f1E} = 0.98 \) plate 2
- \( t_{f2} := tf2 \), \( t_{f2} = 0.75\text{-in} \) (Entire Thickness of Flange 2)
- \( T_{f2E} = 0.98 \)

- \( \text{edge}_1 := \text{edge}_1 \), \( \text{edge}_1 = 0.47\text{-in} \) (Edge Distance for Hole in Plate 1)
- \( \text{edge}_2 := \text{edge}_2 \), \( \text{edge}_2 = 0.844\text{-in} \) (Edge Distance for Hole in Plate 2)
- \( D = 0.5\text{-in} \) (Diameter of Bolt)
- \( D_{\text{shank}} = 0.497\text{-in} \) (Min. Shank Diameter of Bolt)
- \( D_{\text{hole}} = 0.531\text{-in} \) (Diameter of Hole)

\[ \text{Shear area of the mating components} \] (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{\text{shp1}} := \left[ \frac{2 \cdot \text{tf} \cdot \left( \text{edge} - \frac{1}{2} D_{\text{hole}} \right)}{\pi} \right] \]

\[ \begin{align*}
A_{\text{shp1}} &= \left( \frac{0.155}{0.868} \right) \text{-in}^2 \\
A_{\text{shp2}} &= \left( \frac{0.158}{0.868} \right) \text{-in}^2
\end{align*} \]

\[ \begin{align*}
\text{Allowables for plates that fastener goes through} \]
- \( F_{su1} := T_{f1E} \cdot 27\text{-ksi} \), \( F_{su1} = 26.46\text{-ksi} \) (Ultimate Shear Allowable for Plate 1)
- \( F_{su2} := T_{f2E} \cdot 43\text{-ksi} \), \( F_{su2} = 42.14\text{-ksi} \) (Ultimate Shear Allowable for Plate 2)
- \( P_{su} := \left( A_{\text{shp1}} \cdot F_{su1} \right) \), \( P_{su} = \left( \frac{4112}{36567} \right)\text{-lbf} \) (Shear Ultimate Allowable)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Upper Vacuum Case

**MS for Shear Tear-Out**

\[
MS_{su} := \left( \frac{P_{su}}{V \cdot SF_{u} \cdot FF} \right) - 1
\]

\[
MS_{bh1} := \min\{MS_{su}\}
\]

\[MS_{bh1} = 4.008\]

... Shear Tear-Out MS

**Bearing Check**

*Recall bolt hole dimensions*

\[tf_1 = 0.38\text{ in}\]

(Thickness of Plate 1)

\[tf_2 = 0.75\text{ in}\]

(Thickness of Plate 2)

\[edge_1 = 0.47\text{ in}\]

(Edge Distance for thru Hole in Plate 1)

\[edge_2 = 0.844\text{ in}\]

(Edge Distance for tapped Hole in Plate 2)

Typical Bearing Failure

\[A_{br} := (tf \cdot \min(D, D_{shank}))\]

\[A_{br} = \left( \frac{0.189}{0.373} \right)^2 \text{in}^2\]

(Bearing Areas)

\[e_D := \frac{edge}{D_{hole}}\]

\[e_D = \left( \frac{0.885}{1.589} \right)\]

(e/D for Plates)

**Allowables for plates that fastener goes through**

**Bearing strength at e/D = 1.5**

\[F_{bru15,1} := TfE \cdot 67\text{ksi}\]

\[F_{bru15,1} = 65.66\text{ksi}\]

\[F_{br15,1} := TfE \cdot 50\text{ksi}\]

\[F_{br15,1} = 49\text{ksi}\]

\[F_{bru15,2} := TfE \cdot 107\text{ksi}\]

\[F_{bru15,2} = 104.86\text{ksi}\]

\[F_{br15,2} := TfE \cdot 86\text{ksi}\]

\[F_{br15,2} = 84.28\text{ksi}\]

**Bearing strength at e/D = 2.0**

\[F_{bru20,1} := TfE \cdot 88\text{ksi}\]

\[F_{bru20,1} = 86.24\text{ksi}\]

\[F_{br20,1} := TfE \cdot 58\text{ksi}\]

\[F_{br20,1} = 56.84\text{ksi}\]

\[F_{bru20,2} := TfE \cdot 140\text{ksi}\]

\[F_{bru20,2} = 137.2\text{ksi}\]

\[F_{br20,2} := TfE \cdot 101\text{ksi}\]

\[F_{br20,2} = 98.98\text{ksi}\]
**Modified bearing strength**

\[
F_{bru_{m1}} := \begin{cases} 
\frac{e_{D1}}{2.0}, & \text{if } e_{D1} > 2.0, \\
F_{bru_{20}}, & \text{if } e_{D1} > 1.5 \\
\left( e_{D1} < 2.0 \right), & \text{if } F_{bru_{151}} + \frac{e_{D1} - 1.5}{2.0 - 1.5} \left( F_{bru_{20}} - F_{bru_{151}} \right) \left[ F_{bru_{151}} \left( e_{D1} - 0.5 \right) \right] 
\end{cases}
\]

\[
F_{bru_{m2}} := \begin{cases} 
\frac{e_{D2}}{2.0}, & \text{if } e_{D2} > 2.0, \\
F_{bru_{20}}, & \text{if } e_{D2} > 1.5 \\
\left( e_{D2} < 2.0 \right), & \text{if } F_{bru_{152}} + \frac{e_{D2} - 1.5}{2.0 - 1.5} \left( F_{bru_{20}} - F_{bru_{152}} \right) \left[ F_{bru_{152}} \left( e_{D2} - 0.5 \right) \right] 
\end{cases}
\]

\[
F_{bry_{m1}} := \begin{cases} 
\frac{e_{D1}}{2.0}, & \text{if } e_{D1} > 2.0, \\
F_{bry_{20}}, & \text{if } e_{D1} > 1.5 \\
\left( e_{D1} < 2.0 \right), & \text{if } F_{bry_{151}} + \frac{e_{D1} - 1.5}{2.0 - 1.5} \left( F_{bry_{20}} - F_{bry_{151}} \right) \left[ F_{bry_{151}} \left( e_{D1} - 0.5 \right) \right] 
\end{cases}
\]

\[
F_{bry_{m2}} := \begin{cases} 
\frac{e_{D2}}{2.0}, & \text{if } e_{D2} > 2.0, \\
F_{bry_{20}}, & \text{if } e_{D2} > 1.5 \\
\left( e_{D2} < 2.0 \right), & \text{if } F_{bry_{152}} + \frac{e_{D2} - 1.5}{2.0 - 1.5} \left( F_{bry_{20}} - F_{bry_{152}} \right) \left[ F_{bry_{152}} \left( e_{D2} - 0.5 \right) \right] 
\end{cases}
\]

\[
F_{bru_m} = \begin{pmatrix} 25.287 \\ 110.646 \end{pmatrix} \left( \frac{\text{Plate1}}{\text{Plate2}} \right) \quad \text{(Ultimate)} 
\]

\[
F_{bry_m} = \begin{pmatrix} 18.871 \\ 86.91 \end{pmatrix} \left( \frac{\text{Plate1}}{\text{Plate2}} \right) \quad \text{(Yield)} 
\]

\[
P_{bru} := \frac{A_{br} \cdot F_{bru_m}}{1} 
\]

\[
P_{bry} := \frac{A_{br} \cdot F_{bry_m}}{1} 
\]

**MS for Bearing Failure**

\[
MS_{bru} := \frac{P_{bru}}{V \cdot SF_u \cdot FF} - 1 
\]

\[
MS_{bru} = \begin{pmatrix} 4.816 \\ 49.229 \end{pmatrix} \left( \frac{\text{Plate1}}{\text{Plate2}} \right) 
\]

\[
MS_{bb} := \min \{ MS_{bru} \} 
\]

\[
MS_{bb} = 4.816 
\]

... Bearing MS based on Ultimate Strength
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Side - Tab Angle Bracket to Upper Vacuum Case

\[
MS_{bry} := \frac{P_{bry}}{V \cdot S_{FY} \cdot FF} - 1
\]

\[
MS_{bry} = \begin{pmatrix} 5.94 \\ 62.13 \end{pmatrix}
\]

\[
MS_{bb} := \min(\{MS_{bry}\})
\]

\[
MS_{bb} = 5.945
\]

... Bearing MS based on Yield Strength
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
TRD Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1351N4-12, .2500-28, 0.750 L, A-286, Heat Resistant Steel"
Washer := "NAS1149E0463R, .250 Nom Dia, 0.063 T, A-286, Passivate"
Nut := "NAS1291-C4M, .2500-28 UNJF-3B"

Flange_1 := "2.70in Bathtub Bracket"
Part_Number_1 := "SDG39137848-002"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange one edge1 := .347 in

Flange_2 := "Lower Trunnion Bridge Beam"
Part_Number_2 := "SDG39135735"
Material_2 := "AL ALY 7050-T7451"
Minimum edge distance of flange two edge2 := .375 in

Loads (reference)

Applied tensile load
P := 201.lbf

Applied shear load
V := 357.lbf

Applied bending moment
M := 0in-lbf

Factors of Safety (reference)

SFu := 2.00 (Ultimate)

FF := 1.15 (Fitting factor)

SFy := 1.25 (Yield)

SFsep := 1.20 (Joint Separation)

Temperature data (reference)

Assembly Temp_initial := 70-deg
Temp_max := 140-deg (Maximum)
Temp_min := -76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data (Bolt = "NAS1351N4-12, .2500-28, 0.750 L, A-286, Heat Resistant Steel")

Nominal diameter of bolt
D := .2500 in

Number of threads/inch
Nt := 28 \frac{1}{in}

Shank diameter of bolt
D_shank := .2435 in

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Total length of bolt
L := .75 in

Threaded length
Lt := .75 in (If bolt is fully threaded, input Lt = L)

Bolt head dia. across flats
dw := .365 in (dia of pressure boss if it exists, otherwise dia of head)

Bolt head height
bh := .244 in (head height is 0 if bolt is flat head)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer TRD Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>SDG39137848-002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kent Peters</td>
<td>08/21/2008</td>
<td></td>
</tr>
<tr>
<td>C. Bala</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Bolt Data cont. (Bolt = "NAS1351N4-12, .2500-28, 0.750 L, A-286, Heat Resistant Steel")

- **Temperature correction factor for bolt strength**: $T_{Su, bolt} := .96$  
- **Bolt ultimate tensile allowable stress**: $F_{tu, bolt} := 160000$ psi  
- **Bolt ultimate shear allowable stress**: $F_{su, bolt} := 0.6 \times F_{tu, bolt}$
- **Temperature correction factor for bolt modulus**: $T_{E, bolt} := .98$  
- **Modulus of elasticity of bolt**: $E_{bolt} := \left(29.1 \times 10^6 \text{ psi}\right)$
- **Thermal coefficients for bolt**:  
  - **$\beta_{, bolt\_hot} := 9.1 \times 10^{-6} \text{ in}^{-1} \text{ deg}^{-1}$**  
  - **$\beta_{, bolt\_cold} := 8.5 \times 10^{-6} \text{ in}^{-1} \text{ deg}^{-1}$**

### Washer Data (Washer = "NAS1149E0463R, .250 Nom Dia, 0.063 T, A-286, Passivate")

- **Thickess of washers**:  
  - Head: $t_{wh} := .063$ in  
  - Nut: $t_{wn} := .063$ in
- **Diameter of washer under head**:  
  - Outer: $D_{woh} := .500$ in  
  - Inner: $D_{wih} := .265$ in
- **Modulus of elasticity**:  
  - Head: $E_{washeh} := \left(29.1 \times 10^6 \text{ psi}\right)$  
  - Nut: $E_{washern} := \left(29.1 \times 10^6 \text{ psi}\right)$

### Nut Data (Nut = "NAS1291-C4M, .2500-28 UNJF-3B")

- **Height of nut**: $H := .204$ in  
- **Temperature correction factor for nut strength**: $T_{S, nut} := .96$  
- **Ultimate allowable stress, tensile**: $F_{tu, nut} := 125000$ psi  
- **Ultimate axial strength of nut**: $P_{tu, nut} := 4530$ lbf
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
TRD Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole

\[ D_{\text{hole}} = 0.272 \text{ in} \]

Material_1 = "AL ALY 6061-T651"
Material_2 = "AL ALY 7050-T7451"

Flange_1 = "2.70in Bathtub Bracket"
Flange_2 = "Lower Trunnion Bridge Beam"

Thickness of flanges
\[ t_{f1} = 0.100 \text{ in} \]
\[ t_{f2} = 0.250 \text{ in} \]

Compressive Modulus of elasticity
\[ E_{\text{flange1}} = 10.1 \times 10^6 \text{ psi} \]
\[ E_{\text{flange2}} = 10.6 \times 10^6 \text{ psi} \]

Temperature correction factor
\[ T_{f1}E = 0.98 \]
\[ T_{f2}E = 0.98 \]

Coefficient of thermal expansion for flanges
\[ \beta_{\text{flange1, hot}} = 12.8 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange2, hot}} = 12.5 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange1, cold}} = 12.1 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange2, cold}} = 12.1 \times 10^{-6} \text{ in/in deg} \]

Torque/Preload data

Maximum torque
\[ T_{\text{max}} = 103.2 \text{ in-lbf} \]

Minimum torque
\[ T_{\text{min}} = 87.7 \text{ in-lbf} \]

Joint is lubed/dry
Preload
\[ u = 0.25 \]

Uncertainty
\[ k = 0.15 \]

Loading plane factor
\[ n = 0.5 \]

(Shigley’s "Mechanical Engineering Design")

Stiffness and Margin calculations are
This file uses the calculations shown in \escfil02\2i11_mathcad8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Fri Apr 27 14:15:49 2007

5.10.1.1-21 ESCG-4005-05-AMS-0039
### Bolt Load data (cont.)

| Applied Tensile load on the bolt | P = 201.000 lbf | Max. load on the bolt with preload and Factor of safety | Pb = 3604 lbf | (ultimate) |
| Applied shear on the bolt | V = 357.000 lbf | Pby = 3574 lbf | (yield) |
| Applied bending on the bolt | M = 0.000 in-lbf | Max. load on the bolt with preload WithOut factor of safety | Pbapp = 3564 lbf |

| Bolt ultimate tensile strength | PA_t = 5419 lbf | Bolt shear strength | VAu = 3001 lbf |
| Thread pullout strength | PA_s = 4349 lbf | Bolt bending strength | MAu = 150 in-lbf |
| Nut ultimate tensile strength | Pt_u_nut = 4349 lbf |

### General Checks

- **length_check** = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- **cone_check** = "Joint pressure cone does not extend pass flange edge"
- **preload_check** = "Nominal preload >= 65% of bolt yield strength"
- **washer_check** = "Washers under head and nut do not extend past flanges"

### Summary of Margins for bolt:

| Joint separation | MS_1 = 5.12 | Direct Thread shear Ultimate | MS_6 = 8.41 |
| Direct Tension Ultimate | MS_2 = 10.72 | Total Thread shear Ultimate | MS_7 = 0.21 |
| Direct Tension Yield | MS_3 = 13.07 | Shear Ultimate | MS_8 = 2.65 |
| Total Tension Ultimate | MS_4 = 0.5 | Bending Ultimate | MS_9 = 100 |
| Total Tension Yield | MS_5 = 0.14 | Combined shear, tension and bending ultimate | MS_10 = 0.46 |

**Smallest margin of safety for the bolt, and the failure mode:**

- MSbolt = 0.14
- Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

Fail-safe Loads

- Applied tensile load: \[ P_{FS} = 240 \text{ lbf} \]
- Applied shear load: \[ V_{FS} = 666 \text{ lbf} \]
- Applied bending moment: \[ M_{FS} = 0 \text{ in-lbf} \]

Fail-safe Factors of Safety

- Ultimate: \[ SF_{U,FS} = 1.0 \]
- Joint Separation: \[ SF_{Sep,FS} = 1.0 \]

Summary of fail-safe Margins for bolt:

- Joint separation: \[ MS_{FS1} = 5.15 \]
- Direct Tension Ultimate: \[ MS_{FS2} = 18.64 \]
- Total Tension Ultimate: \[ MS_{FS3} = 0.52 \]
- Direct Thread shear Ultimate: \[ MS_{FS4} = 14.76 \]
- Total Thread shear Ultimate: \[ MS_{FS5} = 0.22 \]
- Shear Ultimate: \[ MS_{FS6} = 2.92 \]
- Bending Ultimate: \[ MS_{FS7} = 10 \]
- Combined shear, tension and bending ultimate: \[ MS_{FS8} = 0.48 \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

- \[ MS_{bolt,FS} = 0.22 \]
- Failure Mode _FS_ = "Total Thread Shear Ultimate (Nut)"

Fri Apr 27 14:16:05 2007
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors
- SFu = 2.000 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

Input Loads
- V = 357 lbf (Shear Load)
- P = 201,000 lbf (Axial Load)

Bolt calc results
- Pb = 3604 lbf (Max Bolt Load)

Dimensions
- L = 0.750 in (Length of Bolt)
- twh = 0.063 in (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions
- tf₁ := tf₁ = 0.100 in (Entire Thickness of Flange 1)
- T₁E = 0.980
- tf₂ := tf₂ = 0.250 in (Entire Thickness of Flange 2)
- T₂E = 0.980
- edge₁ := edge₁ = 0.347 in (Edge Distance for Hole in Plate 1)
- edge₂ := edge₂ = 0.375 in (Edge Distance for Hole in Plate 2)

Dimensions
- D = 0.250 in (Diameter of Bolt)
- D_shank = 0.244 in (Min. Shank Diameter of Bolt)
- D_hole = 0.272 in (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shrp1} := 2 \cdot tf_{1} \cdot \text{edge}_{1} \cdot \frac{1}{2} \cdot \text{D}_{hole} \]

\[ A_{shrp1} = \frac{0.042}{0.119} \text{ in}^2 \]

Allowables for plates that fastener goes through

\[ F_{su1} := T_{1E} \cdot 27 \text{ ksi} \]

\[ F_{su2} := T_{2E} \cdot 43 \text{ ksi} \]

\[ P_{su} := \left( A_{shrp1} \cdot F_{su} \right) \]

\[ P_{su} = \left( 1117 \right) \text{ lbf} (Shear Ultimate Allowable) \]

MS for Shear Tear-Out

\[ M_{su} := \frac{P_{su}}{V \cdot SF_{u} \cdot FF} \]

\[ M_{su} = \left( 0.36 \right) (Plate1) \]

\[ M_{su} = \left( 5.13 \right) (Plate2) \]

\[ M_{su} = \text{min}(M_{su}) \]

\[ M_{su} = 0.36 \]

... Shear Tear-Out MS

5.10.1.1-24

ESCG-4005-05-AMS-0039
### Bearing Check

Recall bolt hole dimensions

- \( tf_1 = 0.100 \text{ in} \) (Thickness of Plate 1)
- \( tf_2 = 0.250 \text{ in} \) (Thickness of Plate 2)
- \( \text{edge}_1 = 0.347 \text{ in} \) (Edge Distance for thru Hole in Plate 1)
- \( \text{edge}_2 = 0.375 \text{ in} \) (Edge Distance for tapped Hole in Plate 2)

\[
A_{br} := (tf_{min}(D, D_{shank})) \quad \text{Plate1} \quad \text{Plate2} \\
A_{br} = \left( \frac{0.024}{0.061} \right)^2 \quad \text{(Bearing Areas)}
\]

\[
\text{e}_D := \frac{\text{edge}}{D_{hole}} \quad \text{e}_D = \left( \frac{1.276}{1.379} \right) \quad \text{(e/D for Plates)}
\]

### Allowables for plates that fastener goes through

<table>
<thead>
<tr>
<th>Bearing strength at e/D = 1.5</th>
<th>Bearing strength at e/D = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru15₁ := T11E 67ksi</td>
<td>Fbru15₁ := T11E 88ksi</td>
</tr>
<tr>
<td>Fbry15₁ := T11E 50ksi</td>
<td>Fbry15₁ := T11E 58ksi</td>
</tr>
<tr>
<td>Fbru15₂ := T12E 107ksi</td>
<td>Fbru15₂ := T12E 140ksi</td>
</tr>
<tr>
<td>Fbry15₂ := T12E 86ksi</td>
<td>Fbry15₂ := T12E 101ksi</td>
</tr>
</tbody>
</table>

#### Modified bearing strength

\[
Fbru_{m1} := \begin{cases} 
10.935 & \text{if } e_D > 2.0, Fbru_{201}, \text{if } e_D > 1.5, e_D < 2.0, Fbru_{151} + \frac{e_D - 1.5}{2.0 - 1.5} (Fbru_{201} - Fbru_{151}) \cdot \frac{Fbru_{151} (e_D - 0.5)}{2} 
\end{cases}
\]

\[
Fbru_{m2} := \begin{cases} 
10.935 & \text{if } e_D > 2.0, Fbru_{202}, \text{if } e_D > 1.5, e_D < 2.0, Fbru_{152} + \frac{e_D - 1.5}{2.0 - 1.5} (Fbru_{202} - Fbru_{152}) \cdot \frac{Fbru_{152} (e_D - 0.5)}{2} 
\end{cases}
\]

\[
Fbry_{m1} := \begin{cases} 
8.011 & \text{if } e_D > 2.0, Fbry_{201}, \text{if } e_D > 1.5, e_D < 2.0, Fbry_{151} + \frac{e_D - 1.5}{2.0 - 1.5} (Fbry_{201} - Fbry_{151}) \cdot \frac{Fbry_{151} (e_D - 0.5)}{2} 
\end{cases}
\]

\[
Fbry_{m2} := \begin{cases} 
8.011 & \text{if } e_D > 2.0, Fbry_{202}, \text{if } e_D > 1.5, e_D < 2.0, Fbry_{152} + \frac{e_D - 1.5}{2.0 - 1.5} (Fbry_{202} - Fbry_{152}) \cdot \frac{Fbry_{152} (e_D - 0.5)}{2} 
\end{cases}
\]

\[
Fbru_m = \begin{pmatrix} 50.935 \\ 92.138 \end{pmatrix} \quad \text{(Ultimate)}
\]

\[
Fbry_m = \begin{pmatrix} 38.011 \\ 74.055 \end{pmatrix} \quad \text{(Yield)}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
TRD Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

\[
P_{bru} := \frac{(A_{br} \cdot F_{bru,m})}{V \cdot SFu \cdot FF} - 1
\]

\[
MS_{bru} = \frac{1240}{5609} \text{ lbf} \quad (\text{Bearing Ultimate Allowable})
\]

\[
P_{bry} := \frac{(A_{br} \cdot F_{bry,m})}{V \cdot SFy \cdot FF} - 1
\]

\[
MS_{bry} = \frac{926}{4508} \text{ lbf} \quad (\text{Bearing Yield Allowable})
\]

**MS for Bearing Failure**

\[
MS_{bru} = \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right)
\]

\[
MS_{bry} = \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right)
\]

\[
MS_{bh2} := \min(\{MS_{bru}\})
\]

\[
MS_{bh3} := \min(\{MS_{bry}\})
\]

\[
MS_{bh2} = 0.51
\]

... **Bearing MS based on Ultimate Strength**

\[
MS_{bh3} = 0.804
\]

... **Bearing MS based on Yield Strength**
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
TRD Side - Right Angle to Sill Joint Assy

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1351N4-18, .2500-28, 1.125 L, A-286, Heat Resistant Steel"
Washer := "NAS1149E0463R, .250 Nom Dia, 0.063 T, A-286, Passivate"
Nut := "NAS1291-C4M, .2500-28 UNJF-3B"

Flange_1 := "Right Angle Bracket"
Part_Number_1 := "SDG39137848-003"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange one edge1 := .375 in

Flange_2 := "Sill Joint Assy"
Part_Number_2 := "SDG39135730"
Material_2 := "AL ALY 7050-T7451"
Minimum edge distance of flange two edge2 := .380 in

Loads (reference)
- Applied tensile load
  \( P = 201 \text{ lbf} \)
- Applied shear load
  \( V = 357 \text{ lbf} \)
- Applied bending moment
  \( M = 0 \text{ in-lbf} \)

Factors of Safety (reference)
- SFu := 2.00 (Ultimate)
- SFy := 1.25 (Yield)
- FF := 1.15 (Fitting factor)
- SFsep := 1.20 (Joint Separation)

Temperature data (reference)
- Assembly Temp_initial := 70 deg
- Temp_max := 140 deg (Maximum)
- Temp_min := -76 deg (Minimum)

Bolt Data (Bolt = "NAS1351N4-18, .2500-28, 1.125 L, A-286, Heat Resistant Steel")
- Nominal diameter of bolt
  \( D = .2500 \text{ in} \)
- Number of threads/inch
  \( N_t = 28 \frac{1}{\text{in}} \)
- Shank diameter of bolt
  \( D_{\text{shank}} = .2435 \text{ in} \)
- Total length of bolt
  \( L = 1.125 \text{ in} \)
- Threaded length
  \( L_t = 1.000 \text{ in} \)
- Bolt head dia. across flats
  \( d_w = .365 \text{ in} \)
- Bolt head height
  \( b_h = .244 \text{ in} \)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

(If bolt is fully threaded, input \( L_t = L \))
(dia of pressure boss if it exists, otherwise dia of head)
(head height is 0 if bolt is flat head)

5.10.1.1-27 ESCG-4005-05-AMS-0039
Bolt Data cont. (Bolt = "NAS1351N4-18, 2500-28, 1.125 L, A-286, Heat Resistant Steel")

Thread data lookup table is hidden
This file uses the data shown in \escfil02\2111_mathcad\8307_bolts\Rev_D\thread_data.mcd

<table>
<thead>
<tr>
<th>Temperature correction factor for bolt strength</th>
<th>TSu_bolt := .96</th>
<th>TSy_bolt := .96 (MMPDS-03, Fig. 6.2.1.1.1.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt ultimate tensile allowable stress</td>
<td>Ftu_bolt := 160000 psi</td>
<td>Fty_bolt := 120000 psi</td>
</tr>
<tr>
<td>Bolt ultimate shear allowable stress</td>
<td>Fsu_bolt := 0.6 \cdot Ftu_bolt</td>
<td></td>
</tr>
<tr>
<td>Temperature correction factor for bolt modulus</td>
<td>TE_bolt := .98 (MMPDS-03, Fig. 6.2.1.1.4(a).)</td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity of bolt</td>
<td>E_bolt := ( 29.1 \cdot 10^6 ) \cdot psi (MMPDS-03, Fig. 6.2.1.0(b).)</td>
<td></td>
</tr>
</tbody>
</table>
| Thermal coefficients for bolt                 | \( \beta_{\text{bolt\_hot}} := 9.1 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{deg}} \)
|                                              | \( \beta_{\text{bolt\_cold}} := 8.5 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{deg}} \) (MMPDS-03, Fig. 6.2.1.0.) |

Washer Data (Washer = "NAS1149E0463R, .250 Nom Dia, 0.063 T, A-286, Passivate")

<table>
<thead>
<tr>
<th>Thickness of washers:</th>
</tr>
</thead>
<tbody>
<tr>
<td>head</td>
</tr>
<tr>
<td>twh := .063 in</td>
</tr>
<tr>
<td>(these are total washer thickness, if there are more than one)</td>
</tr>
<tr>
<td>nut</td>
</tr>
<tr>
<td>twn := .063 in</td>
</tr>
</tbody>
</table>

Diameter of washer under head:

<table>
<thead>
<tr>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwoh := .500 in</td>
</tr>
<tr>
<td>Inner</td>
</tr>
<tr>
<td>Dwih := .265 in</td>
</tr>
</tbody>
</table>

Modulus of elasticity:

<table>
<thead>
<tr>
<th>head</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_washerh := ( 29.1 \cdot 10^6 ) \cdot psi</td>
</tr>
<tr>
<td>nut</td>
</tr>
<tr>
<td>E_washern := ( 29.1 \cdot 10^6 ) \cdot psi</td>
</tr>
</tbody>
</table>

Nut Data (Nut = "NAS1291-C4M, .2500-28 UNJF-3B")

<table>
<thead>
<tr>
<th>Height of nut</th>
</tr>
</thead>
<tbody>
<tr>
<td>H := .204 in</td>
</tr>
<tr>
<td>Nut dia. across flats</td>
</tr>
<tr>
<td>Dn := .385 in</td>
</tr>
<tr>
<td>Temperature correction factor for nut strength</td>
</tr>
<tr>
<td>Ultimate allowable stress, tensile</td>
</tr>
<tr>
<td>Ftu_nut := 125000 psi</td>
</tr>
<tr>
<td>Fsu_nut := 0.6 \cdot Ftu_nut (Shear)</td>
</tr>
<tr>
<td>Ultimate axial strength of nut</td>
</tr>
<tr>
<td>Ptu_nut := 4530 lbf</td>
</tr>
</tbody>
</table>
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
TRD Side - Right Angle to Sill Joint Assy

Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole

\[ D_{\text{hole}} := 0.272 \text{ in} \]

Material \(1\) = "Right Angle Bracket"

Material \(2\) = "Sill Joint Assy"

Flange\(_1\) = "Right Angle Bracket"

Flange\(_2\) = "Sill Joint Assy"

Thickness of flanges:

\[ t_{f1} := 0.375 \text{ in} \]

\[ t_{f2} := 0.250 \text{ in} \]

Compressive Modulus of elasticity

\[ E_{\text{flange}1} := 10.1 \times 10^6 \text{ psi} \]

\[ E_{\text{flange}2} := 10.6 \times 10^6 \text{ psi} \]

Temperature correction factor (modulus)

\[ T_{f1E} := 0.98 \]

\[ T_{f2E} := 0.98 \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange}1, \text{hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

\[ \beta_{\text{flange}1, \text{cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

\[ \beta_{\text{flange}2, \text{hot}} := 12.5 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

\[ \beta_{\text{flange}2, \text{cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

Torque/Preload data

Maximum torque

\[ T_{\text{max}} := 103.2 \text{ in-lbf} \]

Minimum torque

\[ T_{\text{min}} := 87.7 \text{ in-lbf} \]

Joint is lubed

Preload Uncertainty

\[ u := 0.25 \]

(0.25 lubed/0.35 dry)

Torque coefficient

\[ k := 0.15 \]

(0.15 lubed/0.20 dry)

Loading plane factor

\[ n := 0.5 \]

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escfil02\2i11\mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

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Bolt Load data

\[ f_m := 0.336 \]

\[ f_L := 0.677 \]

Preload due to temperature

\[ P_{\text{thr, pos}} := 114.4 \text{ lbf} \]

\[ P_{\text{thr, neg}} := -240 \text{ lbf} \]

Uncertainty factor

\[ u = 0.250 \]

Torque coefficient

\[ k = 0.150 \]

Loading plane factor

\[ n = 0.500 \]

Psep = 241.200 lbf
Bolt Load data (cont.)

- Applied Tensile load on the bolt: \( P = 201.000 \text{ lbf} \)
- Applied shear on the bolt: \( V = 357.000 \text{ lbf} \)
- Applied bending on the bolt: \( M = 0.000 \text{ in-lbf} \)

Max. load on the bolt with preload and Factor of safety

- \( \text{Pb} = 3632 \text{ lbf} \) (ultimate)
- \( \text{Pby} = 3603 \text{ lbf} \) (yield)

Max. load on the bolt with preload Without factor of safety

- \( \text{Pbapp} = 3593 \text{ lbf} \)

Bolt ultimate tensile strength: \( \text{PAt} = 5419 \text{ lbf} \)

Thread pullout strength: \( \text{PAs} = 4349 \text{ lbf} \)

Nut ultimate tensile strength: \( \text{Ptu_nut} = 4349 \text{ lbf} \)

Bolt shear strength: \( \text{VAu} = 3001 \text{ lbf} \)

Bolt bending strength: \( \text{MAu} = 150 \text{ in-lbf} \)

General Checks

- length_check = "Bolt length is sufficient and nut fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
<th>Description</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>4.81</td>
<td>MS1</td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>10.72</td>
<td>MS2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.49</td>
<td>MS4</td>
<td>100</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.13</td>
<td>MS5</td>
<td></td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>0.45</td>
<td>MS10</td>
<td></td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

- MSbolt = 0.13
- Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

 Fail-safe Loads

<table>
<thead>
<tr>
<th>Applied load type</th>
<th>Load (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>( P_{FS} = 240 ) lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>( V_{FS} = 666 ) lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>( M_{FS} = 0 ) in-lbf</td>
</tr>
</tbody>
</table>

 Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate applied tensile load ( P_{b_FS} )</td>
<td>3600.7 lbf</td>
</tr>
<tr>
<td>Joint separation load ( V_{FS} )</td>
<td>666 lbf</td>
</tr>
<tr>
<td>Applied bending moment ( M_{FS} )</td>
<td>0 in-lbf</td>
</tr>
<tr>
<td>Joint separation ( P_{sep_FS} )</td>
<td>240.000 lbf</td>
</tr>
<tr>
<td>Total Thread shear Ultimate ( M_{S_FS} )</td>
<td>4.84</td>
</tr>
<tr>
<td>Shear Ultimate ( M_{S_FS} )</td>
<td>18.64</td>
</tr>
<tr>
<td>Bending Ultimate ( M_{S_FS} )</td>
<td>0.51</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate ( M_{S_FS} )</td>
<td>14.76</td>
</tr>
</tbody>
</table>

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{S_FS1} = 4.84 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{S_FS2} = 18.64 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{S_FS3} = 0.51 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{S_FS4} = 14.76 )</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( MS_{S_FS5} = 0.21 )</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>( MS_{S_FS6} = 2.92 )</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( MS_{S_FS7} = 10 )</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>( MS_{S_FS8} = 0.47 )</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt\_FS} = 0.21 \)  
\( Failure\_Mode\_FS = "Total\_Thread\_Shear\_Ultimate\_(Nut)" \)
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors

\[ SFu = 2.000 \quad (Ultimate) \]
\[ FF = 1.150 \quad (Fitting Factor) \]

Input Loads

\[ V = 357 \text{ lbf} \quad (Shear Load) \]
\[ P = 201.000 \text{ lbf} \quad (Axial Load) \]

Bolt calc results

\[ Pb = 3632 \text{ lbf} \quad (Max Bolt Load) \]

Dimensions

\[ L = 1.125 \text{ in} \quad (Length of Bolt) \]
\[ twh = 0.063 \text{ in} \quad (Thickness of Washer) \]

Shear Tear-Out Check

Recall bolt hole dimensions

\[ tf_1 := tf_1 = 0.375 \text{ in} \quad (Entire Thickness of Flange 1) \]
\[ tf_2 := tf_2 = 0.250 \text{ in} \quad (Entire Thickness of Flange 2) \]

\[ edge_1 := edge_1 = 0.375 \text{ in} \quad (Edge Distance for Hole in Plate 1) \]
\[ edge_2 := edge_2 = 0.380 \text{ in} \quad (Edge Distance for Hole in Plate 2) \]

\[ D = 0.250 \text{ in} \quad (Diameter of Bolt) \]
\[ D_{shank} = 0.244 \text{ in} \quad (Min. Shank Diameter of Bolt) \]
\[ D_{hole} = 0.272 \text{ in} \quad (Diameter of Hole) \]

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[
A_{shrpl} = \left[ \frac{2}{\text{plate}} \left( edge - \frac{1}{2} D_{\text{hole}} \right) \right]_{\text{Plate1}} \quad A_{shrpl} = 0.179 \quad (\text{in}^2)
\]

Allowables for plates that fastener goes through

\[ F_{su1} := T_{f1E} \cdot 27 \text{ ksi} \quad \text{(Ultimate Shear Allowable for Plate 1)} \]
\[ F_{su2} := T_{f2E} \cdot 43 \text{ ksi} \quad \text{(Ultimate Shear Allowable for Plate 2)} \]

\[ P_{su} := A_{shrpl} \cdot F_{su} \quad P_{su} = \left( \frac{4743}{5141} \right) \text{ lbf} \quad \text{(Shear Ultimate Allowable)} \]

MS for Shear Tear-Out

\[ MS_{su} := \left( \frac{P_{su}}{V \cdot SFu \cdot FF} - 1 \right) \quad MS_{su} = \left[ 4.78 \quad (\text{Plate1}) \right] \quad \text{5.26} \quad (\text{Plate2}) \]

\[ MS_{bh1} := \min (MS_{su}) \quad MS_{bh1} = 4.776 \]

... Shear Tear-Out MS
Bearing Check

Recall bolt hole dimensions

\[ t_{f1} = 0.375 \text{ in} \quad (\text{Thickness of Plate 1}) \]
\[ t_{f2} = 0.250 \text{ in} \quad (\text{Thickness of Plate 2}) \]
\[ \text{edge}_1 = 0.375 \text{ in} \quad (\text{Edge Distance for thru Hole in Plate 1}) \]
\[ \text{edge}_2 = 0.380 \text{ in} \quad (\text{Edge Distance for tapped Hole in Plate 2}) \]

\[ A_{br} := (t_{f} \cdot \min(D, D_{\text{shank}})) \]
\[ \frac{\text{edge}}{D_{\text{hole}}} \]

\[ e_D := \frac{\text{edge}}{D_{\text{hole}}} \]

\[ A_{br} = \begin{pmatrix} \text{Plate1} \\ \text{Plate2} \end{pmatrix} \]
\[ A_{br} = \begin{pmatrix} 0.091 \\ 0.061 \end{pmatrix} \text{in}^2 \]

\[ e_D = \begin{pmatrix} 1.379 \\ 1.397 \end{pmatrix} \]

Allowables for plates that fastener goes through

Bearing strength at \( e/D = 1.5 \)

\[ F_{bru151} := T11E \cdot 67 \text{ksi} \]
\[ F_{bru152} := T11E \cdot 107 \text{ksi} \]
\[ F_{bury151} := T11E \cdot 50 \text{ksi} \]
\[ F_{bury152} := T11E \cdot 86 \text{ksi} \]

Bearing strength at \( e/D = 2.0 \)

\[ F_{bru201} := T11E \cdot 88 \text{ksi} \]
\[ F_{bru202} := T11E \cdot 140 \text{ksi} \]
\[ F_{bury201} := T11E \cdot 58 \text{ksi} \]
\[ F_{bury202} := T11E \cdot 101 \text{ksi} \]

Modified bearing strength

\[ F_{bru_m1} := \begin{cases} e_D > 2.0, F_{bru201} & (e_D > 1.5) (e_D < 2.0), F_{bru151} + e_D - 1.5 \\ 2.0 - 1.5 \end{cases} \]
\[ (F_{bru201} - F_{bru151}) \cdot [F_{bru151} (e_D - 0.5)] \]

\[ F_{bru_m2} := \begin{cases} e_D > 2.0, F_{bru202} & (e_D > 1.5) (e_D < 2.0), F_{bru152} + e_D - 1.5 \\ 2.0 - 1.5 \end{cases} \]
\[ (F_{bru202} - F_{bru152}) \cdot [F_{bru152} (e_D - 0.5)] \]

\[ F_{bury_m1} := \begin{cases} e_D > 2.0, F_{bury201} & (e_D > 1.5) (e_D < 2.0), F_{bury151} + e_D - 1.5 \\ 2.0 - 1.5 \end{cases} \]
\[ (F_{bury201} - F_{bury151}) \cdot [F_{bury151} (e_D - 0.5)] \]

\[ F_{bury_m2} := \begin{cases} e_D > 2.0, F_{bury202} & (e_D > 1.5) (e_D < 2.0), F_{bury152} + e_D - 1.5 \\ 2.0 - 1.5 \end{cases} \]
\[ (F_{bury202} - F_{bury152}) \cdot [F_{bury152} (e_D - 0.5)] \]

\[ F_{bru_m} = \begin{pmatrix} 57.694 \\ 94.066 \end{pmatrix} \text{ (Ultimate)} \]

\[ F_{bury_m} = \begin{pmatrix} 43.055 \\ 75.604 \end{pmatrix} \text{ (Yield)} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
TRD Side - Right Angle to Sill Joint Assy

\[
P_{bru} := (A_{br} \cdot F_{bru,m})
\]

\[
P_{bru} = \begin{pmatrix} 5268 \\ 5726 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Ultimate Allowable)}
\]

\[
P_{bry} := (A_{br} \cdot F_{bry,m})
\]

\[
P_{bry} = \begin{pmatrix} 3931 \\ 4602 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Yield Allowable)}
\]

**MS for Bearing Failure**

\[
MS_{bru} := \frac{P_{bru}}{V \cdot SF_{u} \cdot FF} - 1
\]

\[
MS_{bru} = \begin{pmatrix} 5.416 \\ 5.974 \end{pmatrix} \quad \text{Plate1, Plate2}
\]

\[
MS_{bh2} := \min(\text{MS}_{bru})
\]

\[
MS_{bh2} = 5.416 \quad \text{... Bearing MS based on Ultimate Strength}
\]

\[
MS_{bry} := \frac{P_{bry}}{V \cdot SF_{y} \cdot FF} - 1
\]

\[
MS_{bry} = \begin{pmatrix} 6.66 \\ 7.97 \end{pmatrix} \quad \text{Plate1, Plate2}
\]

\[
MS_{bh3} := \min(\text{MS}_{bry})
\]

\[
MS_{bh3} = 6.661 \quad \text{... Bearing MS based on Yield Strength}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
TRD Side - Tab Angle to Outer Bumper

CHECK

Note: Figure is for reference only. Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"
Washer := "NAS1149E0332R"
Nut := "MS21076L3N"

Flange_1 := "Outer Bumper"
Part_Number_1 := "SEG39137851"
Material_1 := "AL ALY 2219-T87"

Minimum edge distance of flange one edge1 := .85 in

Flange_2 := "Tab Angle Bracket"
Part_Number_2 := "SDG39137847"
Material_2 := "AL ALY 7075-T7351"

Minimum edge distance of flange two edge2 := .312 in

Loads (reference)

Applied tensile load P := 49.8 lbf
Applied shear load V := 489 lbf
Applied bending moment M := 0 in lbf

(Worst case combination)

Factors of Safety (reference)

SFu := 2.00 (Ultimate)
SFy := 1.25 (Yield)
FF := 1.15 (Fitting factor)
SFsep := 1.20 (Joint Separation)

Temperature data (reference)

Assembly Temp_initial := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := -76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Nominal diameter of bolt D := .19 in

Number of threads/inch Nt := 32 \frac{1}{in}

Shank diameter of bolt D_{shank} := .1885 in

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Total length of bolt L := .526 in

(If bolt is fully threaded, input Lt = L)

Threaded length Lt := .276 in

Bolt head dia. across flats dw := .357 in

(dia of pressure boss if it exists, otherwise dia of head)

Bolt head height bh := .122 in

(head height is 0 if bolt is flat head)
### Bolt Data cont. (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

- Temperature correction factor for bolt strength: $T_{Su_{\text{bolt}}} := 0.96$  
- $T_{Sy_{\text{bolt}}} := 0.96$  

- Bolt ultimate tensile allowable stress: $F_{tu_{\text{bolt}}} := 160000$ psi
- $F_{ty_{\text{bolt}}} := 120000$ psi

- Bolt ultimate shear allowable stress: $F_{su_{\text{bolt}}} := 0.6 \times F_{tu_{\text{bolt}}}$

- Temperature correction factor for bolt modulus: $E_{\text{bolt}} := 29.1 \times 10^6$ psi
- $T_{E_{\text{bolt}}} := 0.98$

### Washer Data (Washer = "NAS1149E0332R")

- Thickness of washers:
  - Head: $t_{\text{wh}} := 0.032$ in
  - Nut: $t_{\text{wn}} := 0.0$ in

- Diameter of washer under head:
  - Outer: $D_{\text{woh}} := 0.438$ in
  - Inner: $D_{\text{wi}} := 0.203$ in

- Diameter of washer under nut: $D_{\text{wn}} := 0.0$ in

- Modulus of elasticity:
  - Head: $E_{\text{washerh}} := (29.1 \times 10^6$ psi
  - Nut: $E_{\text{washerh}} := (0.0 \times 10^6$ psi

- Temperature correction factor for modulus:
  - Head: $T_{E_{\text{wsherh}}} := 0.98$
  - Nut: $T_{E_{\text{wshern}}} := 0.0$

### Nut Data (Nut = "MS21076L3N")

- Height of nut: $H := 0.250$ in
- Nut dia. across flats: $D_{\text{n}} := 0.290$ in

- Temperature correction factor for nut strength: $T_{S_n} := 0.96$

- Ultimate allowable stress, tensile: $F_{tu_{\text{nut}}} := 125000$ psi
- Ultimate axial strength of nut: $P_{tu_{\text{nut}}} := 2460$ lbf

- $F_{su_{\text{nut}}} := 0.6 \times F_{tu_{\text{nut}}}$ (Shear)

---

5.10.1.1-36  
ESCG-4005-05-AMS-0039
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of thru hole</td>
<td>D_hole := .213 in</td>
</tr>
<tr>
<td>Flange_1 = &quot;Outer Bumper&quot;</td>
<td></td>
</tr>
<tr>
<td>Material_1 = &quot;AL ALY 2219-T87&quot;</td>
<td></td>
</tr>
<tr>
<td>Thickness of flanges</td>
<td>tf1 := .100 in</td>
</tr>
<tr>
<td></td>
<td>tf2 := .125 in</td>
</tr>
<tr>
<td>Compressive Modulus of elasticity</td>
<td></td>
</tr>
<tr>
<td>E_flange1 := (10.8 \times 10^6 \text{psi})</td>
<td></td>
</tr>
<tr>
<td>E_flange2 := (10.6 \times 10^6 \text{psi})</td>
<td></td>
</tr>
</tbody>
</table>

Temperature correction factor (modulus)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1E</td>
<td>.96</td>
</tr>
<tr>
<td>T2E</td>
<td>.98</td>
</tr>
</tbody>
</table>

Coefficient of thermal expansion for flanges

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta_{\text{flange1_hot}}) := 12.4 \times 10^{-6} \text{in/in deg}</td>
<td></td>
</tr>
<tr>
<td>(\beta_{\text{flange2_hot}}) := 12.5 \times 10^{-6} \text{in/in deg}</td>
<td></td>
</tr>
<tr>
<td>(\beta_{\text{flange1_cold}}) := 11.6 \times 10^{-6} \text{in/in deg}</td>
<td></td>
</tr>
<tr>
<td>(\beta_{\text{flange2_cold}}) := 12.1 \times 10^{-6} \text{in/in deg}</td>
<td></td>
</tr>
</tbody>
</table>

Torque/Preload data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum torque</td>
<td>Tmax := 44.4 in-lbf</td>
</tr>
<tr>
<td>Minimum torque</td>
<td>Tmin := 37.8 in-lbf</td>
</tr>
<tr>
<td>Joint is lubed/dry</td>
<td></td>
</tr>
<tr>
<td>Preload Uncertainty</td>
<td>(u := 0.25) (0.25 lubed/0.35 dry)</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>(n := 0.5)</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>(k := 0.15) (0.15 lubed/0.20 dry)</td>
</tr>
</tbody>
</table>

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escfii02\2111_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Fri Apr 27 14:15:49 2007

Bolt Load data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>0.331</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td></td>
</tr>
<tr>
<td>PLDmax</td>
<td>2003 lbf</td>
</tr>
<tr>
<td>Pthr_pos</td>
<td>56 lbf</td>
</tr>
<tr>
<td>Pthr_neg</td>
<td>-117.6 lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>780 lbf</td>
</tr>
<tr>
<td>Nom. preload</td>
<td>1558 lbf</td>
</tr>
<tr>
<td>Uncertainty factor</td>
<td>(u = 0.250)</td>
</tr>
<tr>
<td>Preload to yield ratio</td>
<td>PLDratio = 0.703</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>(k = 0.150)</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>Psep = 59,760 lbf</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>(n = 0.500)</td>
</tr>
</tbody>
</table>

5.10.1.1-37

ESCG-4005-05-AMS-0039
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 49.800$ lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety</td>
<td>$P_b = 2022$ lbf $(ultimate)$</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 489.000$ lbf</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0.000$ in·lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload Without factor of safety</td>
<td>$P_{bapp} = 2013$ lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$P_{At} = 2957$ lbf</td>
</tr>
<tr>
<td>Bolt shear strength</td>
<td>$V_{Au} = 2572$ lbf</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>$P_{As} = 2362$ lbf</td>
</tr>
<tr>
<td>Bolt bending strength</td>
<td>$M_{Au} = 61$ in·lbf</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>$P_{tu_nut} = 2362$ lbf</td>
</tr>
</tbody>
</table>

General Checks

- **length_check** = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- **cone_check** = "Joint pressure cone does not extend pass flange edge"
- **preload_check** = "Nominal preload $\geq 65\%$ of bolt yield strength"
- **washer_check** = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_1 = 12.59$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_6 = 19.62$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_2 = 24.81$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_7 = 0.17$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_3 = 29.98$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_8 = 1.29$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_4 = 0.46$</td>
</tr>
<tr>
<td>$MS_9 = 100$</td>
<td></td>
</tr>
<tr>
<td>$MS_5 = 0.1$</td>
<td></td>
</tr>
<tr>
<td>$MS_10 = 0.32$</td>
<td></td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

- **MSbolt = 0.1**
- **Failure_Mode = "Total Tension Yield"**
Fail-safe Analysis

### Fail-safe Loads

- **Applied tensile load**
  
  \[
  P_{FS} = 105.6 \text{ lbf}
  \]

- **Applied shear load**
  
  \[
  V_{FS} = 666.6 \text{ lbf}
  \]

- **Applied bending moment**
  
  \[
  M_{FS} = 0 \text{ in-lbf}
  \]

### Fail-safe Factors of Safety

- **Ultimate**
  
  \[
  SF_{u,FS} = 1.0
  \]

- **Joint Separation**
  
  \[
  SF_{sep,FS} = 1.0
  \]

### Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfl02\2i11\mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

---

**Bolt Fail-safe Load data**

- **Joint separation load**
  
  \[
  P_{sep,FS} = 105.600 \text{ lbf}
  \]

- **Max. load on the bolt (ultimate)**
  
  \[
  P_{b,FS} = 2023.5 \text{ lbf}
  \]

### Summary of fail-safe Margins for bolt:

- **Joint separation**
  
  \[
  MS_{FS1} = 6.69
  \]

- **Direct Tension Ultimate**
  
  \[
  MS_{FS2} = 23.35
  \]

- **Total Tension Ultimate**
  
  \[
  MS_{FS3} = 0.46
  \]

- **Direct Thread shear Ultimate**
  
  \[
  MS_{FS4} = 18.45
  \]

- **Total Thread shear Ultimate**
  
  \[
  MS_{FS5} = 0.17
  \]

- **Shear Ultimate**
  
  \[
  MS_{FS6} = 2.35
  \]

- **Bending Ultimate**
  
  \[
  MS_{FS7} = 10
  \]

- **Combined shear, tension and bending ultimate**
  
  \[
  MS_{FS8} = 0.41
  \]

---

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

- **MS_{bolt,FS} = 0.17**
- **Failure Mode_{FS} = "Total Thread Shear Ultimate (Nut)"**
Bolt Hole Analysis

Recall loads from bolt calculation

<table>
<thead>
<tr>
<th>Safety Factors</th>
<th>SFu = 2.000</th>
<th>(Ultimate)</th>
<th>SFy = 1.250</th>
<th>(Yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>1.150</td>
<td>(Fitting Factor)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Input Loads

| V = 489 lbf | (Shear Load) |
| P = 49.800 lbf | (Axial Load) |

Bolt calc results

| Pb = 2022 lbf | (Max Bolt Load) |

Dimensions

| L = 0.526 in | (Length of Bolt) |
| twh = 0.032 in | (Thickness of Washer) |

Shear Tear-Out Check ( Flange_1 = "Outer Bumper" , Flange_2 = "Tab Angle Bracket" )

Recall bolt hole dimensions

| tf1 := tf1 | tf1 = 0.100 in | (Entire Thickness of Flange 1) |
| tf2 := tf2 | tf2 = 0.125 in | (Entire Thickness of Flange 2) |

edge1 := edge1 | edge1 = 0.850 in | (Edge Distance for Hole in Plate 1) |

edge2 := edge2 | edge2 = 0.312 in | (Edge Distance for Hole in Plate 2) |

D = 0.190 in | (Diameter of Bolt) |

D_shank = 0.188 in | (Min. Shank Diameter of Bolt) |

D_hole = 0.213 in | (Diameter of Hole) |

Typical shear tear-out failure

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{\text{shrpl}} := \left[ 2 \cdot \text{tf1} \cdot \left( \text{edge1} - \frac{1}{2} \text{D_hole} \right) \right] \]

\[ A_{\text{shrpl}} = \left( \frac{0.149}{0.051} \right) \text{in}^2 \]

Allowables for plates that fastener goes through

\[ F_{su_1} := \text{TF1E} \cdot 36 \text{ksi} \]

\[ F_{su_2} := \text{TF2E} \cdot 39 \text{ksi} \]

\[ F_{su_1} = 34.560 \text{ ksi} \] (Ultimate Shear Allowable for Plate 1)

\[ F_{su_2} = 38.220 \text{ ksi} \] (Ultimate Shear Allowable for Plate 2)

\[ P_{su} := \left( A_{\text{shrpl}} \cdot F_{su} \right) \]

\[ P_{su} = \left( \frac{5139}{1964} \right) \text{lbf} \] (Shear Ultimate Allowable)

MS for Shear Tear-Out

\[ \text{MS}_{su} := \left( \frac{P_{su}}{V \cdot SFu \cdot FF} - 1 \right) \]

\[ \text{MS}_{bh_1} := \min \left( \text{MS}_{su} \right) \]

\[ \text{MS}_{bh_1} = 0.746 \]

... Shear Tear-Out MS
Bearing Check

Recall bolt hole dimensions

\[ t_f^1 = 0.100 \text{ in} \]  
\[ t_f^2 = 0.125 \text{ in} \]  
\[ \text{edge}^1 = 0.850 \text{ in} \]  
\[ \text{edge}^2 = 0.312 \text{ in} \]

(Thickness of Plate 1)
(Thickness of Plate 2)
(Edge Distance for thru Hole in Plate 1)
(Edge Distance for tapped Hole in Plate 2)

\[ A_{br} := \frac{\text{edge} \cdot \text{min}(D, D_{shank})}{D_{hole}} \]  
\[ e_D := \frac{\text{edge}}{D_{hole}} \]

(Plate 1)
(Plate 2)

(Bearing Areas)
(e/D for Plates)

Allowables for plates that fastener goes through

Bearing strength at e/D = 1.5

\[ F_{bru15} := T1E \times 99 \text{ksi} \]
\[ F_{bru15} = 95.04 \text{ ksi} \]
\[ F_{bry15} := T1E \times 83 \text{ ksi} \]
\[ F_{bry15} = 79.68 \text{ ksi} \]
\[ F_{bru152} := T1E \times 102 \text{ ksi} \]
\[ F_{bru152} = 99.96 \text{ ksi} \]
\[ F_{bry152} := T1E \times 82 \text{ ksi} \]
\[ F_{bry152} = 80.36 \text{ ksi} \]

Bearing strength at e/D = 2.0

\[ F_{bru20} := T1E \times 126 \text{ ksi} \]
\[ F_{bru20} = 120.96 \text{ ksi} \]
\[ F_{bry20} := T1E \times 96 \text{ ksi} \]
\[ F_{bry20} = 92.16 \text{ ksi} \]
\[ F_{bru202} := T1E \times 132 \text{ ksi} \]
\[ F_{bru202} = 129.36 \text{ ksi} \]
\[ F_{bry202} := T1E \times 97 \text{ ksi} \]
\[ F_{bry202} = 95.06 \text{ ksi} \]

Modified bearing strength

\[ F_{bru_m1} := \begin{cases} e_D > 2.0, F_{bru201}, & \text{if } \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \left( F_{bru15} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru201} - F_{bru15} \right) \right) \\ e_D < 2.0, F_{bru201}, & \end{cases} \]

\[ F_{bru_m2} := \begin{cases} e_D > 2.0, F_{bru202}, & \text{if } \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \left( F_{bru152} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru202} - F_{bru152} \right) \right) \\ e_D < 2.0, F_{bru202}, & \end{cases} \]

\[ F_{bry_m1} := \begin{cases} e_D > 2.0, F_{bry201}, & \text{if } \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \left( F_{bry15} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry201} - F_{bry15} \right) \right) \\ e_D < 2.0, F_{bry201}, & \end{cases} \]

\[ F_{bry_m2} := \begin{cases} e_D > 2.0, F_{bry202}, & \text{if } \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \left( F_{bry152} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry202} - F_{bry152} \right) \right) \\ e_D < 2.0, F_{bry202}, & \end{cases} \]

\[ F_{bru_m} = \left[ \begin{array}{c} 120.96 \\ 96.44 \end{array} \right] \]  
\[ F_{bry_m} = \left[ \begin{array}{c} 92.16 \\ 77.53 \end{array} \right] \]

(Ultimate)
(Yield)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
TRD Side - Tab Angle to Outer Bumper

\[ P_{bru} := (A_{br} \cdot F_{bru \_m}) \]
\[ P_{bruy} := (A_{br} \cdot F_{bruy \_m}) \]

\[ P_{bru} = \begin{pmatrix} 2280 \\ 2272 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Ultimate Allowable)} \]
\[ P_{bruy} = \begin{pmatrix} 1737 \\ 1827 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Yield Allowable)} \]

**MS for Bearing Failure**

\[ MS_{bru} := \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \]
\[ MS_{bruy} := \frac{P_{bruy}}{V \cdot SFy \cdot FF} - 1 \]

\[ MS_{bru} = \begin{pmatrix} 1.027 \\ 1.020 \end{pmatrix} \quad \text{Plate1} \]
\[ MS_{bruy} = \begin{pmatrix} 1.47 \\ 1.6 \end{pmatrix} \quad \text{Plate1} \]

\[ MS_{bry} := \min (MS_{bru}) \]
\[ MS_{bry} := \min (MS_{bruy}) \]

\[ MS_{bh2} = 1.02 \quad \text{... Bearing MS based on Ultimate Strength} \]
\[ MS_{bh3} = 1.471 \quad \text{... Bearing MS based on Yield Strength} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
TRD Side - Bathtub Bracket to Outer Bumper

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"
Washer := "NAS1149E0332R"
Nut := "MS21076L3N"

Flange_1 := "2.70 in Bathtub Bracket"
Part_Number_1 := "SDG39137848-002"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange one
edge1 := .5 in

Flange_2 := "Outer Bumper"
Part_Number_2 := "SEG39137851"
Material_2 := "AL ALY 2219-T87"
Minimum edge distance of flange two
edge2 := .566 in

(Worst case combination)

Loads (reference)

Applied tensile load
P := 49.8 lbf

Applied shear load
V := 489 lbf

Applied bending moment
M := 0 in·lbf

Factors of Safety (reference)

SFu := 2.00 (Ultimate)
SFy := 1.25 (Yield)
FF := 1.15 (Fitting factor)
SFsep := 1.20 (Joint Separation)

Temperature data (reference)

Assembly
Temp_min := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := -76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if
maximun load occurs at a different
temperature this will be conservative

Bolt Data (Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286")

Nominal diameter of bolt
D := .19 in
Number of threads/inch
Nt := 32 \frac{1}{in}

Shank diameter of bolt
D_shank := .1885 in

Total length of bolt
L := .526 in

Threaded length
Lt := .276 in

Bolt head dia. across flats
dw := .357 in

Bolt head height
bh := .122 in

Note: if there is a retainer groove in the fastener, this
should be the calculated diameter to give an equivalent
cross sectional area

(If bolt is fully threaded, input Lt = L)

(dia of pressure boss if it exists, otherwise dia of head)

(head height is 0 if bolt is flat head)
Bolt Data cont. (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Thread data lookup table is hidden

This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

| Temperature correction factor for bolt strength | TSu_bolt := .96 | TSy_bolt := .96 (MMPDS-03, Fig. 6.2.1.1.1.) |
| Bolt ultimate tensile allowable stress | Ftu_bolt := 160000 psi |
| Bolt ultimate shear allowable stress | Fsu_bolt := 0.6 \times Ftu_bolt |

Temperature correction factor for bolt modulus

| Modulus of elasticity of bolt | E_bolt := (29.1 \times 10^6 \text{ psi}) |

Thermal coefficients for bolt

| \beta_{\text{bolt hot}} := 9.1 \times 10^{-6} \text{ in}^-1 \text{in}^{-1} \text{deg}^-1 |
| \beta_{\text{bolt cold}} := 8.5 \times 10^{-6} \text{ in}^-1 \text{in}^{-1} \text{deg}^-1 |

(MMPDS-03, Fig. 6.2.1.0(b).)

Washer Data (Washer = "NAS1149E0332R")

| Thickness of washers: | twh := .032 in | (these are total washer thickness, if there are more than one) |
| nut | twn := 0.0 in |

Diameter of washer under head:

| Outer | Dwoh := .438 in |
| Inner | Dwih := .203 in |

| Modulus of elasticity: |

| head | E_{\text{washer h}} := (29.1 \times 10^6 \text{ psi}) |
| nut | E_{\text{washer n}} := (0.0 \times 10^6 \text{ psi}) |

Nut Data (Nut = "MS21076L3N")

| Height of nut | H := .250 in |
| Nut dia. across flats | Dn := .290 in |

| Temperature correction factor for nut strength |

| TS_nut := .96 |
| Ultimate allowable stress, tensile |

| Ftu_nut := 125000 psi |
| Ultimate axial strength of nut |

| Fsu_nut := 0.6 \times Ftu_nut (Shear) |

| Ptu_nut := 2460 lbf |

5.10.1.1-44 ESCG-4005-05-AMS-0039
Title: Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
TRD Side - Bathtub Bracket to Outer Bumper

Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

- Diameter of thru hole: \( D_{\text{hole}} = 0.226 \text{ in} \)
- Flange 1 = "2.70 in Bathtub Bracket"
- Flange 2 = "Outer Bumper"
- Material 1 = "AL ALY 6061-T651"
- Material 2 = "AL ALY 2219-T87"
- Thickness of flanges: \( t_{f1} = 0.08 \text{ in} \) and \( t_{f2} = 0.10 \text{ in} \)
- Compressive Modulus of elastic:
  - Flange 1: \( E_{\text{flange1}} = 10.1 \times 10^6 \text{ psi} \)
  - Flange 2: \( E_{\text{flange2}} = 10.8 \times 10^6 \text{ psi} \)
- Temperature correction factor (modulus): \( T_{f1E} = 0.98 \) and \( T_{f2E} = 0.96 \)
- Coefficient of thermal expansion for flanges:
  - Flange 1:
    - Hot: \( \beta_{\text{flange1_hot}} = 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
    - Cold: \( \beta_{\text{flange1_cold}} = 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
  - Flange 2:
    - Hot: \( \beta_{\text{flange2_hot}} = 12.4 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)
    - Cold: \( \beta_{\text{flange2_cold}} = 11.6 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \)

Torque/Preload data

- Maximum torque: \( T_{\text{max}} = 44.4 \text{ in-lbf} \)
- Minimum torque: \( T_{\text{min}} = 37.8 \text{ in-lbf} \)

Joint is lubed/dry:
- Preload: \( u = 0.25 \)
- Uncertainty factor: \( k = 0.15 \)
- Torque coefficient: \( k = 0.15 \)
- Loading plane factor: \( n = 0.5 \)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escg\escg\escg-4005-05-AMS-0039

Bolt Load data

- Bolt/joint stiffness factor Max. preload:
  - PLDmax = 1999 lbf
- Nom. preload:
  - PLDnom = 795 lbf
- Preload to yield ratio (nom.):
  - PLDratio = 0.703
- Joint separation load:
  - Psep = 59.760 lbf

- Preload due to temperature:
  - Pthr_pos = 51.4 lbf
- Uncertainty factor:
  - \( u = 0.250 \)
- Load separation factor:
  - \( k = 0.150 \)
- Loading plane factor:
  - \( n = 0.500 \)
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 49.800\ lbf$</td>
<td>Max. load on the bolt with preload and Factor of safety</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 489.000\ lbf$</td>
<td>$P_b = 2019\ lbf$ (ultimate)</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0.000\ in\cdot lbf$</td>
<td>$P_{by} = 2012\ lbf$ (yield)</td>
</tr>
</tbody>
</table>

Max. load on the bolt with preload Without factor of safety:

$P_{app} = 2009\ lbf$

Bolt ultimate tensile strength:

$P_{At} = 2957\ lbf$

Bolt shear strength:

$V_{Au} = 2572\ lbf$

Thread pullout strength:

$P_{As} = 2362\ lbf$

Bolt bending strength:

$M_{Au} = 61\ in\cdot lbf$

Nut ultimate tensile strength:

$P_{tu\_nut} = 2362\ lbf$

General Checks

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>length_check</td>
<td>&quot;Bolt length is sufficient and nut fully engaged&quot;</td>
</tr>
<tr>
<td>cone_check</td>
<td>&quot;Joint pressure cone does not extend past flange edge&quot;</td>
</tr>
<tr>
<td>preload_check</td>
<td>&quot;Nominal preload &gt;= 65% of bolt yield strength&quot;</td>
</tr>
<tr>
<td>washer_check</td>
<td>&quot;Washers under head and nut do not extend past flanges&quot;</td>
</tr>
</tbody>
</table>

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_1 = 13.06$</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_2 = 24.81$</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_3 = 29.98$</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_4 = 0.46$</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_5 = 0.1$</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} = 0.1$  
Failure Mode = "Total Tension Yield"
Fail-safe Analysis

**Fail-safe Loads**

- **Applied tensile load**
  \[ P_{FS} = 105.6 \text{ lbf} \]

- **Applied shear load**
  \[ V_{FS} = 666.6 \text{ lbf} \]

- **Applied bending moment**
  \[ M_{FS} = 0 \text{ in-lbf} \]

**Fail-safe Factors of Safety**

- **Ultimate**
  \[ SF_{UFS} = 1.0 \]

- **Joint Separation**
  \[ SF_{SepFS} = 1.0 \]

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \ escfl02\2i11\mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Fri Apr 27 14:16:05 2007

Bolt Fail-safe Load data

- **Joint separation load**
  \[ P_{SepFS} = 105.600 \text{ lbf} \]

- **Max. load on the bolt (ultimate)**
  \[ P_{BFS} = 2020.4 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

- **Joint separation**
  \[ MS_{FS1} = 6.96 \]

- **Direct Tension Ultimate**
  \[ MS_{FS2} = 23.35 \]

- **Total Tension Ultimate**
  \[ MS_{FS3} = 0.46 \]

- **Direct Thread shear Ultimate**
  \[ MS_{FS4} = 18.45 \]

- **Total Thread shear Ultimate**
  \[ MS_{FS5} = 0.17 \]

- **Shear Ultimate**
  \[ MS_{FS6} = 2.35 \]

- **Bending Ultimate**
  \[ MS_{FS7} = 10 \]

- **Combined shear, tension and bending ultimate**
  \[ MS_{FS8} = 0.41 \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

- **MSbolt_{FS} = 0.17**
- **Failure Mode_{FS} = "Total Thread Shear Ultimate (Nut)"**
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors

- SFu = 2.000 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

Input Loads

- V = 489 lbf (Shear Load)
- P = 49.800 lbf (Axial Load)

Bolt calc results

- Pb = 2019 lbf (Max Bolt Load)

Dimensions

- L = 0.526 in (Length of Bolt)
- twh = 0.032 in (Thickness of Washer)
- D = 0.190 in (Diameter of Bolt)
- D_shank = 0.188 in (Min. Shank Diameter of Bolt)
- D_hole = 0.226 in (Diameter of Hole)

Shear Tear-Out Check

Recall bolt hole dimensions

- tf1 := tf1
- tf2 := tf2
- tf1 = 0.080 in (Entire Thickness of Flange 1)
- tf2 = 0.100 in (Entire Thickness of Flange 2)
- edge1 := edge1
- edge2 := edge2
- edge1 = 0.500 in (Edge Distance for Hole in Plate 1)
- edge2 = 0.566 in (Edge Distance for Hole in Plate 2)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shprl} := 2 \cdot tf \cdot \left( edge - \frac{1}{2} \cdot D_{hole} \right) \]

Allowables for plates that fastener goes through

Fsu1 := Tf1E \cdot Ff = 27 ksi
Fsu1 = 26.460 ksi (Ultimate Shear Allowable for Plate 1)
Fsu2 := Tf2E \cdot Ff = 36 ksi
Fsu2 = 34.560 ksi (Ultimate Shear Allowable for Plate 2)

\[ P_{su} := \left( A_{shprl} \cdot Fsu \right) \]
\[ P_{su} = \begin{bmatrix} 1638 \text{lbf} \\ 3131 \text{lbf} \end{bmatrix} \]

MS for Shear Tear-Out

\[ MS_{su} := \left( \frac{P_{su}}{V \cdot SFu \cdot FF} \right) - 1 \]
MS_{su} = \begin{bmatrix} 0.46 \\ 1.78 \end{bmatrix}

\[ MS_{bh1} := \min (MS_{su}) \]
MS_{bh1} = 0.457

... Shear Tear-Out MS

5.10.1.1-48
ESCG-4005-05-AMS-0039
Bearing Check

Recall bolt hole dimensions

- tf₁ = 0.080 in  (Thickness of Plate 1)
- tf₂ = 0.100 in  (Thickness of Plate 2)
- edge₁ = 0.500 in  (Edge Distance for thru Hole in Plate 1)
- edge₂ = 0.566 in  (Edge Distance for tapped Hole in Plate 2)

\[
A_{br} = (tf_{min} \cdot (D_{shank}) \cdot (Plate1) \cdot A_{br} = \left(\frac{0.015}{0.019}\right) in^2
\]

\[
e_D = \frac{\text{edge}}{D_{hole}} = \left(\frac{2.212}{2.504}\right)
\]

Allowables for plates that fastener goes through

Bearing strength at e/D = 1.5

- Fbru₁₅₁ := Tf₁E 67 ksi
- Fbru₁₅₁ := Tf₁E 65.66 ksi
- Fbry₁₅₁ := Tf₁E 49 ksi
- Fbry₁₅₁ := Tf₁E 49 ksi

Bearing strength at e/D = 2.0

- Fbru₂₀₁ := Tf₁E 88 ksi
- Fbru₂₀₁ := Tf₁E 86.24 ksi
- Fbry₂₀₁ := Tf₁E 58 ksi
- Fbry₂₀₁ := Tf₁E 56.840 ksi

Modified bearing strength

- Fbruₘ₁ := if \[e_D > 2.0, Fbru₂₀₁, \frac{e_D - 1.5}{2.0 - 1.5} (Fbru₂₀₁ - Fbru₁₅₁), Fbru₁₅₁ (e_D - 0.5)\]
- Fbruₘ₂ := if \[e_D > 2.0, Fbru₂₀₂, \frac{e_D - 1.5}{2.0 - 1.5} (Fbru₂₀₂ - Fbru₁₅₂), Fbru₁₅₂ (e_D - 0.5)\]
- Fbryₘ₁ := if \[e_D > 2.0, Fbry₂₀₁, \frac{e_D - 1.5}{2.0 - 1.5} (Fbry₂₀₁ - Fbry₁₅₁), Fbry₁₅₁ (e_D - 0.5)\]
- Fbryₘ₂ := if \[e_D > 2.0, Fbry₂₀₂, \frac{e_D - 1.5}{2.0 - 1.5} (Fbry₂₀₂ - Fbry₁₅₂), Fbry₁₅₂ (e_D - 0.5)\]

\[
Fbru_m = \left(\frac{86.24}{120.96}\right)_{\text{Plate1}} \quad \text{(Ultimate)}
\]

\[
Fbry_m = \left(\frac{56.84}{92.16}\right)_{\text{Plate1}} \quad \text{(Yield)}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
TRD Side - Bathtub Bracket to Outer Bumper

\[ P_{bru} := (A_{bru} \cdot F_{bru}_m) \]

\[ P_{bry} := (A_{bry} \cdot F_{bry}_m) \]

\[ P_{bru} = \begin{pmatrix} 1300 \\ 2280 \end{pmatrix} \text{ lbf} \]  \( \text{(Bearing Ultimate Allowable)} \)

\[ P_{bry} = \begin{pmatrix} 857 \\ 1737 \end{pmatrix} \text{ lbf} \]  \( \text{(Bearing Yield Allowable)} \)

**MS for Bearing Failure**

\[ MS_{bru} := \frac{P_{bru}}{V \cdot SF_u \cdot FF} - 1 \]

\[ MS_{bru} = \begin{pmatrix} 0.156 \\ 1.027 \end{pmatrix} \]  \( \text{Plate1} \)

\[ MS_{bru} = \begin{pmatrix} 0.156 \end{pmatrix} \]  \( \text{Plate2} \)

\[ MS_{bh_2} := \min (MS_{bru}) \]

\[ MS_{bh_2} = 0.156 \]  \( \text{... Bearing MS based on Ultimate Strength} \)

\[ MS_{bry} := \frac{P_{bry}}{V \cdot SF_y \cdot FF} - 1 \]

\[ MS_{bry} = \begin{pmatrix} 0.22 \\ 1.47 \end{pmatrix} \]  \( \text{Plate1} \)

\[ MS_{bry} = \begin{pmatrix} 0.22 \end{pmatrix} \]  \( \text{Plate2} \)

\[ MS_{bh_3} := \min (MS_{bry}) \]

\[ MS_{bh_3} = 0.219 \]  \( \text{... Bearing MS based on Yield Strength} \)
CHECK

Note: Figure is for reference only. Not to scale. Actual joint made differ. Washer may be on nut side, head side, or both

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"
Washer := "NAS1149E0332R"
Nut := "MS21076L3N"

Flange_1 := "Right Angle Bracket"
Part_Number_1 := "SDG39137848-003"
Material_1 := "AL ALY 6061-T651"

Minimum edge distance of flange one
edge1 := .375 in

Minimum edge distance of flange two
edge2 := .44 in

(Worst case combination)

Loads (reference)

Applied tensile load
P := 49.8 lbf

Applied shear load
V := 489 lbf

Applied bending moment
M := 0 in lb

Factors of Safety (reference)

SFu := 2.00 (Ultimate)

SFy := 1.25 (Yield)

FF := 1.15 (Fitting factor)

SFsep := 1.20 (Joint Separation)

Temperature data (reference)

Assembly
Temp_initial := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := -76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data ( Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286" )

Nominal diameter of bolt
D := .19 in

Number of threads/inch
Nt := 32 \ \frac{1}{in}

Shank diameter of bolt
D_shank := .1885 in

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Total length of bolt
L := .526 in

(If bolt is fully threaded, input Lt = L)

Threaded length
Lt := .276 in

(dia of pressure boss if it exists, otherwise dia of head)

Bolt head dia. across flats
dw := .357 in

Bolt head height
bh := .122 in

(head height is 0 if bolt is flat head)
Bolt Data cont. (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Thread data lookup table is hidden

This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength
Bolt ultimate tensile allowable stress
Bolt ultimate shear allowable stress
Temperature correction factor for bolt modulus
Modulus of elasticity of bolt
Thermal coefficients for bolt

\[ \beta_{\text{bolt-hot}} := 9.1 \times 10^{-6} \left( \frac{\text{in}}{\text{deg}} \right) \]
\[ \beta_{\text{bolt-cold}} := 8.5 \times 10^{-6} \left( \frac{\text{in}}{\text{deg}} \right) \]

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:
- Head: \( t_{\text{wh}} := 0.032 \text{ in} \)
- Nut: \( t_{\text{wn}} := 0.0 \text{ in} \)

Diameter of washer under head:
- Outer: \( D_{\text{woh}} := 0.438 \text{ in} \)
- Inner: \( D_{\text{wi}} := 0.203 \text{ in} \)

Modulus of elasticity:
- Head: \( E_{\text{wash}} := 29.1 \times 10^6 \text{ psi} \)
- Nut: \( E_{\text{wash}} := 0.0 \times 10^6 \text{ psi} \)

Nut Data (Nut = "MS21076L3N")

Height of nut: \( H := 0.250 \text{ in} \)

Temperature correction factor for nut strength
Ultimate allowable stress, tensile
Ultimate axial strength of nut

\[ TS_{\text{nut}} := 0.96 \]
\[ F_{\text{tu}} := 125000 \text{ psi} \]
\[ P_{\text{tu}} := 2460 \text{ lbf} \]
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

- Diameter of thru hole: \( D_{\text{hole}} := .226 \text{ in} \)
- Flange: \( _1 \) = "Right Angle Bracket"
- Material: \( _1 \) = "AL ALY 6061-T651"
- Thickness of flanges: \( t_{f1} := .15 \text{ in} \)
- Compressive Modulus of elastic:
  \( E_{\text{flange1}} := (10.1 \times 10^6 \text{ psi}) \)
- Temperature correction factor (modulus):
  \( T_{f1,E} := .98 \)
- Coefficient of thermal expansion for flanges:
  \( \beta_{\text{flange1}}_{\text{hot}} := 12.8 \times 10^{-6} \text{ in/in deg} \)
  \( \beta_{\text{flange1}}_{\text{cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \)

Torque/Preload data

- Maximum torque: \( T_{\text{max}} := 44.4 \text{ in-lbf} \)
- Minimum torque: \( T_{\text{min}} := 37.8 \text{ in-lbf} \)

Joint is lubed/dry

- Preload: \( u := 0.25 \)
- Uncertainty: \( u := 0.25 \) (0.25 lubed/0.35 dry)
- Torque coefficient: \( k := 0.15 \) (0.15 lubed/0.20 dry)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escg\02\211\mathcad\8307\bolts\Rev_D\bolt_stiffness_nut.mcd
Bolt Load data (cont.)

Applied Tensile load on the bolt  
$P = 49.800 \text{ lbf}$  
Max. load on the bolt with preload and Factor of safety  
$Pb = 2027 \text{ lbf}$  
$Pb \text{ (ultimate)}$

Applied shear on the bolt  
$V = 489.000 \text{ lbf}$  
$Pby = 2019 \text{ lbf}$  
$Pby \text{ (yield)}$

Applied bending on the bolt  
$M = 0.000 \text{ in-lbf}$  
Max. load on the bolt with preload Without factor of safety  
$Pb_{app} = 2017 \text{ lbf}$

Bolt ultimate tensile strength  
$PA_t = 2957 \text{ lbf}$  
Bolt shear strength  
$VAu = 2572 \text{ lbf}$

Thread pullout strength  
$PA_s = 2362 \text{ lbf}$  
Bolt bending strength  
$MAu = 61 \text{ in-lbf}$

Nut ultimate tensile strength  
$Ptu_{nut} = 2362 \text{ lbf}$

General Checks

length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"

cone_check = "Joint pressure cone does not extend past flange edge"

preload_check = "Nominal preload >= 65% of bolt yield strength"

washer_check = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

| Joint separation  | $MS_1 = 12.72$ | Direct Thread shear Ultimate  | $MS_6 = 19.62$ |
| Direct Tension Ultimate | $MS_2 = 24.81$ | Total Thread shear Ultimate  | $MS_7 = 0.17$ |
| Direct Tension Yield | $MS_3 = 29.98$ | Shear Ultimate  | $MS_8 = 1.29$ |
| Total Tension Ultimate | $MS_4 = 0.46$ | Bending Ultimate  | $MS_9 = 100$ |
| Total Tension Yield | $MS_5 = 0.1$ | Combined shear, tension and bending ultimate  | $MS_{10} = 0.31$ |

Smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} = 0.1$  
Failure_Mode = "Total Tension Yield"
### Fail-safe Analysis

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P_FS = 105.6 lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V_FS = 666.6 lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_FS = 0 in-lbf</td>
</tr>
</tbody>
</table>

#### Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

**This file uses the calculations shown in `\escg\102\111_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd`**

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt\_FS} = 0.16 \)  \( Failure\_Mode\_FS = "Total\ Thread\ Shear\ Ultimate\ (Nut)" \)
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors
- SFu = 2.000 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

Input Loads
- V = 489 lbf (Shear Load)
- P = 49.800 lbf (Axial Load)

Bolt calc results
- Pb = 2027 lbf (Max Bolt Load)

Dimensions
- L = 0.526 in (Length of Bolt)
- twh = 0.032 in (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions

- tf1 := tf1 = 0.150 in (Entire Thickness of Flange 1)
- tf2 := tf2 = 0.100 in (Entire Thickness of Flange 2)
- edge1 := edge1 = 0.375 in (Edge Distance for Hole in Plate 1)
- edge2 := edge2 = 0.440 in (Edge Distance for Hole in Plate 2)

- D = 0.190 in (Diameter of Bolt)
- D_shank = 0.188 in (Min. Shank Diameter of Bolt)
- D_hole = 0.226 in (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shprl} = \left[ 2 \cdot tf \cdot \left( \frac{1}{2} \cdot D_{\text{hole}} \right) \right] \]

- Plate1 \[ A_{shprl} = 0.079 \text{ in}^2 \]
- Plate2 \[ A_{shprl} = 0.065 \text{ in}^2 \]

Allowables for plates that fastener goes through

- Fsu1 := Tf1E \cdot 27 ksi
- Fsu1 = 26.460 ksi (Ultimate Shear Allowable for Plate 1)
- Fsu2 := Tf2E \cdot 36 ksi
- Fsu2 = 34.560 ksi (Ultimate Shear Allowable for Plate 2)

- Psu := \left( A_{shprl} \cdot Fsu \right)
- Psu = \left( 2080 \right) \text{ lbf} (Shear Ultimate Allowable)

MS for Shear Tear-Out

- MS_{su} := \left( \frac{Psu}{V \cdot SFu \cdot FF} - 1 \right)
- MS_{su} = \left( \frac{0.85}{1.01} \right)

- MS_{bh1} := \min(\{MS_{su}\})
- MS_{bh1} = 0.849

... Shear Tear-Out MS
Bearing Check

Recall bolt hole dimensions

\[ tf_1 = 0.150 \text{ in} \]  \hspace{1cm} (Thickness of Plate 1)

\[ tf_2 = 0.100 \text{ in} \]  \hspace{1cm} (Thickness of Plate 2)

\[ \text{edge}_1 = 0.375 \text{ in} \]  \hspace{1cm} (Edge Distance for thru Hole in Plate 1)

\[ \text{edge}_2 = 0.440 \text{ in} \]  \hspace{1cm} (Edge Distance for tapped Hole in Plate 2)

\[ A_{br} := \left( \frac{\text{tf} \cdot \min(D, D_{shank})}{\text{Plate1}} \right) \left( \frac{\text{tf} \cdot \min(D, D_{shank})}{\text{Plate2}} \right) \]

\[ A_{br} = \begin{pmatrix} \frac{0.028}{0.019} \end{pmatrix} \text{in}^2 \]  \hspace{1cm} (Bearing Areas)

\[ e_D := \frac{\text{edge}}{D_{hole}} \]

\[ e_D = \begin{pmatrix} 1.659 \\ 1.947 \end{pmatrix} \]  \hspace{1cm} (e/D for Plates)

Allowables for plates that fastener goes through

Bearing strength at e/D = 1.5

\[ F_{bru15} := T1E \cdot 67 \text{ksi} \]

\[ F_{bry15} := T1E \cdot 50 \text{ksi} \]

Bearing strength at e/D = 2.0

\[ F_{bru20} := T1E \cdot 88 \text{ksi} \]

\[ F_{bry20} := T1E \cdot 58 \text{ksi} \]

Modified bearing strength

\[ F_{bru_{m1}} := \begin{cases} e_D > 2.0, & F_{bru20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru20} - F_{bru15} \right) \cdot \left( F_{bru15} \left( e_D - 0.5 \right) \right) \\ e_D > 2.0, & F_{bru20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru20} - F_{bru15} \right) \cdot \left( F_{bru15} \left( e_D - 0.5 \right) \right) \end{cases} \]

\[ F_{bru_{m2}} := \begin{cases} e_D > 2.0, & F_{bru20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru20} - F_{bru15} \right) \cdot \left( F_{bru15} \left( e_D - 0.5 \right) \right) \\ e_D > 2.0, & F_{bru20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru20} - F_{bru15} \right) \cdot \left( F_{bru15} \left( e_D - 0.5 \right) \right) \end{cases} \]

\[ F_{bry_{m1}} := \begin{cases} e_D > 2.0, & F_{bry20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry20} - F_{bry15} \right) \cdot \left( F_{bry15} \left( e_D - 0.5 \right) \right) \\ e_D > 2.0, & F_{bry20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry20} - F_{bry15} \right) \cdot \left( F_{bry15} \left( e_D - 0.5 \right) \right) \end{cases} \]

\[ F_{bry_{m2}} := \begin{cases} e_D > 2.0, & F_{bry20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry20} - F_{bry15} \right) \cdot \left( F_{bry15} \left( e_D - 0.5 \right) \right) \\ e_D > 2.0, & F_{bry20} \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \left( e_D > 1.5 \right) \left( e_D < 2.0 \right) \cdot \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry20} - F_{bry15} \right) \cdot \left( F_{bry15} \left( e_D - 0.5 \right) \right) \end{cases} \]

\[ F_{bru_m} := \begin{pmatrix} 72.216 \\ 118.207 \end{pmatrix} \]  \hspace{1cm} (Ultimate)

\[ F_{bry_m} := \begin{pmatrix} 51.498 \\ 90.835 \end{pmatrix} \]  \hspace{1cm} (Yield)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
TRD Side - Right Angle to Outer Bumper

\[ P_{bru} := (A_{br} \times F_{bru\_m}) \]

\[ P_{bry} := (A_{br} \times F_{bry\_m}) \]

\[ P_{bru} = \begin{pmatrix} 2042 \\ 2228 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Ultimate Allowable)} \]

\[ P_{bry} = \begin{pmatrix} 1456 \\ 1712 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Yield Allowable)} \]

**MS for Bearing Failure**

\[ MS_{bru} := \frac{P_{bru}}{V \times SFu \times FF} - 1 \]

\[ MS_{bru} = \begin{pmatrix} 0.816 \\ 0.981 \end{pmatrix} \]

\[ MS_{bh\_2} := \min( MS_{bru} ) \]

\[ MS_{bh\_2} = 0.816 \quad \text{... Bearing MS based on Ultimate Strength} \]

\[ MS_{bry} := \frac{P_{bry}}{V \times SFy \times FF} - 1 \]

\[ MS_{bry} = \begin{pmatrix} 1.07 \\ 1.44 \end{pmatrix} \]

\[ MS_{bh\_3} := \min( MS_{bry} ) \]

\[ MS_{bh\_3} = 1.071 \quad \text{... Bearing MS based on Yield Strength} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
Port (TRD) - Inner Bumper to Standoff B

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both.

Bolt := "NAS1004-1, .2500-28, Length, A-286, 140ksi"

Washer := "NAS1149E0332R"

Insert := "NASM21209F4-20L, .250-28, Assume A-286, Dry Film Lubricant"

Flange_1 := "Debris Shield Inner Plate"
Part_Number_1 := "SDG39137858-001"
Material_1 := "AL ALY2219-T87"

Minimum edge distance of flange 1 edge_1 := 1.162 in

Flange_2 := "Debris Shield Standoff B"
Part_Number_2 := "SDG39137855"
Material_2 := "AL ALY 6061-T651"

Minimum edge distance of flange 2 edge_2 := 0.364 in

Loads (reference)

Applied tensile load P := 11.7 lbf
Applied shear load V := 25.4 lbf
Applied bending moment M := 0 in-lbf

(Worst case combination)

Factors of Safety (reference)

SFu := 2.00 (Ultimate)
SFy := 1.25 (Yield)

FF := 1.15 (Fitting factor)
SFsep := 1.20 (Joint Separation)

Temperature Data (reference)

Assembly Temp_initial := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := -76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data (Bolt = "NAS1004-1, .2500-28, Length, A-286, 140ksi")

Nominal diameter of bolt D := .2500 in
Number of threads/inch Nt := 28 \frac{1}{in}

Shank diameter of bolt D_shank := .2470 in
Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Total length of bolt L := .606 in
(Threaded length Lt := .544 in (If bolt is fully threaded, input Lt = L))

Bolt head dia. across flats dw := .398 in
(dia of pressure boss if it exists, otherwise dia of head)

Bolt head height bh := .156 in (head height is 0 if bolt is flat head)
Bolt Data Continued (Bolt = "NAS1004-1, .2500-28, Length, A-286, 140ksi")

Thread data lookup table is hidden
This file uses the data shown in \escfile\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

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Temperature correction factor for bolt strength

\( T_{Su\_bolt} := .98 \)
\( T_{Sy\_bolt} := .98 \)

Bolt ultimate tensile allowable stress

\( F_{tu\_bolt} := 140000 \text{ psi} \)
\( F_{ty\_bolt} := 95000 \text{ psi} \)

Bolt ultimate shear allowable stress

\( F_{su\_bolt} := 0.6 \times F_{tu\_bolt} \)

Temperature correction factor for bolt modulus

\( T_E\_bolt := .98 \)

Modulus of elasticity of bolt

\( E\_bolt := (29.1 \times 10^6 \text{ psi}) \)

Thermal coefficients for bolt

\[ \beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{bolt\_cold}} := 8.5 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:

- head \( t_{wh} := 0.032 \text{ in} \)

(These are total washer thickness, if there are more than one)

Diameter of washer under head:

- Outer \( D_{wo\_h} := 0.438 \text{ in} \)
- Inner \( D_{wi\_h} := 0.203 \text{ in} \)

Note: If there is no washer - \( t_{w's} \), \( D_{wo's} \) and \( D_{wi's} \) should be zero

Modulus of elasticity:

- head \( E\_washerh := (29.1 \times 10^6 \text{ psi}) \)

Temperature correction factor for modulus:

- head \( T_E\_washerh := .98 \) (same as bolt)

Insert Data (Insert = "NASM21209F4-20L, .250-28, Assume A-286, Dry Film Lubricant")

Length of insert

\( L_{ins} := 0.500 \text{ in} \)

Min. external diameter of insert

\( F_{min} := 0.306 \text{ in} \)

Depth of recess for insert

\( L_r := 0.020 \text{ in} \)

Temperature correction factor for insert strength

\( T_{S\_ins} := .98 \)

Ultimate tensile allowable stress

\( F_{tu\_ins} := 150000 \text{ psi} \)

Ultimate shear allowable stress

\( F_{su\_ins} := 0.6 \times F_{tu\_ins} \)
Flange Data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole \( D_{\text{hole}} := 0.272 \, \text{in} \)

Flange_1 = "Debris Shield Inner Plate"

Flange_2 = "Debris Shield Standoff B"

Material_1 = "AL ALY2219-T87"

Material_2 = "AL ALY 6061-T651"

Thickness of flanges

\( t_{f1} := 0.060 \, \text{in} \) \( t_{f2} := 0.500 \, \text{in} \)

Compressive Modulus of elasticity

\[ E_{\text{flange1}} := (10.8 \times 10^6 \, \text{psi}) \]

\[ E_{\text{flange2}} := (10.1 \times 10^6 \, \text{psi}) \]

Temperature correction factor (modulus)

\( T_{f1}E := .96 \) \( T_{f2}E := .98 \)

Coefficient of thermal expansion for flanges

\( \beta_{\text{flange1\_hot}} := 12.4 \times 10^{-6} \, \text{in/in deg} \)

\( \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \, \text{in/in deg} \)

\( \beta_{\text{flange1\_cold}} := 11.6 \times 10^{-6} \, \text{in/in deg} \)

\( \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \, \text{in/in deg} \)

Shear strength of flange two, with temperature reduction

\( F_{su\_f2} := 27000 \, \text{psi} \)

\( T_{f2s} := .96 \)

(If unavailable, use temperature reduction factor for \( F_tu \))

Torque/Preload Data

Maximum torque \( T_{\text{max}} := 84.2 \, \text{in} \cdot \text{lbf} \)

Minimum torque \( T_{\text{min}} := 71.6 \, \text{in} \cdot \text{lbf} \)

Joint is lubed/dry

Preload Uncertainty \( \mu := 0.25 \)  

(0.25 lubed/0.35 dry)  

Loading plane factor \( n := 0.5 \)  

(0.15 lubed/0.20 dry)

Stiffness and Margin calculations are hidden

This file uses calculations shown in \escg4005-05-AMS-0039

Fri Apr 27 14:11:53 2007

Bolt Load Data

Bolt/joint stiffness factor \( = 0.519 \)

Preload due to temperature

\( P_{\text{thr\_pos}} := 173.3 \, \text{lbf} \)

\( P_{\text{thr\_neg}} := -350.6 \, \text{lbf} \)

Max. preload \( \text{PLDmax} = 2980 \, \text{lbf} \)

Min. preload \( \text{PLDmin} = 941 \, \text{lbf} \)

Nom. preload \( \text{PLDnom} = 2245 \, \text{lbf} \)

Preload to yield ratio (nom.) \( \text{PLDratio} = 0.684 \)

Joint separation load \( P_{\text{sep}} = 14.040 \, \text{lbf} \)

Uncertainty factor \( \mu := 0.250 \)

Torque coefficient \( k := 0.150 \)

Loading plane factor \( n := 0.500 \)
Bolt Load Data Continued

| Applied Tensile load on the bolt | \( P = 11,700 \text{ lbf} \) | Max. load on the bolt with preload and Factor of safety |
| Applied shear on the bolt | \( V = 25,400 \text{ lbf} \) | \( Pb = 2987 \text{ lbf} \) (ultimate) \( Pby = 2984 \text{ lbf} \) (yield) |
| Applied bending on the bolt | \( M = 0.000 \text{ in-lbf} \) | Max. load on the bolt with preload Without factor of safety |
| Bolt ultimate tensile strength | \( PA_t = 4841 \text{ lbf} \) | Bolt shear strength \( VA_u = 2680 \text{ lbf} \) |
| Thread pullout strength | \( PA_s = 6229 \text{ lbf} \) | Bolt bending strength \( MA_u = 134 \text{ in-lbf} \) |

General Checks

- length_check = "Bolt length is sufficient and insert fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washer(s) under head do not extend past flange"
- insert_check = "Flange two is thick enough for insert"

Summary of Margins for Bolt

| Joint separation | \( MS_1 = 77.73 \) | Direct Thread shear Ultimate | \( MS_6 = 230.49 \) |
| Direct Tension Ultimate | \( MS_2 = 178.89 \) | Total Thread shear Ultimate | \( MS_7 = 1.09 \) |
| Direct Tension Yield | \( MS_3 = 194.31 \) | Shear Ultimate | \( MS_8 = 44.88 \) |
| Total Tension Ultimate | \( MS_4 = 0.62 \) | Bending Ultimate | \( MS_9 = 100 \) |
| Total Tension Yield | \( MS_5 = 0.1 \) | Combined shear, tension and bending ultimate | \( MS_{10} = 0.62 \) |

Smallest Margin of Safety for the Bolt, and the Failure Mode

- \( MS_{bolt} = 0.1 \) | Failure_Mode = "Total Tension Yield"
Fail-Safe Analysis

**Fail-Safe Loads**
- Applied tensile load: \( P_{FS} := 25.2 \text{ lbf} \)
- Applied shear load: \( V_{FS} := 57 \text{ lbf} \)
- Applied bending moment: \( M_{FS} := 0 \text{ in-lbf} \)

**Fail-Safe Factors of Safety**
- Ultimate: \( SF_{u,FS} := 1.0 \)
- Joint Separation: \( SF_{sep,FS} := 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated
This file calculations shown in \escf102\211\mathcad\8307_bolts\Rev_D\bolt_insert_stiffness__FS.mcd

Fri Apr 27 14:12:08 2007

Bolt Fail-Safe Load Data
- Joint separation load: \( P_{sep,FS} = 25.200 \text{ lbf} \)
- Max. load on the bolt(ultimate): \( P_{b,FS} = 2987.5 \text{ lbf} \)

Summary of Fail-Safe Margins for Bolt

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Margin</th>
<th>Ultimate Margin</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{FS1} = 42.86</td>
<td>Total Thread shear</td>
<td>MS_{FS5} = 1.09</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{FS2} = 166.04</td>
<td>Shear Ultimate</td>
<td>MS_{FS6} = 39.89</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{FS3} = 0.62</td>
<td>Bending Ultimate</td>
<td>MS_{FS7} = 10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{FS4} = 213.96</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_{FS8} = 0.62</td>
</tr>
</tbody>
</table>

Smallest Fail-Safe Margin of Safety for the Bolt, and the Failure Mode:
- \( MS_{bolt,FS} = 0.62 \)  
  - Failure Mode_{FS} = "Combined Shear Tension Bending Ultimate"
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors
- SFu = 2.000 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

Input Loads
- V = 25.4 lbf (Shear Load)
- P = 11.700 lbf (Axial Load)

Bolt calc results
- Pb = 2987 lbf (Max Bolt Load)

Dimensions
- L = 0.606 in (Length of Bolt)
- twh = 0.032 in (Thickness of Washer)

Recall bolt hole dimensions

- tf1 := tf1, tf1 = 0.060 in (Entire Thickness of Flange 1) T11E = 0.960
- tf2 := tf2, tf2 = 0.500 in (Entire Thickness of Flange 2) T12E = 0.980

- edge1 := edge1, edge1 = 1.162 in (Edge Distance for Hole in Plate 1)
- edge2 := edge2, edge2 = 0.364 in (Edge Distance for Hole in Plate 2)

D = 0.250 in (Diameter of Bolt)
D_shank = 0.247 in (Min. Shank Diameter of Bolt)
D_hole = 0.272 in (Diameter of Hole)

Shear Tear-Out Check

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shp1} := \frac{2 \cdot tf \cdot (edge - \frac{D_{hole}}{2})}{2} \]

\[ A_{shp1} = \begin{cases} \text{Plate1} & 0.123 \\ \text{Plate2} & 0.228 \end{cases} \text{ in}^2 \]

Allowables for plates that fastener goes through

- Fsu1 := T11E \cdot 36 \text{ ksi}
  - Fsu1 = 34.560 ksi (Ultimate Shear Allowable for Plate 1)
- Fsu2 := T12E \cdot 27 \text{ ksi}
  - Fsu2 = 26.460 ksi (Ultimate Shear Allowable for Plate 2)

\[ P_{su} := \frac{A_{shp1} \cdot Fsu}{V \cdot SFu \cdot FF} \]

\[ P_{su} = \begin{cases} \text{Plate1} & 4255 \\ \text{Plate2} & 6033 \end{cases} \text{lbf} \]

MS for Shear Tear-Out

\[ MS_{su} := \left( \frac{P_{su}}{V \cdot SFu \cdot FF} - 1 \right) \]

\[ MS_{bh1} := \min \left( MS_{su} \right) \]

\[ MS_{bh1} = 71.835 \]

Typical shear tear-out failure

5.10.1.1-64 ESCG-4005-05-AMS-0039
Bearing Check

Recall bolt hole dimensions

\[ tf_1 = 0.060 \text{ in} \] (Thickness of Plate 1)
\[ tf_2 = 0.500 \text{ in} \] (Thickness of Plate 2)
\[ \text{edge}_1 = 1.162 \text{ in} \] (Edge Distance for thru Hole in Plate 1)
\[ \text{edge}_2 = 0.364 \text{ in} \] (Edge Distance for tapped Hole in Plate 2)

Typical Bearing Failure

\[
\text{Abr} = \left( \frac{tf_1}{0.015} \right) \times \left( \frac{tf_2}{0.123} \right) \]

Allowables for plates that fastener goes through

<table>
<thead>
<tr>
<th>Bearing strength at e/D = 1.5</th>
<th>Bearing strength at e/D = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru15₁ := T₁₁E 99 ksi</td>
<td>Fbru20₁ := T₁₁E 126 ksi</td>
</tr>
<tr>
<td>Fbry15₁ := T₁₁E 83 ksi</td>
<td>Fbry20₁ := T₁₁E 96 ksi</td>
</tr>
<tr>
<td>Fbru15₂ := T₁₂E 67 ksi</td>
<td>Fbru20₁ := T₁₂E 88 ksi</td>
</tr>
<tr>
<td>Fbry15₂ := T₁₂E 50 ksi</td>
<td>Fbry20₂ := T₁₂E 58 ksi</td>
</tr>
</tbody>
</table>

Modified bearing strength

\[
\text{Fbru}_m₁ := \begin{cases} 
\text{e}_D₁ > 2.0, \text{Fbru}_20₁, & \text{Fbru}_15₁ + \frac{\text{e}_D₁ - 1.5}{2.0 - 1.5} \left( \text{Fbru}_20₁ - \text{Fbru}_15₁ \right) \\
\text{e}_D₁ < 2.0, & \text{Fbru}_15₁ \\
\end{cases}
\]

\[
\text{Fbru}_m₂ := \begin{cases} 
\text{e}_D₂ > 2.0, \text{Fbru}_20₂, & \text{Fbru}_15₂ + \frac{\text{e}_D₂ - 1.5}{2.0 - 1.5} \left( \text{Fbru}_20₂ - \text{Fbru}_15₂ \right) \\
\text{e}_D₂ < 2.0, & \text{Fbru}_15₂ \\
\end{cases}
\]

\[
\text{Fbry}_m₁ := \begin{cases} 
\text{e}_D₁ > 2.0, \text{Fbry}_20₁, & \text{Fbry}_15₁ + \frac{\text{e}_D₁ - 1.5}{2.0 - 1.5} \left( \text{Fbry}_20₁ - \text{Fbry}_15₁ \right) \\
\text{e}_D₁ < 2.0, & \text{Fbry}_15₁ \\
\end{cases}
\]

\[
\text{Fbry}_m₂ := \begin{cases} 
\text{e}_D₂ > 2.0, \text{Fbry}_20₂, & \text{Fbry}_15₂ + \frac{\text{e}_D₂ - 1.5}{2.0 - 1.5} \left( \text{Fbry}_20₂ - \text{Fbry}_15₂ \right) \\
\text{e}_D₂ < 2.0, & \text{Fbry}_15₂ \\
\end{cases}
\]

\[
\text{Fbru}_m = \left( \frac{120.96}{55.039} \right) \text{ ksi} \left( \frac{\text{Plate}1}{\text{Plate}2} \right) \quad (\text{Ultimate})
\]

\[
\text{Fbry}_m = \left( \frac{92.16}{41.074} \right) \text{ ksi} \left( \frac{\text{Plate}1}{\text{Plate}2} \right) \quad (\text{Yield})
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert Port (TRD) - Inner Bumper to Standoff B

\[
P_{bru} := \left( A_{br} \cdot F_{bru_m} \right)
\]

\[
P_{bru} = \left( \frac{1793}{6797} \right) \text{lbf} \quad \text{(Bearing Ultimate Allowable)}
\]

\[
P_{bry} := \left( A_{br} \cdot F_{bry_m} \right)
\]

\[
P_{bry} = \left( \frac{1366}{5073} \right) \text{lbf} \quad \text{(Bearing Yield Allowable)}
\]

**MS for Bearing Failure**

\[
MS_{bru} := \left( \frac{P_{bru}}{V \cdot SF_u \cdot FF} - 1 \right)
\]

\[
MS_{bru} = \left( \frac{29.685}{115.352} \right) \quad \text{(Plate1)} \quad \text{(Plate2)}
\]

\[
MS_{bh_2} := \min\left( MS_{bru} \right)
\]

\[
MS_{bh_2} = 29.685 \quad \ldots \text{Bearing MS based on Ultimate Strength}
\]

\[
MS_{bry} := \left( \frac{P_{bry}}{V \cdot SF_y \cdot FF} - 1 \right)
\]

\[
MS_{bry} = \left( \frac{36.41}{137.93} \right) \quad \text{(Plate1)} \quad \text{(Plate2)}
\]

\[
MS_{bh_3} := \min\left( MS_{bry} \right)
\]

\[
MS_{bh_3} = 36.407 \quad \ldots \text{Bearing MS based on Yield Strength}
\]
CHECK BOLTS (NAS1004-40 0.25"-28 x 1.0" L Material-A-286), Insert MS21209 F4-20L, Washer NAS1587-4C

**Debris Shield Fastener 3 Flange Joint Analysis for Bolt/Washer with Insert Port (TRD) - Outer Bumper to Standoff B**

**Flanges**
- Flange (tf1): Port External Bumper assy
  - Part number: SDG39137853-301
  - Material: 2219-T87
- Mid Flange (ad2): Debris shield Standoff A assy
  - Part number: SDG39137848-005
  - Material: 6061-T651
- Flange (tf2): Debris shield standoff B
  - Part number: SDG39137855-001
  - Material: 6061-T651

**Loads**
- Applied tensile load: \( P = 11.7 \) lbf
- Applied shear load: \( V = 25.4 \) lbf
- Applied bending moment: \( M = 38.9 \) in-lbf

**Factors of Safety**
- Ultimate: \( SF_{u} = 2.0 \)
- Yield: \( SF_{y} = 1.25 \)
- Joint Separation: \( SF_{sep} = 1.2 \)
- Fitting factor: \( FF = 1.15 \)

**Temperature data**
- Assembly: \( Temp_{initial} = 70 \) deg
- Maximum: \( Temp_{max} = 120 \) deg
- Minimum: \( Temp_{min} = -200 \) deg

**Bolt and Insert Data**
- Nominal diameter of bolt: \( D = 0.250 \) in
- Number of threads/inch: \( N_t = 28 \) in
- Total length of bolt: \( L = 3.044 \) in
- Length of insert: \( L_{ins} = 0.50 \) in
- Threaded length: \( L_t = 0.544 \) in
- Min. external diameter of insert: \( F_{min} = 0.306 \) in
- Depth of recess for insert: \( l_r = 0.02 \) in

(If bolt is fully threaded, input \( L_t = L \))

**Washer Data**
- Thickness of washer: \( t_w = 0.078 \) in
- Outer Diameter of washer: \( D_w = 0.531 \) in
- Inner Diameter of washer: \( D_{wi} = 0.252 \) in
- Bolt head dia. across flats: \( d_w = 0.398 \) in

(used only if there is no washer)

**Flange data**
- Thickness of flange 1: \( t_{f1} = 0.10 \) in
- Thickness of flange 2: \( t_{f2} = 0.66 \) in
- Thickness of mid flange: \( t_{midflg_ad2} = 2.25 \) in
- Diameter of hole: \( D_{hole} = 0.26 \) in
- Outer Diameter of standoff: \( D_{w_ad2} = 0.50 \) in
- Inner Diameter of standoff: \( D_{wi_ad2} = 0.272 \) in

Note: If there is no washer, \( t_w, D_w, \) and \( D_{wi} \) should be zero.
Debris Shield Fastener 3 Flange Joint Analysis for Bolt/Washer with Insert Port (TRD) - Outer Bumper to Standoff B

Material Property Data

Bolt
- Temperature correction factor for bolt strength ultimate: $T_{Su\_bolt} = 0.98$, yield $T_{Sy\_bolt} = 0.98$
- Bolt ultimate tensile allowable stress: $F_{tu\_bolt} = 140000$ psi
- Bolt ultimate shear allowable stress: $F_{su\_bolt} = 0.6 \cdot F_{tu\_bolt}$
- Bolt yield tensile allowable: $F_{ty\_bolt} = 95000$ psi
- Temperature correction factor for bolt modulus: $T_{E\_bolt} = 0.94$
- Modulus of elasticity of bolt: $E_{bolt} := \left(29.1 \cdot 10^6 \text{ psi}\right)$

Insert
- Temperature correction factor for insert strength: $T_{S\_ins} = 0.94$
- Ultimate tensile allowable stress: $F_{tu\_ins} = 150000$ psi
- Ultimate shear allowable stress: $F_{su\_ins} = 0.6 \cdot F_{tu\_ins}$

Washer
- Temperature correction factor for washer modulus: $T_{E\_washer} = 1.0$
- Modulus of elasticity of washer: $E_{washer} := \left(29.1 \cdot 10^6 \text{ psi}\right)$

Flanges
- Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.
- Temperature correction factor for flange 1: $T_{f1\_E} := 1.0$ (modulus) $T_{f1\_S} := 0.96$ (strength)
- Temperature correction factor for flange 2: $T_{f2\_E} := 1.0$ (modulus) $F_{su\_f2} := 270000$ psi
- Modulus of elasticity for the parts in the joint: $E_{flange1} := \left(10.8 \cdot 10^6 \text{ psi}\right)$ $E_{flange2} := \left(10.1 \cdot 10^6 \text{ psi}\right)$

Coefficient of thermal expansion for flanges
- $\beta_{flange1\_hot} := 12.3 \cdot 10^{-6} \text{ in/in/deg}$ $\beta_{flange2\_hot} := 12.7 \cdot 10^{-6} \text{ in/in/deg}$ $\beta_{flange1\_cold} := 11.0 \cdot 10^{-6} \text{ in/in/deg}$ $\beta_{flange2\_cold} := 11.3 \cdot 10^{-6} \text{ in/in/deg}$
Debris Shield Fastener 3 Flange Joint Analysis for Bolt/Washer with Insert Port (TRD) - Outer Bumper to Standoff B

**Mid Flange**

Temperature correction factor for mid flange modulus
\[ TE_{\text{mid flg ad2}} = 0.98 \]

Modulus of elasticity of mid flange
\[ E_{\text{mid flg ad2}} = \left(10.1 \times 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for mid flange
\[ \beta_{\text{mid flg ad2 hot}} = 12.7 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{mid flg ad2 cold}} = 11.3 \times 10^{-6} \text{ in/in deg} \]

**Torque/Preload data**

- Maximum torque (50% of yield)
  \[ T_{\text{max}} = 65 \text{ in-lbf} \]
- Minimum torque (85% of Max torque)
  \[ T_{\text{min}} = 55 \text{ in-lbf} \]
- Torque coefficient
  \[ k = 0.15 \]

**Bolt Load data**

- Bolt/joint stiffness factor
  \[ = 0.567 \]
- Preload due to temperature
  \[ P_{\text{thr pos}} = 107.8 \text{ lbf} \]
- Max. preload
  \[ P_{\text{LDmax}} = 2274.5 \text{ lbf} \]
- Min. preload
  \[ P_{\text{LDmin}} = 991.7 \text{ lbf} \]
- Joint separation load
  \[ P_{\text{sep}} = 14,040 \text{ lbf} \]
- Max. load on the bolt (ultimate)
  \[ P_{b} = 2282.1 \text{ lbf} \]
- Max. load on the bolt (yield)
  \[ P_{by} = 2279.2 \text{ lbf} \]
- Bolt ultimate tensile strength
  \[ P_{At} = 4840.8 \text{ lbf} \]

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin Description</th>
<th>Margin Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>[ MS_1 = 84.72 ]</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>[ MS_2 = 178.89 ]</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>[ MS_4 = 1.12 ]</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>[ MS_3 = 194.31 ]</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>[ MS_5 = 0.441 ]</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>[ MS_6 = 230.49 ]</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>[ MS_7 = 1.73 ]</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>[ MS_8 = 44.88 ]</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>[ MS_9 = 1.26 ]</td>
</tr>
<tr>
<td>Combined shear, tension and bending</td>
<td>[ MS_{10} = 0.094 ]</td>
</tr>
</tbody>
</table>

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

\[ MS_{\text{bolt}} = \min (MS) \]

\[ MS_{\text{bolt}} = 0.094 \]

**Failure Mode** = "Combined Shear Tension Bending Ultimate"
Fail-safe Analysis

Fail-safe Loads

<table>
<thead>
<tr>
<th>Applied load type</th>
<th>Load (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load</td>
<td>P(_{FS}) := 23.4</td>
</tr>
<tr>
<td>Shear load</td>
<td>V(_{FS}) := 50.8</td>
</tr>
<tr>
<td>Bending moment load</td>
<td>M(_{FS}) := 77.8</td>
</tr>
</tbody>
</table>

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate P(_{FS})</td>
<td>SF(_{FS}) := 1.0</td>
</tr>
<tr>
<td>Joint Separation V(_{FS})</td>
<td>SF(_{FS}) := 1.0</td>
</tr>
<tr>
<td>Bending M(_{FS})</td>
<td>SF(_{FS}) := 1.0</td>
</tr>
</tbody>
</table>

Bolt Fail-safe Load data

- Joint separation load: P\(_{sep\_FS}\) = 23.400 lb
- Max. load on the bolt (ultimate): Pb\(_{FS}\) = 2282.1 lb

Summary of fail-safe Margins for bolt:

- Joint separation: MS\(_{FS}\)\(_1\) = 50.43
- Direct Tension Ultimate: MS\(_{FS}\)\(_2\) = 178.89
- Total Tension Ultimate: MS\(_{FS}\)\(_3\) = 1.12
- Direct Thread shear Ultimate: MS\(_{FS}\)\(_4\) = 230.49
- Combined shear, tension and bending ultimate: MS\(_{FS}\)\(_8\) = 0.09

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt\_FS} := \min (MS\_{FS}) \]

MS\(_{bolt\_FS}\) = 0.094

Failure Mode\(_{FS}\) = "Combined Shear Tension Bending Ultimate"
Rivet Analysis

Rivet := "NAS 1398DFC4-3, Rivet Blind, Protruding Head, Locked Spindle, .125 Dia, .126 Grip, .323 L"

Flange_1 := "Debris Shield Corner Bracket"
Part_Number_1_1 := "SDG39137849-001"
Part_Number_1_2 := "SDG39137849-002"
Part_Number_1_3 := "SDG39137849-003"
Part_Number_1_4 := "SDG39137849-004"
Material_1 := "AL ALY 6061-T651, AMS-QQ-A-250/11"

Flange_2 := "Port External Bumper Assembly"
Part_Number_2 := "SDG39137853"
Material_2 := "AL ALY 2219-T87, AMS-QQ-A-250/30"

Minimum edge distance of flange one edge1 := .5 in
Minimum edge distance of flange two edge2 := .5 in

Methodology

The Port Debris Shield has 4 Corner Brackets SDG39137849 (-001 thru -004) which support the External Bumper. All 4 Corner Brackets are .08 thick AL ALY 6061-6061-T651; use NAS 1398DFC4-3 rivets which go through .125 holes. Each rivet was modeled in NASTRAN as two spider RBE2s connected by a CBush. 64 Lift Off and 64 Landing load conditions were analyzed using the Integrated Loads FEM. The worst worst case Axial (P) and Total Shear (V) loads from the CBush's were enveloped for all the rivets, for all 4 Corner Brackets, for all 128 load cases. The worst case P and the worst case V were used together to calculate the tensile and shear margins of safety.

For Fail-Safe Analysis, the worst worst case P and V were doubled and then used together to calculate the tensile and shear fail-safe margins of safety.

Allowables

Rivet Strengths (AL ALY 2017-T4 Sleeve)

Fsu := 494 lbf  (Minimum Shear Strength)  (Per Document NAS1400, Table III)
Flt := 230 lbf  (Minimum Tensile Strength)  (Per Document NAS1400, Table IV)

Factors of Safety

FSu := 2  (Ultimate Factor of Safety)
FSy := 1.25  (Yield Factor of Safety)
FF := 1.15  (Fitting Factor of Safety)

Temperature Data

Temp_initial := 70 deg  (Assembly)
Temp_max := 140 deg  (Maximum)
Temp_min := -76 deg  (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative
Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76°F to 140°F. These temperature reduction factors are conservative for liftoff/landing conditions.

\[ \beta_{u1} := 0.99 \]  
(Ultimate Temperature Reduction Factor)  
(Ref. MMPDS-03, Figure 3.2.3.1.4)

Allowable Strengths With Temperature Reduction Factor

\[ F_{su1.a} := \beta_{u1} \cdot F_{su} \] \[ F_{su1.a} = 489 \text{lbf} \]  
(Shear Strength Allowable)

\[ F_{tu1.a} := \beta_{u1} \cdot F_{tu} \] \[ F_{tu1.a} = 227.70 \text{lbf} \]  
(Tensile Strength Allowable)

Loads

\[ P := 33.3 \text{lbf} \]  
(Applied Tensile Load)  
(Worst Case Combination)

\[ V := 35.3 \text{lbf} \]  
(Applied Shear Load)

\[ M := 0 \text{in} \cdot \text{lbf} \]  
(Applied Bending Moment)

Margin of Safety

\[ MS_{tu} := \frac{F_{tu1.a}}{F_{Su} \cdot FF} - 1 \] \[ MS_{tu} = 1.97 \]  
(Tensile Ultimate Margin of Safety)

\[ MS_{su} := \frac{F_{su1.a}}{F_{Su} \cdot FF} - 1 \] \[ MS_{su} = 5.02 \]  
(Shear Ultimate Margin of Safety)
Fail-Safe Analysis

**Fail-Safe Loads**

\[
P_{FS} := 2 \cdot P \quad \text{(Applied Tensile Load)}
\]

\[
P_{FS} = 66.60 \text{lbf}
\]

\[
V_{FS} := 2 \cdot V \quad \text{(Applied Shear Load)}
\]

\[
V_{FS} = 70.60 \text{lbf}
\]

\[
M_{FS} := 0.0 \text{ in} \cdot \text{lbf} \quad \text{(Applied Bending Moment)}
\]

**Fail-Safe Factors of Safety**

\[
SFu_{FS} := 1.0 \quad \text{(Ultimate)}
\]

**Fail-Safe Margin of Safety**

\[
MS_{FSu} := \frac{F_{tu1.a}}{SFu_{FS} \cdot FF \cdot P_{FS}} - 1 \quad \text{(Fail-Safe Tensile Ultimate Margin of Safety)}
\]

\[
MS_{FSu} = 1.97
\]

\[
MS_{FSsu} := \frac{F_{su1.a}}{SFu_{FS} \cdot FF \cdot V_{FS}} - 1 \quad \text{(Fail-Safe Shear Ultimate Margin of Safety)}
\]

\[
MS_{FSsu} = 5.02
\]
5.10.2 Starboard Debris Shield Assembly
### 5.10.2.1 General

#### Minimum Margins of Safety

**Table 5.10.2.1 Parts Minimum Margins of Safety**

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137846-001</td>
<td>Debris Shield UPS Cover</td>
<td>AL ALY 7075-T73</td>
<td>Lift Off</td>
<td>Tensile Ultimate</td>
<td>1.27</td>
<td>5.10.2-26</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Debris Shield Interface Joint Bracket</td>
<td>AL ALY 7075-T7351</td>
<td>Landing</td>
<td>Tensile Ultimate</td>
<td>0.083</td>
<td>5.10.2-43</td>
</tr>
<tr>
<td>SDG39137848-001</td>
<td>Debris Shield Mounting Brackets</td>
<td>AL ALY 6061-T651</td>
<td>Lift Off</td>
<td>Tensile Ultimate</td>
<td>0.27</td>
<td>5.10.2-38</td>
</tr>
<tr>
<td>SDG39137849-001</td>
<td>Debris Shield Corner Bracket</td>
<td>AL ALY 6061-T651</td>
<td>Landing</td>
<td>Tensile Ultimate</td>
<td>0.51</td>
<td>5.10.2-35</td>
</tr>
<tr>
<td>SDG39137854-001</td>
<td>Starboard External Bumper Assy</td>
<td>AL ALY 7075-T73</td>
<td>Landing</td>
<td>Shear Ultimate</td>
<td>0.89</td>
<td>5.10.2-23</td>
</tr>
<tr>
<td>SDG39137858-002</td>
<td>Debris Shield Inner Plate</td>
<td>AL ALY 7075-T73</td>
<td>Lift Off</td>
<td>Shear Ultimate</td>
<td>3.03</td>
<td>5.10.2-30</td>
</tr>
</tbody>
</table>

**Table 5.10.2.2 Fastener Minimum Margins of Safety**

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Fastener</th>
<th>Material</th>
<th>MS&lt;sub&gt;nominal&lt;/sub&gt;</th>
<th>Failure Mode</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137846-001</td>
<td>UPS Cover to External Bumper</td>
<td>NAS1133E4</td>
<td>.1900-32</td>
<td>A286</td>
<td>.11</td>
<td>5.10.2-70</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Lower Vacuum Case</td>
<td>NAS1008-8</td>
<td>.5000-20</td>
<td>A286</td>
<td>.24</td>
<td>5.10.2-6</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Upper Vacuum Case</td>
<td>NAS1008-8</td>
<td>.5000-20</td>
<td>A286</td>
<td>.23</td>
<td>5.10.2-14</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Mounting Bracket to Lower Trunnion Bridge Beam</td>
<td>NAS1351N4-12</td>
<td>.2500-28</td>
<td>A286</td>
<td>.14</td>
<td>5.10.2-22</td>
</tr>
<tr>
<td>SDG39137848-001</td>
<td>Mounting Bracket to Interface Panel A</td>
<td>NAS1351N3-10</td>
<td>.1900-32</td>
<td>A286</td>
<td>.13</td>
<td>5.10.2-30</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>External Bumper to Interface Joint</td>
<td>NAS1133E4</td>
<td>.1900-32</td>
<td>A286</td>
<td>.10</td>
<td>5.10.2-38</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4</td>
<td>.1900-32</td>
<td>A286</td>
<td>.10</td>
<td>5.10.2-46</td>
</tr>
<tr>
<td>SDG39137848-001</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4</td>
<td>.1900-32</td>
<td>A286</td>
<td>.10</td>
<td>5.10.2-54</td>
</tr>
<tr>
<td>SDG39137858-002</td>
<td>Inner Plate to Standoff B</td>
<td>NAS1004-1</td>
<td>.2500-28</td>
<td>A286</td>
<td>.10</td>
<td>5.10.2-62</td>
</tr>
<tr>
<td>SDG39137855-001</td>
<td>External Bumper to Standoff B</td>
<td>NAS1004-40</td>
<td>.2500-28</td>
<td>A286</td>
<td>.09</td>
<td>5.10.2-77</td>
</tr>
<tr>
<td>SDG39137849</td>
<td>Corner Bracket to External Bumper</td>
<td>NAS1398DFC4-3</td>
<td>.125 Dia</td>
<td>AL ALY</td>
<td>1.97</td>
<td>5.10.2-80</td>
</tr>
</tbody>
</table>
### Table 5.10.2.3 Fastener Fail-Safe Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Fastener</th>
<th>Material</th>
<th>$MS_{fail-safe}$</th>
<th>Failure Mode</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137846-001</td>
<td>UPS Cover to External Bumper</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.18</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.2.1-71</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Lower Vacuum Case</td>
<td>NAS1008-8 .5000-20</td>
<td>A286</td>
<td>.82</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.2.1-7</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Interface Joint to Upper Vacuum Case</td>
<td>NAS1008-8 .5000-20</td>
<td>A286</td>
<td>.82</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.2.1-15</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Mounting Bracket to Lower Trunnion Bridge Beam</td>
<td>NAS1351N4-12 .2500-28</td>
<td>A286</td>
<td>.22</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.2.1-23</td>
</tr>
<tr>
<td>SDG39137848-001</td>
<td>Mounting Bracket to Interface Panel A</td>
<td>NAS1351N3-10 .1900-32</td>
<td>A286</td>
<td>.20</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.2.1-31</td>
</tr>
<tr>
<td>SDG39137854-001</td>
<td>External Bumper to Interface Joint</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.17</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.2.1-39</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.17</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.2.1-47</td>
</tr>
<tr>
<td>SDG39137854-001</td>
<td>Mounting Bracket to External Bumper</td>
<td>NAS1133E4 .1900-32</td>
<td>A286</td>
<td>.17</td>
<td>Total Thread Shear Ultimate</td>
<td>5.10.2.1-55</td>
</tr>
<tr>
<td>SDG39137848-002</td>
<td>Inner Plate to Standoff B</td>
<td>NAS1004-1 .2500-28</td>
<td>A286</td>
<td>.62</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.2.1-63</td>
</tr>
<tr>
<td>SDG39137855-001</td>
<td>External Bumper to Standoff B</td>
<td>NAS1004-40 .2500-28</td>
<td>A286</td>
<td>.09</td>
<td>Combined Shear, Tension and Bending Ultimate</td>
<td>5.10.2.1-78</td>
</tr>
<tr>
<td>SDG39137847</td>
<td>Corner Bracket to External Bumper</td>
<td>NAS1398DFC4-3 .125 Dia</td>
<td>AL ALY 2017-T4</td>
<td>1.97</td>
<td>Tensile Ultimate</td>
<td>5.10.2.1-81</td>
</tr>
</tbody>
</table>

**Notes:**

1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Boundary conditions are at ten AMS-2 bolts distributed as three along Interface Panel A, three along the Lower Trunnion Bridge Beam, two along the Lower Vacuum Case, and two along the Upper Vacuum Case.
3. 64 launch load cases, 64 landing load cases were applied to the DS.
4. Factors of Safety for Fail-Safe analysis are 1.0 for Ultimate and 1.0 for Yield.
5.10.2.2 Introduction

The Starboard Side Debris Shield (DS) provides shielding for the Uninterrupted Power Supply (UPS) Box to prevent catastrophic rupture of these tanks in the event of MMOD impact which would release high-velocity fragments creating a potential hazard for the crew, Space Shuttle, and the International Space Station.

Structural Description

The Starboard DS (Figure 5.10.2.1 Starboard Debris Shield Assembly, SEG39137852) consists of two thin aluminum panels sandwiching a ballistic blanket and it’s supports (Figure 5.10.2.5 Starboard Debris Shield Mounting Plates Supporting the Ballistic Blanket). The three layers are separated by aluminum standoffs (Figure 5.10.2.4 Transparent View Looking Through the Side of External Bumper at Standoffs). Bolts are used to connect the various panels.

Figure 5.10.2.1 Starboard Debris Shield Assembly, SEG39137852

Figure 5.10.2.2 Starboard Debris Shield with the Unique Support Structure (USS), shows a top view of where the Starboard DS fits into the USS. While Figure 5.10.2.3 Starboard Debris Shield with the USS, shows the Starboard DS next to Interface Panel A.
Figure 5.10.2.2 Starboard Debris Shield with the Unique Support Structure (USS)
Figure 5.10.2.3 Starboard Debris Shield with the USS
The Starboard DS attaches to the Channel Assembly Interface Panel A with three fasteners, to the Lower Trunnion Bridge Beam with three fasteners, to the Lower Vacuum Case with two fasteners, and to the Upper Vacuum Case with two fasteners (Figure 5.10.2.6 Starboard Debris Shield Mounting Brackets).
An initial assessment of the Shuttle flight loads was made using the secondary structure load factors provided in Table 4-4 of the AMS-02 Structural Verification Plan (JSC-28792, Rev. E). However, these loads are very conservative and the results of the analysis showed that the structural margins were unacceptable. The load factors are provided in Table 5.10.2.4 Launch/Landing Design Limit Load Factors for Small Secondary Structures for reference.

<table>
<thead>
<tr>
<th>Weight (pounds)</th>
<th>Load Factor (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>40</td>
</tr>
<tr>
<td>20-50</td>
<td>31</td>
</tr>
<tr>
<td>50-100</td>
<td>22</td>
</tr>
<tr>
<td>100-200</td>
<td>17</td>
</tr>
<tr>
<td>200-500</td>
<td>13</td>
</tr>
</tbody>
</table>

To reduce the conservatism for the flight loads assessment, the Starboard DS math model was integrated with the math model of the full AMS-02 payload. The liftoff and landing load factors from the AMS-02 design coupled loads analysis (as specified in Table 5-2 of the AMS-02 SVP) were applied to the integrated math model. These loads are provided in Table 5.10.2.5 Second DCLA Liftoff and Landing Load Factors for reference.
Table 5.10.2.5  Second DCLA Liftoff and Landing Load Factors

<table>
<thead>
<tr>
<th>Event</th>
<th>$N_x$</th>
<th>$N_y$</th>
<th>$N_z$</th>
<th>$R_x$</th>
<th>$R_y$</th>
<th>$R_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liftoff</td>
<td>-3.7 / 0.4</td>
<td>-1.4 / 1.6</td>
<td>-1.4 / 1.5</td>
<td>-4.5 / 4.1</td>
<td>-8.4 / 11.0</td>
<td>-3.9 / 4.1</td>
</tr>
<tr>
<td>Abort Landing</td>
<td>-1.2 / 1.3</td>
<td>-0.7 / 0.6</td>
<td>-2.1 / 5.6</td>
<td>-5.2 / 4.7</td>
<td>-10.7 / 13.9</td>
<td>-6.0 / 4.8</td>
</tr>
</tbody>
</table>

A static loads analysis was performed using NASTRAN with 64 subcases representing all combinations of the liftoff load factors and 64 subcases representing all combinations of the landing load factors. Loads and stresses were then recovered from this integrated analysis for the Starboard DS interface and internal components and used to compute the structural strength margins.

**Factors of Safety**

The hardware is designed with an Ultimate Factor of Safety of 2.0 and a Yield Factor of Safety of 1.25 against limit loads.

**Materials and Temperature**

Table of Material Allowables

The materials, and their allowables, used in the Starboard Debris Shield are shown in Table 5.10.2.6  Material Allowables.

Table 5.10.2.6  Material Allowables

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Allowables</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137846-001</td>
<td>Debris Shield UPS Cover</td>
<td>AL ALY 7075-T73 AMS-QQ-A-250/12</td>
<td>(F_{tu} = 67000) psi (F_{ty} = 55000) psi (F_{su} = 38000) psi</td>
</tr>
<tr>
<td>SDG39137847-001</td>
<td>Debris Shield Interface Joint Bracket</td>
<td>AL ALY 7075-T7351 AMS-QQ-A-250/12</td>
<td>(F_{tu} = 66000) psi (F_{ty} = 55000) psi (F_{su} = 39000) psi</td>
</tr>
<tr>
<td>SDG39137848-001</td>
<td>Debris Shield Mounting Brackets</td>
<td>AL ALY 6061-T651 AMS-QQ-A-250/11</td>
<td>(F_{tu} = 42000) psi (F_{ty} = 36000) psi (F_{su} = 27000) psi</td>
</tr>
<tr>
<td>SDG39137849-001</td>
<td>Debris Shield Corner Bracket</td>
<td>AL ALY 6061-T651 AMS-QQ-A-250/11</td>
<td>(F_{tu} = 42000) psi (F_{ty} = 36000) psi (F_{su} = 27000) psi</td>
</tr>
<tr>
<td>SDG39137854-001</td>
<td>Starboard External Bumper Assy</td>
<td>AL ALY 7075-T73 AMS-QQ-A-250/12</td>
<td>(F_{tu} = 67000) psi (F_{ty} = 55000) psi (F_{su} = 38000) psi</td>
</tr>
<tr>
<td>SDG39137858-002</td>
<td>Debris Shield Inner Plate</td>
<td>AL ALY 7075-T73 AMS-QQ-A-250/12</td>
<td>(F_{tu} = 67000) psi (F_{ty} = 55000) psi (F_{su} = 38000) psi</td>
</tr>
</tbody>
</table>

Temperature Degradation

The temperature extremes are -76°F to 140°F.
5.10.2.3 Description of the Starboard DS Finite Element Model

The FEMAP modeling software was used to generate a finite element model of the Starboard DS for structural analysis using NASTRAN.

1. The geometry of each part was identified by a CAD model (Parasolid format) that was provided by the design group. This geometry was used as the basis for generating the finite element mesh.
2. The External Bumper, UPS Cover, Inner Plate (bumper), Corner Brackets, and Mounting Brackets are modeled using plate elements (CQUAD4 and CTRIA3).
3. The Mounting Bracket to USS and the Mounting Bracket to External Bumper fasteners are represented by CBUSH elements with stiffness values for the three translation directions that represent axial and shear stiffness.
4. The standoffs that provide separation between the External Bumper, Ballistic Blanket, and Inner Plate are modeled with beam (CBAR) elements.
5. The Ballistic Blanket and its supports are represented by CMass elements with the total weight of the blanket and its supports evenly distributed at the intersections with the Standoffs.
6. The Starboard DS model is integrated with the USS model.

A summary from NASTRAN of the finite elements comprising the model is provided below.

<table>
<thead>
<tr>
<th>MODEL SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF GRID POINTS = 279432</td>
</tr>
<tr>
<td>NUMBER OF CBAR ELEMENTS = 22467</td>
</tr>
<tr>
<td>NUMBER OF CBEAM ELEMENTS = 15152</td>
</tr>
<tr>
<td>NUMBER OF CBUSH ELEMENTS = 3168</td>
</tr>
<tr>
<td>NUMBER OF CHEXA ELEMENTS = 1640</td>
</tr>
<tr>
<td>NUMBER OF CONM2 ELEMENTS = 1649</td>
</tr>
<tr>
<td>NUMBER OF CPENTA ELEMENTS = 376</td>
</tr>
<tr>
<td>NUMBER OF CQUAD4 ELEMENTS = 229969</td>
</tr>
<tr>
<td>NUMBER OF CROD ELEMENTS = 42</td>
</tr>
<tr>
<td>NUMBER OF CTETRA ELEMENTS = 216</td>
</tr>
<tr>
<td>NUMBER OF CTRIA3 ELEMENTS = 17956</td>
</tr>
<tr>
<td>NUMBER OF RBE2 ELEMENTS = 13701</td>
</tr>
<tr>
<td>NUMBER OF RBE3 ELEMENTS = 194</td>
</tr>
</tbody>
</table>

Description of the Integrated Starboard DS and Full Payload Math Model

The 2-06 version of the AMS-02 loads model was used to represent the payload in the integrated model. The Starboard DS math model described in the preceding sections was connected to the payload model using two rigid elements (RBE2). The independent nodes for the two rigid elements are the nodes on the beam elements representing the Starboard DS interface with the Upper Trunnion Bridge Beam and the Lower Trunnion Bridge Beam. The dependent nodes of the rigid elements are the Starboard DS nodes that represent the interface bolt locations. A view of the full payload math model is shown in Figure 5.10.2.7 Finite Element Model of Starboard DS Integrated with Full Payload.
Constraint and Grounding Checks

Constraint and grounding checks were performed using MSC NASTRAN. The results of these checks are shown below for an unconstrained model. The model passes the checks at all degree-of-freedom set levels with sufficiently low strain energy to indicate that there are no unintended constraints or grounding issues.

**Table: Rigid Body Checks of Matrix Kgg (G-Set)**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Strain Energy</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.899828E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>1.004083E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>4.015733E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>7.521169E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>4.014671E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.324051E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Some possible reasons may lead to the failure:

1. CELASI elements connecting to only one grid point;
2. CELASI elements connecting to non-coincident points;
3. CELASI elements connecting to non-collinear DOF;
4. Improperly defined DMIG matrices;

---

**Figure 5.10.2.7 Finite Element Model of Starboard DS Integrated with Full Payload**

*Checks for the Integrated Starboard DS and Full Payload Math Model*
### Modal Check

A modal analysis was performed using NASTRAN to determine the modal frequencies and confirm that the model has appropriate rigid-body modes. A list of the rigid-body modes and elastic modes are provided below.

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>REAL EIGENVALUE</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2.4799E-07</td>
<td>1.000000E+00</td>
<td>2.4799E-07</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3.9997E-07</td>
<td>1.000000E+00</td>
<td>3.9997E-07</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6.3681E-07</td>
<td>1.000000E+00</td>
<td>6.3681E-07</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1.6092E-06</td>
<td>1.000000E+00</td>
<td>1.2559E-06</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2.5890E-06</td>
<td>1.000000E+00</td>
<td>2.5890E-06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>3.4879E-06</td>
<td>1.000000E+00</td>
<td>3.4879E-06</td>
</tr>
</tbody>
</table>

#### Results of Rigid Body Checks of Matrix KN (N-Set)

---

**Print Results in All Six Directions Against the Limit Of 9.176609E-01**

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2089E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.4996E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.4748E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>6.5117E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.8937E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.9819E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Some Possible Reasons May Lead to the Failure:**

1. Multipoint Constraint Equations which Do Not Satisfy Rigid-Body Motion;
2. RBE3 Elements for Which the Independent Degree-of-Freedom Cannot Describe All Possible Rigid-Body Motions.

#### Results of Rigid Body Checks of Matrix KFF (F-Set)

---

**Print Results in All Six Directions Against the Limit Of 9.176609E-01**

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2089E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.4996E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.4748E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>6.5117E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.8937E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.9819E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

**Some Possible Reasons May Lead to the Failure:**


#### Results of Rigid Body Checks of Matrix KAAL (A-Set)

---

**Print Results in All Six Directions Against the Limit Of 9.176609E-01**

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2089E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.4996E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.4748E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>6.5117E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.8937E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.9819E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

If the Model Has Passed the Previous Checks for the G-Set and N-Set, Then Some Possible Causes Are:

1. The Model Is Not Intended to Be Free-Free Which Indicates That the Model Is Properly Constrained to Ground;
2. The Reference Grid Point (GRID=GID on the Groundcheck Command) Is Located Too Far From the Model's Center of Gravity. It Is Recommended That the Reference Grid Point Be Located as Close as Possible to the Model's Center of Gravity of the Model (See the Grid Point Weight Generator Output);
Mass Properties Check

Since the Starboard DS was run integrated with the full payload model, a NASTRAN mass properties check would not be useful as the Starboard DS is a small portion of the total mass of the integrated model. So, using FEMAP, a mass properties check was performed on just the Starboard DS.

Using FEMAP 9.3.1 > Tools > Mass Properties > Mesh Properties, the Starboard Debris Shield assembly FEM has a mass of 0.0878126 lbf-s^2/in or a weight of 33.90 lbf.

Based on the Unigraphics CAD model, the Starboard Debris Shield assembly SDG39137851 has a weight of 32.58 lbf, without the soft goods.
5.10.2.4  Detailed Stress Analysis

The critical stresses for all components of the Starboard Debris Shield assembly are compared to the Ultimate and Yield strength of the Aluminum Alloy materials used in the assembly. Analysis of the fasteners used to assemble the Starboard DS was also performed. All margins of safety are positive.

The minimum Margins of Safety Summary of the parts are shown in Table 5.10.2.1 Parts Minimum Margins of Safety, Table 5.10.2.2 Fastener Minimum Margins of Safety, and Table 5.10.2.3 Fastener Fail-Safe Minimum Margins of Safety.
Intentionally Left Blank
Intentionally Left Blank
Intentionally Left Blank
CHECK of Debris Shield

Starboard (UPS) - Starboard External Bumper ASSY, SDG39137854

Allowables

Material Properties

AL ALY, 7075-T73, Sheet, 0.040-0.249, A, AMS-QQ-A-250/12

\[
\begin{align*}
F_{tu} & := 67000 \text{ psi} \\
F_{ty} & := 55000 \text{ psi} \\
F_{su} & := 38000 \text{ psi}
\end{align*}
\]

Factors of Safety

\[
\begin{align*}
FS_{u} & := 2.0 \\
FS_{y} & := 1.25
\end{align*}
\]

Temperature Reduction Factors

\[\text{At } 140^\circ \text{F:} \quad \text{(For the Debris Shield, the temperature extremes are } -76^\circ \text{F to } 140^\circ \text{F; These temperature reduction factors are conservative for liftoff/landing conditions)}\]

- Ultimate: \[\beta_{u} := 0.96 \quad (\text{Ref. MMPDS-03, Figure 3.7.7.1.1.(c)})\]
- Yield: \[\beta_{y} := 0.96 \quad (\text{Ref. MMPDS-03, Figure 3.7.7.1.1.(d)})\]

Allowable Stresses

\[
\begin{align*}
F_{tug} & := \beta_{u} \cdot F_{tu} \\
F_{tug} & := 64320 \text{ psi} \\
F_{tyg} & := \beta_{y} \cdot F_{ty} \\
F_{tyg} & := 52800 \text{ psi} \\
F_{sug} & := \beta_{u} \cdot F_{su} \\
F_{sug} & := 36480 \text{ psi}
\end{align*}
\]
Starboard (UPS) - Starboard External Bumper ASSY, SDG39137854

Omitted Elements

NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Launch and Landing Cases, the elements at the bolt holes were removed from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.

(For Omitted Elements, See Appendix A28.4.1.1, p. A28-49)
Starboard (UPS) - Starboard External Bumper ASSY, SDG39137854

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-liftoff-full-rev6.pch

Maximum Stresses

\[
\begin{align*}
\sigma_{tu} &= 12510 \text{ psi} \\
&= \text{LC# 1032, ELEM# 3112633} \\
&\text{(Maximum Principal Stress, p.A28-31)}
\end{align*}
\]

\[
\begin{align*}
\sigma_{ty} &= 14575 \text{ psi} \\
&= \text{LC# 1032, ELEM# 3112633} \\
&\text{(Maximum Von-Mises Stress, p.A28-31)}
\end{align*}
\]

\[
\begin{align*}
\tau_{su} &= 8002 \text{ psi} \\
&= \text{LC# 1032; ELEM# 3112633} \\
&\text{(Maximum Shear Stress, p.A28-31)}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
\text{MS}_{tu} &= \frac{F_{tu}}{F_{SU} \cdot \sigma_{tu}} - 1 \\
&= 1.571 \quad \text{... Margin of Safety Tensile Ultimate}
\end{align*}
\]

\[
\begin{align*}
\text{MS}_{ty} &= \frac{F_{ty}}{F_{SY} \cdot \sigma_{ty}} - 1 \\
&= 1.9 \quad \text{... Margin of Safety Tensile Yield}
\end{align*}
\]

\[
\begin{align*}
\text{MS}_{su} &= \frac{F_{su}}{F_{SU} \cdot \tau_{su}} - 1 \\
&= 1.28 \quad \text{... Margin of Safety Shear Ultimate}
\end{align*}
\]
Starboard (UPS) - Starboard External Bumper ASSY, SDG39137854

**Landing Loads**

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-landing-full-rev6.pch

### Maximum Stresses

<table>
<thead>
<tr>
<th>Element Stress</th>
<th>Value</th>
<th>Load Case</th>
<th>Element Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Principal Stress, $u_{tu}$</td>
<td>14713 psi</td>
<td>LC# 2063</td>
<td>ELEM# 3112347</td>
</tr>
<tr>
<td>Maximum Von-Mises Stress, $u_{ty}$</td>
<td>16928 psi</td>
<td>LC# 2032</td>
<td>ELEM# 3112633</td>
</tr>
<tr>
<td>Maximum Shear Stress, $u_{su}$</td>
<td>9633 psi</td>
<td>LC# 2032</td>
<td>ELEM# 3112593</td>
</tr>
</tbody>
</table>

(See Appendix A28.3.5)

### Margins of Safety

<table>
<thead>
<tr>
<th>Margin of Safety</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margin of Safety Tensile Ultimate</td>
<td>$MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1$</td>
<td>$MS_{tug} = 1.186$</td>
</tr>
<tr>
<td>Margin of Safety Tensile Yield</td>
<td>$MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1$</td>
<td>$MS_{tyg} = 1.5$</td>
</tr>
<tr>
<td>Margin of Safety Shear Ultimate</td>
<td>$MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1$</td>
<td>$MS_{sug} = 0.89$</td>
</tr>
</tbody>
</table>
Starboard (UPS) - Debris Shield UPS Cover, SDG39137846

*Allowables*

**Material Properties**

\[
\begin{align*}
& \text{AL ALY, 7075-T73, Sheet, 0.040-0.249, A, AMS-QQ-A-250/12} \\
& F_{tu} := 67000 \text{ psi} \\
& F_{ty} := 55000 \text{ psi} \\
& F_{su} := 38000 \text{ psi}
\end{align*}
\]

**Factors of Safety**

\[
\begin{align*}
& F_{S_u} := 2.0 \\
& F_{S_y} := 1.25
\end{align*}
\]

**Temperature Reduction Factors**

- At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

  - Ultimate:  \( \beta_u := 0.96 \)  
    (Ref. MMPDS-03, Figure 3.7.7.1.1.(c))
  
  - Yield:  \( \beta_y := 0.96 \)  
    (Ref. MMPDS-03, Figure 3.7.7.1.1.(d))

**Allowable Stresses**

\[
\begin{align*}
& F_{tug} := \beta_u \cdot F_{tu} \\
& F_{tug} = 64320 \text{ psi} \\
& F_{tyg} := \beta_y \cdot F_{ty} \\
& F_{tyg} = 52800 \text{ psi} \\
& F_{sug} := \beta_u \cdot F_{su} \\
& F_{sug} = 36480 \text{ psi}
\end{align*}
\]
Starboard (UPS) - Debris Shield UPS Cover, SDG39137846

Omitted Elements

NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Launch and Landing Cases, the elements at the bolt holes were removed from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.

There were no omitted elements in the UPS Cover
Starboard (UPS) - Debris Shield UPS Cover, SDG39137846

**Liftoff Loads**

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-liftoff-full-rev6.pch

### Maximum Stresses

(See Appendix A28.3.12)

\[ u_{tu} := 14153 \text{ psi} \quad \text{LC# 1018 ELEM# 3200068} \quad \text{(Maximum Principal Stress, p.A28-45)} \]

\[ u_{ty} := 13843 \text{ psi} \quad \text{LC# 1018 ELEM# 3200072} \quad \text{(Maximum Von-Mises Stress, p.A28-45)} \]

\[ u_{su} := 7148 \text{ psi} \quad \text{LC# 1018 ELEM# 3200072} \quad \text{(Maximum Shear Stress, p.A28-45)} \]

### Margins of Safety

**Tensile Ultimate**

\[ MS_{tug} := \frac{F_{tug}}{FS_{u} \cdot u_{tu}} - 1 \]

\[ MS_{tug} = 1.272 \quad \text{... Margin of Safety Tensile Ultimate} \]

**Tensile Yield**

\[ MS_{tyg} := \frac{F_{tyg}}{FS_{y} \cdot u_{ty}} - 1 \]

\[ MS_{tyg} = 2.05 \quad \text{... Margin of Safety Tensile Yield} \]

**Shear Ultimate**

\[ MS_{sug} := \frac{F_{sug}}{FS_{u} \cdot u_{su}} - 1 \]

\[ MS_{sug} = 1.55 \quad \text{... Margin of Safety Shear Ultimate} \]
Starboard (UPS) - Debris Shield UPS Cover, SDG39137846

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-landing-full-rev6.pch

Maximum Stresses

(See Appendix A28.3.11)

\( u_{tu} := 11001 \text{ psi} \)  
\( LC \# 2016 \ ELEM\# 3200167 \)  
(\textit{Maximum Principal Stress, p.A28-43})

\( u_{ty} := 11070 \text{ psi} \)  
\( LC \# 2016 \ ELEM\# 3200167 \)  
(\textit{Maximum Von-Mises Stress, p.A28-43})

\( u_{su} := 5678 \text{ psi} \)  
\( LC \# 2016 \ ELEM\# 3200167 \)  
(\textit{Maximum Shear Stress, p.A28-43})

Margins of Safety

\[
MS_{tu} := \frac{F_{tu}}{FS_{u} \cdot u_{tu}} - 1
\]

\( MS_{tu} = 1.923 \)  
... \textit{Margin of Safety Tensile Ultimate}

\[
MS_{ty} := \frac{F_{ty}}{FS_{y} \cdot u_{ty}} - 1
\]

\( MS_{ty} = 2.82 \)  
... \textit{Margin of Safety Tensile Yield}

\[
MS_{su} := \frac{F_{su}}{FS_{u} \cdot u_{su}} - 1
\]

\( MS_{su} = 2.21 \)  
... \textit{Margin of Safety Shear Ultimate}
**Starboard (UPS) - Debris Shield Inner Plate, SDG39137858-002**

### Allowables

#### Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{tu}$</td>
<td>67000 psi</td>
</tr>
<tr>
<td>$F_{ty}$</td>
<td>55000 psi</td>
</tr>
<tr>
<td>$F_{su}$</td>
<td>38000 psi</td>
</tr>
</tbody>
</table>

#### Factors of Safety

- $FS_u := 2.0$
- $FS_y := 1.25$

#### Temperature Reduction Factors

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: $\beta_u := 0.96$
- Yield: $\beta_y := 0.96$

#### Allowable Stresses

- $F_{tug} := \beta_u \cdot F_{tu}$
  - $F_{tug} = 64320$ psi
- $F_{tyg} := \beta_y \cdot F_{ty}$
  - $F_{tyg} = 52800$ psi
- $F_{sug} := \beta_u \cdot F_{su}$
  - $F_{sug} = 36480$ psi
Starboard (UPS) - Debris Shield Inner Plate, SDG39137858-002

Omitted Elements

NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Launch and Landing Cases, the elements at the bolt holes were removed from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.

(For Omitted Elements, See Appendix A28.4.1.2, p. A28-56)
Starboard (UPS) - Debris Shield Inner Plate, SDG39137858-002

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-liftoff-full-rev6.pch

Maximum Stresses

\( u_{lu} := 7977 \text{ psi} \)  \( LC\# 1018, ELEM\# 3400451 \)  (Maximum Principal Stress, p.A28-32)

\( u_{lv} := 7865 \text{ psi} \)  \( LC\# 1018, ELEM\# 3400219 \)  (Maximum Von-Mises Stress, p.A28-32)

\( u_{su} := 4523 \text{ psi} \)  \( LC\# 1018 ELEM\# 3400219 \)  (Maximum Shear Stress, p.A28-32)

Margins of Safety

\[
MS_{lug} := \frac{F_{lug}}{FS_{u} \cdot u_{lu}} - 1 \quad MS_{lug} = 3.032 \quad \text{... Margin of Safety Tensile Ultimate}
\]

\[
MS_{lyg} := \frac{F_{lyg}}{FS_{y} \cdot u_{ly}} - 1 \quad MS_{lyg} = 4.37 \quad \text{... Margin of Safety Tensile Yield}
\]

\[
MS_{sug} := \frac{F_{sug}}{FS_{u} \cdot u_{su}} - 1 \quad MS_{sug} = 3.03 \quad \text{... Margin of Safety Shear Ultimate}
\]
Starboard (UPS) - Debris Shield Inner Plate, SDG39137858-002

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-landing-full-rev6.pch

Maximum Stresses

(See Appendix A28.3.5)

\[ u_{tu} := 6367 \text{ psi} \quad \text{LC# 2047, ELEM# 3402190} \]  
(Maximum Principal Stress, p.A28-29)

\[ u_{ty} := 6536 \text{ psi} \quad \text{LC# 2047, ELEM# 3400219} \]  
(Maximum Von-Mises Stress, p.A28-29)

\[ u_{su} := 3668 \text{ psi} \quad \text{LC# 2047; ELEM# 3400219} \]  
(Maximum Shear Stress, p.A28-29)

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_{u} \cdot u_{tu}} - 1 \quad \text{MS}_{tug} = 4.051 \quad \text{... Margin of Safety Tensile Ultimate} \]

\[ MS_{tyg} := \frac{F_{tyg}}{FS_{y} \cdot u_{ty}} - 1 \quad \text{MS}_{tyg} = 5.46 \quad \text{... Margin of Safety Tensile Yield} \]

\[ MS_{sug} := \frac{F_{sug}}{FS_{u} \cdot u_{su}} - 1 \quad \text{MS}_{sug} = 3.97 \quad \text{... Margin of Safety Shear Ultimate} \]
Starboard (UPS) - Debris Shield Corner Bracket, SDG39137849

Allowables

Material Properties

AL ALY, 6061-T651, Plate, 0.250-2.000, A, AMS-QQ-A-250/11

\[
F_{tu} := 42000 \text{ psi} \\
F_{ty} := 36000 \text{ psi} \\
F_{su} := 27000 \text{ psi}
\]

(Ref. MMPDS-03, Table 3.6.2.0(d))

Factors of Safety

\[
FS_u := 2.0 \quad FS_y := 1.25
\]

Temperature Reduction Factors

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: \( \beta_u := 0.96 \)  
  (Ref. MMPDS-03, Figure 3.6.2.2.1(a))

- Yield: \( \beta_y := 0.96 \)  
  (Ref. MMPDS-03, Figure 3.6.2.2.1(b))

Allowable Stresses

\[
F_{tug} := \beta_u \cdot F_{tu} \\
F_{tug} = 40320 \text{ psi}
\]

\[
F_{tyg} := \beta_y \cdot F_{ty} \\
F_{tyg} = 34560 \text{ psi}
\]

\[
F_{sug} := \beta_u \cdot F_{su} \\
F_{sug} = 25920 \text{ psi}
\]
**Starboard (UPS) - Debris Shield Corner Bracket, SDG39137849**

**Omitted Elements**

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2's, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.

*For Omitted Elements, See Appendix A28.4.1.3, p. A28-57*
Starboard (UPS) - Debris Shield Corner Bracket, SDG39137849

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-liftoff-full-rev6.pch

Maximum Stresses

\[ u_{tu} := 10574 \text{ psi} \quad \text{LC# 1017, ELEM# 3312670} \quad (\text{Maximum Principal Stress, p.A28-32}) \]

\[ u_{ty} := 10126 \text{ psi} \quad \text{LC# 1017, ELEM# 3314027} \quad (\text{Maximum Von-Mises Stress, p.A28-33}) \]

\[ u_{su} := 5461 \text{ psi} \quad \text{LC# 1017 ELEM# 3314027} \quad (\text{Maximum Shear Stress, p.A28-33}) \]

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \quad MS_{tug} = 0.907 \quad \ldots \text{Margin of Safety Tensile Ultimate} \]

\[ MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1 \quad MS_{tyg} = 1.73 \quad \ldots \text{Margin of Safety Tensile Yield} \]

\[ MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1 \quad MS_{sug} = 1.37 \quad \ldots \text{Margin of Safety Shear Ultimate} \]
Starboard (UPS) - Debris Shield Corner Bracket, SDG39137849

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-landing-full-rev6.pch

Maximum Stresses

\[ u_{tu} := 13340 \text{ psi} \]
\[ LC# \ 2031, \ ELEM# \ 3305939 \]  
(Maximum Principal Stress, p.A28-29)

\[ u_{ty} := 12888 \text{ psi} \]
\[ LC# \ 2031 \ ELEM# \ 3305939 \]  
(Maximum Von-Mises Stress, p.A28-30)

\[ u_{su} := 6670 \text{ psi} \]
\[ LC# \ 2031 \ ELEM# \ 3305939 \]  
(Maximum Shear Stress, p.A28-30)

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \]  
\[ MS_{tug} = 0.511 \]
... Margin of Safety Tensile Ultimate

\[ MS_{ly} := \frac{F_{ly}}{FS_y \cdot u_{ty}} - 1 \]  
\[ MS_{ly} = 1.15 \]
... Margin of Safety Tensile Yield

\[ MS_{su} := \frac{F_{su}}{FS_u \cdot u_{su}} - 1 \]  
\[ MS_{su} = 0.94 \]
... Margin of Safety Shear Ultimate
Starboard (UPS) - Debris Shield Mounting Brackets, SDG39137848

**Allowables**

**Material Properties**

\[
\text{AL ALY 6061-T651, Plate, 0.250-2.000, A, AMS-QQ-A-250/11}
\]

- \( F_{tu} := 42000 \text{ psi} \)  
  \((\text{Ref. MMPDS-03, Table 3.6.2.0(b2)})\)
- \( F_{ty} := 36000 \text{ psi} \)
- \( F_{su} := 27000 \text{ psi} \)

**Factors of Safety**

- \( F_{Su} := 2.0 \)
- \( F_{Sy} := 1.25 \)

**Temperature Reduction Factors**

+ At 140°F:  (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate:  \( \beta_u := 0.96 \)  
  \((\text{Ref. MMPDS-03, Figure 3.6.2.2.1(a)})\)
- Yield:  \( \beta_y := 0.96 \)  
  \((\text{Ref. MMPDS-03, Figure 3.6.2.2.1(b)})\)

**Allowable Stresses**

- \( F_{tug} := \beta_u \cdot F_{tu} \)
  \( F_{tug} = 40320 \text{ psi} \)

- \( F_{tyg} := \beta_y \cdot F_{ty} \)
  \( F_{tyg} = 34560 \text{ psi} \)

- \( F_{sug} := \beta_u \cdot F_{su} \)
  \( F_{sug} = 25920 \text{ psi} \)
Starboard (UPS) - Debris Shield Mounting Brackets, SDG39137848

Omitted Elements

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2's, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.

(For Omitted Elements, See Appendix A28.4.1.4, p. A28-60)
Starboard (UPS) - Debris Shield Mounting Brackets, SDG39137848

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-liftoff-full-rev6.pch

Maximum Stresses

(See Appendix A28.3.2)

<table>
<thead>
<tr>
<th>Stresses</th>
<th>LC# 1016 ELEM# 3303619</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{tu}$ := 15932 psi</td>
<td></td>
<td>(Maximum Principal Stress, p.A28-23)</td>
</tr>
<tr>
<td>$u_{ty}$ := 15986 psi</td>
<td></td>
<td>(Maximum Von-Mises Stress, p.A28-23)</td>
</tr>
<tr>
<td>$u_{su}$ := 8247 psi</td>
<td></td>
<td>(Maximum Shear Stress, p.A28-24)</td>
</tr>
</tbody>
</table>

Margins of Safety

$$MS_{tu} := \frac{F_{tu}}{FS_{u} \cdot u_{tu}} - 1$$

$MS_{tu} = 0.265$  ... Margin of Safety Tensile Ultimate

$$MS_{ty} := \frac{F_{ty}}{FS_{y} \cdot u_{ty}} - 1$$

$MS_{ty} = 0.73$  ... Margin of Safety Tensile Yield

$$MS_{su} := \frac{F_{su}}{FS_{u} \cdot u_{su}} - 1$$

$MS_{su} = 0.57$  ... Margin of Safety Shear Ultimate
Starboard (UPS) - Debris Shield Mounting Brackets, SDG39137848

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-landing-full-rev6.pch

Maximum Stresses

\( u_{tu} := 11150 \text{ psi} \)  
\( LC\# \text{ 2016 ELEM# 3303619} \)  
(See Appendix A28.3.1)  
(Maximum Principal Stress, p.A28-21)

\( u_{ty} := 11184 \text{ psi} \)  
\( LC\# \text{ 2016 ELEM# 3303619} \)  
(Maximum Von-Mises Stress, p.A28-22)

\( u_{su} := 5772 \text{ psi} \)  
\( LC\# \text{ 2016 ELEM# 3303619} \)  
(Maximum Shear Stress, p.A28-22)

Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{F_{S,U} \cdot u_{tu}} - 1 \]
\[ MS_{ty} := \frac{F_{ty}}{F_{S,Y} \cdot u_{ty}} - 1 \]
\[ MS_{su} := \frac{F_{su}}{F_{S,U} \cdot u_{su}} - 1 \]

\[ MS_{tu} = 0.808 \] ... Margin of Safety Tensile Ultimate

\[ MS_{ty} = 1.47 \] ... Margin of Safety Tensile Yield

\[ MS_{su} = 1.25 \] ... Margin of Safety Shear Ultimate
Starboard (UPS) - Debris Shield Interface Joint Bracket, SDG39137847

Allowables

Material Properties

AL ALY 7075-T7351, Plate, 1.501-2.000, A, AMS-QQ-A-250/12

\[
\begin{align*}
F_{tu} & := 66000 \text{ psi} \quad \text{(Ref. MMPDS-03, Table 3.7.7.0(b3))} \\
F_{ty} & := 55000 \text{ psi} \\
F_{su} & := 39000 \text{ psi}
\end{align*}
\]

Factors of Safety

\[
\begin{align*}
FS_u & := 2.0 \\
FS_y & := 1.25
\end{align*}
\]

Temperature Reduction Factors

+ At 140°F: (For the Debris Shield, the temperature extremes are -76°F to 140°F; These temperature reduction factors are conservative for liftoff/landing conditions)

- Ultimate: \[\beta_u := 0.96\] \quad (Ref. MMPDS-03, Figure 3.7.7.1.4.)

- Yield: \[\beta_y := 0.96\] \quad (Ref. MMPDS-03, Figure 3.7.7.1.4.)

Allowable Stresses

\[
\begin{align*}
F_{tug} & := \beta_u \cdot F_{tu} \\
F_{tug} & := 63360 \text{ psi}
\end{align*}
\]

\[
\begin{align*}
F_{tyg} & := \beta_y \cdot F_{ty} \\
F_{tyg} & := 52800 \text{ psi}
\end{align*}
\]

\[
\begin{align*}
F_{sug} & := \beta_u \cdot F_{su} \\
F_{sug} & := 37440 \text{ psi}
\end{align*}
\]
Starboard (UPS) - Debris Shield Interface Joint Bracket, SDG39137847

Omitted Elements

NASPOST V.2.2 is used to sort the maximum stresses across all load cases. For the Launch and Landing Cases, the elements around the perimeter of bolt holes, where the bolts were modeled with RBE2's, were removed from the NASPOST sort (see table below). These elements had artificially high localized stresses because of their proximity to the RBE2.

(For Omitted Elements, See Appendix A28.4.1.4, p. A28-60)
Starboard (UPS) - Debris Shield Interface Joint Bracket, SDG39137847

Liftoff Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-liftoff-full-rev6.pch

Maximum Stresses

- $u_{tu} := 27327 \text{ psi}$  
  $LC# \ 1018\ ELEM#\ 3310604$  
  (Maximum Principal Stress, p.A28-24)

- $u_{ty} := 27889 \text{ psi}$  
  $LC# \ 1018\ ELEM#\ 3310604$  
  (Maximum Von-Mises Stress, p.A28-24)

- $u_{su} := 14209 \text{ psi}$  
  $LC# \ 1018\ ELEM#\ 3310604$  
  (Maximum Shear Stress, p.A28-24)

Margins of Safety

- $MS_{tu} := \frac{F_{tu}}{FSu \cdot u_{tu}} - 1$  
  $MS_{tu} = 0.159$  
  ... Margin of Safety Tensile Ultimate

- $MS_{ty} := \frac{F_{ty}}{FSy \cdot u_{ty}} - 1$  
  $MS_{ty} = 0.51$  
  ... Margin of Safety Tensile Yield

- $MS_{su} := \frac{F_{su}}{FSu \cdot u_{su}} - 1$  
  $MS_{su} = 0.32$  
  ... Margin of Safety Shear Ultimate
Starboard (UPS) - Debris Shield Interface Joint Bracket, SDG39137847

Landing Loads

The Debris Shield model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, Principal, and Shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort the maximum stresses across the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

NASTRAN Punch Filename: static-landing-full-rev6.pch

Maximum Stresses (See Appendix A28.3.1)

\[ \sigma_{tu} := 29247 \, \text{psi} \quad \text{LC# 2031 ELEM# 3306789} \]  
( Maximum Principal Stress, p.A28-22 )

\[ \sigma_{ty} := 28298 \, \text{psi} \quad \text{LC# 2032 ELEM# 3307218} \]  
( Maximum Von-Mises Stress, p.A28-22 )

\[ \tau_{su} := 14960 \, \text{psi} \quad \text{LC# 2032 ELEM# 3307218} \]  
( Maximum Shear Stress, p.A28-23 )

Margins of Safety

\[ M_{Stug} := \frac{F_{tug}}{F_{S_u} \cdot \sigma_{tu}} - 1 \]  
\[ M_{Stug} = 0.083 \]  
... Margin of Safety Tensile Ultimate

\[ M_{Styg} := \frac{F_{tyg}}{F_{S_y} \cdot \sigma_{ty}} - 1 \]  
\[ M_{Styg} = 0.49 \]  
... Margin of Safety Tensile Yield

\[ M_{Suug} := \frac{F_{sug}}{F_{S_u} \cdot \tau_{su}} - 1 \]  
\[ M_{Suug} = 0.25 \]  
... Margin of Safety Shear Ultimate
5.10.2.1  Starboard Debris Shield Assembly Bolt Analysis
Intentionally Left Blank
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
UPS Side - Tab Angle Bracket to Lower Vacuum Case

CHECK
Bolt := "SDG39135892-828, NAS1008-8A, .5000-20, .500 GRIP, CRES A286"
Washer := "NAS1587-8C"
Insert := "MS51831CA206, .500-20, CRES A286, 160 KSI"

Flange_1 := "Tab Angle Bracket"
Part_Number_1 := "SDG39137847"
Material_1 := "AL ALY 6061-T651 Sheet"

Flange_2 := "Lower Vacuum Case"
Part_Number_2 := "SDG39135737"
Material_2 := "AL ALY 7050-T7451"

Loads
Applied tensile load P := 201·lbf
Applied shear load V := 357·lbf
Applied bending moment M := 0·in·lbf

Factors of Safety
Ultimate SFu := 2.0
Yield SFy := 1.25
Assembly SFsep := 1.2
Fitting factor FF := 1.15

Temperature data
Temp_initial := 70-deg
Temp_max := 140-deg
Temp_min := −76-deg

Bolt and Insert Data
Nominal diameter of bolt D := .5·in
Number of threads/inch Nt := 20 \frac{1}{\text{in}}
Total length of bolt L := 1.342·in
Length of insert Lins := .688·in
Threaded length Lt := .842·in
Min. external diameter of insert Fmin := .615·in
(If bolt is fully threaded, input Lt = L)

This file uses the calculations shown in \escfil02\2111_mathcad\8307_bolts\thread_data.mcd

Washer Data
Thickness of washer tw := .078·in
Outer Diameter of washer Dw := .875·in
Inner Diameter of washer Dwi := .504·in
Bolt head dia. across flats dw := .741·in

Flange data
Thickness of flange 1 tf1 := .38·in
Thickness of flange 2 tf2 := .75·in
Diameter of hole D_hole := .531·in

Note: If there is no washer, tw, Dw, and Dwi should be zero.

This file uses the calculations shown in \escfil02\2111_mathcad\8307_bolts\thread_data.mcd
Material Property Data

**Bolt**

Temperature correction factor for bolt strength ultimate

\[ \text{TS}_\text{bolt} := 0.96 \quad \text{yield} \quad \text{TSy}_\text{bolt} := 0.96 \]

Bolt ultimate tensile allowable stress

\[ \text{Ftu}_\text{bolt} := 140000 \text{ psi} \]

Bolt ultimate shear allowable stress

\[ \text{Fsu}_\text{bolt} := 0.6 \times \text{Ftu}_\text{bolt} \]

Bolt yield tensile allowable

\[ \text{Fty}_\text{bolt} := 95000 \text{ psi} \]

Temperature correction factor for bolt modulus

\[ \text{TE}_\text{bolt} := 0.98 \quad \frac{\text{in}}{\text{in}} \quad \beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \quad \frac{\text{in}}{\text{deg}} \]

Modulus of elasticity of bolt

\[ \text{E}_\text{bolt} := \left(29.1 \times 10^6 \text{ psi}\right) \]

**Insert**

Temperature correction factor for insert strength

\[ \text{TS}_\text{ins} := 0.96 \]

Ultimate tensile allowable stress

\[ \text{Ftu}_\text{ins} := 140000 \text{ psi} \]

Ultimate shear allowable stress

\[ \text{Fsu}_\text{ins} := 0.6 \times \text{Ftu}_\text{ins} \]

**Washer**

Temperature correction factor for washer modulus

\[ \text{TE}_\text{washer} := 1.0 \]

Modulus of elasticity of washer

\[ \text{E}_\text{washer} := \left(29.1 \times 10^6 \text{ psi}\right) \]

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ \text{TF1E} := 0.98 \quad \text{(modulus)} \quad \text{TF2s} := 0.91 \quad \text{(strength)} \]

Temperature correction factor for flange 2

\[ \text{TF2E} := 0.98 \quad \text{(modulus)} \quad \text{Fsu}_\text{f2} := 43000 \text{ psi} \]

Modulus of elasticity for the parts in the joint

\[ \text{E}_{\text{flange1}} := \left(10.1 \times 10^6 \text{ psi}\right) \quad \text{E}_{\text{flange2}} := \left(10.8 \times 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \quad \frac{\text{in}}{\text{deg}} \quad \beta_{\text{flange2\_hot}} := 12.5 \times 10^{-6} \quad \frac{\text{in}}{\text{deg}} \]

\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \quad \frac{\text{in}}{\text{deg}} \quad \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \quad \frac{\text{in}}{\text{deg}} \]

**Torque/Preload data**

Maximum torque

\[ T_{\text{max}} := 651 \text{ in-lbf} \]

Loading plane factor:

\[ n := 0.5 \]

Minimum torque

\[ T_{\text{min}} := 553 \text{ in-lbf} \]

Preload Uncertainty:

\[ u := 0.25 \]

Torque coefficient:

\[ k := 0.15 \]
Bolt Load data

Bolt/joint stiffness factor = 0.646
Preload due to temperature
Pthr_pos = 586.1 lbf

Max. preload
PLDmax = 11436.1 lbf

Min. preload
PLDmin = 3731.9 lbf

Joint separation load
Psep = 241.2 lbf

Max. load on the bolt (ultimate)
Pb = 11585.4 lbf

Max. load on the bolt (yield)
Pby = 11529.4 lbf

Bolt ultimate tensile strength
PAt = 21111.4 lbf

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS₁</td>
<td>18.88</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS₂</td>
<td>44.67</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS₃</td>
<td>48.58</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS₄</td>
<td>0.82</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS₅</td>
<td>0.243</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := min(MS)

MSbolt = 0.243
Failure_Mode = "Total Tension Yield"
## Fail-safe Analysis

### Fail-safe Loads

- **Applied tensile load**
  
  \[ P_{FS} := 240 \text{ lbf} \]

- **Applied shear load**
  
  \[ V_{FS} := 666 \text{ lbf} \]

- **Applied bending moment**
  
  \[ M_{FS} := 0 \text{ in-lbf} \]

### Fail-safe Factors of Safety

- **Ultimate**
  
  \[ SF_{U FS} := 1.0 \]

- **Joint Separation**
  
  \[ SF_{FS sep} := 1.0 \]

This file uses the calculations shown in `\escf\mathcad\8307_bolts\bolt_stiffness_insert_FS_RevC`

---

### Bolt Fail-safe Load data

- **Joint separation load**
  
  \[ P_{FS sep} = 240 \text{ lbf} \]

- **Max. load on the bolt (ultimate)**
  
  \[ P_{b FS} = 11525.2 \text{ lbf} \]

### Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Case</th>
<th>Margin of Safety</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS$_{FS 1}$ = 18.97</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS$_{FS 2}$ = 75.49</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS$_{FS 3}$ = 0.83</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS$_{FS 4}$ = 93.23</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

### Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt FS} := \text{min}(MS_{FS}) \]

\[ MS_{bolt FS} = 0.83 \]

Failure Mode $FS$ = "Combined Shear Tension Bending Ultimate"
Bolt Hole Analysis

Minimum edge distance of flange one \( \text{edge}_1 := 0.470\text{-in} \)
Minimum edge distance of flange two \( \text{edge}_2 := 0.812\text{-in} \)
Shank diameter of bolt \( \text{D}_{\text{shank}} := 0.497\text{-in} \)

Recall loads from bolt calculation

Safety Factors

\[
\begin{align*}
\text{SF}_u &= 2.000 \quad \text{(Ultimate)} \\
\text{FF} &= 1.15 \quad \text{(Fitting Factor)} \\
\text{SF}_y &= 1.25 \quad \text{(Yield)}
\end{align*}
\]

Input Loads

\[
\begin{align*}
\text{V} &= 357\text{-lbf} \quad \text{(Shear Load)} \\
\text{P} &= 201\text{-lbf} \quad \text{(Axial Load)}
\end{align*}
\]

Bolt calc results

\[
\begin{align*}
\text{P}_b &= 11585\text{-lbf} \quad \text{(Max Bolt Load)}
\end{align*}
\]

Dimensions

\[
\begin{align*}
\text{L} &= 1.342\text{-in} \quad \text{(Length of Bolt)} \\
\text{t}_w &= 0.078\text{-in} \quad \text{(Thickness of Washer)}
\end{align*}
\]

Shear Tear-Out Check

Recall bolt hole dimensions

\[
\begin{align*}
\text{tf}_1 &= \text{tf}_1 \quad \text{edge}_1 := 0.47\text{-in} \\
\text{tf}_2 &= \text{tf}_2 \quad \text{edge}_2 := 0.812\text{-in}
\end{align*}
\]

\[
\begin{align*}
\text{D} &= 0.5\text{-in} \quad \text{(Diameter of Bolt)} \\
\text{D}_{\text{shank}} &= 0.497\text{-in} \quad \text{(Min. Shank Diameter of Bolt)} \\
\text{D}_{\text{hole}} &= 0.531\text{-in} \quad \text{(Diameter of Hole)}
\end{align*}
\]

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[
\begin{align*}
\text{A}_{\text{shplt}} &= 2 \cdot \text{tf} \left( \text{edge} - \frac{1}{2} \text{D}_{\text{hole}} \right) \\
\text{A}_{\text{shplt}} &= \begin{pmatrix}
\text{Plate1} \\
\text{Plate2}
\end{pmatrix} \quad \text{A}_{\text{shplt}} = \begin{pmatrix}
0.155 \\
0.82
\end{pmatrix}\text{in}^2
\end{align*}
\]

Allowables for plates that fastener goes through

\[
\begin{align*}
\text{F}_{\text{su1}} &= \text{TF}_{\text{E}27}\text{-ksi} \\
\text{F}_{\text{su1}} &= 26.46\text{-ksi} \quad \text{(Ultimate Shear Allowable for Plate 1)} \\
\text{F}_{\text{su2}} &= \text{TF}_{\text{E}43}\text{-ksi} \\
\text{F}_{\text{su2}} &= 42.14\text{-ksi} \quad \text{(Ultimate Shear Allowable for Plate 2)} \\
\text{P}_{\text{su}} &= \left( \frac{\text{A}_{\text{shplt}} \text{F}_{\text{su}}}{\text{Plate1}} \right) \quad \text{P}_{\text{su}} = \left( \frac{4112}{34544} \right)\text{lbf} \quad \text{(Shear Ultimate Allowable)}
\end{align*}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
UPS Side - Tab Angle Bracket to Lower Vacuum Case

**MS for Shear Tear-Out**

\[ MS_{su} = \left(\frac{P_{su}}{V \cdot SFu \cdot FF} - 1\right) \]

\[ MS_{bh} = \min( MS_{su} ) \]

\[ MS_{bh,1} = 4.008 \quad \cdots \text{Shear Tear-Out MS} \]

**Bearing Check**

*Recall bolt hole dimensions*

- \( tf_1 = 0.38 \text{ in} \) (Thickness of Plate 1)
- \( tf_2 = 0.75 \text{ in} \) (Thickness of Plate 2)
- \( edge_1 = 0.47 \text{ in} \) (Edge Distance for thru Hole in Plate 1)
- \( edge_2 = 0.812 \text{ in} \) (Edge Distance for tapped Hole in Plate 2)

**Typical Bearing Failure**

\[ A_{br} := (tf \cdot \min(D, D_{shank})) \]

\[ A_{br,1} = \begin{pmatrix} 0.189 \\ 0.373 \end{pmatrix} \text{ in}^2 \]  
\[ e_D := \frac{edge}{D_{hole}} \]

\[ e_D = \begin{pmatrix} 0.885 \\ 1.529 \end{pmatrix} \] (e/D for Plates)

**Allowables for plates that fastener goes through**

**Bearing strength at e/D = 1.5**

- \( F_{bru,1} := T_{f1E} \cdot 67 \text{ksi} \)
- \( F_{bru,1} = 65.66 \text{ksi} \)
- \( F_{bry,1} := T_{f1E} \cdot 50 \text{ksi} \)
- \( F_{bry,1} = 49 \text{ksi} \)
- \( F_{bru,2} := T_{f2E} \cdot 107 \text{ksi} \)
- \( F_{bru,2} = 104.86 \text{ksi} \)
- \( F_{bry,2} := T_{f2E} \cdot 86 \text{ksi} \)
- \( F_{bry,2} = 84.28 \text{ksi} \)

**Bearing strength at e/D = 2.0**

- \( F_{bru,1} := T_{f1E} \cdot 88 \text{ksi} \)
- \( F_{bru,1} = 86.24 \text{ksi} \)
- \( F_{bry,1} := T_{f1E} \cdot 58 \text{ksi} \)
- \( F_{bry,1} = 56.84 \text{ksi} \)
- \( F_{bru,2} := T_{f2E} \cdot 140 \text{ksi} \)
- \( F_{bru,2} = 137.2 \text{ksi} \)
- \( F_{bry,2} := T_{f2E} \cdot 101 \text{ksi} \)
- \( F_{bry,2} = 98.98 \text{ksi} \)


**Modified bearing strength**

\[
\begin{align*}
F_{bru_1} & := \left\{ \frac{e_D}{2} > 2.0, F_{bru_2} \right\}, \left\{ \frac{e_D}{2} > 1.5 \right\} \left( e_D < 2.0 \right), F_{bru_1} + \frac{e_D - 1.5}{2.0} (F_{bru_1} - F_{bru_1}) \left[ F_{bru_1} \left( e_D - 0.5 \right) \right] \\
F_{bru_2} & := \left\{ \frac{e_D}{2} > 2.0, F_{bru_2} \right\}, \left\{ \frac{e_D}{2} > 1.5 \right\} \left( e_D < 2.0 \right), F_{bru_2} + \frac{e_D - 1.5}{2.0} (F_{bru_2} - F_{bru_2}) \left[ F_{bru_2} \left( e_D - 0.5 \right) \right] \\
F_{bry_1} & := \left\{ \frac{e_D}{2} > 2.0, F_{bry_1} \right\}, \left\{ \frac{e_D}{2} > 1.5 \right\} \left( e_D < 2.0 \right), F_{bry_1} + \frac{e_D - 1.5}{2.0} (F_{bry_1} - F_{bry_1}) \left[ F_{bry_1} \left( e_D - 0.5 \right) \right] \\
F_{bry_2} & := \left\{ \frac{e_D}{2} > 2.0, F_{bry_2} \right\}, \left\{ \frac{e_D}{2} > 1.5 \right\} \left( e_D < 2.0 \right), F_{bry_2} + \frac{e_D - 1.5}{2.0} (F_{bry_2} - F_{bry_2}) \left[ F_{bry_2} \left( e_D - 0.5 \right) \right]
\end{align*}
\]

\[
F_{bru} = \begin{pmatrix} 25.287 \\ 106.748 \end{pmatrix} \text{ (Ultimate)} \quad F_{bry} = \begin{pmatrix} 18.871 \\ 85.138 \end{pmatrix} \text{ (Yield)}
\]

\[
P_{bru} := \left( A_{bru} F_{bru} \right) \quad P_{bru} = \begin{pmatrix} 4776 \\ 39790 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Ultimate Allowable)}
\]

\[
P_{bry} := \left( A_{bry} F_{bry} \right) \quad P_{bry} = \begin{pmatrix} 3564 \\ 31735 \end{pmatrix} \text{ lbf} \quad \text{(Bearing Yield Allowable)}
\]

**MS for Bearing Failure**

\[
MS_{bru} := \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \quad MS_{bru} = \begin{pmatrix} 4.816 \\ 47.46 \end{pmatrix} \text{ (Plate1, Plate2)}
\]

\[
MS_{bry} := \min(\{MS_{bru}\}) \quad MS_{bry} = 4.816 \quad \text{... Bearing MS based on Ultimate Strength}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
UPS Side - Tab Angle Bracket to Lower Vacuum Case

\[
MS_{bry} := \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1
\]

\[
MS_{bry} = \begin{pmatrix} 5.94 \\ 60.84 \end{pmatrix}
\]

\[
MS_{bh3} := \min(MS_{bry})
\]

\[
MS_{bh3} = 5.945
\]

... Bearing MS based on Yield Strength
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
UPS Side - Tab Angle Bracket to Upper Vacuum Case

CHECK

Bolt := "SDG39135892-828, NAS1008-8A,.5000-20,.500 GRIP, CRES A286"
Washer := "NAS1587-8C"
Insert := "MS51831CA206,.500-20, CRES A286, 160 KSI"

Flange_1 := "Tab Angle Bracket"
Part_Number_1 := "SDG39137847"
Material_1 := "AL ALY 6061-T651 Sheet"

Flange_2 := "Upper Vacuum Case"
Part_Number_2 := "SDG39135727"
Material_2 := "AL ALY 7050-T7451"

Loads

Applied tensile load
P := 201-lbf

Applied shear load
V := 357-lbf

Applied bending moment
M := 0-in-lbf

Factors of Safety

Ultimate SFu := 2.0
Yield SFy := 1.25
Assembly

Joint Separation SFsep := 1.2
Fitting factor FF := 1.15
Maximum

Minimum Temp_initial := 70-deg
Temp_max := 140-deg
Temp_min := -76-deg

Bolt and Insert Data

Nominal diameter of bolt D := .5-in
Number of threads/inch Nt := 20-\frac{1}{in}

Total length of bolt L := 1.342-in
Length of insert Lins := .688-in

Threaded length Lt := .842-in
Min. external diameter of insert Fmin := .615-in

(If bolt is fully threaded, input Lt = L)

Depth of recess for insert lr := 0.02-in

Washer Data

Thickness of washer tw := .078-in

Outer Diameter of washer Dw := .875-in

Inner Diameter of washer Dwi := .504-in

Bolt head dia. across flats dw := .741-in
(used only if there is no washer)

Note: If there is no washer, tw, Dw, and Dwi should be zero.

Flange data

Thickness of flange 1 tf1 := .38-in

Thickness of flange 2 tf2 := .75-in

Diameter of hole D_hole := .531-in

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Tue Feb 15 10:38:17 AM 2005

5.10.2.1-11 ESCG-4005-05-AMS-0039
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate
\[ TS_{u\_bolt} = 0.96 \quad \text{yield} \quad TS_{y\_bolt} = 0.96 \]

Bolt ultimate tensile allowable stress
\[ F_{tu\_bolt} = 140000\text{-psi} \]

Bolt ultimate shear allowable stress
\[ F_{su\_bolt} = 0.6\times F_{tu\_bolt} \]

Bolt yield tensile allowable
\[ F_{ty\_bolt} = 95000\text{-psi} \]

Temperature correction factor for bolt modulus
\[ TE_{\_bolt} = 0.98 \]

Modulus of elasticity of bolt
\[ E_{\_bolt} = \left(29.1\times10^6\text{-psi}\right) \]

Thermal coefficient for bolt:
\[ \beta_{\_bolt\_hot} = 9.1\times10^{-6}\text{-in/in/deg} \]
\[ \beta_{\_bolt\_cold} = 8.5\times10^{-6}\text{-in/in/deg} \]

Insert

Temperature correction factor for insert strength
\[ TS_{\_ins} = 0.96 \]

Ultimate tensile allowable stress
\[ F_{tu\_ins} = 140000\text{-psi} \]

Ultimate shear allowable stress
\[ F_{su\_ins} = 0.6\times F_{tu\_ins} \]

Washer

Temperature correction factor for washer modulus
\[ TE_{\_washer} = 1.0 \]

Modulus of elasticity of washer
\[ E_{\_washer} = \left(29.1\times10^6\text{-psi}\right) \]

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1E} = 0.98 \text{ (modulus)} \quad T_{f2s} = 0.91 \text{ (strength)} \]

Temperature correction factor for flange 2
\[ T_{f2E} = 0.98 \text{ (modulus)} \quad F_{su\_f2} = 43000\text{-psi} \]

Modulus of elasticity for the parts in the joint
\[ E_{\_flange1} = \left(10.1\times10^6\text{-psi}\right) \quad E_{\_flange2} = \left(10.8\times10^6\text{-psi}\right) \]

Coefficient of thermal expansion for flanges
\[ \beta_{\_flange1\_hot} = 12.8\times10^{-6}\text{-in/in/deg} \quad \beta_{\_flange2\_hot} = 12.5\times10^{-6}\text{-in/in/deg} \]
\[ \beta_{\_flange1\_cold} = 12.1\times10^{-6}\text{-in/in/deg} \quad \beta_{\_flange2\_cold} = 12.1\times10^{-6}\text{-in/in/deg} \]

Torque/Preload data

Maximum torque
\[ T_{max} = 651\text{-in-lbf} \]

Loading plane factor:
\[ n = 0.5 \]

Minimum torque
\[ T_{min} = 553\text{-in-lbf} \]

Preload Uncertainty:
\[ u = 0.25 \]

Torque coefficient:
\[ k = 0.15 \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
UPS Side - Tab Angle Bracket to Upper Vacuum Case

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\bolt_stiffness_insert_RevC

**Bolt Load data**

- Bolt/joint stiffness factor $= 0.646$
- Preload due to temperature $P_{\text{thr, pos}} = 586.1$ lbf
- Max. preload $P_{\text{LDMax}} = 11436.1$ lbf
- Min. preload $P_{\text{LDMin}} = 3731.9$ lbf
- Joint separation load $P_{\text{sep}} = 241.2$ lbf
- Max. load on the bolt (ultimate) $P_b = 11585.4$ lbf
- Max. load on the bolt (yield) $P_{by} = 11529.4$ lbf
- Bolt ultimate tensile strength $P_{At} = 21111.4$ lbf

Uncertainty factor $u = 0.25$
Torque coefficient $k = 0.15$
Loading plane factor $n = 0.5$
Thread shear pullout load of bolt or insert $P_{ths} = 51164.1$ lbf
Thread shear pullout load in parent metal $P_{pths} = 26007.2$ lbf

Length check = "Bolt length is sufficient"

**Summary of Margins for bolt:**

- Joint separation $M_{S1} = 18.88$
- Direct Tension Ultimate $M_{S2} = 44.67$
- Direct Tension Yield $M_{S3} = 48.58$
- Total Tension Ultimate $M_{S4} = 0.82$
- Total Tension Yield $M_{S5} = 0.243$

- Direct Thread shear Ultimate $M_{S6} = 55.26$
- Total Thread shear Ultimate $M_{S7} = 1.24$
- Shear Ultimate $M_{S8} = 13.6$
- Bending Ultimate $M_{S9} = 10$
- Combined shear, tension and bending ultimate $M_{S10} = 0.82$

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

$M_{\text{Sbolt}} := \min(M_{S})$

$M_{\text{Sbolt}} = 0.243$
Failure Mode = "Total Tension Yield"
**Fail-safe Analysis**

**Fail-safe Loads**
- Applied tensile load: $P_{FS} := 240$ lbf
- Applied shear load: $V_{FS} := 666$ lbf
- Applied bending moment: $M_{FS} := 0$ in-lbf

**Fail-safe Factors of Safety**
- Ultimate load on the bolt (ultimate): $P_{b,FS} := 11525.2$ lbf
- Joint separation load (ultimate): $P_{sep,FS} := 240$ lbf

Summary of fail-safe Margins for bolt:
- Joint separation: $MS_{FS_1} = 18.97$
- Direct Tension Ultimate: $MS_{FS_2} = 75.49$
- Total Tension Ultimate: $MS_{FS_3} = 0.83$
- Direct Thread shear Ultimate: $MS_{FS_4} = 93.23$
- Combined shear, tension and bending ultimate: $MS_{FS_8} = 0.83$

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

$$MS_{bolt,FS} := \min(MS_{FS})$$

**Mon Feb 14 12:51:39 2005**

\[\text{This file uses the calculations shown in } \backslash\text{escfil02/2i11_mathcad8307_bolts/bolt_stiffness_insert_Fs_RevC}\]
Bolt Hole Analysis

Minimum edge distance of flange one: $\text{edge}_1 := 0.470$ in
Minimum edge distance of flange two: $\text{edge}_2 := 0.844$ in
Shank diameter of bolt: $D_{\text{shank}} := 0.4970$ in

Recall loads from bolt calculation

Safety Factors
- SFu = 2.000 (Ultimate)
- SFy = 1.25 (Yield)
- FF = 1.15 (Fitting Factor)

Input Loads
- $V = 357$ lbf (Shear Load)
- $P = 201$ lbf (Axial Load)

Bolt calc results
- $P_b = 11585$ lbf (Max Bolt Load)

Dimensions
- $L = 1.342$ in (Length of Bolt)
- $t_w = 0.078$ in (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions

- $t_f_1 := t_f_1$ (Entire Thickness of Flange 1)
- $t_f_2 := t_f_2$ (Entire Thickness of Flange 2)
- $\text{edge}_1 := \text{edge}_1$ (Edge Distance for Hole in Plate 1)
- $\text{edge}_2 := \text{edge}_2$ (Edge Distance for Hole in Plate 2)

- $D = 0.5$ in (Diameter of Bolt)
- $D_{\text{shank}} = 0.497$ in (Min. Shank Diameter of Bolt)
- $D_{\text{hole}} = 0.531$ in (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

$$A_{\text{shrpl}} := \left[ 2 \cdot t_f \left( \text{edge} - \frac{1}{2} D_{\text{hole}} \right) \right]$$

Allowables for plates that fastener goes through

- $F_{su_1} := T_f 1E \cdot 27$-ksi
- $F_{su_1} = 26.46$-ksi (Ultimate Shear Allowable for Plate 1)
- $F_{su_2} := T_2E \cdot 43$-ksi
- $F_{su_2} = 42.14$-ksi (Ultimate Shear Allowable for Plate 2)
- $P_{su} := \left( A_{\text{shrpl}} \right)$-lbf
- $P_{su} = \left( \frac{4112}{36567} \right)$-lbf (Shear Ultimate Allowable)
MS for Shear Tear-Out

\[ MS_{su} := \left( \frac{P_{su}}{V - SF_{u \cdot FF}} - 1 \right) \]

\[ MS_{bh} := \min(\{MS_{su}\}) \]

\[ MS_{bh} = 4.008 \quad \text{... Shear Tear-Out MS} \]

Bearing Check

Recall bolt hole dimensions

\[ tf_1 = 0.38 \text{ in} \quad (\text{Thickness of Plate 1}) \]
\[ tf_2 = 0.75 \text{ in} \quad (\text{Thickness of Plate 2}) \]
\[ \text{edge}_1 = 0.47 \text{ in} \quad (\text{Edge Distance for thru Hole in Plate 1}) \]
\[ \text{edge}_2 = 0.844 \text{ in} \quad (\text{Edge Distance for tapped Hole in Plate 2}) \]

Typical Bearing Failure

\[ A_{br} := (tf \cdot \min(D, D_{shank})) \]

\[ A_{br} = \left( \frac{0.189}{0.373} \right) \text{in}^2 \quad (\text{Bearing Areas}) \]

\[ e_D := \frac{\text{edge}}{D_{\text{hole}}} \]

\[ e_D = \frac{0.885}{1.589} \quad (e/D \text{ for Plates}) \]

Allowables for plates that fastener goes through

Bearing strength at \(e/D = 1.5\)

\[ Fbru_{15,1} := \text{Ti1E-67 ksi} \quad Fbru_{15,1} = 65.66 \text{ ksi} \]
\[ Fbru_{15,2} := \text{Ti2E-107 ksi} \quad Fbru_{15,2} = 104.86 \text{ ksi} \]

Bearing strength at \(e/D = 2.0\)

\[ Fbru_{20,1} := \text{Ti1E-88 ksi} \quad Fbru_{20,1} = 86.24 \text{ ksi} \]
\[ Fbru_{20,2} := \text{Ti2E-140 ksi} \quad Fbru_{20,2} = 137.2 \text{ ksi} \]
**Modified bearing strength**

\[
F_{bru_m1} := \begin{cases} e_D > 2.0, F_{bru20}, & \text{if } (e_D > 1.5) \text{,} \\ (e_D < 2.0), F_{bru15} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru20} - F_{bru15} \right), & \text{if } (e_D < 1.5) \end{cases}
\]

\[
F_{bru_m2} := \begin{cases} e_D > 2.0, F_{bru20}, & \text{if } (e_D > 1.5) \text{,} \\ (e_D < 2.0), F_{bru15} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bru20} - F_{bru15} \right), & \text{if } (e_D < 1.5) \end{cases}
\]

\[
F_{bry_m1} := \begin{cases} e_D > 2.0, F_{bry20}, & \text{if } (e_D > 1.5) \text{,} \\ (e_D < 2.0), F_{bry15} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry20} - F_{bry15} \right), & \text{if } (e_D < 1.5) \end{cases}
\]

\[
F_{bry_m2} := \begin{cases} e_D > 2.0, F_{bry20}, & \text{if } (e_D > 1.5) \text{,} \\ (e_D < 2.0), F_{bry15} + \frac{e_D - 1.5}{2.0 - 1.5} \left( F_{bry20} - F_{bry15} \right), & \text{if } (e_D < 1.5) \end{cases}
\]

\[
F_{bru_m} = \frac{25.287}{110.646} \begin{pmatrix} \text{Plate1} \\ \text{Plate2} \end{pmatrix} \quad (\text{Ultimate}) \\
F_{bry_m} = \frac{18.871}{86.91} \begin{pmatrix} \text{Plate1} \\ \text{Plate2} \end{pmatrix} \quad (\text{Yield})
\]

\[
P_{bru} := \left( A_{br}, F_{bru_m} \right) \\
P_{bru} = \frac{4776}{41243} \text{lbf} \quad (\text{Bearing Ultimate Allowable})
\]

\[
P_{bry} := \left( A_{br}, F_{bry_m} \right) \\
P_{bry} = \frac{3564}{32396} \text{lbf} \quad (\text{Bearing Yield Allowable})
\]

**MS for Bearing Failure**

\[
M_{Sbru} := \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \\
M_{Sbru} = \begin{pmatrix} 4.816 \\ 49.229 \end{pmatrix} \begin{pmatrix} \text{Plate1} \\ \text{Plate2} \end{pmatrix}
\]

\[
M_{Sbh2} := \min(M_{Sbru}) \\
M_{Sbh2} = 4.816 \quad \text{... Bearing MS based on Ultimate Strength}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert  
UPS Side - Tab Angle Bracket to Upper Vacuum Case

<table>
<thead>
<tr>
<th>$\text{MS}<em>{\text{bry}} := \left( \frac{P</em>{\text{bry}}}{V \cdot S_{F_Y} \cdot FF} - 1 \right)$</th>
<th>$\text{MS}_{\text{bry}} = \left( \begin{array}{c} 5.94 \ 62.13 \end{array} \right)$</th>
<th>$\text{Plate1}$</th>
<th>$\text{Plate2}$</th>
</tr>
</thead>
</table>

| $\text{MS}_{\text{bh3}} := \min(\text{MS}_{\text{bry}})$ | $\text{MS}_{\text{bh3}} = 5.945$ | $\ldots \text{ Bearing MS based on Yield Strength}$ |
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
UPS Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1351N4-12, .2500-28, 0.750 L, A-286, Heat Resistant Steel"
Washer := "NAS1149E0463R, .250 Nom Dia, 0.063 T, A-286, Passivate"
Nut := "NAS1291-C4M, .2500-28 UNJF-3B"

Flange_1 := "2.70in Bathtub Bracket"
Part_Number_1 := "SDG39137848-002"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange edge1 := .347 in one

Flange_2 := "Lower Trunnion Bridge Beam"
Part_Number_2 := "SDG39135735"
Material_2 := "AL ALY 7050-T7451"
Minimum edge distance of flange edge2 := .375 in two

Loads (reference)
Applied tensile load P := 201 lbf
Applied shear load V := 357 lbf
Applied bending moment M := 0 in-lbf

Factors of Safety (reference)
SFu := 2.00 (Ultimate)
SFy := 1.25 (Yield)
FF := 1.15 (Fitting factor)
SFsep := 1.20 (Joint Separation)

Temperature data (reference)
Assembly Temp_initial := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := -76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data ( Bolt = "NAS1351N4-12, .2500-28, 0.750 L, A-286, Heat Resistant Steel" )
Nominal diameter of bolt D := .2500 in
Number of threads/inch Nt := 28 \frac{1}{in}

Shank diameter of bolt D_shank := .2435 in

Total length of bolt L := .75 in
Threaded length Lt := .75 in (If bolt is fully threaded, input Lt = L)

Bolt head dia. across flats dw := .365 in (dia of pressure boss if it exists, otherwise dia of head)

Bolt head height bh := .244 in (head height is 0 if bolt is flat head)
Bolt Data cont. (Bolt = "NAS1351N4-12, .2500-28, 0.750 L, A-286, Heat Resistant Steel")

Thread data lookup table is hidden

This file uses the data shown in \escfil02\2111_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength
Bolt ultimate tensile allowable stress
Bolt ultimate shear allowable stress

Temperature correction factor for bolt modulus
Modulus of elasticity of bolt
Thermal coefficients for bolt

\[
\beta_{\text{bolt}} \text{hot} = 9.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \\
\beta_{\text{bolt}} \text{cold} = 8.5 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]

Washer Data (Washer = "NAS1149E0463R, .250 Nom Dia, 0.063 T, A-286, Passivate")

Thickness of washers:
- Head: \( t_{wh} = .063 \) in
- Nut: \( t_{wn} = .063 \) in

Diameter of washer under head:
- Outer: \( D_{woh} = .500 \) in
- Inner: \( D_{wih} = .265 \) in

Modulus of elasticity:
- Head: \( E_{\text{washerh}} = (29.1 \times 10^6 \text{ psi}) \)
- Nut: \( E_{\text{washern}} = (29.1 \times 10^6 \text{ psi}) \)

Nut Data (Nut = "NAS1291-C4M, .2500-28 UNJF-3B")

Height of nut: \( H = .204 \) in

Temperature correction factor for nut strength
Ultimate allowable stress, tensile
Ultimate axial strength of nut

\[
\text{TS}_{\text{nut}} := .96 \\
\text{Ftu}_{\text{nut}} := 125000 \text{ psi} \\
\text{Pt}_{\text{nut}} := 4530 \text{ lbf}
\]

Note: If there is no washer - \( t_{w} \)'s, \( D_{wo} \)'s and \( D_{wi} \)'s should be zero

Nut dia. across flats: \( D_n = .386 \) in (same as bolt)

\( \text{Fsu}_{\text{nut}} := 0.6 \cdot \text{Ftu}_{\text{nut}} \) (Shear)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
UPS Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole

<table>
<thead>
<tr>
<th>Flange</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_1</td>
<td>.272 in</td>
</tr>
<tr>
<td>Flange_2</td>
<td>.250 in</td>
</tr>
</tbody>
</table>

Material

<table>
<thead>
<tr>
<th>Flange</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_1</td>
<td>AL ALY 6061-T651</td>
</tr>
<tr>
<td>Flange_2</td>
<td>AL ALY 7050-T7451</td>
</tr>
</tbody>
</table>

Thickness of flanges

<table>
<thead>
<tr>
<th>Flange</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_1</td>
<td>.100 in</td>
</tr>
<tr>
<td>Flange_2</td>
<td>.250 in</td>
</tr>
</tbody>
</table>

Compressive Modulus of elasticity

<table>
<thead>
<tr>
<th>Flange</th>
<th>Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_1</td>
<td>$10.1 \cdot 10^6$ psi</td>
</tr>
<tr>
<td>Flange_2</td>
<td>$10.6 \cdot 10^6$ psi</td>
</tr>
</tbody>
</table>

Temperature correction factors

<table>
<thead>
<tr>
<th>Flange</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_1</td>
<td>.98</td>
</tr>
<tr>
<td>Flange_2</td>
<td>.98</td>
</tr>
</tbody>
</table>

Coefficient of thermal expansion for flanges

<table>
<thead>
<tr>
<th>Flange</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange_1</td>
<td>$12.8 \cdot 10^{-6}$ in/deg</td>
</tr>
<tr>
<td>Flange_2</td>
<td>$12.5 \cdot 10^{-6}$ in/deg</td>
</tr>
</tbody>
</table>

Torque/Preload data

- Maximum torque $T_{\text{max}} = 103.2$ in-lbf
- Minimum torque $T_{\text{min}} = 87.7$ in-lbf

Joint is lubed/dry

Preload $u = 0.25$

Torque coefficient $k = 0.15$

Loading plane factor $n = 0.5$

Stiffness and Margin calculations are
This file uses the calculations shown in \escgl02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Bolt Load data

- Bolt/joint stiffness factor Max. preload
- Min. preload
- Nom. preload
- Preload to yield ratio (nom.)
- Joint separation load

- $= 0.348$
- $P_{\text{LDmax}} = 3524$ lbf
- $P_{\text{LDmin}} = 1402$ lbf
- $P_{\text{LDnom}} = 2752$ lbf
- $P_{\text{LDratio}} = 0.677$
- $P_{\text{sep}} = 241.200$ lbf

Preload due to temperature

- $P_{\text{thr\_pos}} = 83.5$ lbf
- $P_{\text{thr\_neg}} = -180$ lbf

Uncertainty factor

- $u = 0.250$
- $k = 0.150$
- $n = 0.500$
Bolt Load data (cont.)

| Applied Tensile load on the bolt | \( P = 201.000 \text{lbf} \) | Max. load on the bolt with preload and Factor of safety | \( \text{P}_b = 3604 \text{lbf} \) (ultimate) |
| Applied shear on the bolt | \( V = 357.000 \text{lbf} \) | \( \text{P}_by = 3574 \text{lbf} \) (yield) |
| Applied bending on the bolt | \( M = 0.000 \text{in} \cdot \text{lbf} \) | Max. load on the bolt with preload Without factor of safety | \( \text{P}_{b_{app}} = 3564 \text{lbf} \) |

| Bolt ultimate tensile strength | \( \text{P}_{At} = 5419 \text{lbf} \) | Bolt shear strength | \( \text{V}_{Au} = 3001 \text{lbf} \) |
| Thread pullout strength | \( \text{P}_{As} = 4349 \text{lbf} \) | Bolt bending strength | \( \text{M}_{Au} = 150 \text{in} \cdot \text{lbf} \) |
| Nut ultimate tensile strength | \( \text{P}_{t_{\text{nut}}} = 4349 \text{lbf} \) |

General Checks

- length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

| Joint separation | \( \text{MS}_1 = 5.12 \) | Direct Thread shear Ultimate | \( \text{MS}_6 = 8.41 \) |
| Direct Tension Ultimate | \( \text{MS}_2 = 10.72 \) | Total Thread shear Ultimate | \( \text{MS}_7 = 0.21 \) |
| Direct Tension Yield | \( \text{MS}_3 = 13.07 \) | Shear Ultimate | \( \text{MS}_8 = 2.65 \) |
| Total Tension Ultimate | \( \text{MS}_4 = 0.5 \) | Bending Ultimate | \( \text{MS}_9 = 100 \) |
| Total Tension Yield | \( \text{MS}_5 = 0.14 \) | Combined shear, tension and bending ultimate | \( \text{MS}_{10} = 0.46 \) |

Smallest margin of safety for the bolt, and the failure mode:

\( \text{MS}_{\text{bolt}} = 0.14 \)  \( \text{Failure Mode} = \text{"Total Tension Yield"} \)
**Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer**

**UPS Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam**

---

**Fail-safe Analysis**

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Force (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>$P_{FS} = 240$</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>$V_{FS} = 666$</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>$M_{FS} = 0$</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>$SF_u_{FS} = 1.0$</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>$SF_{sep_{FS}} = 1.0$</td>
</tr>
</tbody>
</table>

---

**Bolt Fail-safe Load data**

- Joint separation load: $P_{sep_{FS}} = 240.000$ lbf
- Max. load on the bolt (ultimate): $P_{b_{FS}} = 3571.6$ lbf

**Summary of fail-safe Margins for bolt:**

- Joint separation: $MS_{FS1} = 5.15$
- Direct Tension Ultimate: $MS_{FS2} = 18.64$
- Total Tension Ultimate: $MS_{FS3} = 0.52$
- Direct Thread shear Ultimate: $MS_{FS4} = 14.76$
- Total Thread shear Ultimate: $MS_{FS5} = 0.22$
- Shear Ultimate: $MS_{FS6} = 2.92$
- Bending Ultimate: $MS_{FS7} = 10$
- Combined shear, tension and bending ultimate: $MS_{FS8} = 0.48$

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

- $MS_{bolt_{FS}} = 0.22$
- Failure Mode $FS = "Total Thread Shear Ultimate (Nut)"$
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
UPS Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors
- SFu = 2.000 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

Input Loads
- V = 357 lbf (Shear Load)
- P = 201.000 lbf (Axial Load)

Bolt calc results
- Pb = 3604 lbf (Max Bolt Load)

Dimensions
- L = 0.750 in (Length of Bolt)
- twh = 0.063 in (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions
- tf1 := tf1 = 0.100 in (Entire Thickness of Flange 1)
- tf2 := tf2 = 0.250 in (Entire Thickness of Flange 2)
- edge1 := edge1 edge1 = 0.347 in (Edge Distance for Hole in Plate 1)
- edge2 := edge2 edge2 = 0.375 in (Edge Distance for Hole in Plate 2)

- D = 0.250 in (Diameter of Bolt)
- D_shank = 0.244 in (Min. Shank Diameter of Bolt)
- D_hole = 0.272 in (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shrp1} = 2 \cdot tf \cdot \left( \frac{edge - 1}{2 \cdot D_{hole}} \right) \]

Allowables for plates that fastener goes through

Fsu1 := Tf1E \cdot 27 ksi
Fsu1 = 26.460 ksi (Ultimate Shear Allowable for Plate 1)
Fsu2 := Tf2E \cdot 43 ksi
Fsu2 = 42.140 ksi (Ultimate Shear Allowable for Plate 2)

\[ P_{su} := A_{shrp1} \cdot Fsu \]
Psu = \left( \frac{1117}{5036} \right) lbf (Shear Ultimate Allowable)

MS for Shear Tear-Out

\[ MS_{su} := \left( \frac{P_{su}}{V \cdot SFu \cdot FF} \right) \]
MSu = \left( \frac{0.36}{5.13} \right)

MSbh1 := \min (MSu)

MSbh1 = 0.36 ... Shear Tear-Out MS
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer 
UPS Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

**Bearing Check**

Recall bolt hole dimensions

\[ tf_1 = 0.100 \text{ in} \]  
(Thickness of Plate 1)

\[ tf_2 = 0.250 \text{ in} \]  
(Thickness of Plate 2)

\[ \text{edge}_1 = 0.347 \text{ in} \]  
(Edge Distance for thru Hole in Plate 1)

\[ \text{edge}_2 = 0.375 \text{ in} \]  
(Edge Distance for tapped Hole in Plate 2)

\[ A_{br} := (tf \cdot \text{min}(D, D_{shank})) \]  

\[ A_{br} = \begin{pmatrix} 0.024 \\ 0.061 \end{pmatrix} \text{ in}^2 \]  
(Bearing Areas)

\[ e_D := \frac{\text{edge}}{D_{\text{hole}}} \]  
\[ e_D = \begin{pmatrix} 1.276 \\ 1.379 \end{pmatrix} \]  
(e/D for Plates)

Allowables for plates that fastener goes through

<table>
<thead>
<tr>
<th>e/D</th>
<th>Bearing strength at e/D = 1.5</th>
<th>Bearing strength at e/D = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>Fbru15 = 65.66 ksi</td>
<td>Fbru20 = 86.24 ksi</td>
</tr>
<tr>
<td>1.5</td>
<td>Fbry15 = 49 ksi</td>
<td>Fbry20 = 56.840 ksi</td>
</tr>
<tr>
<td>2.0</td>
<td>Fbru152 = 104.86 ksi</td>
<td>Fbru202 = 137.2 ksi</td>
</tr>
<tr>
<td>2.0</td>
<td>Fbry152 = 84.28 ksi</td>
<td>Fbry202 = 98.980 ksi</td>
</tr>
</tbody>
</table>

Modified bearing strength

\[ Fbru_m := \begin{cases} 
\frac{e_D - 1.5}{2.0 - 1.5} & \text{if } e_D > 2.0, Fbru15 \text{ or } Fbry15 \\
\frac{e_D - 1.5}{2.0 - 1.5} & \text{if } e_D > 2.0, Fbru20 \text{ or } Fbry20 \\
\frac{e_D - 1.5}{2.0 - 1.5} & \text{if } e_D > 2.0, Fbru152 \text{ or } Fbry152 \\
\frac{e_D - 1.5}{2.0 - 1.5} & \text{if } e_D > 2.0, Fbru202 \text{ or } Fbry202 \\
\end{cases} 
\]

\[ Fbru_m = \begin{pmatrix} 50.935 \\ 92.138 \end{pmatrix} \text{ (Ultimate)} \]

\[ Fbry_m = \begin{pmatrix} 38.011 \\ 74.055 \end{pmatrix} \text{ (Yield)} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nut/Washer
UPS Side - 2.70in Bathtub Bracket to Lower Trunnion Bridge Beam

\[ P_{bru} := \left( A_{bru} \cdot F_{bru, m} \right) \]
\[ P_{bry} := \left( A_{bry} \cdot F_{bry, m} \right) \]

\[ P_{bru} = \left( \frac{1240}{5609} \right) \text{lbf} \quad \text{(Bearing Ultimate Allowable)} \]
\[ P_{bry} = \left( \frac{926}{4508} \right) \text{lbf} \quad \text{(Bearing Yield Allowable)} \]

**MS for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right) \]
\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right) \]

\[ MS_{bru} = \left( \frac{0.510}{5.831} \right) \quad \text{Plate1} \]
\[ MS_{bry} = \left( \frac{0.8}{7.78} \right) \quad \text{Plate2} \]

\[ MS_{bh2} = 0.51 \quad \text{... Bearing MS based on Ultimate Strength} \]

\[ MS_{bh3} = 0.804 \quad \text{... Bearing MS based on Yield Strength} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - 2.38in Bathtub Bracket to Angle E Assy Interface Panel A

CHECK

Note: Figure is for reference only. Not to scale. Actual joint made differ. Washer may be on nut side, head side, or both

Bolt := "NAS1351N3-10, .1900-32, 0.625 L, A-286, Heat Resistant Steel"
Washer := "NAS1149E0363R, No. 10, 0.063 T, A-286, 160 KSI, Passivate"
Nut := "MS21076L3N, .1900-32UNJF-3B, Dry Film Lube, w/o Eyelets, A-286, 125 KSI"

Flange_1 := "2.38" Bathtub Bracket"
Part_Number_1 := "SDG39137848-001"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange one edge1 := .347 in

Flange_2 := "Interface Panel A Angle E Assy"
Part_Number_2 := "SEG39137686-705"
Material_2 := "AL ALY 7075-T7351"
Minimum edge distance of flange two edge2 := .312 in

Load (reference)
Applied tensile load P := 201 lbf
Applied shear load V := 357 lbf
Applied bending moment M := 0 in-lbf

Factors of Safety (reference)
SFu := 2.00 (Ultimate)
SFy := 1.25 (Yield)
FF := 1.15 (Fitting factor)
SFsep := 1.20 (Joint Separation)

Temperature data (reference)
Assembly Temp_initial := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := -76 deg (Minimum)

Bolt Data ( Bolt = "NAS1351N3-10, .1900-32, 0.625 L, A-286, Heat Resistant Steel"
Nominal diameter of bolt D := .1900 in
Number of threads/inch Nt := 32 \( \frac{1}{\text{in}} \)
Shank diameter of bolt D_shank := .1840 in
Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area
Total length of bolt L := .625 in
If bolt is fully threaded, input Lt = L
Threaded length Lt := .625 in
Bolt head dia. across flats dw := .303 in
(dia of pressure boss if it exists, otherwise dia of head)
Bolt head height bh := .185 in
(head height is 0 if bolt is flat head)
**Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer UPS Side - 2.38in Bathtub Bracket to Angle E Assy Interface Panel A**

**Bolt Data cont.** (Bolt = "NAS1351N3-10, .1900-32, 0.625 L, A-286, Heat Resistant Steel")

Temperature correction factor for bolt strength
Bolt ultimate tensile allowable stress
Bolt ultimate shear allowable stress
Temperature correction factor for bolt modulus
Modulus of elasticity of bolt
Thermal coefficients for bolt

\[
\begin{align*}
\beta_{\text{bolt\_hot}} &:= 9.1 \times 10^{-6} \text{ in}^{-1} \text{deg}^{-1} \\
\beta_{\text{bolt\_cold}} &:= 8.5 \times 10^{-6} \text{ in}^{-1} \text{deg}^{-1}
\end{align*}
\]

**Washer Data** (Washer = "NAS1149E0363R, No. 10, 0.063 T, A-286, 160 KSI, Passivate")

Thickness of washers:
- Head: \( t_{\text{wh}} := 0.063 \text{ in} \)
- Nut: \( t_{\text{wn}} := 0.0 \text{ in} \)

Diameter of washer under head:
- Outer: \( D_{\text{woh}} := 0.438 \text{ in} \)
- Inner: \( D_{\text{wih}} := 0.203 \text{ in} \)

Diameter of washer under nut:
- Outer: \( D_{\text{won}} := 0.0 \text{ in} \)
- Inner: \( D_{\text{win}} := 0.0 \text{ in} \)

Modulus of elasticity:
- Head: \( E_{\text{washerh}} := 29.1 \times 10^6 \text{ psi} \)
- Nut: \( E_{\text{washerl}} := 0.0 \times 10^6 \text{ psi} \)

**Nut Data** (Nut = "MS21076L3N, .1900-32UNJF-3B, Dry Film Lube, w/o Eyelets, A-286, 125 KSI")

Height of nut\( H := 0.250 \text{ in} \)

Temperature correction factor for nut strength
Ultimate allowable stress, tensile
Ultimate axial strength of nut

\[
\begin{align*}
\text{TS}_{\text{nut}} &:= 0.96 \\
\text{F}_{\text{tu\_nut}} &:= 125000 \text{ psi} \\
\text{F}_{\text{tu\_nut}} &:= 2460 \text{ lbf}
\end{align*}
\]
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole D-hole := .226 in

Flange_1 = "2.38" Bathtub Bracket"
Material_1 = "AL ALY 6061-T651"
Thickness of flanges tf1 := .100 in
Compressive Modulus of elasticity E_flange1 := (10.1 \times 10^6 psi)

Temperatures
(modules) T1E := .98
Coefficient of thermal expansion for flanges β_flange1_hot := 12.8 \times 10^{-6} \text{ in/in deg}
β_flange1_cold := 12.1 \times 10^{-6} \text{ in/in deg}

Flange_2 = "Interface Panel A Angle E Assy"
Material_2 = "AL ALY 7075-T7351"
f2 := .120 in
E_flange2 := (10.6 \times 10^6 psi)

T2E := .98

Temperature correction factor

Joint is lubed/dry Preload u := 0.25 (0.25 lubed/0.35 dry)
Uncertainty
Torque coefficient k := 0.15 (0.15 lubed/0.20 dry)

Torque/Preload data
Maximum torque Tmax := 42.8 in-lbf
Minimum torque Tmin := 36.4 in-lbf

Loading plane factor n := 0.5

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escfl02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd
Bolt Load data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor Max. preload</td>
<td>0.322</td>
</tr>
<tr>
<td>PLDmax</td>
<td>1920 lbf</td>
</tr>
<tr>
<td>PLDmin</td>
<td>773 lbf</td>
</tr>
<tr>
<td>Nom. preload</td>
<td>1502 lbf</td>
</tr>
<tr>
<td>Preload to yield ratio (nom.)</td>
<td>0.677</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>241.200 lbf</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td>Pthr_pos = 42.7 lbf</td>
</tr>
<tr>
<td></td>
<td>Pthr_neg = -90.6 lbf</td>
</tr>
<tr>
<td>Preload to yield ratio (yield)</td>
<td>k = 0.150</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td>n = 0.500</td>
</tr>
</tbody>
</table>

---

Applied Tensile load on the bolt

P = 201.000 lbf

Applied shear on the bolt

V = 357.000 lbf

Applied bending on the bolt

M = 0.000 in·lbf

Max. load on the bolt with preload and Factor of safety

Pb = 1994 lbf

Pby = 1966 lbf

Max. load on the bolt with preload WithOut factor of safety

Pbapp = 1957 lbf

---

Bolt ultimate tensile strength

PAt = 2957 lbf

Bolt shear strength

VAu = 1616 lbf

Bolt bending strength

MAu = 61 in·lbf

Nut ultimate tensile strength

Ptu_nut = 2362 lbf

---

General Checks

length_check = "Bolt length is sufficient and nut fully engaged"

cone_check = "Joint pressure cone does not extend pass flange edge"

preload_check = "Nominal preload >= 65% of bolt yield strength"

washer_check = "Washers under head and nut do not extend past flanges"

---

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS1 Joint separation</td>
<td>2.32</td>
</tr>
<tr>
<td>MS2 Direct Tension Ultimate</td>
<td>5.4</td>
</tr>
<tr>
<td>MS3 Direct Tension Yield</td>
<td>6.67</td>
</tr>
<tr>
<td>MS4 Total Tension Ultimate</td>
<td>0.48</td>
</tr>
<tr>
<td>MS5 Total Tension Yield</td>
<td>0.13</td>
</tr>
<tr>
<td>MS6 Direct Thread shear Ultimate</td>
<td>4.11</td>
</tr>
<tr>
<td>MS7 Total Thread shear Ultimate</td>
<td>0.18</td>
</tr>
<tr>
<td>MS8 Shear Ultimate</td>
<td>0.97</td>
</tr>
<tr>
<td>MS9 Bending Ultimate</td>
<td>100</td>
</tr>
<tr>
<td>MS10 Combined shear, tension and bending ultimate</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

MSbolt = 0.13

Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

**Fail-safe Loads**

- Applied tensile load: $P_{FS} = 240 \text{ lbf}$
- Applied shear load: $V_{FS} = 666 \text{ lbf}$
- Applied bending moment: $M_{FS} = 0 \text{ in-lbf}$

**Fail-safe Factors of Safety**

- Ultimate: $SFu_{FS} = 1.0$
- Joint Separation: $SFsep_{FS} = 1.0$

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Fri Apr 27 14:16:05 2007

**Bolt Fail-safe Load data**

- Joint separation load: $P_{sep_{FS}} = 240.000 \text{ lbf}$
- Max. load on the bolt (ultimate): $P_{b_{FS}} = 1964.3 \text{ lbf}$

**Summary of fail-safe Margins for bolt:**

- Joint separation: $MS_{FS1} = 2.34$
- Direct Tension Ultimate: $MS_{FS2} = 9.71$
- Total Tension Ultimate: $MS_{FS3} = 0.51$
- Direct Thread shear Ultimate: $MS_{FS4} = 7.56$
- Total Thread shear Ultimate: $MS_{FS5} = 0.2$
- Shear Ultimate: $MS_{FS6} = 1.11$
- Bending Ultimate: $MS_{FS7} = 10$
- Combined shear, tension and bending ultimate: $MS_{FS8} = 0.31$

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

- $MS_{bolt_{FS}} = 0.2$
- $Failure\_Mode_{FS} = "Total\_Thread\_Shear\_Ultimate\_(Nut)"$

5.10.2.1-31

ESCG-4005-05-AMS-0039
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors
- SFu = 2.000 (Ultimate)
- FF = 1.150 (Fitting Factor)

Input Loads
- V = 357 lbf (Shear Load)
- P = 201,000 lbf (Axial Load)

Bolt calc results
- Pb = 1994 lbf (Max Bolt Load)

Dimensions
- L = 0.625 in (Length of Bolt)
- tw = 0.063 in (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions
- tf1 := tf1 = 0.100 in (Entire Thickness of Flange 1)
- tf2 := tf2 = 0.120 in (Entire Thickness of Flange 2)
- edge1 := edge1 = 0.347 in (Edge Distance for Hole in Plate 1)
- edge2 := edge2 = 0.312 in (Edge Distance for Hole in Plate 2)

- D = 0.190 in (Diameter of Bolt)
- D_shank = 0.184 in (Min. Shank Diameter of Bolt)
- D_hole = 0.226 in (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shプリ} := 2 \times \left( \text{edge} - \frac{1}{2} \times D_{\text{hole}} \right) \]

Allowables for plates that fastener goes through

- Fsu1 := Tf1E 27 ksi (Ultimate Shear Allowable for Plate 1)
- Fsu2 := Tf2E 38 ksi (Ultimate Shear Allowable for Plate 2)
- Pu := \left( \frac{A_{shプリ} \times Fsu}{V \times SFu \times FF} \right) (Shear Ultimate Allowable)

MS for Shear Tear-Out

\[ MS_{su} := \left( \frac{P_u}{V \times SFu \times FF} - 1 \right) \]

MS_{bh1} := min\left( MS_{su} \right)

\[ MS_{bh1} = 0.508 \]

... Shear Tear-Out MS
Bearings Check

**Recall bolt hole dimensions**

- \( t_f_1 = 0.100 \text{ in} \) (Thickness of Plate 1)
- \( t_f_2 = 0.120 \text{ in} \) (Thickness of Plate 2)
- \( \text{edge}_1 = 0.347 \text{ in} \) (Edge Distance for thru Hole in Plate 1)
- \( \text{edge}_2 = 0.312 \text{ in} \) (Edge Distance for tapped Hole in Plate 2)

**Allowables for plates that fastener goes through**

<table>
<thead>
<tr>
<th>Bearing strength at e/D = 1.5</th>
<th>Bearing strength at e/D = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{bru15} = 65.66 \text{ ksi} )</td>
<td>( F_{bru20} = 86.24 \text{ ksi} )</td>
</tr>
<tr>
<td>( F_{bry15} = 49 \text{ ksi} )</td>
<td>( F_{bry20} = 56.840 \text{ ksi} )</td>
</tr>
<tr>
<td>( F_{bru15} = 104.86 \text{ ksi} )</td>
<td>( F_{bru20} = 137.2 \text{ ksi} )</td>
</tr>
<tr>
<td>( F_{bry15} = 84.28 \text{ ksi} )</td>
<td>( F_{bry20} = 98.980 \text{ ksi} )</td>
</tr>
</tbody>
</table>

**Modified bearing strength**

\[
F_{bru,m1} := \begin{cases} 
F_{bru15}, & \text{if } e_D_1 > 2.0, F_{bru20}, & \text{if } \left[e_D_1 > 1.5 \right], F_{bru15} + \frac{e_D_1 - 1.5}{2.0 - 1.5} = \left[F_{bru20} - F_{bru15}, \left[e_D_1 - 0.5] \right]\right] \\
F_{bru20}, & \text{if } e_D_2 > 2.0, F_{bru20}, & \text{if } \left[e_D_2 > 1.5 \right], F_{bru15} + \frac{e_D_2 - 1.5}{2.0 - 1.5} = \left[F_{bru20} - F_{bru15}, \left[e_D_2 - 0.5] \right]\right] \\
F_{bry,m1} := \begin{cases} 
F_{bry15}, & \text{if } e_D_1 > 2.0, F_{bry20}, & \text{if } \left[e_D_1 > 1.5 \right], F_{bry15} + \frac{e_D_1 - 1.5}{2.0 - 1.5} = \left[F_{bry20} - F_{bry15}, \left[e_D_1 - 0.5] \right]\right] \\
F_{bry20}, & \text{if } e_D_2 > 2.0, F_{bry20}, & \text{if } \left[e_D_2 > 1.5 \right], F_{bry15} + \frac{e_D_2 - 1.5}{2.0 - 1.5} = \left[F_{bry20} - F_{bry15}, \left[e_D_2 - 0.5] \right]\right] \\
\end{cases}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - 2.38in Bathtub Bracket to Angle E Assy Interface Panel A

\[ F_{bru,m} = \frac{67.117}{92.332} \text{ (Ultimate)} \]

\[ F_{bry,m} = \frac{49.555}{74.211} \text{ (Yield)} \]

\[ P_{bru} := (A_{br} \cdot F_{bru,m}) \]
\[ P_{bry} := (A_{br} \cdot F_{bry,m}) \]

\[ P_{bru} = \frac{1235}{2039} \text{ lbf (Bearing Ultimate Allowable)} \]
\[ P_{bry} = \frac{912}{1639} \text{ lbf (Bearing Yield Allowable)} \]

**MS for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right) \]
\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right) \]

\[ MS_{bru} = \frac{0.504}{1.483} \text{ (Plate1)} \]
\[ MS_{bry} = \frac{0.78}{2.19} \text{ (Plate1)} \]

\[ MS_{bh2} := \min (MS_{bru}) \]
\[ MS_{bh3} := \min (MS_{bry}) \]

**MS_{bh2} = 0.504**  
... Bearing MS based on Ultimate Strength

**MS_{bh3} = 0.777**  
... Bearing MS based on Yield Strength
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer

UPS Side - Tab Angle to Outer Bumper

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"
Washer := "NAS1149E0332R"
Nut := "MS21076L3N"

Flange_1 := "Outer Bumper"
Part_Number_1 := "SDG39137854"
Material_1 := "AL ALY 2219-T87"
Minimum edge distance of flange one

edge1 := .75 in

Flange_2 := "Tab Angle Bracket"
Part_Number_2 := "SDG39137847"
Material_2 := "AL ALY 7075-T731"
Minimum edge distance of flange two

edge2 := .312 in

(Worst case combination)

Loads (reference)

Applied tensile load
P := 49.8 lbf

Applied shear load
V := 489 lbf

Applied bending moment
M := 0 in-lbf

Factors of Safety (reference)

SFu := 2.00 (Ultimate)
SFy := 1.25 (Yield)
FF := 1.15 (Fitting factor)
SFsep := 1.20 (Joint Separation)

Temperature data (reference)

Assembly Temp_initial := 70 deg
Temp_max := 140 deg (Maximum)
Temp_min := −76 deg (Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data (Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"

Nominal diameter of bolt
D := .19 in

Number of threads/inch
Nt := 32 \frac{1}{in}

Shank diameter of bolt
D_{shank} := .1885 in

Total length of bolt
L := .526 in

Threaded length
Lt := .276 in (If bolt is fully threaded, input Lt = L)

Bolt head dia. across flats
dw := .357 in (dia of pressure boss if it exists, otherwise dia of head)

Bolt head height
bh := .122 in (head height is 0 if bolt is flat head)
Bolt Data cont. (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Thread data lookup table is hidden
This file uses the data shown in \escfil02\2111_mathcadc8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength
Bolt ultimate tensile allowable stress
Bolt ultimate shear allowable stress

Temperature correction factor for bolt modulus
Modulus of elasticity of bolt
Thermal coefficients for bolt

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:
- Head: \( t_{wh} = 0.032 \text{ in} \)
- Nut: \( t_{wn} = 0.0 \text{ in} \)

Diameter of washer under head:
- Outer: \( D_{woh} = 0.438 \text{ in} \)
- Inner: \( D_{wih} = 0.203 \text{ in} \)

Modulus of elasticity:
- Head: \( E_{washerh} := (29.1 \cdot 10^6 \text{ psi}) \)
- Nut: \( E_{washern} := (0.0 \cdot 10^6 \text{ psi}) \)

Nut Data (Nut = "MS21076L3N")

Height of nut \( H := 0.250 \text{ in} \)

Temperature correction factor for nut strength
Ultimate allowable stress, tensile
Ultimate axial strength of nut

5.10.2.1-36 ESCG-4005-05-AMS-0039
Debris Shield Fastener Joint Analysis for Bolt/ Washer with Nutplate/No Washer 
UPS Side - Tab Angle to Outer Bumper

Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole

\[ D_{\text{hole}} := 0.213 \text{ in} \]

Material_1 = "AL ALY 2219-T87"
Material_2 = "AL ALY 7075-T7351"

\[ E_{\text{flange1}} := 10.8 \times 10^6 \text{ psi} \]
\[ E_{\text{flange2}} := 10.6 \times 10^6 \text{ psi} \]

Temperature correction factor (modulus)

\[ T_{11E} := 0.96 \]
\[ T_{22E} := 0.98 \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange1_hot}} := \frac{12.4 \times 10^{-6}}{\text{in} \cdot \text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange2_hot}} := \frac{12.5 \times 10^{-6}}{\text{in} \cdot \text{in} \cdot \text{deg}} \]

\[ \beta_{\text{flange1_cold}} := \frac{11.6 \times 10^{-6}}{\text{in} \cdot \text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange2_cold}} := \frac{12.1 \times 10^{-6}}{\text{in} \cdot \text{in} \cdot \text{deg}} \]

Torque/Preload data

Maximum torque \( T_{\text{max}} := 44.4 \text{ in-lbf} \)
Minimum torque \( T_{\text{min}} := 37.8 \text{ in-lbf} \)

Preload \( u := 0.25 \)
\( (0.25 \text{ lube}/0.35 \text{ dry}) \)
\( (0.15 \text{ lube}/0.20 \text{ dry}) \)

Loading plane factor \( n := 0.5 \)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \textbackslash escfl02\2i11\mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Fri Apr 27 14:15:49 2007

Bolt Load data

Bolt/joint stiffness factor Max. PLDmax = 2003 lbf
Min. PLDmin = 780 lbf
Nom. preload PLDnom = 1558 lbf

Preload to yield ratio (nom.) PLDRatio = 0.703
Joint separation load Psep = 59.760 lbf

Preload due to temperature Pthr_pos = 56 lbf
Preload due to temperature Pthr_neg = -117.6 lbf
Uncertainty factor u = 0.250
Torque coefficient k = 0.150
Loading plane factor n = 0.500
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Applied Tensile load on the bolt</th>
<th>$P = 49.800$ lbf</th>
<th>Max. load on the bolt with preload and Factor of safety</th>
<th>$P_b = 2022$ lbf $P_{by} = 2015$ lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 489.000$ lbf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0.000$ in lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Max. load on the bolt with preload WithOut factor of safety

<table>
<thead>
<tr>
<th>Bolt ultimate tensile strength</th>
<th>$P_{At} = 2957$ lbf</th>
<th>Bolt shear strength</th>
<th>$V_{Au} = 2572$ lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread pullout strength</td>
<td>$P_{As} = 2362$ lbf</td>
<td>Bolt bending strength</td>
<td>$M_{Au} = 61$ in lbf</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>$P_{tu_nut} = 2362$ lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

General Checks

- length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>$MS_1 = 12.59$</th>
<th>Direct Thread shear Ultimate</th>
<th>$MS_6 = 19.62$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_2 = 24.81$</td>
<td>Total Thread shear Ultimate</td>
<td>$MS_7 = 0.17$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_3 = 29.98$</td>
<td>Shear Ultimate</td>
<td>$MS_8 = 1.29$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_4 = 0.46$</td>
<td>Bending Ultimate</td>
<td>$MS_9 = 100$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_5 = 0.1$</td>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_{10} = 0.32$</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} = 0.1$, $Failure\_Mode = "Total Tension Yield"$
Fail-safe Analysis

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>$P_{FS} = 105.6$ lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>$V_{FS} = 950.4$ lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>$M_{FS} = 0$ in-lbf</td>
</tr>
</tbody>
</table>

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated
This file uses the calculations shown in \escfl02\2i11\mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Fri Apr 27 14:16:05 2007

Bolt Fail-safe Load data

- Joint separation load $P_{Sep_{FS}} = 105.600$ lbf
- Max. load on the bolt (ultimate) $P_{b_{FS}} = 2023.5$ lbf

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_{FS1} = 6.69$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_{FS2} = 23.35$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_{FS3} = 0.46$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$MS_{FS4} = 18.45$</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>$MS_{FS5} = 0.17$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$MS_{FS6} = 1.35$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_{FS7} = 10$</td>
</tr>
<tr>
<td>Combined shear, tension and bending</td>
<td>$MS_{FS8} = 0.32$</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

$MS_{bolt_{FS}} = 0.17$  
$Failure_{Mode_{FS}} = "Total Thread Shear Ultimate (Nut)"$
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors

\[
\begin{align*}
\text{SF}_{u} & = 2.000 \\
\text{SF}_{y} & = 1.250 \\
\text{FF} & = 1.150
\end{align*}
\]

(Ultimate)  (Yield)  (Fitting Factor)

Input Loads

\[
\begin{align*}
V & = 489 \text{ lbf} \\
P & = 49.800 \text{ lbf}
\end{align*}
\]

(Shear Load)  (Axial Load)

Bolt calc results

\[
\begin{align*}
P_b & = 2022 \text{ lbf}
\end{align*}
\]

(Max Bolt Load)

Dimensions

\[
\begin{align*}
L & = 0.526 \text{ in} \\
t_{\text{wh}} & = 0.032 \text{ in}
\end{align*}
\]

(Length of Bolt)  (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions

\[
\begin{align*}
\text{tf}_1 & := \text{tf} \\
\text{tf}_1 & = 0.100 \text{ in} \\
\text{tf}_2 & := \text{tf}_2 \\
\text{tf}_2 & = 0.125 \text{ in} \\
\text{edge}_1 & := \text{edge}_1 \\
\text{edge}_1 & = 0.750 \text{ in} \\
\text{edge}_2 & := \text{edge}_2 \\
\text{edge}_2 & = 0.312 \text{ in}
\end{align*}
\]

(Entire Thickness of Flange 1)  (Entire Thickness of Flange 2)  (Edge Distance for Hole in Plate 1)  (Edge Distance for Hole in Plate 2)

\[
\begin{align*}
D & = 0.190 \text{ in} \\
D_{\text{shank}} & = 0.188 \text{ in} \\
D_{\text{hole}} & = 0.213 \text{ in}
\end{align*}
\]

(Diameter of Bolt)  (Min. Shank Diameter of Bolt)  (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[
A_{\text{shrpl}} = \left[ 2 \cdot \text{tf} \cdot \left( \text{edge} - \frac{1}{2} D_{\text{hole}} \right) \right] \left( \frac{\text{Plate 1}}{\text{Plate 2}} \right)
\]

\[
\frac{0.129}{0.051} \text{ in}^2
\]

Allowables for plates that fastener goes through

\[
\begin{align*}
\text{F}_{su1} & := \text{Ft1E} \cdot 36 \text{ ksi} \\
\text{F}_{su2} & := \text{Ft2E} \cdot 39 \text{ ksi} \\
\text{P}_{su} & := \left( A_{\text{shrpl}} \cdot \text{F}_{su} \right)
\end{align*}
\]

\[
\begin{align*}
\text{F}_{su1} & = 34.560 \text{ ksi} \\
\text{F}_{su2} & = 38.220 \text{ ksi} \\
\text{P}_{su} & = \left( \frac{4448}{1964} \right) \text{lbf}
\end{align*}
\]

(Ultimate Shear Allowable for Plate 1)  (Ultimate Shear Allowable for Plate 2)  (Shear Ultimate Allowable)

MS for Shear Tear-Out

\[
\begin{align*}
\text{MS}_{su} & := \left( \frac{\text{P}_{su}}{V \cdot \text{SFu} \cdot \text{FF}} \right) \\
\text{MS}_{bh1} & := \min \left( \text{MS}_{su} \right)
\end{align*}
\]

\[
\begin{align*}
\text{MS}_{bh1} & = 0.746
\end{align*}
\]

... Shear Tear-Out MS
Bearing Check

Recall bolt hole dimensions

\[ t_f = 0.100 \text{ in} \]  
\[ t_f = 0.125 \text{ in} \]  
\[ \text{edge}_1 = 0.750 \text{ in} \]  
\[ \text{edge}_2 = 0.312 \text{ in} \]

\[ A_{br} = (t_f \text{ min}(D, D_{shank})) \left(\begin{array}{c} \text{Plate}_1 \\ \text{Plate}_2 \end{array}\right) \]

\[ e_D = \frac{\text{edge}}{D_{hole}} \]

Typical Bearing Failure

Allowables for plates that fastener goes through

<table>
<thead>
<tr>
<th>Bearing strength at e/D = 1.5</th>
<th>Bearing strength at e/D = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{bru_1} = 95.04 \text{ ksi} )</td>
<td>( F_{bru_1} = 120.96 \text{ ksi} )</td>
</tr>
<tr>
<td>( F_{bry_1} = 79.68 \text{ ksi} )</td>
<td>( F_{bry_1} = 92.16 \text{ ksi} )</td>
</tr>
<tr>
<td>( F_{bru_2} = 99.96 \text{ ksi} )</td>
<td>( F_{bru_2} = 129.36 \text{ ksi} )</td>
</tr>
<tr>
<td>( F_{bry_2} = 80.36 \text{ ksi} )</td>
<td>( F_{bry_2} = 95.060 \text{ ksi} )</td>
</tr>
</tbody>
</table>

Modified bearing strength

\[ F_{bru_m} = \left\{ \begin{array}{l} F_{bru_1} \text{ if } e_D > 2.0, F_{bru_2} \text{ if } e_D < 2.0, F_{bru_1} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bru_2} - F_{bru_1}) \text{ if } e_D = 2.0 \end{array} \right\} \]

\[ F_{bry_m} = \left\{ \begin{array}{l} F_{bry_1} \text{ if } e_D > 2.0, F_{bry_2} \text{ if } e_D < 2.0, F_{bry_1} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bry_2} - F_{bry_1}) \text{ if } e_D = 2.0 \end{array} \right\} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - Tab Angle to Outer Bumper

$$P_{bru} := \left( A_{bru} \cdot F_{bru} \right)$$

$$P_{bry} := \left( A_{bry} \cdot F_{bry} \right)$$

$$(\text{Bearing Ultimate Allowable})$$

$$P_{bru} = \begin{pmatrix} 2280 \\ 2272 \end{pmatrix} \text{ lbf}$$

$$P_{bry} = \begin{pmatrix} 1737 \\ 1827 \end{pmatrix} \text{ lbf}$$

$$\text{MS for Bearing Failure}$$

$$\text{MS}_{bru} := \frac{P_{bru}}{V \cdot S_{Fu} \cdot FF} - 1$$

$$\text{MS}_{bry} := \frac{P_{bry}}{V \cdot S_{Fy} \cdot FF} - 1$$

$$\text{MS}_{bru} = \begin{pmatrix} 1.027 \\ 1.020 \end{pmatrix}$$

$$\text{MS}_{bry} = \begin{pmatrix} 1.47 \\ 1.6 \end{pmatrix}$$

$$\text{MS}_{bry} := \text{min}(\text{MS}_{bru})$$

$$\text{MS}_{bry} := \text{min}(\text{MS}_{bry})$$

$$\text{MS}_{bry} = \begin{pmatrix} 1.02 \\ 1.02 \end{pmatrix}$$

$$\text{MS}_{bry} = \begin{pmatrix} 1.47 \\ 1.47 \end{pmatrix}$$

$$\text{MS}_{bry} = \begin{pmatrix} 1.02 \end{pmatrix}$$

$$\text{MS}_{bry} = \begin{pmatrix} 1.47 \end{pmatrix}$$

$$\text{MS}_{bru} = \begin{pmatrix} 1.027 \\ 1.020 \end{pmatrix}$$

$$\text{MS}_{bry} = \begin{pmatrix} 1.47 \\ 1.6 \end{pmatrix}$$

$$\text{Plate1}$$

$$\text{Plate2}$$

$$\text{Plate1}$$

$$\text{Plate2}$$

$$\text{... Bearing MS based on Ultimate Strength}$$

$$\text{... Bearing MS based on Yield Strength}$$
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - Bathtub Bracket to Outer Bumper

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"
Washer := "NAS1149E0332R"
Nut := "MS21076L3N"

Flange_1 := "2.70 in Bathtub Bracket"
Part_Number_1 := "SDG39137848-002"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange one edge1 := .5 in

Flange_2 := "Outer Bumper"
Part_Number_2 := "SDG39137854"
Material_2 := "AL ALY 2219-T87"
Minimum edge distance of flange two edge2 := .475 in

Loads (reference)

Applied tensile load
P := 49.8lbf

Applied shear load
V := 489.lbf

Applied bending moment
M := 0in-lbf

(Worst case combination)

Factors of Safety (reference)

SFu := 2.00
(Ultimate)

SFy := 1.25
(Yield)

FF := 1.15
(Fitting factor)

SFsep := 1.20
(Joint Separation)

Temperature data (reference)

Assembly
Temp_initial := 70-deg
Temp_max := 140-deg
(Maximum)
Temp_min := -76 deg
(Minimum)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data ( Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286" )

Nominal diameter of bolt
D := .19 in

Number of threads/inch
Nt := 32 \frac{1}{in}

Shank diameter of bolt
D_shank := .1885 in

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Total length of bolt
L := .526 in

(If bolt is fully threaded, input Lt = L)

Threaded length
Lt := .276 in

(dia of pressure boss if it exists, otherwise dia of head)

Bolt head dia. across flats
dw := .357 in

Bolt head height
bh := .122 in

(head height is 0 if bolt is flat head)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - Bathtub Bracket to Outer Bumper

Bolt Data cont. (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Thread data lookup table is hidden

This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength
Bolt ultimate tensile allowable stress
Bolt ultimate shear allowable stress

Temperature correction factor for bolt modulus
Modulus of elasticity of bolt
Thermal coefficients for bolt

\( \beta_{\text{bolt\_hot}} := 9.1 \cdot 10^{-6} \text{ in}^3/\text{in}^2/\text{deg} \)
\( \beta_{\text{bolt\_cold}} := 8.5 \cdot 10^{-6} \text{ in}^3/\text{in}^2/\text{deg} \)

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:
- Head: \( t_{\text{wh}} := 0.032 \text{ in} \)
- Nut: \( t_{\text{wn}} := 0.0 \text{ in} \)

Diameter of washer under head:
- Outer: \( D_{\text{woh}} := 0.438 \text{ in} \)
- Inner: \( D_{\text{wih}} := 0.203 \text{ in} \)

Modulus of elasticity:
- Head: \( E_{\text{washerh}} := (29.1 \cdot 10^6 \text{ psi}) \)
- Nut: \( E_{\text{washern}} := (0.0 \cdot 10^6 \text{ psi}) \)

Nut Data (Nut = "MS21076L3N")

Height of nut
\( H := 0.250 \text{ in} \)

Temperature correction factor for nut strength
Ultimate allowable stress, tensile
Ultimate axial strength of nut

\( TS_{\text{nut}} := 0.96 \)
\( F_{\text{tu\_nut}} := 125000 \text{ psi} \)
\( P_{\text{tu\_nut}} := 2460 \text{ lbf} \)

\( \text{Note: If there is no washer - tw's, Dwo's and DwI's should be zero} \)
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole

\[ D_{\text{hole}} := .226 \text{ in} \]

Material \(_1 = \text{"AL ALY 6061-T651"}\)

Material \(_2 = \text{"AL ALY 2219-T87"}\)

Thickness of flanges

\[ t_{f1} := .08 \text{ in} \]

\[ t_{f2} := .10 \text{ in} \]

Compressive Modulus of elasticity

\[ E_{\text{flange}1} := (10.1 \times 10^6 \text{ psi}) \]

\[ E_{\text{flange}2} := (10.8 \times 10^6 \text{ psi}) \]

Temperature correction factor

\[ T_{f1}E := .98 \]

\[ T_{f2}E := .96 \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange}1\text{,hot}} := 12.8 \times 10^{-6} \text{ in/in deg} \]

\[ \beta_{\text{flange}1\text{,cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \]

\[ \beta_{\text{flange}2\text{,hot}} := 12.4 \times 10^{-6} \text{ in/in deg} \]

\[ \beta_{\text{flange}2\text{,cold}} := 11.6 \times 10^{-6} \text{ in/in deg} \]

Torque/Preload data

Maximum torque

\[ T_{\text{max}} := 44.4 \text{ in-lbf} \]

Minimum torque

\[ T_{\text{min}} := 37.8 \text{ in-lbf} \]

Preload due to temperature

\[ P_{\text{thr\_pos}} := 51.4 \text{ lbf} \]

\[ P_{\text{thr\_neg}} := -102.5 \text{ lbf} \]

Uncertainty factor

\[ u := 0.25 \]

\[ u := 0.25 \text{ (0.25 lubed/0.35 dry)} \]

\[ u := 0.25 \text{ (0.15 lubed/0.20 dry)} \]

Joint is lubed/dry

Preload

\[ u := 0.25 \]

Uncertainty

\[ k := 0.15 \]

Torque coefficient

\[ k := 0.15 \text{ (0.15 lubed/0.20 dry)} \]

Loading plane factor

\[ n := 0.5 \]

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \\escfg\211_mathcad8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Fri Apr 27 14:15:49 2007

Bolt Load data

Bolt/joint stiffness factor

\[ \alpha := 0.355 \]

Maximum preload

\[ \text{PLD}_{\text{max}} = 1999 \text{ lbf} \]

\[ \text{PLD}_{\text{min}} = 795 \text{ lbf} \]

\[ \text{PLD}_{\text{nom}} = 1558 \text{ lbf} \]

Preload to yield ratio

\[ \text{PLD}_{\text{ratio}} = 0.703 \]

Joint separation load

\[ P_{\text{sep}} = 59.760 \text{ lbf} \]

Preload due to temperature

\[ P_{\text{thr\_pos}} = 51.4 \text{ lbf} \]

\[ P_{\text{thr\_neg}} = -102.5 \text{ lbf} \]

Uncertainty factor

\[ u := 0.250 \]

Torque coefficient

\[ k := 0.150 \]

Loading plane factor

\[ n := 0.500 \]
Bolt Load data (cont.)

Applied Tensile load on the bolt \[ P = 49.800 \text{ lbf} \]
Applied shear on the bolt \[ V = 489.000 \text{ lbf} \]
Applied bending on the bolt \[ M = 0.000 \text{ in. lbf} \]

Max. load on the bolt with preload and Factor of safety
\[ P_b = 2019 \text{ lbf} \]
\[ P_{by} = 2012 \text{ lbf} \]

Max. load on the bolt with preload WithOut factor of safety \[ P_{bapp} = 2009 \text{ lbf} \]

Bolt ultimate tensile strength \[ P_{At} = 2957 \text{ lbf} \]
Thread pullout strength \[ P_{As} = 2362 \text{ lbf} \]
Nut ultimate tensile strength \[ P_{tu\_nut} = 2362 \text{ lbf} \]

Bolt shear strength \[ V_{Au} = 2572 \text{ lbf} \]
Bolt bending strength \[ M_{Au} = 61 \text{ in. lbf} \]

General Checks

length_check = "Bolt length is sufficient and nut fully engaged"
cone_check = "Joint pressure cone does not extend pass flange edge"
preload_check = "Nominal preload >= 65% of bolt yield strength"
washer_check = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>MS_1 = 13.06</th>
<th>Direct Thread shear Ultimate</th>
<th>MS_6 = 19.62</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_2 = 24.81</td>
<td>Total Thread shear Ultimate</td>
<td>MS_7 = 0.17</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_3 = 29.98</td>
<td>Shear Ultimate</td>
<td>MS_8 = 1.29</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_4 = 0.46</td>
<td>Bending Ultimate</td>
<td>MS_9 = 100</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_5 = 0.1</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_{10} = 0.32</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

MS_{bolt} = 0.1  Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

Fail-safe Loads

| Applied Load          | P_FS = 105.6 lbf | V_FS = 950.4 lbf | M_FS = 0 in\cdot lbf |

Fail-safe Factors of Safety

| Load Type            | SFu_FS = 1.0 | SFsep_FS = 1.0 |

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfii02\2i11_mathcad8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Fri Apr 27 14:16:05 2007

Bolt Fail-safe Load data

| Joint separation load | Psep FS = 105.600 lbf |
| Max. load on the bolt (ultimate) | Pb_FS = 2020.4 lbf |

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS_FS1 = 6.96</th>
<th>MS_FS2 = 23.35</th>
<th>MS_FS3 = 0.46</th>
<th>MS_FS4 = 18.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Thread Shear Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSb_FS = 0.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure_Mode_FS = &quot;Total Thread Shear Ultimate (Nut)&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Bolt Hole Analysis
Recall loads from bolt calculation

| Safety Factors | SFu = 2.000 | (Ultimate) |
| FF = 1.150 | (Fitting Factor) |

Input Loads
V = 489 lbf | (Shear Load) |
P = 49.800 lbf | (Axial Load) |

Bolt calc results
Pb = 2019 lbf | (Max Bolt Load) |

Dimensions
L = 0.526 in | (Length of Bolt) |
twh = 0.032 in | (Thickness of Washer) |

Shear Tear-Out Check
Recall bolt hole dimensions

tf1 := tf1 | tf1 = 0.080 in | ( Entire Thickness of Flange 1 ) |
tf2 := tf2 | tf2 = 0.100 in | ( Entire Thickness of Flange 2 ) |
edge1 := edge1 | edge1 = 0.500 in | ( Edge Distance for Hole in Plate 1 ) |
edge2 := edge2 | edge2 = 0.475 in | ( Edge Distance for Hole in Plate 2 ) |

Dimensions
D = 0.190 in | ( Diameter of Bolt ) |
D_shank = 0.188 in | ( Min. Shank Diameter of Bolt ) |
D_hole = 0.226 in | ( Diameter of Hole ) |

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shrpl} = 2 \cdot tf \left( \frac{edge}{2} - \frac{1}{2}D_{hole} \right) \]

| Plate1 | A_{shrpl} = 0.062 in^2 |
| Plate2 | |

Allowables for plates that fastener goes through

\[ F_{su1} := Tf1E \cdot 27 \text{ ksi} \]
\[ F_{su1} = 26.460 \text{ ksi} \] | (Ultimate Shear Allowable for Plate 1) |
\[ F_{su2} := Tf2E \cdot 36 \text{ ksi} \]
\[ F_{su2} = 34.560 \text{ ksi} \] | (Ultimate Shear Allowable for Plate 2) |
\[ P_{su} := \frac{A_{shrpl} \cdot F_{su}}{\text{Plate1}} \]
\[ P_{su} = 1638 \text{ lbf} \] | (Shear Ultimate Allowable) |

MS for Shear Tear-Out

\[ MS_{su} := \frac{P_{su}}{V \cdot SFu \cdot FF} \]
\[ MS_{su} = \left( \frac{P_{su}}{\text{Plate1}} \right) \]
\[ MS_{bh1} := \min( MS_{su} ) \]

\[ MS_{bh1} = 0.457 \]

... Shear Tear-Out MS
Bearing Check

Recall bolt hole dimensions

\[ tf_1 = 0.080 \text{ in} \]
\[ tf_2 = 0.100 \text{ in} \]
\[ \text{edge}_1 = 0.500 \text{ in} \]
\[ \text{edge}_2 = 0.475 \text{ in} \]

\[ A_{br} := \frac{\min(t_f, D_{shank}) \cdot (\text{Plate}_1 \cdot \text{Plate}_2)}{2} \]
\[ e_D := \frac{\text{edge}}{D_{hole}} \]

Allowables for plates that fastener goes through

Bearing strength at \( e/D = 1.5 \)

\[ F_{bru15} := T11 \times E \]
\[ F_{bru15} := T11 \times 66 \text{ ksi} \]
\[ F_{bru15} := T11 \times 66 \text{ ksi} \]
\[ F_{bru20} := T11 \times 88 \text{ ksi} \]
\[ F_{bru20} := T11 \times 88 \text{ ksi} \]
\[ F_{bry15} := T11 \times 50 \text{ ksi} \]
\[ F_{bry15} := T11 \times 49 \text{ ksi} \]
\[ F_{bry20} := T11 \times 58 \text{ ksi} \]
\[ F_{bry20} := T11 \times 58 \text{ ksi} \]

Bearing strength at \( e/D = 2.0 \)

\[ F_{bru15} := T12 \times 99 \text{ ksi} \]
\[ F_{bru15} := T12 \times 95 \text{ ksi} \]
\[ F_{bry15} := T12 \times 83 \text{ ksi} \]
\[ F_{bry15} := T12 \times 79 \text{ ksi} \]
\[ F_{bry20} := T12 \times 126 \text{ ksi} \]
\[ F_{bry20} := T12 \times 120 \text{ ksi} \]

Modified bearing strength

\[ F_{bru1} := \left\{ e_D > 2.0, F_{bru20} \right\}, \left\{ e_D > 1.5 \right\}, \left\{ e_D < 2.0 \right\}, F_{bru1} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bru20} - F_{bru15}) \cdot F_{bru15} + \left( e_D - 0.5 \right) \]

\[ F_{bru2} := \left\{ e_D > 2.0, F_{bru20} \right\}, \left\{ e_D > 1.5 \right\}, \left\{ e_D < 2.0 \right\}, F_{bru2} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bru20} - F_{bru15}) \cdot F_{bru15} + \left( e_D - 0.5 \right) \]

\[ F_{bry1} := \left\{ e_D > 2.0, F_{bru20} \right\}, \left\{ e_D > 1.5 \right\}, \left\{ e_D < 2.0 \right\}, F_{bry1} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bru20} - F_{bru15}) \cdot F_{bru15} + \left( e_D - 0.5 \right) \]

\[ F_{bry2} := \left\{ e_D > 2.0, F_{bru20} \right\}, \left\{ e_D > 1.5 \right\}, \left\{ e_D < 2.0 \right\}, F_{bry2} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bru20} - F_{bru15}) \cdot F_{bru15} + \left( e_D - 0.5 \right) \]

\[ F_{bru} := \frac{86.24}{120.96} \left\{ \text{Plate}_1 \right\}, \left\{ \text{Plate}_2 \right\} \]

\[ F_{bry} := \frac{56.84}{92.16} \left\{ \text{Plate}_1 \right\}, \left\{ \text{Plate}_2 \right\} \]
### Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer

**Title**: UPS Side - Bathtub Bracket to Outer Bumper

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{bru} := \frac{A_{br} \cdot F_{bru _m}}{V \cdot SF_{u _m} \cdot FF}$</td>
<td>Bearing Ultimate Allowable</td>
</tr>
<tr>
<td>$P_{bry} := \frac{A_{br} \cdot F_{bry _m}}{V \cdot SF_{y _m} \cdot FF}$</td>
<td>Bearing Yield Allowable</td>
</tr>
</tbody>
</table>

**MS for Bearing Failure**

$$MS_{bru} := \frac{P_{bru}}{V \cdot SF_{u \_m} \cdot FF} - 1$$

$$MS_{bry} := \frac{P_{bry}}{V \cdot SF_{y \_m} \cdot FF} - 1$$

<table>
<thead>
<tr>
<th>$MS_{bru}$</th>
<th>Plate 1</th>
<th>Plate 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.156</td>
<td>1.027</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$MS_{bry}$</th>
<th>Plate 1</th>
<th>Plate 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>1.47</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$MS_{bh2}$</th>
<th>Plate 1</th>
<th>Plate 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.156</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$MS_{bh3}$</th>
<th>Plate 1</th>
<th>Plate 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.219</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer

UPS Side - Bathtub Bracket to Outer Bumper

**CHECK**

Note: Figure is for reference only. Not to scale. Actual joint made differ. Washer may be on nut side, head side, or both.

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"
Washer := "NAS1149E0332R"
Nut := "MS21076L3N"

Flange_1 := "2.38 in Bathtub Bracket"
Part_Number_1 := "SDG39137848-001"
Material_1 := "AL ALY 6061-T651"
Minimum edge distance of flange one edge1 := .5 in

Flange_2 := "Outer Bumper"
Part_Number_2 := "SDG39137854"
Material_2 := "AL ALY 2219-T87"
Minimum edge distance of flange two edge2 := .952 in

**Loads (reference)**

<table>
<thead>
<tr>
<th>Applied</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>tensile load</td>
<td>P := 49.8lbf</td>
</tr>
<tr>
<td>shear load</td>
<td>V := 489.1bf</td>
</tr>
<tr>
<td>bending moment</td>
<td>M := 0in·lbf</td>
</tr>
</tbody>
</table>

**Factors of Safety (reference)**

- SFu := 2.00 (Ultimate)
- SFy := 1.25 (Yield)
- FF := 1.15 (Fitting factor)
- SFsep := 1.20 (Joint Separation)

**Temperature data (reference)**

- Assembly Temp_initial := 70 deg
- Temp_max := 140 deg (Maximum)
- Temp_min := -76 deg (Minimum)

**Bolt Data (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")**

| Nominal diameter of bolt | D := .19 in |
| Number of threads/inch   | Nt := 32 \( \frac{1}{in} \) |
| Shank diameter of bolt    | D_shank := .1885 in |
| Total length of bolt      | L := .526 in |
| Threaded length           | Lt := .276 in |
| Bolt head dia. across flats | dw := .357 in |
| Bolt head height          | bh := .122 in |

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area.

Note: if bolt is fully threaded, input Lt = L

(dia of pressure boss if it exists, otherwise dia of head)

(head height is 0 if bolt is flat head)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative.
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - Bathtub Bracket to Outer Bumper

Bolt Data cont. (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Thread data lookup table is hidden

This file uses the data shown in `\escfil\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd`

Temperature correction factor for bolt strength
Bolt ultimate tensile allowable stress
Bolt ultimate shear allowable stress

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSu_bolt</td>
<td>.96</td>
</tr>
<tr>
<td>TSy_bolt</td>
<td>.96</td>
</tr>
<tr>
<td>Ftu_bolt</td>
<td>160000 psi</td>
</tr>
<tr>
<td>Fty_bolt</td>
<td>120000 psi</td>
</tr>
<tr>
<td>Fsu_bolt</td>
<td>0.6 · Ftu_bolt</td>
</tr>
</tbody>
</table>

Temperature correction factor for bolt modulus
Modulus of elasticity of bolt
Thermal coefficients for bolt

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE_bolt</td>
<td>.98</td>
</tr>
<tr>
<td>E_bolt</td>
<td>$29.1 \cdot 10^6$ psi</td>
</tr>
<tr>
<td>$\beta_{\text{bolt_hot}}$</td>
<td>$9.1 \cdot 10^{-6}$ in$^{-1}$deg</td>
</tr>
<tr>
<td>$\beta_{\text{bolt_cold}}$</td>
<td>$8.5 \cdot 10^{-6}$ in$^{-1}$deg</td>
</tr>
</tbody>
</table>

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:
- Head: $t_{wh} := 0.032$ in
- Nut: $t_{wn} := 0.0$ in

Diameter of washer under head:
- Outer: $D_{woh} := 0.438$ in
- Inner: $D_{wi} := 0.203$ in

Diameter of washer under nut:
- Outer: $D_{wn} := 0.0$ in
- Inner: $D_{wi} := 0.0$ in

Modulus of elasticity:
- Head: $E_{\text{washerh}} := (29.1 \cdot 10^6$ psi
- Nut: $E_{\text{washern}} := (0.0 \cdot 10^6$ psi

Temperature correction factor for modulus:
- Head: $TE_{\text{washerh}} := .98$
- Nut: $TE_{\text{washern}} := 0.0$

Nut Data (Nut = "MS21076L3N")

Height of nut
Temperature correction factor for nut strength
Ultimate allowable stress, tensile
Ultimate axial strength of nut

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>.250 in</td>
</tr>
<tr>
<td>TS_nut</td>
<td>.96</td>
</tr>
<tr>
<td>Ftu_nut</td>
<td>125000 psi</td>
</tr>
<tr>
<td>Fsu_nut</td>
<td>0.6 · Ftu_nut</td>
</tr>
<tr>
<td>Ftu_nut</td>
<td>2460 lbf</td>
</tr>
</tbody>
</table>
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - Bathtub Bracket to Outer Bumper

Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole

\[ D_{\text{hole}} := 0.226 \text{ in} \]

Material 1 = "AL ALY 6061-T651"
Material 2 = "AL ALY 2219-T87"

Thickness of flanges

\[ t_{f1} := 0.08 \text{ in} \]
\[ t_{f2} := 0.10 \text{ in} \]

Compressive Modulus of elasticity

\[ E_{\text{flange1}} := (10.1 \times 10^6 \text{ psi}) \]
\[ E_{\text{flange2}} := (10.8 \times 10^6 \text{ psi}) \]

Temperature correction factor (modulus)

\[ T_{f1E} := 0.98 \]
\[ T_{f2E} := 0.96 \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange2\_hot}} := 12.4 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange2\_cold}} := 11.6 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

Torque/Preload data

Maximum torque

\[ T_{\text{max}} := 44.4 \text{ in-lbf} \]

Minimum torque

\[ T_{\text{min}} := 37.8 \text{ in-lbf} \]

Joint is lubed/dry

Preload

\[ u := 0.25 \]

Uncertainty

\[ (0.25 \text{ lubed}/0.35 \text{ dry}) \]

Torque coefficient

\[ k := 0.15 \]

Loading plane factor

\[ n := 0.5 \]

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Fri Apr 27 14:15:49 2007

Bolt Load data

Bolt/joint stiffness factor

\[ \text{MAX.} \]

\[ \text{MIN.} \]

Preload

Nom. preload

Preload to yield ratio

Joint separation load

\[ = 0.355 \]

\[ \text{PLDmax} = 1999 \text{ lbf} \]
\[ \text{PLDmin} = 795 \text{ lbf} \]
\[ \text{PLDnom} = 1558 \text{ lbf} \]
\[ \text{PLDratio} = 0.703 \]
\[ \text{Psep} = 59.760 \text{ lbf} \]

Preload due to temperature

\[ \text{Pthr\_pos} = 51.4 \text{ lbf} \]
\[ \text{Pthr\_neg} = -102.5 \text{ lbf} \]

Uncertainty factor

\[ u = 0.250 \]

Torque coefficient

\[ k = 0.150 \]

Loading plane factor

\[ n = 0.500 \]
# Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer

## UPS Side - Bathtub Bracket to Outer Bumper

### Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 49.800$ lbf</td>
<td></td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 489.000$ lbf</td>
<td></td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0.000$ in·lbf</td>
<td></td>
</tr>
</tbody>
</table>

Max. load on the bolt with preload and Factor of safety

- $P_b = 2019$ lbf (ultimate)
- $P_{by} = 2012$ lbf (yield)

- Max. load on the bolt with preload Without factor of safety
  - $P_{bapp} = 2009$ lbf

### Bolt Ultimate tensile strength
- $P_{At} = 2957$ lbf

### Bolt Shear strength
- $V_{Au} = 2572$ lbf

### Thread pullout strength
- $P_{As} = 2362$ lbf

### Bolt Bending strength
- $M_{Au} = 61$ in·lbf

### Nut ultimate tensile strength
- $P_{tu\_nut} = 2362$ lbf

### General Checks
- length_check = "Bolt length is sufficient and nut fully engaged"
- cone_check = "Joint pressure cone does not extend past flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

### Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$M_{S1} = 13.06$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$M_{S2} = 24.81$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$M_{S3} = 29.98$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$M_{S4} = 0.46$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$M_{S5} = 0.1$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$M_{S6} = 19.62$</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>$M_{S7} = 0.17$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$M_{S8} = 1.29$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$M_{S9} = 100$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$M_{S10} = 0.32$</td>
</tr>
</tbody>
</table>

**Smallest margin of safety for the bolt, and the failure mode:**

- $M_{S\_bolt} = 0.1$
- Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

Fail-safe Loads

- Applied tensile load: \( P_{FS} = 105.6 \text{ lbf} \)
- Applied shear load: \( V_{FS} = 950.4 \text{ lbf} \)
- Applied bending moment: \( M_{FS} = 0 \text{ in-lbf} \)

Fail-safe Factors of Safety

- Ultimate: \( SF_{u,FS} = 1.0 \)
- Joint Separation: \( SF_{sep,FS} = 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfl02\2i11\mathcad8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Fri Apr 27 14:16:05 2007

Bolt Fail-safe Load data

- Joint separation load: \( P_{sep,FS} = 105.600 \text{ lbf} \)
- Max. load on the bolt (ultimate): \( P_{b,FS} = 2020.4 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

- Joint separation: \( MS_{FS1} = 6.96 \)
- Direct Tension Ultimate: \( MS_{FS2} = 23.35 \)
- Total Tension Ultimate: \( MS_{FS3} = 0.46 \)
- Direct Thread shear Ultimate: \( MS_{FS4} = 18.45 \)
- Total Thread shear Ultimate: \( MS_{FS5} = 0.17 \)
- Shear Ultimate: \( MS_{FS6} = 1.35 \)
- Bending Ultimate: \( MS_{FS7} = 10 \)
- Combined shear, tension and bending ultimate: \( MS_{FS8} = 0.33 \)

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt,FS} = 0.17 \)

Failure Mode FS = "Total Thread Shear Ultimate (Nut)"

5.10.2.1-55  ESCG-4005-05-AMS-0039
Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors

\( SF_u = 2.000 \) (Ultimate)
\( FF = 1.150 \) (Fitting Factor)
\( SF_y = 1.250 \) (Yield)

Input Loads

\( V = 489 \) lbf (Shear Load)
\( P = 49.800 \) lbf (Axial Load)

Bolt calc results

\( P_b = 2019 \) lbf (Max Bolt Load)

Dimensions

\( L = 0.526 \) in (Length of Bolt)
\( t_{wh} = 0.032 \) in (Thickness of Washer)

Shear Tear-Out Check

Recall bolt hole dimensions

\( t_{f1} = t_{f1} = 0.080 \) in (Entire Thickness of Flange 1)
\( t_{f2} = t_{f2} = 0.100 \) in (Entire Thickness of Flange 2)
\( t_{edge1} = t_{edge1} = 0.500 \) in (Edge Distance for Hole in Plate 1)
\( t_{edge2} = t_{edge2} = 0.952 \) in (Edge Distance for Hole in Plate 2)

\( D = 0.190 \) in (Diameter of Bolt)
\( D_{shank} = 0.188 \) in (Min. Shank Diameter of Bolt)
\( D_{hole} = 0.226 \) in (Diameter of Hole)

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[
A_{shrpl} = \left[ 2 \cdot tf \cdot \left( edge - \frac{1}{2} D_{-hole} \right) \right] \quad \text{(Plate1)}
\]

\[
A_{shrpl} = \left[ \text{in}^2 \right] \quad \text{Plate2}
\]

\[
F_{su1} := T_{f1E} \cdot 27 \text{ ksi}
\]
\( F_{su1} = 26.460 \) ksi (Ultimate Shear Allowable for Plate 1)

\[
F_{su2} := T_{f2E} \cdot 36 \text{ ksi}
\]
\( F_{su2} = 34.560 \) ksi (Ultimate Shear Allowable for Plate 2)

\[
P_{su} := \left( A_{shrpl} \cdot F_{su} \right)
\]
\( P_{su} = 1638 \text{ lbf} \) (Shear Ultimate Allowable)

MS for Shear Tear-Out

\[
MS_{su} := \left( \frac{P_{su}}{V \cdot SF_{u} \cdot FF} - 1 \right) \quad \text{(Plate1)}
\]

\[
MS_{su} = \left( \text{Plate2} \right) \quad MS_{su} = \left( \text{in} \right)
\]

\[
MS_{bh1} := \min \left( MS_{su} \right)
\]

\[
MS_{bh1} = 0.457 \quad \text{... Shear Tear-Out MS}
\]
Bearing Check

Recall bolt hole dimensions

- \( tf_1 = 0.080 \text{ in} \) (Thickness of Plate 1)
- \( tf_2 = 0.100 \text{ in} \) (Thickness of Plate 2)
- \( \text{edge}_1 = 0.500 \text{ in} \) (Edge Distance for thru Hole in Plate 1)
- \( \text{edge}_2 = 0.952 \text{ in} \) (Edge Distance for tapped Hole in Plate 2)

\[
A_{br} := (tf \cdot \text{min}(D, D_{shank})) \\
\text{edge} \quad \text{D}_{hole}
\]

- \( e_D := \frac{\text{edge}}{\text{D}_{hole}} \) (e/D for Plates)

 Allowables for plates that fastener goes through

- Bearing strength at e/D = 1.5
  - \( F_{bru15} := T11E \ 67\text{ksi} \)
  - \( F_{bry15} := T11E \ 50\text{ksi} \)
  - \( F_{bru15} := T12E \ 99\text{ksi} \)
  - \( F_{bry15} := T12E \ 83\text{ksi} \)

- Bearing strength at e/D = 2.0
  - \( F_{bru20} := T11E \ 88\text{ksi} \)
  - \( F_{bry20} := T11E \ 58\text{ksi} \)
  - \( F_{bru20} := T12E \ 126\text{ksi} \)
  - \( F_{bry20} := T12E \ 96\text{ksi} \)

Modified bearing strength

- \( F_{bru\_m1} := \begin{cases} 
      \text{if } e_D > 2.0 \text{, } F_{bru20} \\
      \frac{e_D - 1.5}{2.0 - 1.5} \cdot (F_{bru20} - F_{bru15}) + F_{bru15} \\
   \end{cases} \)

- \( F_{bru\_m2} := \begin{cases} 
      \text{if } e_D > 2.0 \text{, } F_{bru20} \\
      \frac{e_D - 1.5}{2.0 - 1.5} \cdot (F_{bru20} - F_{bru15}) + F_{bru15} \\
   \end{cases} \)

- \( F_{bry\_m1} := \begin{cases} 
      \text{if } e_D > 2.0 \text{, } F_{bry20} \\
      \frac{e_D - 1.5}{2.0 - 1.5} \cdot (F_{bry20} - F_{bry15}) + F_{bry15} \\
   \end{cases} \)

- \( F_{bry\_m2} := \begin{cases} 
      \text{if } e_D > 2.0 \text{, } F_{bry20} \\
      \frac{e_D - 1.5}{2.0 - 1.5} \cdot (F_{bry20} - F_{bry15}) + F_{bry15} \\
   \end{cases} \)

\[
F_{bru\_m} = \begin{pmatrix} 
F_{bru15} \\
F_{bru20} 
\end{pmatrix} \text{ (Ultimate)} \\
F_{bry\_m} = \begin{pmatrix} 
F_{bry15} \\
F_{bry20} 
\end{pmatrix} \text{ (Yield)}
\]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Nutplate/No Washer
UPS Side - Bathtub Bracket to Outer Bumper

\[ P_{bru} := \left( A_{br} \cdot F_{bru \_m} \right) \]
\[ P_{bry} := \left( A_{br} \cdot F_{bry \_m} \right) \]

\[ P_{bru} = \begin{bmatrix} 1300 \\ 2280 \end{bmatrix} \text{ lbf} \quad \text{(Bearing Ultimate Allowable)} \]
\[ P_{bry} = \begin{bmatrix} 857 \\ 1737 \end{bmatrix} \text{ lbf} \quad \text{(Bearing Yield Allowable)} \]

**MS for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right) \]
\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right) \]

\[ MS_{bru} = \begin{bmatrix} 0.156 \\ 1.027 \end{bmatrix} \text{ Plate1} \text{ Plate2} \]
\[ MS_{bry} = \begin{bmatrix} 0.22 \\ 1.47 \end{bmatrix} \text{ Plate1} \text{ Plate2} \]

\[ MS_{bh\_2} = 0.156 \quad \text{... Bearing MS based on Ultimate Strength} \]

\[ MS_{bh\_3} = 0.219 \quad \text{... Bearing MS based on Yield Strength} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
Starboard (UPS) - Inner Bumper to Standoff B

CHECK

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1004-1, .2500-28, Length, A-286, 140ksi"
Washer := "NAS1149E0332R"
Insert := "NASM21209F4-20L, .250-28, Assume A-286, Dry Film Lubricant"

Flange_1 := "Debris Shield Inner Plate"
Part_Number_1 := "SDG39137858-002"
Material_1 := "AL ALY2219-T87"

Flange_2 := "Debris Shield Standoff B"
Part_Number_2 := "SDG39137855"
Material_2 := "AL ALY 6061-T651"

Minimum edge distance of flange 1 \(\text{edge1} := 1.408\) in
Minimum edge distance of flange 2 \(\text{edge2} := 0.364\) in

Loads (reference)
Applied tensile load \(P := 11.7\) lb
Applied shear load \(V := 25.4\) lb
Applied bending moment \(M := 0\) in-lb

(Worst case combination)

Factors of Safety (reference)
\[ SFu := 2.00 \quad (\text{Ultimate}) \]
\[ SFy := 1.25 \quad (\text{Yield}) \]
\[ FF := 1.15 \quad (\text{Fitting factor}) \]
\[ SFsep := 1.20 \quad (\text{Joint Separation}) \]

Temperature Data (reference)
Assembly \(\text{Temp_initial} := 70\) deg
\(\text{Temp_max} := 140\) deg \(\text{(Maximum)}\)
\(\text{Temp_min} := -76\) deg \(\text{(Minimum)}\)

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

Bolt Data (Bolt := "NAS1004-1, .2500-28, Length, A-286, 140ksi")

Nominal diameter of bolt \(D := .2500\) in
Number of threads/inch \(Nt := 28\) \(\frac{1}{\text{in}}\)

Shank diameter of bolt \(D_{\text{shank}} := .2470\) in

Total length of bolt \(L := .606\) in
Threaded length \(L_t := .544\) in \(\text{(If bolt is fully threaded, input } L_t = L)\)

Bolt head dia. across flats \(d_w := .398\) in \(\text{(dia of pressure boss if it exists, otherwise dia of head)}\)

Bolt head height \(b_h := .156\) in \(\text{(head height is 0 if bolt is flat head)}\)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert Starboard (UPS) - Inner Bumper to Standoff B

Bolt Data Continued (Bolt = "NAS1004-1, .2500-28, Length, A-286, 140ksi")

Thread data lookup table is hidden
This file uses the data shown in \\escfil02\i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength
TSu_bolt := .98
TSy_bolt := .98

Bolt ultimate tensile allowable stress
Ftu_bolt := 140000 psi
Fty_bolt := 95000 psi

Bolt ultimate shear allowable stress
Fsu_bolt := 0.6 * Ftu_bolt

Temperature correction factor for bolt modulus
TE_bolt := .98

Modulus of elasticity of bolt
E_bolt := \(29.1 \times 10^6\) psi

Thermal coefficients for bolt
\(
\beta_{\text{hot}} := 9.1 \times 10^{-6} \text{in} / \text{in} / \text{deg} \\
\beta_{\text{cold}} := 8.5 \times 10^{-6} \text{in} / \text{in} / \text{deg}
\)

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:
head twh := 0.032 in

Diameter of washer under head:
Outer Dwoh := 0.438 in
Inner Dwih := 0.203 in

Modulus of elasticity:
head E_washerh := \(29.1 \times 10^6\) psi

Temperature correction factor for modulus:
head TE_washerh := .98 (same as bolt)

Insert Data (Insert = "NASM21209F4-20L, .250-28, Assume A-286, Dry Film Lubricant")

Length of insert
Lins := 0.500 in

Min. external diameter of insert
Fmin := 0.306 in

Depth of recess for insert
lr := 0.020 in

Temperature correction factor for insert strength
TS_ins := .98

Ultimate tensile allowable stress
Ftu_ins := 150000 psi

Ultimate shear allowable stress
Fsu_ins := 0.6 * Ftu_ins

Note: If there is no washer - tw's, Dwo's and Dw's should be zero

(These are total washer thickness, if there are more than one)
### Flange Data

(Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

<table>
<thead>
<tr>
<th>Diameter of thru hole</th>
<th>$D_{\text{hole}} := 0.272\text{in}$</th>
</tr>
</thead>
</table>
| Flange $1 =$ "Debris Shield Inner Plate" | Flange $2 =$ "Debris Shield Standoff B"
| Material $1 =$ "AL Y2219-T87" | Material $2 =$ "AL ALY 6061-T651"
| Thickness of flanges | $t_{f1} := 0.060\text{in}$, $t_{f2} := 0.500\text{in}$ (Using Length of Insert) |
| Compressive Modulus of elasticity | $E_{\text{flange1}} := (10.8 \times 10^6 \text{psi})$, $E_{\text{flange2}} := (10.1 \times 10^6 \text{psi})$ |
| Temperature correction factor (modulus) | $T_{f1E} := .96$, $T_{f2E} := .98$ |

Coefficient of thermal expansion for flanges

- $\beta_{\text{flange1\_hot}} := 12.4 \times 10^{-6} \text{in/in/deg}$
- $\beta_{\text{flange1\_cold}} := 11.6 \times 10^{-6} \text{in/in/deg}$
- $\beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \text{in/in/deg}$
- $\beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{in/in/deg}$ (If unavailable, use temperature reduction factor for $F_t$)

Shear strength of flange two, with temperature reduction

- $F_{su\_t2\_flange2\_hot} := 27000\text{psi}$
- $T_{f2} := .96$

### Torque/Preload Data

- Maximum torque $T_{\text{max}} := 84.2\text{ in\cdotlbf}$
- Minimum torque $T_{\text{min}} := 71.6\text{ in\cdotlbf}$
- Joint is lubed/dry $u := 0.25$ (0.25 lubed/0.35 dry)
- Loading plane factor $n := 0.5$

Stiffness and Margin calculations are hidden

This file uses calculations shown in \escfl02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness.mcd

Fri Apr 27 14:11:53 2007

### Bolt Load Data

<table>
<thead>
<tr>
<th>Bolt/joint stiffness factor</th>
<th>$= 0.519$</th>
<th>Preload due to temperature $P_{\text{thr_pos}} = 173.3\text{lbf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. preload</td>
<td>$PLD_{\text{max}} = 2980\text{lbf}$</td>
<td>$PLD_{\text{neg}} = -350.6\text{lbf}$</td>
</tr>
<tr>
<td>Min. preload</td>
<td>$PLD_{\text{min}} = 941\text{lbf}$</td>
<td></td>
</tr>
<tr>
<td>Nom. preload</td>
<td>$PLD_{\text{nom}} = 2245\text{lbf}$</td>
<td></td>
</tr>
<tr>
<td>Preload to yield ratio (nom.)</td>
<td>$PLD_{\text{ratio}} = 0.684$</td>
<td></td>
</tr>
<tr>
<td>Joint separation load</td>
<td>$P_{\text{sep}} = 14.040\text{lbf}$</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainty factor $u := 0.250$  
Torque coefficient $k := 0.150$  
Loading plane factor $n := 0.500$
Bolt Load Data Continued

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 11.700 \text{lbf}$</td>
<td>Max. load on the bolt with preload and Factor of safety</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 25.400 \text{lbf}$</td>
<td>$P_b = 2987 \text{lbf}$ (ultimate)</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0.000 \text{in-lbf}$</td>
<td>Max. load on the bolt with preload Without factor of safety $P_{b\text{app}} = 2983 \text{lbf}$</td>
</tr>
</tbody>
</table>

Bolt ultimate tensile strength $P_{At} = 4841 \text{lbf}$

Thread pullout strength $P_{As} = 6229 \text{lbf}$

General Checks

- length_check = "Bolt length is sufficient and insert fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washer(s) under head do not extend past flange"
- insert_check = "Flange two is thick enough for insert"

Summary of Margins for Bolt

<table>
<thead>
<tr>
<th>Description</th>
<th>MS1 = 77.73</th>
<th>MS2 = 178.89</th>
<th>MS3 = 194.31</th>
<th>MS4 = 0.62</th>
<th>MS5 = 0.1</th>
<th>MS6 = 230.49</th>
<th>MS7 = 1.09</th>
<th>MS8 = 44.88</th>
<th>MS9 = 100</th>
<th>MS10 = 0.62</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS1 = 77.73</td>
<td>MS2 = 178.89</td>
<td>MS3 = 194.31</td>
<td>MS4 = 0.62</td>
<td>MS5 = 0.1</td>
<td>MS6 = 230.49</td>
<td>MS7 = 1.09</td>
<td>MS8 = 44.88</td>
<td>MS9 = 100</td>
<td>MS10 = 0.62</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS4 = 0.62</td>
<td>MS5 = 0.1</td>
<td>MS6 = 230.49</td>
<td>MS7 = 1.09</td>
<td>MS8 = 44.88</td>
<td>MS9 = 100</td>
<td>MS10 = 0.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS4 = 0.62</td>
<td>MS5 = 0.1</td>
<td>MS6 = 230.49</td>
<td>MS7 = 1.09</td>
<td>MS8 = 44.88</td>
<td>MS9 = 100</td>
<td>MS10 = 0.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS5 = 0.1</td>
<td>MS6 = 230.49</td>
<td>MS7 = 1.09</td>
<td>MS8 = 44.88</td>
<td>MS9 = 100</td>
<td>MS10 = 0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS5 = 0.1</td>
<td>MS6 = 230.49</td>
<td>MS7 = 1.09</td>
<td>MS8 = 44.88</td>
<td>MS9 = 100</td>
<td>MS10 = 0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS5 = 0.1</td>
<td>MS6 = 230.49</td>
<td>MS7 = 1.09</td>
<td>MS8 = 44.88</td>
<td>MS9 = 100</td>
<td>MS10 = 0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Smallest Margin of Safety for the Bolt, and the Failure Mode

MSbolt = 0.1

Failure_Mode = "Total Tension Yield"
Fail-Safe Analysis

**Fail-Safe Loads**

Applied tensile load: \( P_{FS} := 25.2 \text{ lbf} \)

Applied shear load: \( V_{FS} := 57 \text{ lbf} \)

Applied bending moment: \( M_{FS} := 0 \text{ in-lbf} \)

**Fail-Safe Factors of Safety**

Ultimate: \( SF_{u_{FS}} := 1.0 \)

Joint Separation: \( SF_{sep_{FS}} := 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file calculations shown in \`\escfill02\i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness__FS.mcd`
Bolt Hole Analysis

**Recall loads from bolt calculation**

Safety Factors
- SFu = 2.000  (Ultimate)
- SFy = 1.250  (Yield)
- FF = 1.150  (Fitting Factor)

Input Loads
- V = 25.4 lbf  (Shear Load)
- P = 11.700 lbf  (Axial Load)

Bolt calc results
- Pb = 2987 lbf  (Max Bolt Load)

Dimensions
- L = 0.606 in  (Length of Bolt)
- twh = 0.032 in  (Thickness of Washer)

Shear Tear-Out Check

**Recall bolt hole dimensions**

- tf1 := tf1  tf1 = 0.060 in  ( Entire Thickness of Flange 1 )
- T11E = 0.960
- tf2 := tf2  tf2 = 0.500 in  ( Entire Thickness of Flange 2 )
- T12E = 0.980

- edge1 := edge1  edge1 = 1.408 in  ( Edge Distance for Hole in Plate 1 )
- edge2 := edge2  edge2 = 0.364 in  ( Edge Distance for Hole in Plate 2 )

- D = 0.250 in  ( Diameter of Bolt )
- D_shank = 0.247 in  ( Min. Shank Diameter of Bolt )
- D_hole = 0.272 in  ( Diameter of Hole )

Typical shear tear-out failure

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. 11.5)

\[ A_{shrpl} = \left( 2 \cdot tf \cdot \left( \frac{edge}{2} - \frac{D_{hole}}{2} \right) \right) \]

\[ A_{shrpl} = \begin{bmatrix} 0.153 \\ 0.228 \end{bmatrix} \text{in}^2 \]

**Allowables for plates that fastener goes through**

- Fsu1 := T11E \cdot 36 ksi
- Fsu1 = 34.560 ksi  (Ultimate Shear Allowable for Plate 1)
- Fsu2 := T12E \cdot 27 ksi
- Fsu2 = 26.460 ksi  (Ultimate Shear Allowable for Plate 2)

- Psu := \left( A_{shrpl} \cdot Fsu \right)
- Psu = \left( 5275 \right) \text{lbf}  (Shear Ultimate Allowable)

**MS for Shear Tear-Out**

- MSsu := \left( \frac{Psu}{V \cdot SFu \cdot FF} - 1 \right)
- MSsu = \begin{bmatrix} 89.3 \\ 102.27 \end{bmatrix}

- MSbh1 := min\left( MSsu \right)
- MSbh1 = 89.299

... Shear Tear-Out MS
Recall bolt hole dimensions

- tf₁ = 0.060 in (Thickness of Plate 1)
- tf₂ = 0.500 in (Thickness of Plate 2)
- edge₁ = 1.408 in (Edge Distance for thru Hole in Plate 1)
- edge₂ = 0.364 in (Edge Distance for tapped Hole in Plate 2)

Typical Bearing Failure

\[ A_{br} := \frac{\text{tf-min(D, D Shank)}}{\text{edge}} \]
\[ e_D := \frac{\text{edge}}{\text{D hole}} \]
\[ A_{br} \text{ (Plate1)} = \frac{0.015}{\frac{0.123}{\text{in}^2}} \]  
\[ A_{br} \text{ (Plate2)} = \frac{5.176}{\frac{1.338}{\text{in}^2}} \]

Allowables for plates that fastener goes through

Bearing strength at e/D = 1.5

- Fbru₁₅₁ := T₁₁E·99ksi  
  Fbru₁₅₁ = 95.04 ksi  
- Fbru₂₀₁ := T₁₁E·126ksi  
  Fbru₂₀₁ = 120.96 ksi
- Fbru₁₅₂ := T₁₂E·67ksi  
  Fbru₁₅₂ = 65.66 ksi  
- Fbru₂₀₂ := T₁₂E·88ksi  
  Fbru₂₀₂ = 86.24 ksi

Bearing strength at e/D = 2.0

- Fbru₁₅₁ := T₁₁E·83ksi  
  Fbru₁₅₁ = 79.68 ksi  
- Fbru₂₀₁ := T₁₁E·96ksi  
  Fbru₂₀₁ = 92.160 ksi
- Fbru₁₅₂ := T₁₂E·50ksi  
  Fbru₁₅₂ = 49 ksi  
- Fbru₂₀₂ := T₁₂E·58ksi  
  Fbru₂₀₂ = 56.840 ksi

Modified bearing strength

\[ Fbru_{m1} := \begin{cases} \frac{e_D - 1.5}{2.0} & \text{if } e_D > 2.0, Fbru_{201}, Fbrυ_{151} \\ \frac{e_D - 1.5}{2.0} & \text{if } e_D < 2.0, Fbru_{151} \end{cases} \]
\[ Fbru_{m2} := \begin{cases} \frac{e_D - 1.5}{2.0} & \text{if } e_D > 2.0, Fbru_{202}, Fbrυ_{152} \\ \frac{e_D - 1.5}{2.0} & \text{if } e_D < 2.0, Fbru_{152} \end{cases} \]
\[ Fbrυ_{m1} := \begin{cases} \frac{e_D - 1.5}{2.0} & \text{if } e_D > 2.0, Fbru_{201}, Fbrυ_{151} \\ \frac{e_D - 1.5}{2.0} & \text{if } e_D < 2.0, Fbru_{151} \end{cases} \]
\[ Fbrυ_{m2} := \begin{cases} \frac{e_D - 1.5}{2.0} & \text{if } e_D > 2.0, Fbru_{202}, Fbrυ_{152} \\ \frac{e_D - 1.5}{2.0} & \text{if } e_D < 2.0, Fbru_{152} \end{cases} \]

\[ Fbru_m = \frac{120.96}{55.039} \text{ ksi (Ultimate)} \]
\[ Fbrυ_m = \frac{92.16}{41.074} \text{ ksi (Yield)} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
Starboard (UPS) - Inner Bumper to Standoff B

\[ P_{bru} := \left( A_{bru} \cdot F_{bru \_m} \right) \]
\[ P_{bry} := \left( A_{bry} \cdot F_{bry \_m} \right) \]

\[ P_{bru} = \begin{bmatrix} 1793 \\ 6797 \end{bmatrix} \text{lbf} \]  
\[ (\text{Bearing Ultimate Allowable}) \]

\[ P_{bry} = \begin{bmatrix} 1366 \\ 5073 \end{bmatrix} \text{lbf} \]  
\[ (\text{Bearing Yield Allowable}) \]

**MS for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right) \]
\[ MS_{bru} = \begin{bmatrix} 29.685 \\ 115.352 \end{bmatrix} \]  
\[ \text{Plate1} \]
\[ \text{Plate2} \]

\[ MS_{bh\_2} := \min(\text{MS}_{bru}) \]
\[ MS_{bh\_2} = 29.685 \]  
\[ \ldots \text{ Bearing MS based on Ultimate Strength} \]

\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right) \]
\[ MS_{bry} = \begin{bmatrix} 36.41 \\ 137.93 \end{bmatrix} \]  
\[ \text{Plate1} \]
\[ \text{Plate2} \]

\[ MS_{bh\_3} := \min(\text{MS}_{bry}) \]
\[ MS_{bh\_3} = 36.407 \]  
\[ \ldots \text{ Bearing MS based on Yield Strength} \]
**Title**

Bolt Joint Analysis for Bolt/Washer with Nutplate

**UPS Side - UPS Cover to Bumper External**

**CHECK**

Note: Figure is for reference only.
Not to scale. Actual joint made differ.
Washer may be on nut side, head side, or both

Bolt := "NAS1133E4, .1900-32, 0.526 L, A-286"

Washer := "NAS1149E0332R"

Nut := "MS21076L3N"

Flange_1 := "Bumper External UPS Cover"
Part_Number_1 := "SDG39137846"
Material_1 := "AL ALY 2219-T37"

Minimum edge distance of flange 1 edge1 := .325 in

Flange_2 := "Bumper External"
Part_Number_2 := "SDG39137854"
Material_2 := "AL ALY2219-T87"

Minimum edge distance of flange 2 edge2 := .430 in

**Loads (reference)**

Applied tensile load

\[ P := 25.9 \text{ lbf} \]  
\( \text{(Worst case combination)} \)

Applied shear load

\[ V := 41.6 \text{ lbf} \]

Applied bending moment

\[ M := 0 \text{ in-lbf} \]

**Factors of Safety (reference)**

\[
SF_u := 2.00 \quad \text{(Ultimate)}
\]

\[
SF_y := 1.25 \quad \text{(Yield)}
\]

\[
FF := 1.15 \quad \text{(Fitting factor)}
\]

\[
SF_{sep} := 1.20 \quad \text{(Joint Separation)}
\]

**Temperature Data (reference)**

Assembly Temp-initial := 70 deg

\[
\text{Temp}_\text{max} := 140 \text{ deg} \quad \text{(Maximum)}
\]

\[
\text{Temp}_\text{min} := -76 \text{ deg} \quad \text{(Minimum)}
\]

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative

**Bolt Data** (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Nominal diameter of bolt
\[ D := .1900 \text{ in} \]

Number of threads/inch \[ N_t := 32 \frac{1}{in} \]

Shank diameter of bolt \[ D_{\text{shank}} := .1885 \text{ in} \]

Note: if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Total length of bolt \[ L := .526 \text{ in} \]

(If bolt is fully threaded, input Lt = L)

Threaded length \[ Lt := .276 \text{ in} \]

Bolt head dia. across flats \[ dw := .357 \text{ in} \]  
\( \text{(dia of pressure boss if it exists, otherwise dia of head)} \)

Bolt head height \[ bh := .122 \text{ in} \]  
\( \text{(head height is 0 if bolt is flat head)} \)
Bolt Joint Analysis for Bolt/Washer with Nutplate
UPS Side - UPS Cover to Bumper External

Bolt Data Continued (Bolt = "NAS1133E4, .1900-32, 0.526 L, A-286")

Temperature correction factor for bolt strength
TSu_bolt := .96       TSy_bolt := .96  (MMPDS-03, Fig. 6.2.1.1.1.)

Bolt ultimate tensile allowable stress
Ftu_bolt := 160000 psi  Fty_bolt := 120000 psi

Bolt ultimate shear allowable stress
Fsu_bolt := 0.6*Ftu_bolt

Temperature correction factor for bolt modulus
TE_bolt := .98  (MMPDS-03, Fig. 6.2.1.1.4(a).)

Modulus of elasticity of bolt
E_bolt := \((29.1\times10^6)\) psi  (MMPDS-03, Fig. 6.2.1.0(b).)

Thermal coefficients for bolt
\(\alpha_{\text{bolt\_hot}} := 9.1\times10^{-6} \text{ in/in deg}\)
\(\alpha_{\text{bolt\_cold}} := 8.5\times10^{-6} \text{ in/in deg}\)  (MMPDS-03, Fig. 6.2.1.0.)

Washer Data (Washer = "NAS1149E0332R")

Thickness of washers:
- head: \(twh := 0.032\) in
- nut: \(twn := 0.0\) in

Diameter of washer under head:
- Outer: \(Dwoh := 0.438\) in
- Inner: \(Dwih := 0.203\) in

Diameter of washer under nut:
- Outer: \(Dwon := 0.0\) in
- Inner: \(Dwin := 0.0\) in

Modulus of elasticity:
- head: \(E_{\text{washerh}} := (29.1\times10^6)\) psi
- nut: \(E_{\text{washern}} := (0.0\times10^6)\) psi

Temperature correction factor for modulus:
- head: \(TE_{\text{washerh}} := 0.98\)  (same as bolt)
- nut: \(TE_{\text{washern}} := 0.0\)

Nut Data (Nut = "MS21076L3N")

Height of nut
\(H := 0.250\) in

Nut dia. across flats
\(Dn := 0.290\) in

Temperature correction factor for nut strength
TS_nut := 0.96  (same as bolt)

Ultimate allowable stress, tensile
\(Ftu_{\text{nut}} := 125000\) psi
\(Fsu_{\text{nut}} := 0.6*Ftu_{\text{nut}}\)  (Shear)

Ultimate axial strength of nut
\(Ptu_{\text{nut}} := 2460\) lbf
Flange Data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Diameter of thru hole \( D_{\text{hole}} := 0.213 \text{ in} \)

Flange_1 = "Bumper External UPS Cover"
Flange_2 = "Bumper External"

Material_1 = "AL ALY 2219-T37"
Material_2 = "AL ALY 2219-T87"

Thickness of flanges \( t_{f1} := 0.080 \text{ in} \) \( t_{f2} := 0.100 \text{ in} \)

Compressive Modulus of elasticity

\[ E_{\text{flange}1} := (10.8 \times 10^6 \text{ psi}) \]
\[ E_{\text{flange}2} := (10.8 \times 10^6 \text{ psi}) \]

Temperature correction factor (modulus)

\( T_{f1} E := 0.96 \)
\( T_{f2} E := 0.96 \)

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange}1, \text{hot}} := 12.4 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \beta_{\text{flange}1, \text{cold}} := 11.6 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \beta_{\text{flange}2, \text{hot}} := 12.4 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \beta_{\text{flange}2, \text{cold}} := 11.6 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload Data

Maximum torque \( T_{\text{max}} := 44.4 \text{ in-lbf} \)
Minimum torque \( T_{\text{min}} := 37.8 \text{ in-lbf} \)

Joint is lubed/dry Preload Uncertainty \( \mu := 0.25 \)
Torque coefficient \( k := 0.15 \)

(0.25 lubed/0.35 dry)\) (0.15 lubed/0.20 dry)

Loading plane factor \( n := 0.5 \)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \textbackslash escfl02\2i11\mathcad\8307_bolts\Rev_D\bolt\stiffness\nut.mcd

Fri Apr 27 14:15:49 2007

Bolt Load Data

Bolt/joint stiffness factor \( = 0.334 \)
Preload due to temperature \( P_{\text{thr, pos}} = 50.4 \text{ lbf} \)

Max. preload \( P_{\text{LDmax}} = 1998 \text{ lbf} \)

Min. preload \( P_{\text{LDmin}} = 799 \text{ lbf} \)

Nom. preload \( P_{\text{LDnom}} = 1558 \text{ lbf} \)
Uncertainty factor \( \mu = 0.250 \)

Preload to yield ratio (nom.) \( P_{\text{LDratio}} = 0.703 \)
Torque coefficient \( k = 0.150 \)

Joint separation load \( P_{\text{sep}} = 31.080 \text{ lbf} \)
Loading plane factor \( n = 0.500 \)
### Bolt Load Data Continued

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 25.900$ lbf</td>
<td>Max. load on the bolt with preload and Factor of safety</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 41.600$ lbf</td>
<td></td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0.000$ in-lbf</td>
<td>Max. load on the bolt with preload Without factor of safety</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$PA_t = 2957$ lbf</td>
<td>Bolt shear strength</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>$PA_s = 2362$ lbf</td>
<td>Bolt bending strength</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>$Ptu_nut = 2362$ lbf</td>
<td></td>
</tr>
</tbody>
</table>

### General Checks

- `length_check = "Bolt length is sufficient and nut fully engaged"`
- `cone_check = "Joint pressure cone does not extend pass flange edge"
- `preload_check = "Nominal preload >= 65% of bolt yield strength"
- `washer_check = "Washers under head and nut do not extend past flanges"

### Summary of Margins for Bolt

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_1 = 25.82$</td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_2 = 48.63$</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_3 = 58.56$</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_4 = 0.47$</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_5 = 0.11$</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
<tr>
<td><strong>Smallest Margin of Safety for the Bolt, and the Failure Mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$MS_{\text{bolt}} = 0.11$</td>
<td>Failure Mode = &quot;Total Tension Yield&quot;</td>
<td></td>
</tr>
</tbody>
</table>
Fail-Safe Analysis

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Applied Value</th>
<th>Fail-safe Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Load</td>
<td>P FS := 51.8 lbf</td>
<td></td>
</tr>
<tr>
<td>Shear Load</td>
<td>V FS := 83.2 lbf</td>
<td></td>
</tr>
<tr>
<td>Bending Moment</td>
<td>M FS := 0.0 in lbf</td>
<td></td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Load</td>
<td>SFu_FS := 1.0</td>
</tr>
<tr>
<td>Joint Separation Load</td>
<td>SFsep_FS := 1.0</td>
</tr>
</tbody>
</table>

**Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated**

This file uses the calculations shown in \escf\02\2i11\mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Fri Apr 27 14:16:05 2007

---

Bolt Fail-safe Load data

Joint separation load \( P_{sep}_FS = 51.800 \) lbf

Max. load on the bolt (ultimate) \( P_{b}_FS = 2007.7 \) lbf

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS FS1 := 15.09</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS FS2 := 48.63</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS FS3 := 0.47</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS FS4 := 38.64</td>
</tr>
</tbody>
</table>

Smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt}_FS = 0.18 \]

\[ Failure\_Mode\_FS = "Total\_Thread\_Shear\_Ultimate\_(Nut)" \]
Bolt Joint Analysis for Bolt/Washer with Nutplate
UPS Side - UPS Cover to Bumper External

Bolt Hole Analysis

Recall loads from bolt calculation

Safety Factors

SFu = 2.000  \quad \text{(Ultimate)}

SFy = 1.250  \quad \text{(Yield)}

FF = 1.150  \quad \text{(Fitting Factor)}

Input Loads

V = 41.6 lbf \quad \text{(Shear Load)}

P = 25.900 lbf \quad \text{(Axial Load)}

Bolt calc results

Pb = 2008 lbf \quad \text{(Max Bolt Load)}

Dimensions

L = 0.526 in \quad \text{(Length of Bolt)}

twh = 0.032 in \quad \text{(Thickness of Washer)}

Shear Tear-Out Check

Recall bolt hole dimensions

\( tf_1 := tf, \quad tf_1 = 0.080 \text{in} \quad \text{(Entire Thickness of Flange 1)} \)

\( tf_2 := tf, \quad tf_2 = 0.100 \text{in} \quad \text{(Entire Thickness of Flange 2)} \)

\( edge_1 := edge_1, \quad edge_1 = 0.325 \text{in} \quad \text{(Edge Distance for Hole in Plate 1)} \)

\( edge_2 := edge_2, \quad edge_2 = 0.430 \text{in} \quad \text{(Edge Distance for Hole in Plate 2)} \)

\( D = 0.190 \text{in} \quad \text{(Diameter of Bolt)} \)

\( D_{\text{shank}} = 0.188 \text{in} \quad \text{(Min. Shank Diameter of Bolt)} \)

\( D_{\text{hole}} = 0.213 \text{in} \quad \text{(Diameter of Hole)} \)

Typical shear tear-out failure

Shear area of the mating components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[
A_{\text{shrep l}} := 2 \cdot tf \cdot \left( \frac{edge}{2} - \frac{D_{\text{hole}}}{2} \right)
\]

\[
A_{\text{shrep l}} = \begin{cases} 
\frac{0.035}{0.065} \text{in}^2 & \text{Plate 1} \\
\text{Plate 2} & 
\end{cases}
\]

Allowables for plates that fastener goes through

\( F_{su 1} := T_{f1 E} \cdot 24.5 \text{ ksi} \quad F_{su 1} = 23.520 \text{ ksi} \quad \text{(Ultimate Shear Allowable for Plate 1)} \)

\( F_{su 2} := T_{f2 E} \cdot 36 \text{ ksi} \quad F_{su 2} = 34.560 \text{ ksi} \quad \text{(Ultimate Shear Allowable for Plate 2)} \)

\( P_{su} := \left( A_{\text{shrep l}} \cdot F_{su} \right) \quad P_{su} = \begin{cases} 
822 \text{lbf} & \text{Plate 1} \\
2236 \text{lbf} & \text{Plate 2} 
\end{cases} \quad \text{(Shear Ultimate Allowable)} \)

MS for Shear Tear-Out

\[
MS_{su} := \frac{P_{su}}{V \cdot SFu \cdot FF}
\]

\[
MS_{su} = \begin{cases} 
\text{Plate 1} & MS_{su} = \frac{7.59}{22.37} \\
\text{Plate 2} & 
\end{cases}
\]

\( MS_{bh 1} := \min( MS_{su} ) \quad MS_{bh 1} = 7.594 \quad \text{... Shear Tear-Out MS} \)
### Bearing Check

**Recall bolt hole dimensions**

- \( t_{f1} = 0.080 \text{in} \)  
- \( t_{f2} = 0.100 \text{in} \)  
- \( edge_1 = 0.325 \text{in} \)  
- \( edge_2 = 0.430 \text{in} \)

**Typical Bearing Failure**

- (Bearing Areas)
- (Plates)

**Allowables for plates that fastener goes through**

<table>
<thead>
<tr>
<th>Bearing strength at ( e/D = 1.5 )</th>
<th>Bearing strength at ( e/D = 2.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Fbru15_1 := T_{f1}1E \cdot 77 \text{ksi} )</td>
<td>( Fbru20_1 := T_{f1}1E \cdot 98 \text{ksi} )</td>
</tr>
<tr>
<td>( Fbry15_1 := T_{f1}1E \cdot 60 \text{ksi} )</td>
<td>( Fbry20_1 := T_{f1}1E \cdot 70 \text{ksi} )</td>
</tr>
<tr>
<td>( Fbru15_2 := T_{f2}2E \cdot 99 \text{ksi} )</td>
<td>( Fbru20_2 := T_{f2}2E \cdot 126 \text{ksi} )</td>
</tr>
<tr>
<td>( Fbry15_2 := T_{f2}2E \cdot 83 \text{ksi} )</td>
<td>( Fbry20_2 := T_{f2}2E \cdot 96 \text{ksi} )</td>
</tr>
</tbody>
</table>

**Modified bearing strength**

\[
Fbru_m = \begin{cases} 74.961 \text{ksi} & \text{Plate1} \\
120.96 \text{ksi} & \text{Plate2} \end{cases} \quad \text{(Ultimate)}
\]

\[
Fbry_m = \begin{cases} 58.096 \text{ksi} & \text{Plate1} \\
92.16 \text{ksi} & \text{Plate2} \end{cases} \quad \text{(Yield)}
\]
### Bolt Joint Analysis for Bolt/Washer with Nutplate
**UPS Side - UPS Cover to Bumper External**

**Equations**

\[
P_{bru} := \left( A_{bru} F_{bru\_m} \right)
\]

\[
P_{bry} := \left( A_{bry} F_{bry\_m} \right)
\]

\[
P_{bru} = \left( \begin{array}{c} 1130 \\ 2280 \end{array} \right) \text{lbf} \quad (Bearing \text{ Ultimate Allowable})
\]

\[
P_{bry} = \left( \begin{array}{c} 876 \\ 1737 \end{array} \right) \text{lbf} \quad (Bearing \text{ Yield Allowable})
\]

**MS for Bearing Failure**

\[
MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right)
\]

\[
MS_{bru} = \left( \begin{array}{c} 10.815 \\ 22.830 \end{array} \right) \quad (Plate1 \quad Plate2)
\]

\[
MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right)
\]

\[
MS_{bry} = \left( \begin{array}{c} 13.65 \\ 28.05 \end{array} \right) \quad (Plate1 \quad Plate2)
\]

\[
MS_{bh\_2} := \min\{MS_{bru}\}
\]

\[
MS_{bh\_2} = 10.815 \quad ... \text{Bearing MS based on Ultimate Strength}
\]

\[
MS_{bh\_3} := \min\{MS_{bry}\}
\]

\[
MS_{bh\_3} = 13.65 \quad ... \text{Bearing MS based on Yield Strength}
\]
Debris Shield Fastener 3 Flange Joint Analysis for Bolt/Washer with Insert Starboard (UPS) - Outer Bumper to Standoff B

CHECK BOLTS (NAS1004-40 0.25"-28 x 1.0" L Material-A-286), Insert MS21209 F4-20L, Washer NAS1587-4C

- **Flange (tf1):** Starboard External Bumper assy
  - Part number: SDG39137854-301
  - Material: 2219-T87

- **Mid Flange (ad2):** Debris shield Standoff A assy
  - Part number: SDG39137848-005
  - Material: 6061-T651

- **Flange (tf2):** Debris shield standoff B
  - Part number: SDG39137855-001
  - Material: 6061-T651

**Loads**

- **Applied tensile load:** \( P = 11.7 \) lbf
- **Applied shear load:** \( V = 25.4 \) lbf
- **Applied bending moment:** \( M = 38.9 \) in-lbf

**Factors of Safety**

- **Ultimate:** \( SF_u = 2.0 \)
- **Yield:** \( SF_y = 1.25 \)
- **Assembly:** \( SF_{sep} = 1.2 \)
- **Fitting factor:** \( FF = 1.15 \)

**Temperature data**

- **Temporary initial:** \( Temp_{initial} = 70 \) deg
- **Maximum:** \( Temp_{max} = 120 \) deg
- **Minimum:** \( Temp_{min} = -200 \) deg

**Bolt and Insert Data**

- **Nominal diameter of bolt:** \( D = 0.250 \) in
- **Number of threads/inch:** \( N_t = \frac{28}{1} \) in
- **Total length of bolt:** \( L = 3.044 \) in
- **Length of insert:** \( L_{ins} = 0.50 \) in
- **Threaded length:** \( L_t = 0.544 \) in
- **Min. external diameter of insert:** \( F_{min} = 0.306 \) in
- **Depth of recess for insert:** \( l_r = 0.02 \) in

(If bolt is fully threaded, input \( L_t = L \))

**Washer Data**

- **Thickness of washer:** \( tw = 0.078 \) in
- **Outer Diameter of washer:** \( D_w = 0.531 \) in
- **Inner Diameter of washer:** \( D_{wi} = 0.252 \) in
- **Bolt head dia. across flats:** \( d_w = 0.398 \) in

**Flange data**

- **Thickness of flange 1:** \( tf_1 = 0.10 \) in
- **Thickness of flange 2:** \( tf_2 = 0.66 \) in
- **Thickness of mid flange:** \( t_{midflg_ad2} = 2.25 \) in
- **Diameter of hole:** \( D_{hole} = 0.26 \) in
- **Outer Diameter of standoff:** \( D_{w_ad2} = 0.50 \) in
- **Inner Diameter of standoff:** \( D_{wi_ad2} = 0.272 \) in

Note: If there is no washer, \( tw, D_w, \) and \( D_{wi} \) should be zero.
### Material Property Data

**Bolt**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature correction factor for bolt strength ultimate</td>
<td>( T_{Su_bolt} := 0.98 )</td>
</tr>
<tr>
<td>Bolt ultimate tensile allowable stress</td>
<td>( F_{tu_bolt} := 140000 ) psi</td>
</tr>
<tr>
<td>Bolt ultimate shear allowable stress</td>
<td>( F_{su_bolt} := 0.6 \cdot F_{tu_bolt} )</td>
</tr>
<tr>
<td>Bolt yield tensile allowable</td>
<td>( F_{ty_bolt} := 95000 ) psi</td>
</tr>
<tr>
<td>Temperature correction factor for bolt modulus</td>
<td>( T_{E_bolt} := 0.94 )</td>
</tr>
<tr>
<td>Modulus of elasticity of bolt</td>
<td>( E_{bolt} := \left(29.1 \cdot 10^6\right) ) psi</td>
</tr>
</tbody>
</table>

Thermal coefficient for bolt:

\[
\beta_{bolt\_hot} := 9.1 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{in}} \cdot \text{deg} \\
\beta_{bolt\_cold} := 7.8 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{in}} \cdot \text{deg}
\]

**Insert**

Temperature correction factor for insert strength \( T_{S\_ins} := 0.94 \)

Ultimate tensile allowable stress \( F_{tu\_ins} := 150000 \) psi

Ultimate shear allowable stress \( F_{su\_ins} := 0.6 \cdot F_{tu\_ins} \)

**Washer**

Temperature correction factor for washer modulus \( T_{E\_washer} := 1.0 \)

Modulus of elasticity of washer \( E_{washer} := \left(29.1 \cdot 10^6\right) \) psi

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{f1\_E} := 1.0 \) (modulus) \( T_{f1\_S} := 0.96 \) (strength)

Temperature correction factor for flange 2 \( T_{f2\_E} := 1.0 \) (modulus) \( F_{su\_f2} := 270000 \) psi

Modulus of elasticity for the parts in the joint \( E_{\text{flange1}} := \left(10.8 \cdot 10^6\right) \) psi \( E_{\text{flange2}} := \left(10.1 \cdot 10^6\right) \) psi

Coefficient of thermal expansion for flanges \( \beta_{\text{flange1\_hot}} := 12.3 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{in}} \cdot \text{deg} \\
\beta_{\text{flange1\_cold}} := 11.0 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{in}} \cdot \text{deg} \\
\beta_{\text{flange2\_hot}} := 12.7 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{in}} \cdot \text{deg} \\
\beta_{\text{flange2\_cold}} := 11.3 \cdot 10^{-6} \cdot \frac{\text{in}}{\text{in}} \cdot \text{deg} \)
Debris Shield Fastener 3 Flange Joint Analysis for Bolt/Washer with Insert
Starboard (UPS) - Outer Bumper to Standoff B

Mid Flange
Temperature correction factor for mid flange modulus
\[ \text{TE}_{\text{mid flg ad2}} = 0.98 \]
Modulus of elasticity of mid flange
\[ \text{E}_{\text{mid flg ad2}} = \left(10.1 \cdot 10^6 \text{ psi}\right) \]
Coefficient of thermal expansion for mid flange
\[ \beta_{\text{midflg ad2 hot}} = 12.7 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{\text{midflg ad2 cold}} = 11.3 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data
Maximum torque (50 % of yield)
\[ T_{\text{max}} = 65 \text{ in-lbf} \]
Minimum torque (85 % of Max torque)
\[ T_{\text{min}} = 55 \text{ in-lbf} \]
Torque coefficient
\[ k = 0.15 \]

Bolt Load data
Bolt/joint stiffness factor
\[ = 0.567 \]
Preload due to temperature
\[ \text{Pthr}_{\text{pos}} = 107.8 \text{ lbf} \]
Max. preload
\[ \text{PLD}_{\text{max}} = 2274.5 \text{ lbf} \]
Min. preload
\[ \text{PLD}_{\text{min}} = 991.7 \text{ lbf} \]
Joint separation load
\[ \text{P}_{\text{sep}} = 14.04 \text{ lbf} \]
Max. load on the bolt(ultimate)
\[ \text{P}_{\text{b}} = 2282.1 \text{ lbf} \]
Max. load on the bolt(yield)
\[ \text{P}_{\text{by}} = 2279.2 \text{ lbf} \]
Bolt ultimate tensile strength
\[ \text{P}_{\text{At}} = 4840.8 \text{ lbf} \]

Summary of Margins for bolt:
Joint separation
\[ \text{MS}_1 = 84.72 \]
Direct Tension Ultimate
\[ \text{MS}_2 = 178.89 \]
Direct Tension Yield
\[ \text{MS}_3 = 194.31 \]
Total Tension Ultimate
\[ \text{MS}_4 = 1.12 \]
Total Tension Yield
\[ \text{MS}_5 = 0.441 \]

Determination of the smallest margin of safety for the bolt, and the failure mode:
\[ \text{MS}_{\text{bolt}} = \min (\text{MS}) \]
\[ \text{MS}_{\text{bolt}} = 0.094 \]
Failure Mode = "Combined Shear Tension Bending Ultimate"
Fail-safe Analysis

Fail-safe Loads

- **Applied tensile load**
  \[ P_{FS} := 23.4 \text{ lbf} \]

- **Applied shear load**
  \[ V_{FS} := 50.8 \text{ lbf} \]

- **Applied bending moment**
  \[ M_{FS} := 77.8 \text{ in-lbf} \]

Fail-safe Factors of Safety

- **Ultimate**
  \[ SF_{u,FS} := 1.0 \]

- **Joint Separation**
  \[ SF_{sep,FS} := 1.0 \]

Bolt Fail-safe Load data

- **Joint separation load**
  \[ P_{sep,FS} = 23.4 \text{ lbf} \]

- **Max. load on the bolt (ultimate)**
  \[ P_{b,FS} = 2282.1 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

- **Joint separation**
  \[ MS_{FS1} = 50.43 \text{ lbf} \]

- **Direct Tension Ultimate**
  \[ MS_{FS2} = 178.89 \text{ lbf} \]

- **Total Tension Ultimate**
  \[ MS_{FS3} = 1.12 \text{ in-lbf} \]

- **Direct Thread shear Ultimate**
  \[ MS_{FS4} = 230.49 \text{ lbf} \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
MS_{bolt,FS} := \min(\{MS_{FS}\})
\]

\[ MS_{bolt,FS} = 0.094 \text{ lbf} \]

Failure Mode \( FS = \) “Combined Shear Tension Bending Ultimate”
Rivet Analysis

Rivet := "NAS 1398DFC4-3, Rivet Blind, Protruding Head, Locked Spindle, .125 Dia, .126 Grip, .323 L"

Flange_1 := "Debris Shield Corner Bracket"
Part_Number_1_1 := "SDG39137849-001"
Part_Number_1_2 := "SDG39137849-002"
Part_Number_1_3 := "SDG39137849-003"
Part_Number_1_4 := "SDG39137849-004"
Part_Number_1_5 := "SDG39137849-005"
Material_1 := "AL ALY 6061-T651, AMS-QQ-A-250/11"

Flange_2 := "Starboard External Bumper Assembly"
Part_Number_2 := "SDG39137854"
Material_2 := "AL ALY 2219-T87, AMS-QQ-A-250/30"

Minimum edge distance of flange one edge1 := .5 in
Minimum edge distance of flange two edge2 := .5 in

Methodology

The Starboard Debris Shield has 5 Corner Brackets SDG39137849 (-001 thru -005) which support the External Bumper. All 5 Corner Brackets are .08 thick AL ALY 6061-T651; use NAS 1398DFC4-3 rivets which go through .125 holes. Each rivet was modeled in NASTRAN as two spider RBE2s connected by a CBush. 64 Lift Off and 64 Landing load conditions were analyzed using the Integrated Loads FEM.

The worst worst case Axial (P) and Total Shear (V) loads from the CBush's were enveloped for all the rivets, for all 5 Corner Brackets, for all 128 load cases. The worst case P and the worst case V were used together to calculate the tensile and shear margins of safety.

For Fail-Safe Analysis, the worst worst case P and V were doubled and then used together to calculate the tensile and shear fail-safe margins of safety.

Allowables

Rivet Strengths (AL ALY 2017-T4 Sleeve)

<table>
<thead>
<tr>
<th>Fsu</th>
<th>494 lbf</th>
<th>(Minimum Shear Strength)</th>
<th>(Per Document NAS1400, Table III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ftu</td>
<td>230 lbf</td>
<td>(Minimum Tensile Strength)</td>
<td>(Per Document NAS1400, Table IV)</td>
</tr>
</tbody>
</table>

Factors of Safety

<table>
<thead>
<tr>
<th>FSu</th>
<th>2</th>
<th>(Ultimate Factor of Safety)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSy</td>
<td>1.25</td>
<td>(Yield Factor of Safety)</td>
</tr>
<tr>
<td>FF</td>
<td>1.15</td>
<td>(Fitting Factor of Safety)</td>
</tr>
</tbody>
</table>

Temperature Data

<table>
<thead>
<tr>
<th>Temp_initial</th>
<th>70 deg</th>
<th>(Assembly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp_max</td>
<td>140 deg</td>
<td>(Maximum)</td>
</tr>
<tr>
<td>Temp_min</td>
<td>-76 deg</td>
<td>(Minimum)</td>
</tr>
</tbody>
</table>

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative
Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are \(-76^\circ F\) to \(140^\circ F\). These temperature reduction factors are conservative for liftoff/landing conditions.

\[ \beta_{u1} = 0.99 \]  
(Ultimate Temperature Reduction Factor)  
(Ref. MMPDS-03, Figure 3.2.3.1.4)

Allowable Stresses With Temperature Reduction Factor

\[ F_{su1.a} := \beta_{u1} \cdot F_{su} \]  
\[ F_{su1.a} = 489 \text{lbf} \]  
(Shear Strength Allowable)

\[ F_{tu1.a} := \beta_{u1} \cdot F_{tu} \]  
\[ F_{tu1.a} = 227.70 \text{lbf} \]  
(Tensile Strength Allowable)

Loads

\[ P := 33.3 \text{lbf} \]  
(Applied Tensile Load)  
(Worst Case Combination)

\[ V := 35.3 \text{lbf} \]  
(Applied Shear Load)

\[ M := 0 \text{in-lbf} \]  
(Applied Bending Moment)

Margin of Safety

\[ MS_{ult} := \frac{F_{tu1.a}}{FSu \cdot FF \cdot P} - 1 \]  
\[ MS_{ult} = 1.97 \]  
(Tensile Ultimate Margin of Safety)

\[ MS_{shear} := \frac{F_{su1.a}}{FSu \cdot FF \cdot V} - 1 \]  
\[ MS_{shear} = 5.02 \]  
(Shear Ultimate Margin of Safety)
Fail-Safe Analysis

Fail-Safe Loads

\[ P_{FS} := 2 \cdot P \]  
\( P_{FS} = 66.60 \text{lbf} \)

\[ V_{FS} := 2 \cdot V \]  
\( V_{FS} = 70.60 \text{lbf} \)

\[ M_{FS} := 0.0 \text{ in} \cdot \text{lbf} \]  
\( M_{FS} = 0.0 \text{ in} \cdot \text{lbf} \)

Fail-Safe Factors of Safety

\[ SFu_{FS} := 1.0 \]  
\( (\text{Ultimate}) \)

Fail-Safe Margin of Safety

\[ MS_{FS_{ult}} := \frac{F_{tu1.a}}{SFu_{FS} \cdot FF \cdot P_{FS}} - 1 \]  
\( MS_{FS_{ult}} = 1.97 \)  
\( (\text{Fail-Safe Tensile Ultimate Margin of Safety}) \)

\[ MS_{FS_{shear}} := \frac{F_{su1.a}}{SFu_{FS} \cdot FF \cdot V_{FS}} - 1 \]  
\( MS_{FS_{shear}} = 5.02 \)  
\( (\text{Fail-Safe Shear Ultimate Margin of Safety}) \)
5.10.3 TRD Gas Ballistic Cover Assembly and Bolt Analysis
## 5.10.3.1 TRD Gas Ballistic Cover Assembly Stress Report

### 5.10.3.1.1 Minimum Margins of Safety

#### Table 5.10.3.1.1 Parts Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLG39137916-503</td>
<td>TRD Gas Ballistic Cover Outer Skin</td>
<td>AL ALY 6061-T6</td>
<td>Landing</td>
<td>Shear Ultimate</td>
<td>0.50</td>
<td>5.10.3-18</td>
</tr>
<tr>
<td>SLG39137916-502</td>
<td>TRD Gas Ballistic Cover Inner Skin</td>
<td>AL ALY 6061-T6</td>
<td>Landing</td>
<td>Tensile Ultimate</td>
<td>5.98</td>
<td>5.10.3-21</td>
</tr>
<tr>
<td>SDG39137917-001</td>
<td>TRD Gas Ballistic Cover Standoff Bracket A</td>
<td>AL ALY 7075-T7351</td>
<td>Landing</td>
<td>Shear Ultimate</td>
<td>0.09</td>
<td>5.10.3-24</td>
</tr>
<tr>
<td>SDG39137918-001</td>
<td>TRD Gas Ballistic Cover Standoff Bracket B</td>
<td>AL ALY 7075-T7351</td>
<td>Landing</td>
<td>Tensile Ultimate</td>
<td>1.66</td>
<td>5.10.3-28</td>
</tr>
<tr>
<td>SDG39137927</td>
<td>TRD Gas Ballistic Cover Splice Plates</td>
<td>AL ALY 6061-T651</td>
<td>Landing</td>
<td>Tensile Yield</td>
<td>5.02</td>
<td>5.10.3-58</td>
</tr>
</tbody>
</table>

#### Table 5.10.3.1.2 Parts Minimum Margins of Safety, Fail-Safe

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLG39137916-503</td>
<td>TRD Gas Ballistic Cover Outer Skin</td>
<td>AL ALY 6061-T6</td>
<td>Landing</td>
<td>Tensile Yield</td>
<td>0.65</td>
<td>5.10.3-33</td>
</tr>
<tr>
<td>SLG39137916-502</td>
<td>TRD Gas Ballistic Cover Inner Skin</td>
<td>AL ALY 6061-T6</td>
<td>Landing</td>
<td>Tensile Yield</td>
<td>5.67</td>
<td>5.10.3-38</td>
</tr>
<tr>
<td>SDG39137917-001</td>
<td>TRD Gas Ballistic Cover Standoff Bracket A</td>
<td>AL ALY 7075-T7351</td>
<td>Landing</td>
<td>Tensile Yield</td>
<td>0.006</td>
<td>5.10.3-44</td>
</tr>
<tr>
<td>SDG39137918-001</td>
<td>TRD Gas Ballistic Cover Standoff Bracket B</td>
<td>AL ALY 7075-T7351</td>
<td>Landing</td>
<td>Tensile Ultimate</td>
<td>4.02</td>
<td>5.10.3-49</td>
</tr>
<tr>
<td>SDG39137927</td>
<td>TRD Gas Ballistic Cover Splice Plates</td>
<td>AL ALY 6061-T651</td>
<td>Landing</td>
<td>Tensile Yield</td>
<td>4.15</td>
<td>5.10.3-64</td>
</tr>
</tbody>
</table>

#### Table 5.10.3.1.3 Fastener Minimum Margins of Safety

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Fastener</th>
<th>Material</th>
<th>Failure Mode</th>
<th>MS_{nominal}</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39137917-001</td>
<td>Standoff Bracket A to Cover</td>
<td>NAS1351N3LB10 .1900-32</td>
<td>HRES A286</td>
<td>Total Tension Yield</td>
<td>0.95</td>
<td>5.10.3-80</td>
</tr>
<tr>
<td>SDG39137916-701</td>
<td>Standoff Bracket B to Cover</td>
<td>NAS1351N3LB10 .1900-32</td>
<td>HRES A286</td>
<td>Total Tension Yield</td>
<td>0.95</td>
<td>5.10.3-91</td>
</tr>
<tr>
<td>SDG39137917-001</td>
<td>Standoff Bracket A to Box S</td>
<td>NAS1351N3LB8 .1900-32</td>
<td>HRES A286</td>
<td>Total Tension Yield</td>
<td>0.16</td>
<td>5.10.3-101</td>
</tr>
<tr>
<td>SDG39137918-001</td>
<td>Box S to Standoff Bracket B</td>
<td>NAS1351N3LB10 .1900-32</td>
<td>HRES A286</td>
<td>Total Tension Yield</td>
<td>0.14</td>
<td>5.10.3-111</td>
</tr>
<tr>
<td>SEG39137926</td>
<td>Splice Plate to Outer Skin</td>
<td>NAS1398BFC6-3</td>
<td>AL</td>
<td>Shear Tear Out</td>
<td>3.73</td>
<td>5.10.3-120</td>
</tr>
<tr>
<td>Dwg/Part Number</td>
<td>Description</td>
<td>Fastener</td>
<td>Material</td>
<td>Failure Mode</td>
<td>MS_{fail-safe}</td>
<td>Reference Page</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------------</td>
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<td>----------------------------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>SDG39137917-001 SLG39137916-701</td>
<td>Standoff Bracket A to Cover</td>
<td>NAS1351N3LB10 .1900-32</td>
<td>HRES A286</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>1.60</td>
<td>5.10.3-81</td>
</tr>
<tr>
<td>SDG39137918-001 SLG39137916-701</td>
<td>Standoff Bracket B to Cover</td>
<td>NAS1351N3LB10 .1900-32</td>
<td>HRES A286</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>1.60</td>
<td>5.10.3-92</td>
</tr>
<tr>
<td>SDG39137917-001 SLG39137916-701</td>
<td>Standoff Bracket A to Box S</td>
<td>NAS1351N3LB8     .1900-32</td>
<td>HRES A286</td>
<td>Total Thread Shear Ultimate</td>
<td>0.41</td>
<td>5.10.3-102</td>
</tr>
<tr>
<td>SDG39137918-001 SLG39137916-701</td>
<td>Box S to Standoff Bracket B</td>
<td>NAS1351N3LB10 .1900-32</td>
<td>HRES A286</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.51</td>
<td>5.10.3-112</td>
</tr>
<tr>
<td>SEG39137926</td>
<td>Splice Plate to Outer Skin</td>
<td>NAS1398BFC6-3</td>
<td>AL</td>
<td>Shear Ultimate</td>
<td>18.63</td>
<td>5.10.3-118</td>
</tr>
</tbody>
</table>

**Notes:**
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Boundary conditions are at four AMS-02 bolts going into Box S.
3. 64 launch load cases, 64 landing load cases were applied.
4. Factors of Safety for Fail-Safe analysis are 1.0 for Ultimate and 1.0 for Yield.
5.10.3.2 Introduction

The TRD Gas Ballistic Cover Assy SEG39137915 provides shielding for the pressurized vessels on AMS-02 Transition Radiation Detector (TRD) tanks (Xenon, CO2 and Mixing) to prevent catastrophic rupture of these tanks in the event of MMOD impact which would release high-velocity fragments creating a potential hazard for the crew, Space Shuttle, and the International Space Station.

5.10.3.2.1 Structural Description

The TRD Gas Ballistic Cover Assembly consists of an AL Inner Skin brazed to an AL DUOCEL foam core. There is an AL Outer Skin that is not directly connected to the Core and Inner Skin. Rather, both the Inner Skin/Core and Outer Skin attach to the same Standoff Brackets. Figure 5.10.3.2-1 shows two side views of the Ballistic Cover Assembly.

![Figure 5.10.3.2-1](image)

The Outer Skin is formed out of folded sheet metal, starting at the top of the cover and folding the cut sides down. The adjacent free edges that constitute the seams, see red lines in Figure 5.10.3.2-2, are tack welded but are considered nonstructural. Eight Splice Plates hold the adjacent free edges in the Outer Skin together to ensure structural integrity.

![Figure 5.10.3.2-2](image)

Each Standoff Bracket attaches to the Ballistic Cover by (2) NAS 1351N3LB10 fasteners with NAS 1587A3C washers, going into SOS-032-16 Self Clinching Standoffs in the TRD Gas Ballistic Cover.
The TRD Gas Ballistic Cover, SLG39137915, Figure 5.10.3.2-1, is attached to Box S with (3) Standoff Bracket A, SDG39137917-001, and (1) Standoff Bracket B, SDG39137918-301, Figure 5.10.3.2-3. Standoff Bracket A attaches to Box S with one NAS1351N3LB8 .1900-32 fastener. Standoff Bracket B attaches to Box S with one NAS1351N3LB10 .1900-32 fastener. All 4 brackets are AL ALY 7075-T7351.

Figure 5.10.3.2-3   TRD Gas Ballistic Cover Standoff Bracket A (green) and Standoff Bracket B

5.10.3.2.2  Load Conditions

The stand-alone math model of the TRD Gas Ballistic Cover Assembly described in the previous sections was used to assess the structure for the Shuttle flight loads. An initial assessment was made using the secondary structure load factors provided in Table 5.10.3.2.1 Launch/Landing Design Limit Load Factors for Small Secondary Structures, of the AMS-02 Structural Verification Plan (JSC-28792, Rev. E). However, these loads are very conservative and the results of the analysis showed that the structural margins were unacceptable. The load factors are provided in Table 5.10.3.2.1   Launch/Landing Design Limit Load Factors for Small Secondary Structures for reference.

<table>
<thead>
<tr>
<th>Weight (pounds)</th>
<th>Load Factor (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>40</td>
</tr>
<tr>
<td>20-50</td>
<td>31</td>
</tr>
<tr>
<td>50-100</td>
<td>22</td>
</tr>
<tr>
<td>100-200</td>
<td>17</td>
</tr>
<tr>
<td>200-500</td>
<td>13</td>
</tr>
</tbody>
</table>

To reduce the conservatism for the flight loads assessment, the TRD Gas Ballistic Cover Assembly math model was integrated with the math model of the full AMS-02 payload. The liftoff and landing load factors from the AMS-02 design coupled loads analysis (as specified in Table 5-2 of the AMS-02 SVP) were applied to the integrated math model. These loads are provided in Table 5.10.3.2.2   Second DCLA Liftoff and Landing Load Factors for reference.

<table>
<thead>
<tr>
<th>Event</th>
<th>Nx</th>
<th>Ny</th>
<th>Nz</th>
<th>Rx</th>
<th>Ry</th>
<th>Rz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liftoff</td>
<td>-3.7  / 0.4</td>
<td>-1.4 / 1.6</td>
<td>-1.4 / 1.5</td>
<td>-4.5 / 4.1</td>
<td>-8.4 / 11.0</td>
<td>-3.9 / 4.1</td>
</tr>
<tr>
<td>Abort Landing</td>
<td>-1.2 / 1.3</td>
<td>-0.7 / 0.6</td>
<td>-2.1 / 5.6</td>
<td>-5.2 / 4.7</td>
<td>-10.7 / 13.9</td>
<td>-6.0 / 4.8</td>
</tr>
</tbody>
</table>

Static loads analyses were performed using NASTRAN with 64 subcases representing all combinations of the liftoff load factors and 64 subcases representing all combinations of the landing load factors. Loads, stresses, and other structural responses were recovered from this integrated analysis for the TRD Gas Ballistic Cover Assembly and used to compute the structural strength and Margins of Safety.
5.10.3.2.3 Factors of Safety

The hardware is designed with an Ultimate Factor of Safety of 2.0 and a Yield Factor of Safety of 1.25 against limit loads per JSC-28792, Rev. D Alpha Magnetic Spectrometer -02 Structural Verification Plan for the Space Transportation System and the International Space Station.

5.10.3.2.4 Materials and Temperature

5.10.3.2.4.1 Table of Material Allowables

The materials, and their allowables, used in the TRD Gas Ballistic Cover Assembly are shown in Table 5.10.3.2.3 Material Allowables.

<table>
<thead>
<tr>
<th>Dwg/Part Number</th>
<th>Description</th>
<th>Material</th>
<th>Allowables</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLG39137916-501</td>
<td>TRD Gas Ballistic Cover Core</td>
<td>DUOCEL AL Foam 6101-T6, 10 PPI, 6-8% Relative Density</td>
<td>At 0.410in thick, the Core is treated as non-structural mass</td>
</tr>
<tr>
<td>SLG39137916-502</td>
<td>TRD Gas Ballistic Cover Inner Skin</td>
<td>AL ALY 6061-T6 SAE-AMS-4027</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
<tr>
<td>SLG39137916-503</td>
<td>TRD Gas Ballistic Cover Outer Skin</td>
<td>AL ALY 6061-T6 SAE-AMS-4027</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
<tr>
<td>SDG39137917-001</td>
<td>TRD Gas Ballistic Cover Standoff Bracket A</td>
<td>AL ALY 7075-T7351 AMS-QQ-A-250/12</td>
<td>$F_{tu} = 68000$ psi $F_{ty} = 57000$ psi $F_{su} = 38000$ psi</td>
</tr>
<tr>
<td>SDG39137918-001</td>
<td>TRD Gas Ballistic Cover Standoff Bracket B</td>
<td>AL ALY 7075-T7351 AMS-QQ-A-250/12</td>
<td>$F_{tu} = 68000$ psi $F_{ty} = 57000$ psi $F_{su} = 38000$ psi</td>
</tr>
<tr>
<td>SDG39137927-001</td>
<td>TRD Gas Ballistic Cover Splice Plate A</td>
<td>AL ALY 6061-T651 AMS-QQ-A-250/11</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
<tr>
<td>SDG39137928-001</td>
<td>TRD Gas Ballistic Cover Splice Plate A</td>
<td>AL ALY 6061-T651 AMS-QQ-A-250/11</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
<tr>
<td>SDG39137929-001</td>
<td>TRD Gas Ballistic Cover Splice Plate A</td>
<td>AL ALY 6061-T651 AMS-QQ-A-250/11</td>
<td>$F_{tu} = 42000$ psi $F_{ty} = 36000$ psi $F_{su} = 27000$ psi</td>
</tr>
</tbody>
</table>

5.10.3.2.4.2 Temperature Degradation

The temperature extremes are -76°F to 140°F.
5.10.3.3 Description of the TRD Gas Ballistic Cover Assy FEM

FEMAP modeling software was used to generate a finite element model of the TRD Gas Ballistic Cover Assembly for structural analysis using NASTRAN.

1. The geometry of each part was identified by a CAD model (Parasolid format) that was provided by the design group. This geometry was used as the basis for generating the finite element mesh.
2. The Core, Inner Skin, Outer Skin, and Standoff Bracket A are modeled using plate elements (CQUAD4 and CTRIA3).
3. The Core and Inner Skin are represented as Ply2 and Ply1 respectively in a composite (PCOMP).
4. Standoff Bracket B is modeled with solid elements (CTETRA).
5. The Standoff Bracket A to Cover and the Standoff Bracket B to Cover fasteners are represented by CBUSH elements with stiffness values for the three translation directions that represent axial and shear stiffness.
6. The TRD Gas Ballistic Cover model is integrated with the USS model.
7. MSC/NASTRAN v.2005 is used as a solver for analyzing the math model.
8. NASPOST is used to sort the maximum absolute value of Principal, Von-Mises, and Shear, for Composite Ply stresses, CQUAD4 stresses, and CTETRA stresses; and the maximum absolute value of axial and shear for CBUSH forces.

5.10.3.3.1 Description of the TRD Gas Ballistic Cover Assy FEM

The FEM of the TRD Gas Ballistic Cover assembly was attached to the integrated loads model at the 4 attachment points to Box S. The attachments between the Standoff Brackets and the TRD Gas Ballistic Cover are represented by Spider RBE3's (with the center dependent node given 6 DOF T1 T2 T3 R1 R2 R3, and the outer independent nodes given T1 T2 T3) in the fastener holes of each flange, connected by CBUSH elements. The fastener loads between the Standoff Brackets and Cover are recovered as CBUSH Forces.

The largest absolute CBUSH Axial (P) load and the largest absolute CBUSH Total Shear (V) load, are enveloped across all 4 Standoff Brackets, for all load cases, and then used to calculate the Margins of Safety for the joints.

For Fail-Safe Analysis, two separate scenarios were analyzed. The first scenario assumed one of the Outer Skin Splice Plates failed (was removed). The second assumed one of the Standoff Bracket to Box S attachments failed. Both scenarios were run for all Landing and Liftoff conditions. The worst case Axial and Total Shear loads were then used to calculate the Fail-Safe Margins of Safety for the joints.

5.10.3.3.2 Description of the Integrated TRD Gas Ballistic Cover Assy and Full Payload FEM

The high-fidelity finite element model of the TRD Gas Ballistic Cover Assembly was integrated with the finite element model of the full payload. The full model consisted of the standard 2-07 loads model components plus high-fidelity models of Interface Panel A, the Starboard debris shield, and the outer Port debris shield for the TRD Gas Supply. The math model of the USS was modified to provide attachment points for these high-fidelity stress models.

The detailed stress-model of the TRD Gas Ballistic Cover Assembly was attached to the base plate of the TRD Gas Supply (Box S) using CBUSH elements. Views of the full payload math model are shown below with various depictions of the debris shield.

A summary from NASTRAN of the finite elements comprising the model is provided below.
### Table: Model Summary

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF CBAR</td>
<td>22421</td>
</tr>
<tr>
<td>NUMBER OF CBEAM</td>
<td>15158</td>
</tr>
<tr>
<td>NUMBER OF CBUSH</td>
<td>3023</td>
</tr>
<tr>
<td>NUMBER OF CHEXA</td>
<td>1640</td>
</tr>
<tr>
<td>NUMBER OF CONN2</td>
<td>1619</td>
</tr>
<tr>
<td>NUMBER OF CPENTA</td>
<td>176</td>
</tr>
<tr>
<td>NUMBER OF CQUAD4</td>
<td>191405</td>
</tr>
<tr>
<td>NUMBER OF CROD</td>
<td>42</td>
</tr>
<tr>
<td>NUMBER OF CTETRA</td>
<td>9864</td>
</tr>
<tr>
<td>NUMBER OF CTRIA3</td>
<td>15241</td>
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<tr>
<td>NUMBER OF RBE2</td>
<td>11474</td>
</tr>
<tr>
<td>NUMBER OF RBE3</td>
<td>210</td>
</tr>
</tbody>
</table>

---

**Figure 5.10.3.3-1** View of full payload showing Port debris shield covering outer side of TRD Gas Supply

**Figure 5.10.3.3-2** View of full payload with Port debris shield covering outer side of TRD Gas Supply removed for clarity

- **Outer debris shield**
- **Inner debris shield**
Figure 5.10.3.3-3  Isolated View of TRD Gas Ballistic Cover Assembly for the TRD Gas Supply (surrounding structure removed for clarity)

Figure 5.10.3.3-4  Isolated View of TRD Gas Ballistic Cover Assembly for the TRD Gas Supply (surrounding structure removed for clarity)
5.10.3.3.3 Checks for the Integrated TRD Gas Ballistic Cover Assy and Full Payload FEM

5.10.3.3.3.1 Constrained

Constraint and Grounding Checks

Constraint and grounding checks were performed using MSC NASTRAN. The results of these checks are shown below for the unconstrained and constrained models. The model passes the checks at all degree-of-freedom set levels with sufficiently low strain energy to indicate that there are no unintended constraints or grounding issues.

```
$ cat ds-trd-gas-inner-modes-20.txt

RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.417700E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>9.929751E-07</td>
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</tr>
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<td>3</td>
<td>3.02383E-06</td>
<td>PASS</td>
</tr>
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<td>4</td>
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<td>PASS</td>
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<td>5</td>
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<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>1.930375E-04</td>
<td>PASS</td>
</tr>
</tbody>
</table>

RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:

<table>
<thead>
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<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>7.619799E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>8.710456E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>2.812508E-06</td>
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<td>3.500685E-03</td>
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</tr>
<tr>
<td>5</td>
<td>2.335165E-03</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.201617E-03</td>
<td>PASS</td>
</tr>
</tbody>
</table>

RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET) FOLLOW:

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.412554E+06</td>
<td>FAIL</td>
</tr>
<tr>
<td>2</td>
<td>1.104724E+06</td>
<td>FAIL</td>
</tr>
<tr>
<td>3</td>
<td>1.282511E+07</td>
<td>FAIL</td>
</tr>
<tr>
<td>4</td>
<td>1.207519E+11</td>
<td>FAIL</td>
</tr>
<tr>
<td>5</td>
<td>2.475778E+10</td>
<td>FAIL</td>
</tr>
<tr>
<td>6</td>
<td>5.753186E+10</td>
<td>FAIL</td>
</tr>
</tbody>
</table>

RESULTS OF RIGID BODY CHECKS OF MATRIX KAA (A-SET) FOLLOW:

<table>
<thead>
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<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.412554E+06</td>
<td>FAIL</td>
</tr>
<tr>
<td>2</td>
<td>1.104724E+06</td>
<td>FAIL</td>
</tr>
<tr>
<td>3</td>
<td>1.282511E+07</td>
<td>FAIL</td>
</tr>
<tr>
<td>4</td>
<td>1.207519E+11</td>
<td>FAIL</td>
</tr>
<tr>
<td>5</td>
<td>2.475778E+10</td>
<td>FAIL</td>
</tr>
<tr>
<td>6</td>
<td>5.753186E+10</td>
<td>FAIL</td>
</tr>
</tbody>
</table>
```
Mass Properties Check

The weight of the integrated system math model is 15190 pounds. This is a conservative (slightly greater than the budget) weight for analysis purposes and can not be verified at the present time because assembly of the payload flight article is not complete. The mass properties for the integrated math model are shown below as computed by NASTRAN.

**Modal Check**

A model analysis was performed using NASTRAN to determine the modal frequencies of the constrained system to verify that there are no mechanisms or other unexpected low-frequency modes. A modal analysis of the unconstrained system was also performed to confirm that the model has appropriate rigid-
body modes. Lists of the modes for the unconstrained and constrained configurations are provided on the next two pages.

Excerpt from the NASTRAN f06 file showing the modal frequencies for the constrained system model:

<table>
<thead>
<tr>
<th>MODE EXTR. ORDER</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>REAL EIGENVALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5.690311e+02</td>
<td>2.385437e-01</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>6.832136e+02</td>
<td>2.613840e-01</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>6.895743e+02</td>
<td>2.625975e-01</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>1.003018e+03</td>
<td>3.167046e-01</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>1.174660e+03</td>
<td>3.427332e-01</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>1.600173e+03</td>
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<tr>
<td>1</td>
<td>7</td>
<td>3.575692e+03</td>
<td>9.517002e+01</td>
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<tr>
<td>1</td>
<td>8</td>
<td>5.337512e+03</td>
<td>7.305827e+01</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>5.632689e+03</td>
<td>7.505124e+01</td>
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<tr>
<td>1</td>
<td>10</td>
<td>6.464812e+03</td>
<td>8.040405e+01</td>
</tr>
</tbody>
</table>

5.10.3.3.2 Free-Free

Constraint and Grounding Check

Mass Properties Check

The weight of the integrated system math model is 15190 pounds. This is a conservative (slightly greater than the budget) weight for analysis purposes and can not be verified at the present time because assembly of the payload flight article is not complete. The mass properties for the integrated math model are shown below as computed by NASTRAN.
Modal Check

A model analysis was performed using NASTRAN to determine the modal frequencies of the constrained system to verify that there are no mechanisms or other unexpected low-frequency modes. A modal analysis of the unconstrained system was also performed to confirm that the model has appropriate rigid-body modes. Lists of the modes for the unconstrained and constrained configurations are provided on the next two pages.

Excerpt from the NASTRAN f06 file showing the modal frequencies for the constrained system model:

```
CHECKS OF FULL SYSTEM WITH TRD GAS-SUPPLY DEBRIS SHIELD FEBRUARY 9, 2009 MSC.NASTRAN 6/17/05 PAGE 286
MODE EXTRATION EIGENVALE REAL EIGENVALUES
NO. ORDER RADIANS CYCLES GENERALIZED MASS GENERALIZED STIFFNESS
1 1 1.683914E-07 4.103532E-04 6.531005E-05 1.000000E+00 1.683914E-07
2 2 2.611013E-07 5.109807E-04 8.132510E-05 1.000000E+00 2.611013E-07
3 3 3.471296E-07 5.891771E-04 9.377044E-04 1.000000E+00 3.471296E-07
4 4 4.002902E-07 6.326850E-04 1.000000E+00 4.002902E-07
5 5 1.056261E-06 1.027745E-03 1.635708E-04 1.000000E+00 1.056261E-06
6 6 1.291598E-06 1.364853E-03 1.808772E-04 1.000000E+00 1.291598E-06
7 7 6.922528E-06 1.817478E-03 1.817478E-04 1.000000E+00 6.922528E-06
8 8 1.031431E-03 3.211590E-01 5.111404E-00 1.000000E+00 1.031431E-03
9 9 1.036418E-03 3.219344E-01 5.123745E-00 1.000000E+00 1.036418E-03
10 10 1.124062E-03 3.553642E-01 5.337487E-00 1.000000E+00 1.124062E-03
```

5.10.3.3.4 Mass Properties Check of the TRD Gas Ballistic Cover Assy

Since the TRD Gas Ballistic Cover Assembly was run integrated with the full payload model, the NASTRAN mass properties check is of the total mass of the integrated model. The TRD Gas Ballistic
Cover Assembly is a small portion. So, using FEMAP, a mass properties check was performed on just the TRD Gas Ballistic Cover Assembly.

Using FEMAP 9.3.1 > Tools > Mass Properties > Mesh Properties, the TRD Gas Ballistic Cover Assembly FEM has a mass of 0.0242424 lbf-s²/in or a weight of 9.360 lbf.

FEMAP: Check Mass Properties for ds-trd-gas-inner-css-v20.MOD
126367 Element(s) Selected...

<table>
<thead>
<tr>
<th>Mass</th>
<th>Center of Gravity in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>0.0242424 x= 29.91607 y= 54.50499 z= 398.4029</td>
</tr>
<tr>
<td>NonStructural</td>
<td>0. x= 0. y= 0. z= 0.</td>
</tr>
<tr>
<td>Total Mass</td>
<td>0.0242424 x= 29.91607 y= 54.50499 z= 398.4029</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inertias about CSys 0</th>
<th>Inertias about C.G. in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ixx = 3922.727 Ixy= 39.50089 Ixz = 2.833514 Ixy= -0.0281794</td>
<td></td>
</tr>
<tr>
<td>Iyy = 3872.006 Iyz = 526.4195 Iyy = 2.435502 Iyz = -3.2034E-3</td>
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</tr>
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<td>Izz = 94.49491 Izz = 288.8637 Izz = 0.779443 Izz = -0.07308</td>
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</tr>
</tbody>
</table>

Total Length (Line Elements only) = 9.497021
Total Area (Area Elements only) = 1634.473
Total Volume (All Elements) = 407.6413

5.10.3.4 Detailed Stress Analysis

The critical stresses for all components of the TRD Gas Ballistic Cover Assembly are compared to the Ultimate and Yield strength of the Aluminum Alloy. Fastener, bearing, and tear-out analysis is performed for all mechanically fastened joints. All margins of safety are positive.

The minimum Margins of Safety Summary are shown in Table 5.10.3.1.1 Parts Minimum Margins of Safety, Table 5.10.3.1.3 Fastener Minimum Margins of Safety, and Table 5.10.3.1.4 Fastener Minimum Margins of Safety.
CHECK OF TRD GAS BALLISTIC COVER ASSEMBLY, SEG39137915

TRD Gas Ballistic Cover - Outer Skin, SLG39137916-503

Allowables

Material Properties

\[
\text{AL ALY 6061-T6, SAE-AMS-4027, Sheet, 0.010-0.249, A}
\]

\[
F_u := 42000 \text{ psi} \quad \text{(Ref. MMPDS-04, Table 3.6.2.0(b1))}
\]

\[
F_y := 36000 \text{ psi}
\]

\[
F_s := 27000 \text{ psi}
\]

Factors of Safety

\[
F_{S_u} := 2.0 \quad F_{S_y} := 1.25
\]

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76 °F to +140 °F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 °F:

- Ultimate:
  \[
  \beta_u := 0.96 \quad \text{(Ref. MMPDS-04, Figure 3.6.2.2.1(a))}
  \]

- Yield:
  \[
  \beta_y := 0.96 \quad \text{(Ref. MMPDS-04, Figure 3.6.2.2.1(b))}
  \]

Allowable Stresses

\[
F_{tug} := \beta_u \cdot F_u \quad F_{tug} = 40320 \text{ psi}
\]

\[
F_{tyg} := \beta_y \cdot F_y \quad F_{tyg} = 34560 \text{ psi}
\]

\[
F_{sug} := \beta_u \cdot F_s \quad F_{sug} = 25920 \text{ psi}
\]
TRD Gas Ballistic Cover - Outer Skin, SLG39137916-503

Omitted Elements

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Skin representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3's, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

excluded 1 row of elements around holes
TRD Gas Ballistic Cover - Outer Skin, SLG39137916-503

Liftoff

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff.pch"

Maximum Stresses

\[
\begin{align*}
  \sigma_{tu} &= 5.755 \times 10^3 \text{ psi} \\
  \sigma_{ty} &= 7.056 \times 10^3 \text{ psi} \\
  \tau_{su} &= 4.021 \times 10^3 \text{ psi}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
  MS_{tug} &= \frac{F_{tug}}{FS_u \cdot \sigma_{tu}} - 1 \\
  MS_{tyg} &= \frac{F_{tyg}}{FS_y \cdot \sigma_{ty}} - 1 \\
  MS_{sug} &= \frac{F_{sug}}{FS_u \cdot \tau_{su}} - 1
\end{align*}
\]

\[
\begin{align*}
  MS_{tug} &= 2.503 \quad \text{... Margin of Safety Tensile Ultimate} \\
  MS_{tyg} &= 2.92 \quad \text{... Margin of Safety Tensile Yield} \\
  MS_{sug} &= 2.22 \quad \text{... Margin of Safety Shear Ultimate}
\end{align*}
\]
TRD Gas Ballistic Cover - Outer Skin, SLG39137916-503

Landing

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing.pch"

Maximum Stresses

\[ u_{tu} := 1.234 \times 10^4 \text{ psi} \]
\[ u_{ty} := 1.492 \times 10^4 \text{ psi} \]
\[ u_{su} := 8.616 \times 10^3 \text{ psi} \]

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \quad MS_{tug} = 0.634 \quad \text{... Margin of Safety Tensile Ultimate} \]
\[ MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1 \quad MS_{tyg} = 0.85 \quad \text{... Margin of Safety Tensile Yield} \]
\[ MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1 \quad MS_{sug} = 0.50 \quad \text{... Margin of Safety Shear Ultimate} \]
TRD Gas Ballistic Cover - Inner Skin, SLG39137916-502

Omitted Elements

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Skin representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3’s, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

Excluded one row of elements around holes
TRD Gas Ballistic Cover - Inner Skin, SLG39137916-502

Liftoff

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: “ds-trd-gas-inner-liftoff.pch”

Maximum Stresses

<table>
<thead>
<tr>
<th>Laminate: MaxABSPrin Stress -</th>
<th>Laminate: Max Von-Mises Stress -</th>
<th>Laminate: Max Shear Stress -</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>SUBCASE</td>
<td>IPLY</td>
</tr>
<tr>
<td>u_{tu} := 2.32 \times 10^3 \text{ psi}</td>
<td>6534361</td>
<td>1026</td>
</tr>
<tr>
<td>u_{ty} := 2.158 \times 10^3 \text{ psi}</td>
<td>6534361</td>
<td>1026</td>
</tr>
<tr>
<td>u_{su} := 1.16 \times 10^3 \text{ psi}</td>
<td>6534361</td>
<td>1026</td>
</tr>
</tbody>
</table>

Margins of Safety

\[ \text{MS}_{tu} := \frac{F_{tu}}{FS_u \cdot u_{tu}} - 1 \quad \text{MS}_{tu} = 7.690 \quad \text{... Margin of Safety Tensile Ultimate} \]

\[ \text{MS}_{ty} := \frac{F_{ty}}{FS_y \cdot u_{ty}} - 1 \quad \text{MS}_{ty} = 11.81 \quad \text{... Margin of Safety Tensile Yield} \]

\[ \text{MS}_{su} := \frac{F_{su}}{FS_u \cdot u_{su}} - 1 \quad \text{MS}_{su} = 10.17 \quad \text{... Margin of Safety Shear Ultimate} \]
TRD Gas Ballistic Cover - Inner Skin, SLG39137916-502

Landing

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing.pch"

Maximum Stresses

<table>
<thead>
<tr>
<th>Laminate: MaxABSPrin Stress -</th>
<th>LAMINATE</th>
<th>SUBCASE</th>
<th>IP/PLY</th>
<th>MAXABSPRIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1NASMINPRIN</td>
<td>1NORMAL-1</td>
<td>1NORMAL-2</td>
<td>1MAJOR</td>
</tr>
<tr>
<td>tu := 2.89 × 10^3 psi</td>
<td>6525696</td>
<td>2030</td>
<td>1.000000E+00</td>
<td>2.889582E+03</td>
</tr>
<tr>
<td></td>
<td>2.166046E+02</td>
<td>2.492209E+03</td>
<td>6.139689E+02</td>
<td>9.509176E+02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laminate: Max Von-Mises Stress -</th>
<th>LAMINATE</th>
<th>SUBCASE</th>
<th>IP/PLY</th>
<th>VONMISES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ty := 3.13 × 10^3 psi</td>
<td>6549540</td>
<td>2030</td>
<td>1.000000E+00</td>
<td>3.130455E+03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laminate: Max Shear Stress -</th>
<th>LAMINATE</th>
<th>SUBCASE</th>
<th>IP/PLY</th>
<th>MAX-SHEAR</th>
<th>NASMAXSHEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>su := 1.787 × 10^3 psi</td>
<td>6549540</td>
<td>2014</td>
<td>1.000000E+00</td>
<td>1.786832E+03</td>
<td>1.785356E+03</td>
</tr>
</tbody>
</table>

Margins of Safety

\[
MS_{tu} := \frac{F_{tu}}{FS_u \cdot tu} - 1
\]

\[
MS_{ty} := \frac{F_{ty}}{FS_y \cdot ty} - 1
\]

\[
MS_{su} := \frac{F_{su}}{FS_u \cdot su} - 1
\]

**... Margin of Safety Tensile Ultimate**

\[
MS_{tu} = 5.976
\]

\[
MS_{ty} = 7.83
\]

\[
MS_{su} = 6.25
\]

**... Margin of Safety Tensile Yield**

**... Margin of Safety Shear Ultimate**
Standoff Bracket A, SDG39137917-001

Allowables

Material Properties

<table>
<thead>
<tr>
<th>AL ALY 7075-T7351, AMS-QQ-A-250/12, Plate, 0.500-1.000, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{tu} := 68000 \text{ psi}$ (Ref. MMPDS-04 Table 3.7.7.0(b4))</td>
</tr>
<tr>
<td>$F_{ty} := 57000 \text{ psi}$</td>
</tr>
<tr>
<td>$F_{su} := 38000 \text{ psi}$</td>
</tr>
</tbody>
</table>

Factors of Safety

| $F_{Su} := 2.0$ | $F_{Sy} := 1.25$ |

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76 °F to +140 °F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 °F:

- Ultimate: $\beta_u := 0.96$ (Ref. MMPDS-04, Figure 3.7.7.1.1(c))
- Yield: $\beta_y := 0.96$ (Ref. MMPDS-04, Figure 3.7.7.1.1(d))

Allowable Stresses

<table>
<thead>
<tr>
<th>$F_{lug} := \beta_u \cdot F_{tu}$</th>
<th>$F_{lug} = 65280 \text{ psi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{lyg} := \beta_y \cdot F_{ty}$</td>
<td>$F_{lyg} = 54720 \text{ psi}$</td>
</tr>
<tr>
<td>$F_{sug} := \beta_u \cdot F_{su}$</td>
<td>$F_{sug} = 36480 \text{ psi}$</td>
</tr>
</tbody>
</table>
**Standoff Bracket A, SDG39137917-001**

**Omitted Elements**

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Bracket representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3’s, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

1 to 2 rows of elements around a hole were excluded
Standoff Bracket A, SDG39137917-001

Landing

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-inner-landing.pch"

Maximum Stresses

CQuad4s: Max ABS Principal Stress - SB A's
ID SUBCASE MAXABS-PRIN-M MAX-PRIN-TOP- MIN-PRIN-TOP- MAX-PRIN-BOT- MIN-PRIN-BOT-
6300017 2014 2.961541E+04 2.909306E+04 -2.774425E+03 2.909117E+03 -2.961541E+04

CQuad4s: Max ABS Von-Mises Stress - SB A's
ID SUBCASE MAXABS-VON-MI VON-MISES-TOP VON-MISES-BOT
6300017 2014 3.117194E+04 3.057483E+04 3.117194E+04

CQuad4s: Max ABS Shear Stress - SB A's
ID SUBCASE MAXABS-SHR-M MAX-SHEAR-TOP MAX-SHEAR-BOT
6300067 2013 1.676620E+04 1.676620E+04 1.621514E+04

Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{FS_{u \cdot tu}} - 1 \]
\[ MS_{ty} := \frac{F_{ty}}{FS_{y \cdot ty}} - 1 \]
\[ MS_{su} := \frac{F_{su}}{FS_{u \cdot su}} - 1 \]

\[ MS_{tu} = 0.102 \] ... Margin of Safety Tensile Ultimate

\[ MS_{ty} = 0.4 \] ... Margin of Safety Tensile Yield

\[ MS_{su} = 0.09 \] ... Margin of Safety Shear Ultimate
Standoff Bracket A, SDG39137917-001

Liftoff

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: “ds-trd-gas-inner-liftoff.pch”

Maximum Stresses

\[
\begin{align*}
u_{tug} & := 1.666 \times 10^4 \text{ psi} \\
u_{tyg} & := 1.726 \times 10^4 \text{ psi} \\
u_{sug} & := 8.918 \times 10^3 \text{ psi}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
\text{MS}_{tug} & := \frac{F_{tug}}{F_{Su} \cdot u_{tug}} - 1 & \text{MS}_{tug} = 0.959 & \text{... Margin of Safety Tensile Ultimate} \\
\text{MS}_{tyg} & := \frac{F_{tyg}}{F_{Sy} \cdot u_{tyg}} - 1 & \text{MS}_{tyg} = 1.54 & \text{... Margin of Safety Tensile Yield} \\
\text{MS}_{sug} & := \frac{F_{sug}}{F_{Su} \cdot u_{sug}} - 1 & \text{MS}_{sug} = 1.05 & \text{... Margin of Safety Shear Ultimate}
\end{align*}
\]
Standoff Bracket B, SDG39137918-001

Allowables

Material Properties

<table>
<thead>
<tr>
<th>AL ALY 7075-T7351, AMS-QQ-A-250/12, Plate, 0.500-1.000, A</th>
</tr>
</thead>
</table>

\[ F_{tu} := 68000 \text{ psi} \]  
\[ F_{ty} := 57000 \text{ psi} \]  
\[ F_{su} := 38000 \text{ psi} \]  

(Ref. MMPDS-04 Table 3.7.7.0(b4))

Factors of Safety

\[ FS_u := 2.0 \]  
\[ FS_y := 1.25 \]

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76 °F to +140 °F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 °F:

- Ultimate:  
  \[ \beta_u := 0.96 \]  
  (Ref. MMPDS-04, Figure 3.7.7.1.1(c))

- Yield:  
  \[ \beta_y := 0.96 \]  
  (Ref. MMPDS-04, Figure 3.7.7.1.1(d))

Allowable Stresses

\[ F_{tug} := \beta_u \cdot F_{tu} \]  
\[ F_{tug} = 65280 \text{ psi} \]

\[ F_{tyg} := \beta_y \cdot F_{ty} \]  
\[ F_{tyg} = 54720 \text{ psi} \]

\[ F_{sug} := \beta_u \cdot F_{su} \]  
\[ F_{sug} = 36480 \text{ psi} \]
Omitted Elements

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Bracket representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3's, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

5.10.3-27 ESCG-4005-05-AMS-0039
Standoff Bracket B, SDG39137918-001

Landing

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: “ds-trd-gas-inner-landing.pch”

Maximum Stresses

\[ u_{tu} := 1.229 \times 10^4 \text{ psi} \]

\[ u_{ty} := 1.103 \times 10^4 \text{ psi} \]

\[ u_{su} := 6.317 \times 10^3 \text{ psi} \]

Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{FS_u \cdot u_{tu}} - 1 \quad \text{MS}_{tu} = 1.656 \quad \text{Margin of Safety Tensile Ultimate} \]

\[ MS_{ty} := \frac{F_{ty}}{FS_y \cdot u_{ty}} - 1 \quad \text{MS}_{ty} = 2.97 \quad \text{Margin of Safety Tensile Yield} \]

\[ MS_{su} := \frac{F_{su}}{FS_u \cdot u_{su}} - 1 \quad \text{MS}_{su} = 1.89 \quad \text{Margin of Safety Shear Ultimate} \]
Standoff Bracket B, SDG39137918-001

**Liftoff**

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff.pch"

**Maximum Stresses**

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>NO_LABEL</th>
<th>MAX-MAX-PRIN</th>
<th>MAX-MIN-PRIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>6703546</td>
<td>1030</td>
<td></td>
<td>7.054525E+03</td>
<td>2.788419E+03</td>
</tr>
</tbody>
</table>

\[ u_{tu} := 7.055 \times 10^3 \text{ psi} \]

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>NO_LABEL</th>
<th>MAX-VONM</th>
</tr>
</thead>
<tbody>
<tr>
<td>6701935</td>
<td>1030</td>
<td></td>
<td>5.422713E+03</td>
</tr>
</tbody>
</table>

\[ u_{ty} := 5.423 \times 10^3 \text{ psi} \]

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>NO_LABEL</th>
<th>MAX-MAX-SHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6701935</td>
<td>1030</td>
<td></td>
<td>3.128141E+03</td>
</tr>
</tbody>
</table>

\[ u_{su} := 3.128 \times 10^3 \text{ psi} \]

**Margins of Safety**

\[ MS_{tu} := \frac{F_{tu}}{FS_{u} \cdot u_{tu}} - 1 \]

\[ MS_{ty} := \frac{F_{ty}}{FS_{y} \cdot u_{ty}} - 1 \]

\[ MS_{su} := \frac{F_{su}}{FS_{u} \cdot u_{su}} - 1 \]

\[ MS_{tu} = 3.627 \quad ... \text{Margin of Safety Tensile Ultimate} \]

\[ MS_{ty} = 7.07 \quad ... \text{Margin of Safety Tensile Yield} \]

\[ MS_{su} = 4.83 \quad ... \text{Margin of Safety Shear Ultimate} \]
CHECK OF TRD GAS BALLISTIC COVER ASSEMBLY, SEG39137915

TRD Gas Ballistic Cover - Outer Skin SLG39137916-503, Fail-Safe

**Allowables**

**Material Properties**

\[
\begin{align*}
\text{AL ALY 6061-T6, SAE-AMS-4027, Sheet, 0.010-0.249, A} \\
F_{tu} & := 42000 \text{ psi} \\
F_{ty} & := 36000 \text{ psi} \\
F_{su} & := 27000 \text{ psi}
\end{align*}
\]

(Ref. MMPDS-04, Table 3.6.2.0(b1))

**Factors of Safety**

\[
\begin{align*}
FS_u & := 1.0 \\
FS_y & := 1.0
\end{align*}
\]

**Temperature Reduction Factors**

**Note:** For the Debris Shield, the temperature extremes are -76 \(^{\circ}\)F to +140 \(^{\circ}\)F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 \(^{\circ}\)F:

- Ultimate: \[ \beta_u := 0.96 \] (Ref. MMPDS-04, Figure 3.6.2.2.1(a))
- Yield: \[ \beta_y := 0.96 \] (Ref. MMPDS-04, Figure 3.6.2.2.1(b))

**Allowable Stresses**

\[
\begin{align*}
F_{tug} & := \beta_u \cdot F_{tu} \\
F_{tug} & := 40320 \text{ psi} \\
F_{tyg} & := \beta_y \cdot F_{ty} \\
F_{tyg} & := 34560 \text{ psi} \\
F_{sug} & := \beta_u \cdot F_{su} \\
F_{sug} & := 25920 \text{ psi}
\end{align*}
\]
TRD Gas Ballistic Cover - Outer Skin SLG39137916-503, Fail-Safe

Omitted Elements

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Skin representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3’s, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

excluded 1 row of elements around holes
Maximum Stresses

TRD Gas Ballistic Cover - Outer Skin SLG39137916-503, Fail-Safe

Landing, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-21.pch"

Maximum Stresses

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>MAXABS-PRIN-M</th>
<th>MAX-PRIN-TOP</th>
<th>MIN-PRIN-TOP</th>
<th>MAX-PRIN-BOT</th>
<th>MIN-PRIN-BOT</th>
<th>MAX-PRIN-BOT</th>
<th>MIN-PRIN-BOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>6648763</td>
<td>2030</td>
<td>1.283763×10^4</td>
<td>1.246252×10^4</td>
<td>1.674976×10^3</td>
<td>6.729791×10^3</td>
<td>1.283763×10^4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CQuad4s: Max ABS Principal Stress - Outer Skin


**u_{tu} := 1.284 \times 10^4 \text{ psi}**

**u_{ty} := 1.46 \times 10^4 \text{ psi}**

**u_{su} := 8.421 \times 10^3 \text{ psi}**

Margins of Safety

\[
MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1
\]

\[
MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1
\]

\[
MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1
\]

**MS_{tug} = 2.140**  ... Margin of Safety Tensile Ultimate

**MS_{tyg} = 1.37**  ... Margin of Safety Tensile Yield

**MS_{sug} = 2.08**  ... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Outer Skin SLG39137916-503, Fail-Safe

Landing, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-22.pch"

Maximum Stresses

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6648763</td>
<td>2030</td>
<td>1.842702E+04</td>
<td>1.781990E+04</td>
<td>-9.871152E+03</td>
<td>1.011868E+04</td>
<td>-1.842702E+04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6648759</td>
<td>2030</td>
<td>2.098432E+04</td>
<td>2.098432E+04</td>
<td>2.060351E+04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\sigma_{tu} & := 1.843 \times 10^4 \text{ psi} \\
\sigma_{ty} & := 2.098 \times 10^4 \text{ psi} \\
\sigma_{su} & := 1.209 \times 10^4 \text{ psi}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
MS_{tu} & := \frac{F_{tug}}{FS_{u-tu}} - 1 \\
MS_{ty} & := \frac{F_{tyg}}{FS_{y-ty}} - 1 \\
MS_{su} & := \frac{F_{sug}}{FS_{u-su}} - 1
\end{align*}
\]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( MS_{tu} )</td>
<td>( 1.188 )</td>
</tr>
<tr>
<td>( MS_{ty} )</td>
<td>( 0.65 )</td>
</tr>
<tr>
<td>( MS_{su} )</td>
<td>( 1.14 )</td>
</tr>
</tbody>
</table>

... Margin of Safety Tensile Ultimate

... Margin of Safety Tensile Yield

... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Outer Skin SLG39137916-503, Fail-Safe

Liftoff, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-21.pch"

Maximum Stresses

ds-trd-gas-cover-21-quad-lo.txt

\[ \sigma_{tu} := 7551.591 \text{ psi} \]
\[ \sigma_{ty} := 6816.634 \text{ psi} \]
\[ \sigma_{su} := 3914.028 \text{ psi} \]

Margins of Safety

\[ MS_{lug} := \frac{F_{lug}}{F_{Su} \cdot \sigma_{tu}} - 1 \]
\[ MS_{lug} = 4.339 \quad \text{... Margin of Safety Tensile Ultimate} \]

\[ MS_{lyg} := \frac{F_{lyg}}{F_{Sy} \cdot \sigma_{ty}} - 1 \]
\[ MS_{lyg} = 4.07 \quad \text{... Margin of Safety Tensile Yield} \]

\[ MS_{sug} := \frac{F_{sug}}{F_{Su} \cdot \sigma_{su}} - 1 \]
\[ MS_{sug} = 5.62 \quad \text{... Margin of Safety Shear Ultimate} \]
TRD Gas Ballistic Cover - Outer Skin SLG39137916-503, Fail-Safe

Liftoff, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-22.pch"

Maximum Stresses

ds-trd-gas-cover-22-quad-lo.txt

\[ u_{tu} := 1.21 \times 10^4 \text{ psi} \]

\[ u_{ty} := 1.101 \times 10^4 \text{ psi} \]

\[ u_{su} := 6.306 \times 10^3 \text{ psi} \]

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \quad \text{MS}_{tug} = 2.332 \quad \text{... Margin of Safety Tensile Ultimate} \]

\[ MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1 \quad \text{MS}_{tyg} = 2.14 \quad \text{... Margin of Safety Tensile Yield} \]

\[ MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1 \quad \text{MS}_{sug} = 3.11 \quad \text{... Margin of Safety Shear Ultimate} \]
TRD Gas Ballistic Cover - Inner Skin SLG39137916-502, Fail-Safe

**Omitted Elements**

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Skin representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3’s, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

Excluded one row of elements around holes
TRD Gas Ballistic Cover - Inner Skin SLG39137916-502, Fail-Safe

Landing, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-21.pch"

Maximum Stresses

<table>
<thead>
<tr>
<th>Laminate: MaxABSPrin Stress</th>
<th>ID</th>
<th>SUBCASE</th>
<th>1PLY</th>
<th>1MAXABSPrin</th>
<th>1MAJOR</th>
<th>1MINOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6525696</td>
<td>2014</td>
<td>1.000000E+00</td>
<td>3.800818E+03</td>
<td>3.800818E+03</td>
<td>-4.934973E+00</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laminate: Max Von-Mises Stress</th>
<th>ID</th>
<th>SUBCASE</th>
<th>1PLY</th>
<th>1VONMISES</th>
</tr>
</thead>
<tbody>
<tr>
<td>6549540</td>
<td>2014</td>
<td>1.000000E+00</td>
<td>4.177771E+03</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laminate: Max Shear Stress</th>
<th>ID</th>
<th>SUBCASE</th>
<th>1PLY</th>
<th>1MAX-SHEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6549540</td>
<td>2014</td>
<td>1.000000E+00</td>
<td>2.377622E+03</td>
<td></td>
</tr>
</tbody>
</table>

Margins of Safety

\[
MS_{tu} := \frac{F_{tu}}{FS_{u} \cdot u_{tu}} - 1
\]

\[
MS_{ty} := \frac{F_{ty}}{FS_{y} \cdot u_{ty}} - 1
\]

\[
MS_{su} := \frac{F_{su}}{FS_{u} \cdot u_{su}} - 1
\]

\[
MS_{tu} = 9.608
\]

\[
MS_{ty} = 7.27
\]

\[
MS_{su} = 9.90
\]

... Margin of Safety Tensile Ultimate

... Margin of Safety Tensile Yield

... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Inner Skin SLG39137916-502, Fail-Safe

Landing, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-22.pch"

Maximum Stresses

\[
\begin{align*}
\sigma_{tu} &= 4.641 \times 10^3 \text{ psi} \\
\sigma_{ty} &= 5.181 \times 10^3 \text{ psi} \\
\sigma_{su} &= 2.981 \times 10^3 \text{ psi}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
MS_{tug} &= \frac{F_{tug}}{FS_u \cdot \sigma_{tu}} - 1 \\
MS_{tyg} &= \frac{F_{tyg}}{FS_y \cdot \sigma_{ty}} - 1 \\
MS_{sug} &= \frac{F_{sug}}{FS_u \cdot \sigma_{su}} - 1
\end{align*}
\]

\[
\begin{align*}
MS_{tug} &= 7.688 \\
MS_{tyg} &= 5.67 \\
MS_{sug} &= 7.70
\end{align*}
\]

... Margin of Safety Tensile Ultimate

... Margin of Safety Tensile Yield

... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Inner Skin SLG39137916-502, Fail-Safe

Liftoff, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-21.pch"

**Maximum Stresses**

\[
\begin{align*}
\sigma_{tu} &= 2.392 \times 10^3 \text{ psi} \\
\sigma_{ty} &= 2.294 \times 10^3 \text{ psi} \\
\sigma_{su} &= 1.324 \times 10^3 \text{ psi}
\end{align*}
\]

**Margins of Safety**

\[
\begin{align*}
MS_{tug} &= \frac{F_{tug}}{FS_u \cdot \sigma_{tu}} - 1 \\
MS_{tyg} &= \frac{F_{tyg}}{FS_y \cdot \sigma_{ty}} - 1 \\
MS_{sug} &= \frac{F_{sug}}{FS_u \cdot \sigma_{su}} - 1
\end{align*}
\]

\[
\begin{align*}
MS_{tug} &= 15.856 \\
MS_{tyg} &= 14.07 \\
MS_{sug} &= 18.58
\end{align*}
\]

... Margin of Safety Tensile Ultimate

... Margin of Safety Tensile Yield

... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Inner Skin SLG39137916-502, Fail-Safe

**Liftoff, One Standoff Bracket to Box S Removed**

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-22.pch"

### Maximum Stresses

<table>
<thead>
<tr>
<th>Laminate: MaxABSPrin Stress -</th>
<th>6538030</th>
<th>1020</th>
<th>1.000000E+00</th>
<th>3.934517E+03</th>
<th>3.934517E+03</th>
<th>-6.663421E+01</th>
</tr>
</thead>
<tbody>
<tr>
<td>ds-trd-gas-cover-22-laminate-lo.txt</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>u_{tu} := 3.935 \times 10^3 \text{ psi}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>u_{ty} := 3.957 \times 10^3 \text{ psi}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>u_{su} := 2.194 \times 10^3 \text{ psi}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{F_{Su} \cdot u_{tu}} - 1 \]

\[ MS_{ty} := \frac{F_{ty}}{F_{Sy} \cdot u_{ty}} - 1 \]

\[ MS_{su} := \frac{F_{su}}{F_{Su} \cdot u_{su}} - 1 \]

Last Saved 2/20/2009

5.10.3-40

ESCG-4005-05-AMS-0039
TRD Gas Ballistic Cover - Standoff Bracket A SDG39137917-001, Fail-Safe

Allowables

Material Properties

AL ALY 7075-T7351, AMS-QQ-A-250/12, Plate, 0.500-1.000, A

\( F_{tu} := 68000 \text{ psi} \quad (\text{Ref. MMPDS-04 Table 3.7.7.0(b4)}) \\
F_{ty} := 57000 \text{ psi} \\
F_{su} := 38000 \text{ psi} \\

Factors of Safety

\( FS_u := 1.0 \quad FS_y := 1.0 \)

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76 °F to +140 °F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 °F:

- Ultimate: \( \beta_u := 0.96 \quad (\text{Ref. MMPDS-04, Figure 3.7.7.1.1(c)}) \\
- Yield: \( \beta_y := 0.96 \quad (\text{Ref. MMPDS-04, Figure 3.7.7.1.1(d)}) \\

Allowable Stresses

\( F_{tug} := \beta_u \cdot F_{tu} \Rightarrow F_{tug} = 65280 \text{ psi} \)

\( F_{tyg} := \beta_y \cdot F_{ty} \Rightarrow F_{tyg} = 54720 \text{ psi} \)

\( F_{sug} := \beta_u \cdot F_{su} \Rightarrow F_{sug} = 36480 \text{ psi} \)
TRD Gas Ballistic Cover - Standoff Bracket A SDG39137917-001, Fail-Safe

Omitted Elements

Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Bracket representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3's, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.

1 to 2 rows of elements around a hole were excluded
TRD Gas Ballistic Cover - Standoff Bracket A SDG39137917-001, Fail-Safe

Landing, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-21.pch"

Maximum Stresses

### Tensile Ultimate

\[ u_{tu} := 3.91 \times 10^4 \text{ psi} \]

### Von-Mises Stress

\[ u_{ty} := 4.013 \times 10^4 \text{ psi} \]

### Shear Ultimate

\[ u_{su} := 2.17 \times 10^4 \text{ psi} \]

Margins of Safety

### Margin of Safety Tensile Ultimate

\[ MS_{tug} := \frac{F_{tug}}{FS_u \cdot u_{tu}} - 1 \]

\[ MS_{tug} = 0.670 \]

### Margin of Safety Tensile Yield

\[ MS_{tyg} := \frac{F_{tyg}}{FS_y \cdot u_{ty}} - 1 \]

\[ MS_{tyg} = 0.36 \]

### Margin of Safety Shear Ultimate

\[ MS_{sug} := \frac{F_{sug}}{FS_u \cdot u_{su}} - 1 \]

\[ MS_{sug} = 0.68 \]
TRD Gas Ballistic Cover - Standoff Bracket A SDG39137917-001, Fail-Safe

Landing, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-22.pch"

Maximum Stresses

<table>
<thead>
<tr>
<th>Stiffness</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tu</td>
<td>$6.214 \times 10^4$ psi</td>
</tr>
<tr>
<td>ty</td>
<td>$5.438 \times 10^4$ psi</td>
</tr>
<tr>
<td>su</td>
<td>$3.203 \times 10^4$ psi</td>
</tr>
</tbody>
</table>

Margins of Safety

<table>
<thead>
<tr>
<th>Margin</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margin of Safety Tensile Ultimate</td>
<td>$F_{tu} / (S_y \cdot \text{tu}) - 1$</td>
<td>$0.051$</td>
</tr>
<tr>
<td>Margin of Safety Tensile Yield</td>
<td>$F_{ty} / (S_y \cdot \text{ty}) - 1$</td>
<td>$0.006$</td>
</tr>
<tr>
<td>Margin of Safety Shear Ultimate</td>
<td>$F_{su} / (S_y \cdot \text{su}) - 1$</td>
<td>$0.14$</td>
</tr>
</tbody>
</table>

*Note: Omitted Elements 6300025, 6300018, and 6300017 from CQuad4 Max ABS Von-Mises Stress sort because of their close proximity to the circumference of bolt holes, where the bolt attachment was modeled with RBE3's. The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.
TRD Gas Ballistic Cover - Standoff Bracket A SDG39137917-001, Fail-Safe

Liftoff, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-21.pch"

Maximum Stresses

ds-trd-gas-cover-bracket-v21-quad-lo.txt

\( u_{tu} := 2.028 \times 10^4 \) psi

\( u_{ty} := 2.025 \times 10^4 \) psi

\( u_{su} := 1.014 \times 10^4 \) psi

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{F_{Su} \cdot u_{tu}} - 1 \]

\( MS_{tug} = 2.219 \)  ... Margin of Safety Tensile Ultimate

\[ MS_{tyg} := \frac{F_{tyg}}{F_{Sy} \cdot u_{ty}} - 1 \]

\( MS_{tyg} = 1.7 \)  ... Margin of Safety Tensile Yield

\[ MS_{sug} := \frac{F_{sug}}{F_{Su} \cdot u_{su}} - 1 \]

\( MS_{sug} = 2.60 \)  ... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Standoff Bracket A SDG39137917-001, Fail-Safe

Liftoff, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-22.pch"

Maximum Stresses

\[
\begin{align*}
\sigma_{tu} &= 3.901 \times 10^4 \text{ psi} \\
\sigma_{ty} &= 4.136 \times 10^4 \text{ psi} \\
\tau_{su} &= 2.225 \times 10^4 \text{ psi}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
MS_{tu} &= \frac{F_{tu}}{\sigma_{tu}} - 1 \quad \Rightarrow \quad MS_{tu} = 0.673 \quad \text{... Margin of Safety Tensile Ultimate} \\
MS_{ty} &= \frac{F_{ty}}{\sigma_{ty}} - 1 \quad \Rightarrow \quad MS_{ty} = 0.32 \quad \text{... Margin of Safety Tensile Yield} \\
MS_{su} &= \frac{F_{su}}{\tau_{su}} - 1 \quad \Rightarrow \quad MS_{su} = 0.64 \quad \text{... Margin of Safety Shear Ultimate}
\end{align*}
\]
TRD Gas Ballistic Cover - Standoff Bracket B SDG39137918-001, Fail-Safe

Allowables

Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL ALY 7075-T7351, AMS-QQ-A-250/12, Plate, 0.500-1.000, A</td>
<td></td>
</tr>
</tbody>
</table>

\[ F_{tu} := 68000 \text{ psi} \]  
\[ F_{ty} := 57000 \text{ psi} \]  
\[ F_{su} := 38000 \text{ psi} \]  

Factors of Safety

\[ FS_u := 1.0 \]  
\[ FS_y := 1.0 \]

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76 °F to +140 °F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 °F:

- Ultimate: \[ \beta_u := 0.96 \]  
  \[ (Ref. \ MMPDS-04, Figure 3.7.7.1.1(c)) \]

- Yield: \[ \beta_y := 0.96 \]  
  \[ (Ref. \ MMPDS-04, Figure 3.7.7.1.1(d)) \]

Allowable Stresses

\[ F_{tug} := \beta_u \cdot F_{tu} \]  
\[ F_{tug} = 65280 \text{ psi} \]

\[ F_{tyg} := \beta_y \cdot F_{ty} \]  
\[ F_{tyg} = 54720 \text{ psi} \]

\[ F_{sug} := \beta_u \cdot F_{su} \]  
\[ F_{sug} = 36480 \text{ psi} \]
Note: NASPOST V.2.2 was used to sort the maximum stresses across all load cases. The finite elements in the Bracket representing the area under the washers, around the circumference of bolt holes, where the bolt attachment was modeled with RBE3's, were removed from the NASPOST sort (see table below). The strength analysis of this area is performed in the corresponding Faster/Joint/Bearing analysis.
TRD Gas Ballistic Cover - Standoff Bracket B SDG39137918-001, Fail-Safe

Landing, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-21.pch"

Maximum Stresses

\[
\begin{align*}
\sigma_{tu} &= 1.301 \times 10^4 \text{ psi} \\
\sigma_{ty} &= 1.047 \times 10^4 \text{ psi} \\
\sigma_{su} &= 6.045 \times 10^3 \text{ psi}
\end{align*}
\]

Margins of Safety

\[
\begin{align*}
MS_{tug} &= \frac{F_{tug}}{FS_u \cdot \sigma_{tu}} - 1 & MS_{tug} &= 4.018 & \text{... Margin of Safety Tensile Ultimate} \\
MS_{tyg} &= \frac{F_{tyg}}{FS_y \cdot \sigma_{ty}} - 1 & MS_{tyg} &= 4.23 & \text{... Margin of Safety Tensile Yield} \\
MS_{sug} &= \frac{F_{sug}}{FS_u \cdot \sigma_{su}} - 1 & MS_{sug} &= 5.03 & \text{... Margin of Safety Shear Ultimate}
\end{align*}
\]
TRD Gas Ballistic Cover - Standoff Bracket B SDG39137918-001, Fail-Safe

Landing, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-landing-22.pch"

Maximum Stresses

ds-trd-gas-cover-bracket-v22-tetra-la.txt

\[ u_{tu} := 80.753 \text{ psi} \]
\[ u_{ty} := 83.667 \text{ psi} \]
\[ u_{su} := 46.256 \text{ psi} \]

Margins of Safety

\[ MS_{tug} := \frac{F_{tug}}{F_{S_u} \cdot u_{tu}} - 1 \]
\[ MS_{tug} = 807.391 \] ... Margin of Safety Tensile Ultimate

\[ MS_{tyg} := \frac{F_{tyg}}{F_{S_y} \cdot u_{ty}} - 1 \]
\[ MS_{tyg} = 653.02 \] ... Margin of Safety Tensile Yield

\[ MS_{sug} := \frac{F_{sug}}{F_{S_u} \cdot u_{su}} - 1 \]
\[ MS_{sug} = 787.65 \] ... Margin of Safety Shear Ultimate
TRD Gas Ballistic Cover - Standoff Bracket B SDG39137918-001, Fail-Safe

Liftoff, One Splice Plate Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-21.pch"

Maximum Stresses

ds-trd-gas-cover-bracket-v21-tetra-lo.txt
+++ --------------------------------------------- +++
TETRA: Max ABS Principal Stress - SB B
ID SUBCASE NO_LABEL MAX-MAX-PRIN MAX-MIN-PRIN
6703466 1030 7.656533E+03 3.001652E+03 7.656533E+03
+++ --------------------------------------------- +++
TETRA: Max ABS Von-Mises Stress - SB B
ID SUBCASE NO_LABEL MAX-VONM
6701935 1030 5.529602E+03 5.529602E+03
+++ --------------------------------------------- +++
TETRA: Max ABS Shear Stress - SB B
ID SUBCASE NO_LABEL MAX-MAX-SHR
6701935 1030 3.177905E+03 3.177905E+03

Margins of Safety

\[ \text{MS}_{\text{tu}} := \frac{F_{\text{tu}}}{F_{\text{u}} \cdot u_{\text{tu}}} - 1 \]
\[ \text{MS}_{\text{ty}} := \frac{F_{\text{ty}}}{F_{\text{y}} \cdot u_{\text{ty}}} - 1 \]
\[ \text{MS}_{\text{sug}} := \frac{F_{\text{sug}}}{F_{\text{u}} \cdot u_{\text{sug}}} - 1 \]

\[ \text{MS}_{\text{tu}} = 7.526 \] \hspace{2cm} \text{... Margin of Safety Tensile Ultimate}

\[ \text{MS}_{\text{ty}} = 8.9 \] \hspace{2cm} \text{... Margin of Safety Tensile Yield}

\[ \text{MS}_{\text{sug}} = 10.48 \] \hspace{2cm} \text{... Margin of Safety Shear Ultimate}
TRD Gas Ballistic Cover - Standoff Bracket B SDG39137918-001, Fail-Safe

Liftoff, One Standoff Bracket to Box S Removed

Note: For the following analysis, the maximum Principal, Von-Mises, and Shear stresses of plate elements are selected. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. The elements at the bolt holes were omitted from the NASPOST sort.

NASTRAN Punch Filename: "ds-trd-gas-inner-liftoff-22.pch"

Maximum Stresses

ds-trd-gas-cover-bracket-v22-tetra-10.txt

\[ \sigma_{tu} := 49.04 \text{ psi} \]

\[ \sigma_{ty} := 52.606 \text{ psi} \]

\[ \sigma_{su} := 29.144 \text{ psi} \]

Margins of Safety

\[ MS_{tu} := \frac{F_{tu}}{FS_{u} \cdot \sigma_{tu}} - 1 \]

\[ MS_{ty} := \frac{F_{ty}}{FS_{y} \cdot \sigma_{ty}} - 1 \]

\[ MS_{su} := \frac{F_{su}}{FS_{u} \cdot \sigma_{su}} - 1 \]

\[ MS_{tu} = 1330.158 \quad \text{... Margin of Safety Tensile Ultimate} \]

\[ MS_{ty} = 1.04 \times 10^3 \quad \text{... Margin of Safety Tensile Yield} \]

\[ MS_{su} = 1.25 \times 10^3 \quad \text{... Margin of Safety Shear Ultimate} \]
CHECK OF TRD GAS BALLISTIC COVER ASSEMBLY, SEG39137915

TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9

Allowables

Material Properties

AL ALY 6061-T651, AMS-QQ-A-250/11, Sheet, 0.010-0.249, A

\[ F_{tu} := 42000 \text{ psi} \quad \text{(Ref. MMPDS-04, Table 3.6.2.0(b1))} \]

\[ F_{ty} := 36000 \text{ psi} \]

\[ F_{su} := 27000 \text{ psi} \]

Factors of Safety

\[ F_{S_u} := 1.0 \quad F_{S_y} := 1.0 \]

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76 °F to +140 °F. These temperature reduction factors are conservative for liftoff/landing conditions. At +140 °F:

- Ultimate:
  \[ \beta_u := 0.96 \quad \text{(Ref. MMPDS-04, Figure 3.6.2.2.1(a))} \]

- Yield:
  \[ \beta_y := 0.96 \quad \text{(Ref. MMPDS-04, Figure 3.6.2.2.1(b))} \]

Allowable Stresses

\[ F_{tug} := \beta_u \cdot F_{tu} \quad F_{tug} = 40320 \text{ psi} \]

\[ F_{tyg} := \beta_y \cdot F_{ty} \quad F_{tyg} = 34560 \text{ psi} \]

\[ F_{sug} := \beta_u \cdot F_{su} \quad F_{sug} = 25920 \text{ psi} \]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9

Section Properties

\[
\begin{align*}
\text{Item} & := \begin{pmatrix} 1 \\ 2 \end{pmatrix} & \text{bb} & := \begin{pmatrix} t \\ t \end{pmatrix} & \text{dd} & := \begin{pmatrix} h \cdot d - 2 \cdot \frac{d}{2} \\ h \cdot d - 2 \cdot \frac{d}{2} \end{pmatrix} & \text{z} & := \begin{pmatrix} 0 \\ 0 \end{pmatrix} & \text{y} & := \begin{pmatrix} \frac{h \cdot d}{4} + \frac{d}{2} \\ -h + \frac{d}{2} \end{pmatrix}
\end{align*}
\]

\[
i := 1 \ldots \text{rows(Item)}
\]

\[
\begin{align*}
A_i & := \text{bb}_i \cdot \text{dd}_i & A & := \begin{pmatrix} 0.027 \\ 0.027 \end{pmatrix} \text{in}^2 & \text{Asum} & := \left( \sum A \right)
\end{align*}
\]

\[
\begin{align*}
A_{zi} & := A_i \cdot z_i & A_{zzi} & := A_{zi} \cdot z_i & A_{yi} & := A_i \cdot y_i & A_{yy} & := A_i \cdot y_i
\end{align*}
\]

\[
\begin{align*}
A_{z} & := \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}^2 & A_{zz} & := \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}^4 & A_y & := \begin{pmatrix} 5.515 \times 10^{-3} \\ -5.515 \times 10^{-3} \end{pmatrix} \text{in}^3 & A_{yy} & := \begin{pmatrix} 1.129 \times 10^{-3} \\ 1.129 \times 10^{-3} \end{pmatrix} \text{in}^4
\end{align*}
\]

\[
\begin{align*}
\text{Asum} & := \left( \sum A_{z} \right) & \text{Azzsum} & := \left( \sum A_{zz} \right) & \text{Aysum} & := \left( \sum A_y \right) & \text{Ayysum} & := \left( \sum A_{yy} \right)
\end{align*}
\]

\[
\begin{align*}
\text{Azsum} & := 0 & \text{Azzsum} & := 0 & \text{Aysum} & := 0 \text{in}^3 & \text{Ayysum} & := 0.002 \text{in}^4
\end{align*}
\]

\[
\begin{align*}
I_{zzi} & := \frac{\text{bb}_i \cdot (\text{dd}_i)^3}{12} & I_{yy} & := \frac{(\text{bb}_i)^3 \cdot \text{dd}_i}{12}
\end{align*}
\]

\[
\begin{align*}
I_{zz} & := \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}^4 & I_{yy} & := \begin{pmatrix} 0 \\ 0 \end{pmatrix} \text{in}^4
\end{align*}
\]

Last Saved 2/24/2009
**TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9**

**Section Properties**

\[ I_{zsum} := \sum I_{zz} \]
\[ I_{ysum} := \sum I_{yy} \]
\[ Z_{bar} := \frac{A_{zsum}}{A_{sum}} \]
\[ Y_{bar} := \frac{A_{ysum}}{A_{sum}} \]

\[ Z_{bar} = 0 \times 10^0 \quad Y_{bar} = 0 \times 10^0 \text{ in} \quad A_{sum} = 0 \text{in}^3 \]

\[ I_y := I_{ysum} + A_{zsum} \cdot A_{sum} \cdot Z_{bar}^2 \]
\[ I_z := I_{zsum} + A_{ysum} \cdot A_{sum} \cdot Y_{bar}^2 \]

\[ I_y = 7.015 \times 10^{-5} \text{ in}^4 \quad 4 \times 10^0 \]
\[ I_z = 2.467 \times 10^{-3} \text{ in}^4 \quad 4 \times 10^0 \]

**Moment of Inertia About zy Axis**

\[ I_{zy} := 0 \cdot \text{in}^4 \]

**Area**

\[ A := A_{sum} \quad A = 0.054 \text{in}^2 \]

**Enclosed Area**

\[ A_e := (h \cdot t) \cdot \text{in}^2 \]
\[ A_e = 0.078 \text{in}^2 \]

**Thickness**

\[ t = 0.125 \text{in} \]

**Stress Recovery Point Coordinates**

\[ \begin{align*}
  c_y & := \begin{bmatrix}
    \frac{h}{2} \\
    h \\
    \frac{-h}{2} \\
    \frac{-h}{2}
  \end{bmatrix} \\
  c_z & := \begin{bmatrix}
    \frac{-t}{2} \\
    \frac{t}{2} \\
    \frac{-t}{2} \\
    \frac{-t}{2}
  \end{bmatrix} \\
  i & := 1 \ldots \text{rows}(c_z)
\end{align*} \]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing

64 Landing Conditions - Loads

Zero Out All Variables

\[
\begin{align*}
M2 & := 0 \\
S1 & := 0 \\
M1 & := 0 \\
S2 & := 0 \\
MSu & := 0 \\
\text{umax} & := 0 \\
p1 & := 0 \\
v & := 0 \\
M2 & := 0 \\
S1 & := 0 \\
M1 & := 0 \\
S2 & := 0 \\
MSu & := 0 \\
\text{max} & := 0 \\
p1 & := 0 \\
v & := 0 \\
\text{max} & := 0 \\
p1 & := 0 \\
v & := 0 \\
\text{max} & := 0 \\
p1 & := 0 \\
v & := 0 \\
\text{max} & := 0 \\
p1 & := 0 \\
v & := 0 \\
\end{align*}
\]

forces := READPRN("Beams-20-la.txt")

\[
\begin{align*}
& j := 1 \ldots \text{rows(forces)} \\
& \text{idj} := \text{forces}_j, 1 \\
& \text{casesj} := \text{forces}_j, 2 \\
& M1j := \text{forces}_j, 3 \ \text{in-lbf} \\
& M2j := \text{forces}_j, 4 \ \text{in-lbf} \\
& Txj := \text{forces}_j, 8 \ \text{in-lbf} \\
& S1j := \text{forces}_j, 5 \ \text{lbf} \\
& S2j := \text{forces}_j, 6 \ \text{lbf} \\
& Faxj := \text{forces}_j, 7 \ \text{lbf} \\
& M1j+\text{rows(forces)} := \text{forces}_j, 9 \ \text{in-lbf} \\
& M2j+\text{rows(forces)} := \text{forces}_j, 10 \ \text{in-lbf} \\
& S2j+\text{rows(forces)} := \text{forces}_j, 12 \ \text{lbf} \\
& S1j+\text{rows(forces)} := \text{forces}_j, 11 \ \text{lbf} \\
& \text{idj+rows(forces)} := \text{forces}_j, 1 \\
& \text{casesj+rows(forces)} := \text{forces}_j, 2 \\
& \text{cases} := 0 \\
& \text{M1} := \text{M1j} \\
& \text{M2} := \text{M2j} \\
& \text{Fax} := \text{Faxj} \\
& \text{Fx} := \text{Fx} \\
& \text{Fy} := \text{Fy} \\
& \text{Fz} := \text{Fz} \\
& \text{Mz} := \text{Mz} \\
& \text{My} := \text{My} \\
& \text{T} := \text{T} \\
& \text{MaxTension} := \sqrt{(\text{Fz})^2} \\
& \text{MaxShear} := \sqrt{(\text{Fx})^2 + (\text{Fy})^2} \\
& \text{max} := \text{12.875 lbf} \\
& \text{max} := \text{1.402 lbf} \\
& \text{max} := \text{14.659 lbf} \\
& \text{max} := \text{2.792 in lbf} \\
& \text{max} := \text{5.591 in lbf} \\
& \text{max} := \text{1.784 in lbf} \\
& \text{max} := \text{14.659 lbf} \\
& \text{max} := \text{23.41 lbf} \\
& \text{max} := \text{0 lbf} \\
& \text{max} := \text{0.04 lbf} \\
& \text{min} := \text{1.392 in lbf} \\
& \text{min} := \text{9.301 in lbf} \\
& \text{min} := \text{5.584 in lbf} \\
& \text{min} := \text{1.675 in lbf} \\
& \text{min} := \text{2.051 in lbf} \\
& \text{min} := \text{23.37 lbf} \\
& \text{min} := \text{2.051 in lbf} \\
& \text{min} := \text{12.875 lbf} \\
& \text{min} := \text{14.659 lbf} \\
& \text{min} := \text{14.659 lbf} \\
& \text{min} := \text{0.04 lbf} \\
& \text{max} := \text{0 lbf} \\
& \text{min} := \text{0 lbf} \\
& \text{min} := \text{0 lbf} \\
\end{align*}
\]

Rivet Hole Loads

\[
\begin{align*}
\text{MaxTension} & := \sqrt{(\text{Fz})^2} \\
\text{MaxShear} & := \sqrt{(\text{Fx})^2 + (\text{Fy})^2} \\
\end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing

64 Landing Conditions - Maximum Stresses on Cross Section

Normal is Direct Axial Plus Bending

\[
\text{i, j} := \frac{F_{x_j}}{A} + \frac{(M_{y_j} \cdot I_{y} - M_{z_j} \cdot I_{z}) \cdot c_{z_j}}{I_{y} \cdot I_{z} - I_{z}^2} \ - \ \frac{(M_{z_j} \cdot I_{y} + M_{y_j} \cdot I_{z}) \cdot c_{y_j}}{I_{y} \cdot I_{z} - I_{z}^2}
\]

\[
\text{max( )} = 4921.308 \text{ psi}
\]

Shear Due to Transverse Loading

\[
u_{v_j} := \sqrt{\left(\frac{F_{y_j}}{A}\right)^2 + \left(\frac{F_{z_j}}{A}\right)^2}
\]

\[
\text{max( } u_v) = 272.396 \text{ psi}
\]

Combined Shear

\[
u_{j} := u_{v_j}
\]

\[
\text{max( } u) = 272.396 \text{ psi}
\]

Principal Stresses

\[
p_{1,i,j} := \frac{i,j}{2} + \left[\left(\frac{i,j}{2}\right)^2 + (u_{j})^2\right]^{\frac{1}{2}}
\]

\[
\text{max( } p_1) = 4932.814 \text{ psi}
\]

Principal Stresses (cont.)

\[
p_{2,i,j} := \frac{i,j}{2} - \left[\left(\frac{i,j}{2}\right)^2 + (u_{j})^2\right]^{\frac{1}{2}}
\]

\[
\text{max( } p_2) = -0 \text{ psi}
\]

Von-Mises Stress

\[
v_{m,i,j} := \sqrt{\left(p_{1,i,j}\right)^2 + \left(p_{2,i,j}\right)^2 - p_{1,i,j} \cdot p_{2,i,j}}
\]

\[
\text{max( } v_m) = 5737.026 \text{ psi}
\]

Maximum Shear Stress

\[
u_{max,i,j} := \sqrt{\frac{1}{4} \left(\left(i_j\right)^2 + (u_{j})^2\right)}
\]

\[
\text{max( } u_{max}) = 2868.612 \text{ psi}
\]

\[
MS_{u1,i,j} := \frac{F_{tug}}{FS_u \cdot p_{1,i,j}} - 1
\]

\[
\text{min( } MSu1) = 7.17
\]

\[
MS_{u2,i,j} := \frac{F_{tug}}{FS_u \cdot p_{2,i,j}} - 1
\]

\[
\text{min( } MSu2) = 6.028
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing

64 Landing Conditions - Margins of Safety

\[
\begin{align*}
MS_{u,i,j} &:= \min(MS_{u1,i,j}, MS_{u2,i,j}) & \text{min}(MS_{u}) &= 6.028 & \text{Ultimate (using Principal)} \\
MS_{y,i,j} &:= \left( \frac{F_{yg}}{FS_{y} \cdot v_{mm,i,j}} \right) - 1 & \text{min}(MS_{y}) &= 5.024 & \text{Yield (using Von-Mises)} \\
MS_{sui,i,j} &:= \left( \frac{F_{sug}}{FS_{u} \cdot umax_{i,j}} \right) - 1 & \text{min}(MS_{sui}) &= 8.036 & \text{Ultimate (Shear)}
\end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing, Fail-Safe

One Splice Plate Removed - Loads

Zero Out All Variables

\[
\begin{align*}
M_2 &= 0 & S_1 &= 0 & M_1 &= 0 & S_2 &= 0 & MSu &= 0 & \text{umax} &= 0 & p_1 &= 0 & u &= 0 \\
\text{MaxShear} &= 0 & MSy &= 0 & MSu1 &= 0 & p_2 &= 0 & T_x &= 0 & id &= 0 \\
\text{MaxTension} &= 0 & MSsu &= 0 & MSu2 &= 0 & v_m &= 0 & Fax &= 0 & \text{cases} &= 0
\end{align*}
\]

\[
\text{forces} := \text{READPRN} \left( \text{"Beams-21-la.txt"} \right)
\]

\[
\begin{align*}
j &:= 1 \ldots \text{rows} \left( \text{forces} \right) & \text{id}_j &:= \text{forces}_{j, 1} & \text{cases}_j &:= \text{forces}_{j, 2} \\
M_{1j} &:= \text{forces}_{j, 3} \cdot \text{in} \cdot \text{lbf} & M_{2j} &:= \text{forces}_{j, 4} \cdot \text{in} \cdot \text{lbf} & T_{xj} &:= \text{forces}_{j, 8} \cdot \text{in} \cdot \text{lbf} \\
S_{1j} &:= \text{forces}_{j, 5} \cdot \text{lbf} & S_{2j} &:= \text{forces}_{j, 6} \cdot \text{lbf} & Fax_j &:= \text{forces}_{j, 7} \cdot \text{lbf} \\
M_{1j+\text{rows} \left( \text{forces} \right)} &:= \text{forces}_{j, 9} \cdot \text{in} \cdot \text{lbf} \\
M_{2j+\text{rows} \left( \text{forces} \right)} &:= \text{forces}_{j, 10} \cdot \text{in} \cdot \text{lbf} \\
S_{2j+\text{rows} \left( \text{forces} \right)} &:= \text{forces}_{j, 12} \cdot \text{lbf} \\
S_{1j+\text{rows} \left( \text{forces} \right)} &:= \text{forces}_{j, 11} \cdot \text{lbf} \\
\text{id}_j+\text{rows} \left( \text{forces} \right) &:= \text{forces}_{j, 1} \\
\text{cases}_j+\text{rows} \left( \text{forces} \right) &:= \text{forces}_{j, 2} \\
j &:= 1 \ldots \text{rows} \left( \text{forces} \right) \cdot 2
\end{align*}
\]

\[
\begin{align*}
\text{Fx} &:= Fax & \max(\text{Fx}) &= 13.469 \text{ lbf} & \min(\text{Fx}) &= -23.892 \text{ lbf} \\
\text{Fy} &:= S_1 & \max(\text{Fy}) &= 1.609 \text{ lbf} & \min(\text{Fy}) &= -1.843 \text{ lbf} \\
\text{Fz} &:= S_2 & \max(\text{Fz}) &= 7.348 \text{ lbf} & \min(\text{Fz}) &= -12.753 \text{ lbf} \\
M_z &:= M_1 & \max(M_z) &= 3.469 \text{ in lbf} & \min(M_z) &= -2.011 \text{ in lbf} \\
\text{My} &:= -M_2 & \max(\text{My}) &= 5.85 \text{ in lbf} & \min(\text{My}) &= -5.851 \text{ in lbf} \\
T &:= T_x & \max(T) &= 1.16 \text{ in lbf} & \min(T) &= -1.9 \text{ in lbf}
\end{align*}
\]

Rivet Hole Loads

\[
\begin{align*}
\text{MaxTension}_j &:= \sqrt{\left( F_{zj} \right)^2} & \max(\text{MaxTension}) &= 12.753 \text{ lbf} & \min(\text{MaxTension}) &= 0 \text{ lbf} \\
\text{MaxShear}_j &:= \sqrt{\left( F_{xj} \right)^2 + \left( F_{yj} \right)^2} & \max(\text{MaxShear}) &= 23.911 \text{ lbf} & \min(\text{MaxShear}) &= 0.04 \text{ lbf}
\end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing, Fail-Safe
One Splice Plate Removed - Maximum Stresses on Cross Section

Normal is Direct Axial Plus Bending

\[
i_{i,j} := \frac{F_{x_j}}{A} + \frac{(M_{y_j} \cdot l_z + M_{z_j} \cdot l_y \cdot c_{z_i})}{I_y \cdot l_z - l_y^2} - \frac{(M_{z_j} \cdot l_y + M_{y_j} \cdot l_z \cdot c_{y_i})}{I_z \cdot l_z - l_z^2}
\]

\[
\text{max}(i) = 5196.67 \text{ psi}
\]

Shear Due to Transverse Loading

\[
u_{v_j} := \sqrt{\left(\frac{F_{y_j}}{A}\right)^2 + \left(\frac{F_{z_j}}{A}\right)^2}
\]

\[
\text{max}(uv) = 236.98 \text{ psi}
\]

Combined Shear

\[
u_j := uv_j
\]

\[
\text{max}(u) = 236.98 \text{ psi}
\]

Principal Stresses

\[
p_{1i,j} := \frac{i_{i,j}}{2} + \left[\left(\frac{i_{i,j}}{2}\right)^2 + (u_j)^2\right]^{\frac{1}{2}}
\]

\[
\text{max}(p1) = 5206.574 \text{ psi}
\]

Principal Stresses (cont.)

\[
p_{2i,j} := \frac{i_{i,j}}{2} - \left[\left(\frac{i_{i,j}}{2}\right)^2 + (u_j)^2\right]^{\frac{1}{2}}
\]

\[
\text{max}(p2) = -0.001 \text{ psi}
\]

Von-Mises Stress

\[
v_{m_{i,j}} := \sqrt{\left(\frac{p_{1i,j}}{2}\right)^2 + \left(\frac{p_{2i,j}}{2}\right)^2 - \frac{p_{1i,j}}{2} \cdot p_{2i,j}}
\]

\[
\text{max}(vm) = 6074.716 \text{ psi}
\]

Maximum Shear Stress

\[
u_{\text{max}_{i,j}} := \sqrt{\frac{1}{4} \left(\frac{i_{i,j}}{2}\right)^2 + (u_j)^2}
\]

\[
\text{max}(umax) = 3037.579 \text{ psi}
\]

\[
M_{Su1_{i,j}} := \frac{F_{\text{tug}}}{\left(F_{Su} \cdot p_{1i,j}\right)} - 1
\]

\[
\text{min}(M_{Su1}) = 6.74
\]

\[
M_{Su2_{i,j}} := \frac{F_{\text{tug}}}{\left(F_{Su} \cdot p_{2i,j}\right)} - 1
\]

\[
\text{min}(M_{Su2}) = 5.638
\]
### TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing, Fail-Safe

**One Splice Plate Removed - Margins of Safety**

\[
MSu_{i,j} := \min(\text{MSu}_{1i,j}, \text{MSu}_{2i,j}) \quad \min(\text{MSu}) = 5.638 \quad \text{...Ultimate (using Principal)}
\]

\[
MSy_{i,j} := \left( \frac{F_{\text{tyg}}}{\text{FS}_y \cdot \text{vm}_{i,j}} \right) - 1 \quad \min(\text{MSy}) = 4.69 \quad \text{...Yield (using Von-Mises)}
\]

\[
MSu_{i,j} := \left( \frac{F_{\text{sug}}}{\text{FS}_u \cdot \text{um}_{i,j}} \right) - 1 \quad \min(\text{MSsu}) = 7.53 \quad \text{...Ultimate (Shear)}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing, Fail-Safe

One Standoff Bracket to Box S Removed - Loads

Zero Out All Variables

\[ M_2 := 0 \quad S_1 := 0 \quad M_1 := 0 \quad S_2 := 0 \quad M_{Su} := 0 \quad u_{max} := 0 \quad p_1 := 0 \quad u_v := 0 \]
\[ u := 0 \quad \text{MaxShear} := 0 \quad M_{Sy} := 0 \quad M_{Su1} := 0 \quad p_2 := 0 \quad T_x := 0 \quad id := 0 \]
\[ := 0 \quad \text{MaxTension} := 0 \quad M_{Su} := 0 \quad M_{Su2} := 0 \quad v_m := 0 \quad \text{Fax} := 0 \quad \text{cases} := 0 \]

forces := READPRN("Beams-22-la.txt")

\[ j := 1 .. \text{rows(forces)} \]
\[ \text{id}_j := \text{forces}_j, 1 \]
\[ \text{cases}_j := \text{forces}_j, 2 \]
\[ M_{1j} := \text{forces}_j, 3 \text{ in} \cdot \text{lbf} \]
\[ M_{2j} := \text{forces}_j, 4 \text{ in} \cdot \text{lbf} \]
\[ T_x := \text{forces}_j, 8 \text{ in} \cdot \text{lbf} \]
\[ S_{1j} := \text{forces}_j, 5 \text{ lbf} \]
\[ S_{2j} := \text{forces}_j, 6 \text{ lbf} \]
\[ \text{Fax}_j := \text{forces}_j, 7 \text{ lbf} \]
\[ M_{1j+\text{rows(forces)}} := \text{forces}_j, 9 \text{ in} \cdot \text{lbf} \]
\[ M_{2j+\text{rows(forces)}} := \text{forces}_j, 10 \text{ in} \cdot \text{lbf} \]
\[ S_{2j+\text{rows(forces)}} := \text{forces}_j, 12 \text{ lbf} \]
\[ S_{1j+\text{rows(forces)}} := \text{forces}_j, 11 \text{ lbf} \]
\[ \text{id}_{j+\text{rows(forces)}} := \text{forces}_j, 1 \]
\[ \text{cases}_{j+\text{rows(forces)}} := \text{forces}_j, 2 \]
\[ j := 1 .. \text{rows(forces)} \cdot 2 \]

\[ F_x := \text{Fax} \]
\[ \text{max}(F_x) = 16.242 \text{ lbf} \]
\[ \text{min}(F_x) = -27.946 \text{ lbf} \]
\[ F_y := S_1 \]
\[ \text{max}(F_y) = 2.394 \text{ lbf} \]
\[ \text{min}(F_y) = -2.679 \text{ lbf} \]
\[ F_z := S_2 \]
\[ \text{max}(F_z) = 11.451 \text{ lbf} \]
\[ \text{min}(F_z) = -17.412 \text{ lbf} \]
\[ M_z := M_1 \]
\[ \text{max}(M_z) = 4.487 \text{ in} \cdot \text{lbf} \]
\[ \text{min}(M_z) = -2.734 \text{ in} \cdot \text{lbf} \]
\[ M_y := -M_2 \]
\[ \text{max}(M_y) = 6.325 \text{ in} \cdot \text{lbf} \]
\[ \text{min}(M_y) = -6.334 \text{ in} \cdot \text{lbf} \]
\[ T := T_x \]
\[ \text{max}(T) = 1.774 \text{ in} \cdot \text{lbf} \]
\[ \text{min}(T) = -2.748 \text{ in} \cdot \text{lbf} \]

Rivet Hole Loads

\[ \text{MaxTension}_j := \sqrt{(F_z)^2} \]
\[ \text{max}(\text{MaxTension}) = 17.412 \text{ lbf} \]
\[ \text{min}(\text{MaxTension}) = 0.002 \text{ lbf} \]
\[ \text{MaxShear}_j := \sqrt{(F_x)^2 + (F_y)^2} \]
\[ \text{max}(\text{MaxShear}) = 28.074 \text{ lbf} \]
\[ \text{min}(\text{MaxShear}) = 0.019 \text{ lbf} \]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing, Fail-Safe
One Standoff Bracket to Box S Removed - Maximum Stresses on Cross Section

**Normal is Direct Axial Plus Bending**

\[
i, j := \frac{F_{x_j}}{A} + \frac{(M_{y_j} \cdot I_{y} - M_{z_j} \cdot I_{z}) \cdot c_{z_j}}{I_{y} \cdot I_{z} - I_{z}^2} - \frac{(M_{z_j} \cdot I_{y} + M_{y_j} \cdot I_{z}) \cdot c_{y_j}}{I_{y} \cdot I_{z} - I_{z}^2}
\]

\[
\text{max}(\ ) = 5676.197 \text{ psi}
\]

**Shear Due to Transverse Loading**

\[
u_{v_j} := \sqrt{\left(\frac{F_{y_j}}{A}\right)^2 + \left(\frac{F_{z_j}}{A}\right)^2}
\]

\[
\text{max}(uv) = 325.656 \text{ psi}
\]

**Combined Shear**

\[
u_j := uv_j
\]

\[
\text{max}(u) = 325.656 \text{ psi}
\]

**Principal Stresses**

\[
p_{1i,j} := \frac{i,j}{2} + \left[\left(\frac{i,j}{2}\right)^2 + (u_j)^2\right]^{\frac{1}{2}}
\]

\[
\text{max}(p1) = 5676.878 \text{ psi}
\]

**Principal Stresses (cont.)**

\[
p_{2i,j} := \frac{i,j}{2} - \left[\left(\frac{i,j}{2}\right)^2 + (u_j)^2\right]^{\frac{1}{2}}
\]

\[
\text{max}(p2) = -0.001 \text{ psi}
\]

**Von-Mises Stress**

\[
v_{m_{k,j}} := \sqrt{(p_{1i,j})^2 + (p_{2i,j})^2 - p_{1i,j} \cdot p_{2i,j}}
\]

\[
\text{max}(vm) = 6714.495 \text{ psi}
\]

**Maximum Shear Stress**

\[
u_{\text{max}_{i,j}} := \sqrt{\frac{1}{4}\left[\frac{1}{(i,j)^2 + (u_j)^2}\right]}
\]

\[
\text{max}(\text{umax}) = 3357.391 \text{ psi}
\]

\[
\text{MSu}_{1i,j} := \frac{F_{\text{tug}}}{\left|FS_{u_i} \cdot p_{1i,j}\right|} - 1
\]

\[
\text{min}(\text{MSu1}) = 6.1
\]

\[
\text{MSu}_{2i,j} := \frac{F_{\text{tug}}}{\left|FS_{u_i} \cdot p_{2i,j}\right|} - 1
\]

\[
\text{min}(\text{MSu2}) = 5.005
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Landing, Fail-Safe
One Standoff Bracket to Box S Removed - Margins of Safety

\[ MSu_{i,j} := \min (MSu_{1_{i,j}}, MSu_{2_{i,j}}) \]  \( \min (MSu) = 5.005 \)  \( \ldots \text{Ultimate (using Principal)} \)

\[ MSy_{i,j} := \left( \frac{F_{lyg}}{F_{sy} \cdot vm_{i,j}} \right) - 1 \]  \( \min (MSy) = 4.15 \)  \( \ldots \text{Yield (using Von-Mises)} \)

\[ MSsu_{i,j} := \left( \frac{F_{aug}}{FS_{u} \cdot umax_{i,j}} \right) - 1 \]  \( \min (MSsu) = 6.72 \)  \( \ldots \text{Ultimate (Shear)} \)
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff

64 Liftoff Conditions - Loads

Zero Out All Variables

\[
\begin{align*}
M2 &: = 0 & S1 &: = 0 & M1 &: = 0 & S2 &: = 0 & MSu &: = 0 & u_{\max} &: = 0 & p1 &: = 0 & u_{v} &: = 0 \\
u &: = 0 & \text{MaxShear} &: = 0 & MSy &: = 0 & MSu1 &: = 0 & p2 &: = 0 & Tx &: = 0 & id &: = 0 \\
: &: = 0 & \text{MaxTension} &: = 0 & MSsu &: = 0 & MSu2 &: = 0 & \text{vm} &: = 0 & Fax &: = 0 & \text{cases} &: = 0
\end{align*}
\]

\text{forces} := \text{READPRN("Beams-20-lo.txt")}

\[
\begin{align*}
j & := 1 \ldots \text{rows(\text{forces})} & \text{id}_{j} & := \text{forces}_{j, 1} & \text{cases}_{j} & := \text{forces}_{j, 2} \\
\text{M1}_{j} & := \text{forces}_{j, 3} \cdot \text{in} \cdot \text{lbf} & \text{M2}_{j} & := \text{forces}_{j, 4} \cdot \text{in} \cdot \text{lbf} & \text{Tx}_{j} & := \text{forces}_{j, 8} \cdot \text{in} \cdot \text{lbf} \\
\text{S1}_{j} & := \text{forces}_{j, 5} \cdot \text{lbf} & \text{S2}_{j} & := \text{forces}_{j, 6} \cdot \text{lbf} & \text{Fax}_{j} & := \text{forces}_{j, 7} \cdot \text{lbf} \\
\text{M1}_{\text{rows(\text{forces})}} & := \text{forces}_{j, 9} \cdot \text{in} \cdot \text{lbf} & \text{M2}_{\text{rows(\text{forces})}} & := \text{forces}_{j, 10} \cdot \text{in} \cdot \text{lbf} \\
\text{S2}_{\text{rows(\text{forces})}} & := \text{forces}_{j, 12} \cdot \text{lbf} & \text{S1}_{\text{rows(\text{forces})}} & := \text{forces}_{j, 11} \cdot \text{lbf} \\
\text{id}_{\text{rows(\text{forces})}} & := \text{forces}_{j, 1} \\
\text{cases}_{\text{rows(\text{forces})}} & := \text{forces}_{j, 2} \\
\text{Fx} & := \text{Fax} & \max(\text{Fx}) &= 10.548 \text{ lbf} & \min(\text{Fx}) &= -9.216 \text{ lbf} \\
\text{Fy} & := \text{S1} & \max(\text{Fy}) &= 1.556 \text{ lbf} & \min(\text{Fy}) &= -1.559 \text{ lbf} \\
\text{Fz} & := \text{S2} & \max(\text{Fz}) &= 6.21 \text{ lbf} & \min(\text{Fz}) &= -7.363 \text{ lbf} \\
\text{Mz} & := \text{M1} & \max(\text{Mz}) &= 1.555 \text{ in} \cdot \text{lbf} & \min(\text{Mz}) &= -1.188 \text{ in} \cdot \text{lbf} \\
\text{My} & := -\text{M2} & \max(\text{My}) &= 2.358 \text{ in} \cdot \text{lbf} & \min(\text{My}) &= -2.359 \text{ in} \cdot \text{lbf} \\
\text{T} & := \text{Tx} & \max(\text{T}) &= 0.921 \text{ in} \cdot \text{lbf} & \min(\text{T}) &= -0.923 \text{ in} \cdot \text{lbf}
\end{align*}
\]

\textbf{Rivet Hole Loads}

\[
\begin{align*}
\text{MaxTension}_{j} & := \sqrt{\left(\text{Fz}_{j}\right)^{2}} & \max(\text{MaxTension}) &= 7.363 \text{ lbf} & \min(\text{MaxTension}) &= 0.001 \text{ lbf} \\
\text{MaxShear}_{j} & := \sqrt{\left(\text{Fx}_{j}\right)^{2} + \left(\text{Fy}_{j}\right)^{2}} & \max(\text{MaxShear}) &= 10.548 \text{ lbf} & \min(\text{MaxShear}) &= 0.03 \text{ lbf}
\end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff

64 Liftoff Conditions - Maximum Stresses on Cross Section

Normal is Direct Axial Plus Bending

\[
\frac{F_{x_{ij}}}{A} + \frac{(M_{y_{ij}}\cdot I_{z} + M_{z_{ij}}\cdot I_{y})\cdot c_{z_{ij}}}{I_{y}\cdot I_{z} - I_{y}^2} - \frac{(M_{z_{ij}}\cdot I_{y} + M_{y_{ij}}\cdot I_{z})\cdot c_{y_{ij}}}{I_{y}\cdot I_{z} - I_{y}^2} \]

\[
\text{max}(\ ) = 2404.391 \text{ psi}
\]

Shear Due to Transverse Loading

\[
\frac{F_{y_{ij}}}{A}^2 + \frac{F_{z_{ij}}}{A}^2 \]

\[
\text{max}(\text{uv}) = 136.778 \text{ psi}
\]

Combined Shear

\[
u_{ij} := \sqrt{\left(\frac{F_{y_{ij}}}{A}\right)^2 + \left(\frac{F_{z_{ij}}}{A}\right)^2} \]

\[
\text{max}(\text{u}) = 136.778 \text{ psi}
\]

Principal Stresses

\[
p_{1_{ij}} := \frac{i_{ij}}{2} + \left[\frac{i_{ij}}{2}\right]^2 + \left(u_{ij}\right)^2 \]

\[
\text{max}(\text{p1}) = 2404.695 \text{ psi}
\]

Principal Stresses (cont.)

\[
p_{2_{ij}} := \frac{i_{ij}}{2} - \left[\frac{i_{ij}}{2}\right]^2 + \left(u_{ij}\right)^2 \]

\[
\text{max}(\text{p2}) = -0.001 \text{ psi}
\]

Von-Mises Stress

\[
\sqrt{\left(p_{1_{ij}}\right)^2 + \left(p_{2_{ij}}\right)^2 - p_{1_{ij}}\cdot p_{2_{ij}}} \]

\[
\text{max}(\text{vm}) = 2404.847 \text{ psi}
\]

Maximum Shear Stress

\[
\frac{1}{4} \left(\frac{i_{ij}}{2}\right)^2 + \left(u_{ij}\right)^2 \]

\[
\text{max}(\text{umax}) = 1202.499 \text{ psi}
\]

Max

\[
\frac{1}{\text{FS}_{u_{1_{ij}}}} + 1 \]

\[
\text{min}(\text{MSu1}) = 15.77
\]

\[
\frac{1}{\text{FS}_{u_{2_{ij}}}} + 1 \]

\[
\text{min}(\text{MSu2}) = 15.856
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff

64 Liftoff Conditions - Margins of Safety

\[
MS_{u_{ij}} := \min\left( MSu_{1_{ij}}, MSu_{2_{ij}} \right) \quad \text{min}(MSu) = 15.767 \quad \text{...Ultimate (using Principal)}
\]

\[
MS_{y_{ij}} := \left( \frac{F_{yg}}{FS_{y_{vm_{ij}}}} \right) - 1 \quad \text{min}(MSy) = 13.371 \quad \text{...Yield (using Von-Mises)}
\]

\[
MS_{su_{ij}} := \left( \frac{F_{sug}}{FS_{u_{umax_{ij}}}} \right) - 1 \quad \text{min}(MSsu) = 20.555 \quad \text{...Ultimate (Shear)}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff, Fail-Safe

One Splice Plate Removed - Loads

Zero Out All Variables

\[
\begin{align*}
M2 &:= 0 & S1 &:= 0 & M1 &:= 0 & S2 &:= 0 & MSu &:= 0 & \text{umax} &:= 0 & p1 &:= 0 & uv &:= 0 \\
u &:= 0 & \text{MaxShear} &:= 0 & MSy &:= 0 & MSu1 &:= 0 & p2 &:= 0 & Tx &:= 0 & id &:= 0 \\
:= 0 & \text{MaxTension} &:= 0 & MSsu &:= 0 & MSu2 &:= 0 & \text{vm} &:= 0 & Fax &:= 0 & \text{cases} &:= 0
\end{align*}
\]

\[
\text{forces} := \text{READPRN("Beams-21-lo.txt")}
\]

\[
\begin{align*}
j &:= 1 \ldots \text{rows(\text{forces})} & \text{id}_{j} &:= \text{forces}_{j, 1} & \text{cases}_{j} &:= \text{forces}_{j, 2} \\
M1_{j} &:= \text{forces}_{j, 3} \text{in} \cdot \text{lbf} & M2_{j} &:= \text{forces}_{j, 4} \text{in} \cdot \text{lbf} & Tx_{j} &:= \text{forces}_{j, 8} \text{in} \cdot \text{lbf} & \text{cases}_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 2} \\
S1_{j} &:= \text{forces}_{j, 5} \text{lbf} & S2_{j} &:= \text{forces}_{j, 6} \text{lbf} & Fax_{j} &:= \text{forces}_{j, 7} \text{lbf} & \text{M1}_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 9} \text{in} \cdot \text{lbf} \\
M2_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 10} \text{in} \cdot \text{lbf} & S2_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 12} \text{lbf} & Fax_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 7} \text{lbf} \\
S1_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 11} \text{lbf} & \text{id}_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 1} & \text{cases}_{j+\text{rows(\text{forces})}} &:= \text{forces}_{j, 2} \\
Fx &:= Fax & \max(Fx) &= 11.032 \text{lbf} & \min(Fx) &= -9.254 \text{lbf} \\
Fy &:= S1 & \max(Fy) &= 1.624 \text{lbf} & \min(Fy) &= -1.685 \text{lbf} \\
Fz &:= S2 & \max(Fz) &= 6.906 \text{lbf} & \min(Fz) &= -5.341 \text{lbf} \\
Mz &:= M1 & \max(Mz) &= 1.639 \text{in} \cdot \text{lbf} & \min(Mz) &= -1.504 \text{in} \cdot \text{lbf} \\
My &:= -M2 & \max(My) &= 2.691 \text{in} \cdot \text{lbf} & \min(My) &= -2.694 \text{in} \cdot \text{lbf} \\
T &:= Tx & \max(T) &= 1.076 \text{in} \cdot \text{lbf} & \min(T) &= -1.052 \text{in} \cdot \text{lbf}
\end{align*}
\]

Rivet Hole Loads

\[
\begin{align*}
\text{MaxTension}_{j} &:= \sqrt{(Fz_{j})^{2}} & \max(\text{MaxTension}) &= 6.906 \text{lbf} & \min(\text{MaxTension}) &= 0.001 \text{lbf} \\
\text{MaxShear}_{j} &:= \sqrt{(Fx_{j})^{2} + (Fy_{j})^{2}} & \max(\text{MaxShear}) &= 11.036 \text{lbf} & \min(\text{MaxShear}) &= 0.033 \text{lbf}
\end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff, Fail-Safe
One Splice Plate Removed - Maximum Stresses on Cross Section

Normal is Direct Axial Plus Bending
\[ i,j := \frac{F_{xj}}{A} + \frac{(My_j + Mz_j) \cdot cz_i}{ly \cdot lz - lzy^2} - \frac{(Mz_j \cdot ly + My_j \cdot lzy) \cdot cy_i}{ly \cdot lz - lzy^2} \]
\[ \text{max( } ) = 2771.204 \text{ psi} \]

Shear Due to Transverse Loading
\[ u_{vj} := \sqrt{\left(\frac{F_{yj}}{A}\right)^2 + \left(\frac{F_{zj}}{A}\right)^2} \]
\[ \text{max( } uv \text{ )} = 128.754 \text{ psi} \]

Combined Shear
\[ u_j := u_{vj} \]
\[ \text{max( } u \text{ )} = 128.754 \text{ psi} \]

Principal Stresses
\[ p_{1i,j} := \frac{i,j}{2} + \left[\left(\frac{i,j}{2}\right)^2 + (u_j)^2\right]^{1/2} \]
\[ \text{max( } p1 \text{ )} = 2771.588 \text{ psi} \]

Principal Stresses (cont.)
\[ p_{2i,j} := \frac{i,j}{2} - \left[\left(\frac{i,j}{2}\right)^2 + (u_j)^2\right]^{1/2} \]
\[ \text{max( } p2 \text{ )} = -0.004 \text{ psi} \]

Von-Mises Stress
\[ v_{mi,j} := \sqrt{(p_{1i,j})^2 + (p_{2i,j})^2 - p_{1i,j} \cdot p_{2i,j}} \]
\[ \text{max( } v_{m} \text{ )} = 2771.78 \text{ psi} \]

Maximum Shear Stress
\[ u_{\text{maxi,j}} := \sqrt{\frac{1}{4} \cdot (i,j)^2 + (u_j)^2} \]
\[ \text{max( } u_{\text{max}} \text{ )} = 1385.986 \text{ psi} \]

\[ \text{MSu}_{1i,j} := \frac{F_{\text{tug}}}{F_{\text{S}u^{-p1i,j}}} - 1 \]
\[ \text{min( } \text{MSu1} \text{ )} = 13.55 \]

\[ \text{MSu}_{2i,j} := \frac{F_{\text{tug}}}{F_{\text{S}u^{-p2i,j}}} - 1 \]
\[ \text{min( } \text{MSu2} \text{ )} = 15.425 \]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff, Fail-Safe
One Splice Plate Removed - Margins of Safety

\[
\begin{align*}
MS_{u_{1, j}} &= \min(MS_{u_{1, j}}, MS_{u_{2, j}}) \quad \text{min}(MS_u) = 13.548 \quad \ldots \text{Ultimate (using Principal)} \\
MS_{y_{i, j}} &= \left( \frac{F_{y_{g}}}{FS_{y_i}} \right) - 1 \quad \text{min}(MS_y) = 11.47 \quad \ldots \text{Yield (using Von-Mises)} \\
MS_{su_{i, j}} &= \left( \frac{F_{s_{ug}}}{FS_{u_i} \cdot \mu_{max_{i, j}}} \right) - 1 \quad \text{min}(MS_{su}) = 17.7 \quad \ldots \text{Ultimate (Shear)}
\end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff, Fail-Safe
One Standoff Bracket to Box S Removed - Loads

Zero Out All Variables

\[ M_2 := 0 \quad S_1 := 0 \quad M_1 := 0 \quad S_2 := 0 \quad MSu := 0 \quad v_{\text{max}} := 0 \quad p_1 := 0 \quad u_{\text{v}} := 0 \]
\[ u := 0 \quad \text{MaxShear} := 0 \quad MSy := 0 \quad MSu1 := 0 \quad p_2 := 0 \quad Tx := 0 \quad id := 0 \]
\[ \quad := 0 \quad \text{MaxTension} := 0 \quad MSsu := 0 \quad MSu2 := 0 \quad \v_f := 0 \quad Fax := 0 \quad \text{cases} := 0 \]

\[ \text{forces} := \text{READPRN} ("\text{Beams-22-lo.txt}" ) \]

\[ j := 1 \ldots \text{rows(forces)} \quad \text{id}_j := \text{forces}_j, 1 \quad \text{cases}_j := \text{forces}_j, 2 \]
\[ \text{M1}_j := \text{forces}_j, 3 \cdot \text{in} \cdot \text{lbf} \quad \text{M2}_j := \text{forces}_j, 4 \cdot \text{in} \cdot \text{lbf} \quad \text{Tx}_j := \text{forces}_j, 8 \cdot \text{in} \cdot \text{lbf} \]
\[ \text{S1}_j := \text{forces}_j, 5 \cdot \text{lbf} \quad \text{S2}_j := \text{forces}_j, 6 \cdot \text{lbf} \quad \text{Fax}_j := \text{forces}_j, 7 \cdot \text{lbf} \]
\[ \quad := \text{forces}_j, 9 \cdot \text{in} \cdot \text{lbf} \quad \quad := \text{forces}_j, 10 \cdot \text{in} \cdot \text{lbf} \]
\[ \quad := \text{forces}_j, 12 \cdot \text{lbf} \quad \quad := \text{forces}_j, 11 \cdot \text{lbf} \]
\[ \quad := \text{forces}_j, 1 \quad \quad := \text{forces}_j, 2 \]
\[ \quad := \text{forces}_j, 1 \quad \quad := \text{forces}_j, 2 \]
\[ \quad := \text{forces}_j, 2 \]

\[ F_x := Fax \quad \max (F_x) = 11.822 \text{ lbf} \quad \min (F_x) = -13.191 \text{ lbf} \]
\[ F_y := S_1 \quad \max (F_y) = 2.497 \text{ lbf} \quad \min (F_y) = -2.586 \text{ lbf} \]
\[ F_z := S_2 \quad \max (F_z) = 9.172 \text{ lbf} \quad \min (F_z) = -8.215 \text{ lbf} \]
\[ M_z := M_1 \quad \max (M_z) = 2.637 \text{ in lbf} \quad \min (M_z) = -2.07 \text{ in lbf} \]
\[ M_y := -M_2 \quad \max (M_y) = 3.472 \text{ in lbf} \quad \min (M_y) = -3.47 \text{ in lbf} \]
\[ \quad := Tx \quad \max (T) = 1.802 \text{ in lbf} \quad \min (T) = -1.864 \text{ in lbf} \]

Rivet Hole Loads

\[ \text{MaxTension}_j := \sqrt{(F_x)_j^2} \quad \max (\text{MaxTension}) = 9.172 \text{ lbf} \quad \min (\text{MaxTension}) = 0 \text{ lbf} \]
\[ \text{MaxShear}_j := \sqrt{(F_x)_j^2 + (F_y)_j^2} \quad \max (\text{MaxShear}) = 13.442 \text{ lbf} \quad \min (\text{MaxShear}) = 0.088 \text{ lbf} \]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff, Fail-Safe

One Standoff Bracket to Box S Removed - Maximum Stresses on Cross Section

Normal is Direct Axial Plus Bending

\[
\begin{align*}
  i, j := & \frac{F_{x_j}}{A} + \frac{(M_{y_j} \cdot I_y - M_{z_j} \cdot I_{z_y}) \cdot c_{z_i}}{I_y \cdot I_{z_y}} - \frac{(M_{z_j} \cdot I_y + M_{y_j} \cdot I_{z_y}) \cdot c_{y_i}}{I_y \cdot I_{z_y}} \\
  \text{max}(\quad) &= 3194.14 \text{ psi}
\end{align*}
\]

Shear Due to Transverse Loading

\[
  \begin{align*}
  u_{v_j} &= \sqrt{\left(\frac{F_{y_j}}{A}\right)^2 + \left(\frac{F_{z_j}}{A}\right)^2} \\
  \text{max}(u_v) &= 172 \text{ psi}
  \end{align*}
\]

Combined Shear

\[
  u_j := u_{v_j} \\
  \text{max}(u) &= 172 \text{ psi}
\]

Principal Stresses

\[
  \begin{align*}
  p_{1_{i,j}} &= \frac{i, j}{2} + \left[ \frac{i, j}{2} + (u_j)^2 \right]^{1/2} \\
  \text{max}(p_1) &= 3197.401 \text{ psi}
  \end{align*}
\]

Principal Stresses (cont.)

\[
  \begin{align*}
  p_{2_{i,j}} &= \frac{i, j}{2} - \left[ \frac{i, j}{2} + (u_j)^2 \right]^{1/2} \\
  \text{max}(p_2) &= -0.001 \text{ psi}
  \end{align*}
\]

Von-Mises Stress

\[
  \begin{align*}
  v_{m_{i,j}} &= \sqrt{\left( p_{1_{i,j}} \right)^2 + \left( p_{2_{i,j}} \right)^2 - p_{1_{i,j}} \cdot p_{2_{i,j}}} \\
  \text{max}(v_m) &= 3561.7 \text{ psi}
  \end{align*}
\]

Maximum Shear Stress

\[
  \begin{align*}
  u_{\text{max}_{i,j}} &= \sqrt{\frac{1}{4} \left( i_{,} \right)^2 + (u_j)^2} \\
  \text{max}(u_{\text{max}}) &= 1781.369 \text{ psi}
  \end{align*}
\]

\[
  \begin{align*}
  \text{MSu}_{1_{i,j}} &= \left( \frac{F_{tug}}{F_{Su_i \cdot p_{1_{i,j}}}} \right) - 1 \\
  \text{min}(\text{MSu1}) &= 11.61
  \end{align*}
\]

\[
  \begin{align*}
  \text{MSu}_{2_{i,j}} &= \left( \frac{F_{tug}}{F_{Su_i \cdot p_{2_{i,j}}}} \right) - 1 \\
  \text{min}(\text{MSu2}) &= 10.324
  \end{align*}
\]
TRD Gas Ballistic Cover - Splice Plates SDG39137927/8/9, Liftoff, Fail-Safe
One Standoff Bracket to Box S Removed - Margins of Safety

\[ \text{MSu}_{i,j} := \min \left( \text{MSu}_{1,i,j}, \text{MSu}_{2,i,j} \right) \quad \text{min}(\text{MSu}) = 10.324 \quad \text{...Ultimate (using Principal)} \]

\[ \text{MSy}_{i,j} := \left( \frac{F_{\text{lyg}}}{F_{\text{Sy}} \cdot \nu_{\text{m},i,j}} \right) - 1 \quad \text{min}(\text{MSy}) = 8.703 \quad \text{...Yield (using Von-Mises)} \]

\[ \text{MSsu}_{i,j} := \left( \frac{F_{\text{aug}}}{F_{\text{Su}} \cdot \text{umax}_{i,j}} \right) - 1 \quad \text{min}(\text{MSsu}) = 13.551 \quad \text{...Ultimate (Shear)} \]
CHECK

Note: Figure is for reference only. Not to scale. Actual joint made differ. Washer may be on nut side, head side, or both.

Bolt := "NAS 1351N3LB10, .1900-32, .625L, HRES A286, Self Locking, Passivate, 160ksi"
Washer := "NAS 1149E0332R, .438 OD, .203 ID, .032 THK, Countersunk, CRES A286, 160ksi, Passivate"
Insert := "PEM SOS-032-16-Passivated, .1900-32, .495L, 303 Stainless Steel, Thru-Hole Threaded Standoff"

Flange_1 := "Standoff Bracket A"
Part_Number_1 := "SDG39137917-001"
Material_1 := "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 0.80 Thk, A"
edge1 := 0.500 in  (Minimum Edge Distance of Flange 1)

Flange_2 := "TRD Gas Ballistic Cover - Inner Skin"
Part_Number_2 := "SLG39137916-502"
Material_2 := "AL ALY 6061-T6, SAE-AMS-4027, Sheet, 0.050 Thk, A"
edge2 := 0.500 in  (Minimum Edge Distance of Flange 2)

Methodology

The TRD Gas Ballistic Cover, SLG39137916-701, is attached to Box S with (3) Standoff Bracket A, SDG39137917-001, and (1) Standoff Bracket B, SDG39137918-301. All 4 brackets are AL ALY 7075-T7351. Each Standoff Bracket attaches to the Ballistic Cover by (2) NAS 1351N3LB10 fasteners with NAS 1587A3C washers, going into SOS-032-16 Self Clinching Standoffs in the TRD Gas Ballistic Cover.

A stand-alone FEM of the TRD Gas Ballistic Cover and Standoff Brackets was created. It was constrained at the 4 attachment points to Box S. Twenty-four g-load combinations, using the 40 (g) Load Factor from Table 4-4: Launch/Landing Design Limit Load Factors for Small Secondary Structures, JSC-28792, Rev. E, were analyzed.

The attachments between the Standoff Brackets and the TRD Gas Ballistic Cover are represented by Spider RBE3's (with the center dependent node given 6 dof T1 T2 T3 R1 R2 R3, and the outer independent nodes given T1 T2 T3) in the fastner holes of each flange, connected by CBush elements. The fastener loads between the Standoff Brackets and Cover are recovered as CBush Forces.

The largest absolute CBush Axial (P) load and the largest absolute Cbush Total Shear (V) load, are enveloped across all 4 Standoff Brackets, for all 24 load cases, and then used to calculate the Margins of Safety for the joints. Since each Bracket attaches to the Cover with two fasteners, for Fail-Safe Analysis, the worst case Axial and Total Shear loads were doubled and then used to calculate the Fail-Safe Margins of Safety for the joints.
Allowables

Factors of Safety (reference)

\[ SF_u := 2.00 \] (Ultimate Factor of Safety)

\[ SF_y := 1.25 \] (Yield Factor of Safety)

\[ FF := 1.15 \] (Fitting Factor)

\[ SF_{sep} := 1.20 \] (Joint Separation)

Temperature Data (reference)

\[ Temp_{\text{initial}} := 70 \text{ deg} \] (Assembly)

\[ Temp_{\text{max}} := 140 \text{ deg} \] (Maximum)

\[ Temp_{\text{min}} := -76 \text{ deg} \] (Minimum)

Note: These are maximum temperatures that hardware sees. If maximum load occurs at a different temperature, this will be conservative.

Bolt Data (Bolt = "NAS 1351N3LB10, .1900-32, .625L, HRES A286, Self Locking, Passivate, 160ksi")

\[ D := 0.1900 \text{ in} \] (Nominal Diameter of Bolt)

\[ N_t := 32 \frac{1}{in} \] (Number of Threads/Inch)

\[ D_{\text{shank}} := 0.1840 \text{ in} \] (Shank Diameter of Bolt)

\[ L := 0.625 \text{ in} \] (Total Length of Bolt)

\[ L_t := 0.625 \text{ in} \] (Threaded Length - bolt is fully threaded, input \( L_t = L \))

\[ d_w := 0.303 \text{ in} \] (Bolt Head Dia. Across Flats - dia of pressure boss if it exists, otherwise dia of head)

\[ b_h := 0.185 \text{ in} \] (Bolt Head Height - head height is 0 if bolt is flat head)

Thread data lookup table is hidden
This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

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Bolt Data (Bolt = "NAS 1351N3LB10, .1900-32, .625L, HRES A286, Self Locking, Passivate, 160ksi")

\[ TS_{u\text{-bolt}} := 0.98 \] (Temperature Correction Factor for Bolt Strength)

\[ TS_{y\text{-bolt}} := 0.98 \] (Bolt Ultimate Tensile Allowable Stress)

\[ F_{tu\text{-bolt}} := 160000 \text{ psi} \] (Bolt Ultimate Shear Allowable Stress)

\[ F_{sy\text{-bolt}} := 120000 \text{ psi} \] (Bolt Ultimate Shear Allowable Stress)

\[ F_{su\text{-bolt}} := 0.6 \cdot F_{tu\text{-bolt}} \]

\[ TE_{\text{bolt}} := 0.98 \] (Temperature Correction Factor for Bolt Modulus)

\[ E_{\text{bolt}} := (29.1 \cdot 10^6 \text{ psi}) \] (Modulus of Elasticity of Bolt)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Gas Supply - Standoff Bracket A to TRD Gas Ballistic Cover

**Bolt Thermal Coefficients**

<table>
<thead>
<tr>
<th>Bolt Temperature</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>$9.1 \times 10^{-6}$ in/in/deg</td>
</tr>
<tr>
<td>Cold</td>
<td>$8.5 \times 10^{-6}$ in/in/deg</td>
</tr>
</tbody>
</table>

**Washer Data**

Washer = "NAS 1149E0332R, .438 OD, .203 ID, .032 THK, Countersunk, CRES A286, 160ksi, Passivate"

**Thickness of Washers**

$$tw := 0.032 \text{ in}$$  $$L_{\text{unthreaded}} := 0.197 \text{ in}$$

$$twh := tw + L_{\text{unthreaded}} = 0.229 \text{ in}$$ (Head)

**Diameter of Washer Under Head**

$$D_{\text{woh}} := 0.275 \text{ in}$$ (Outer - Limited to Minimum External Diameter of Standoff)

$$D_{\text{wih}} := 0.203 \text{ in}$$ (Inner)

**Modulus of Elasticity**

$$E_{\text{washerh}} := 29.1 \times 10^6 \text{ psi}$$ (Head)

**Temperature Correction Factor for Modulus**

$$TE_{\text{washerh}} := 0.98$$ (Head) [same as bolt]

**Insert Data**

Insert = "PEM SOS-032-16-Passivated, .1900-32, .495L, 303 Stainless Steel, Thru-Hole Threaded Standoff"

**Temperature Correction Factor for Insert Strength**

$$TS_{\text{ins}} := 0.98$$

**Insert Allowable Stress**

$$F_{\text{tu_ins}} := 73000 \text{ psi}$$ (Ultimate Tensile Allowable Stress)

$$F_{\text{su_ins}} := 0.6 \times F_{\text{tu_ins}}$$ (Ultimate Shear Allowable Stress)

**Dimensions and Notes**

- **Lins** := 0.298 in
- **Fmin** := 0.275 in
- **Ir** := 0.020 in
- **TS_{\text{ins}}** := 0.98
- **F_{\text{tu_ins}}** := 73000 psi
- **F_{\text{su_ins}}** := 0.6 \times F_{\text{tu_ins}}

**Notes:**

- **Lins** := Using threaded length of standoff, L - D, See Appendix A28.7.4
- **Fmin** := Min. External Diameter of Insert
- **Ir** := Depth of Recess for Insert
- **TS_{\text{ins}}** := Temperature Correction Factor for Insert Strength
- **F_{\text{tu_ins}}** := Ultimate Tensile Allowable Stress
- **F_{\text{su_ins}}** := Ultimate Shear Allowable Stress

**Condition/Temp Condition:**

Assuming Lins = Threaded Length of Standoff

- 0.500 Length of Standoff, "L"
- 0.005 Tolerance
- 0.495
- 0.187 Unthreaded Length of Standoff, "D"
- 0.010 Tolerance
- 0.298 Threaded Length of Standoff = Lins

Minimum External Diameter = C - .005 = .275 in

**Condition/Temp Notes:**

- Condition/Temp Condition: UNKNOWN. Could be Annealed, 1/4 1/2 3/4 or Full Hard. So, assuming the weakest, Annealed.

Last Saved 2/24/2009 4:46 PM

5.10.3-76

ESCG-4005-05-AMS-0039
**Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)**

Flange_1 = "Standoff Bracket A"
Material_1 = "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 0.80 Thk, A"

Flange_2 = "TRD Gas Ballistic Cover - Inner Skin"
Material_2 = "AL ALY 6061-T6, SAE-AMS-4027, Sheet, 0.050 Thk, A"

D\_hole := 0.213 in \(\) (Diameter of Thru Hole in Flange 2)

**Thickness of Flanges**

\[ t_{f1} := 0.120 \text{ in} \]
\[ t_{f2} := 0.050 \text{ in} \]

**Compressive Modulus of Elasticity**

\[ E_{\text{flange1}} := \left(10.6 \times 10^6 \text{ psi}\right) \]
\[ E_{\text{flange2}} := \left(10.1 \times 10^6 \text{ psi}\right) \]

**Temperature Correction Factor (Modulus)**

\[ T_{f1E} := 0.98 \]
\[ T_{f2E} := 0.98 \]

**Coefficient of thermal expansion for Flanges**

\[ \beta_{\text{flange1\_hot}} := 12.5 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]
\[ \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

\[ F_{\text{su\_f2}} := 27000 \text{ psi} \] \(\) (Shear Strength of Flange 2, with Temperature Reduction)
\[ T_{f2s} := 0.96 \] \(\) (If Unavailable, Use Temperature Reduction Factor for Ftu)
Debris Shield Fastener Joint Analysis for Bolt/ WASHER with Insert
TRD Gas Supply - Standoff Bracket A to TRD Gas Ballistic Cover

<table>
<thead>
<tr>
<th>Applied Loads (reference)</th>
<th>CBush: ABS Axial Force - Standoff Brackets</th>
</tr>
</thead>
<tbody>
<tr>
<td>P := 52.1 lbf (Tensile)</td>
<td>CBUSH: MAG Shear Force - Standoff Brackets</td>
</tr>
<tr>
<td>V := 71.7 lbf (Shear)</td>
<td></td>
</tr>
<tr>
<td>M := 0.0 in lbf (Bending)</td>
<td></td>
</tr>
</tbody>
</table>

Torque/Preload

| Tmax := 25.6 in lbf (Maximum Torque) |
| Tmin := 21.8 in-lbf (Minimum Torque) |
| n := 0.5 (Loading Plane Factor) |

Joint is lubed/dry

| u := 0.25 (Preload Uncertainty - 0.25 lubed/0.35 dry) |
| k := 0.15 (Torque Coefficient - 0.15 lubed/0.20 dry) |

Stiffness and Margin calculations are hidden

This file uses calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness.mcd

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**Bolt Load**

<table>
<thead>
<tr>
<th>(Bolt/Joint Stiffness Factor)</th>
<th>Pthr_pos = 22.8 lbf (Preload Due to Temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLDmax = 1146 lbf (Max. Preload)</td>
<td>Pthr_neg = -49.1 lbf</td>
</tr>
<tr>
<td>PLDmin = 468 lbf (Min. Preload)</td>
<td></td>
</tr>
<tr>
<td>PLDnom = 898 lbf (Nom. Preload)</td>
<td></td>
</tr>
<tr>
<td>PLDratio = 0.397 (Preload to Yield Ratio nom.)</td>
<td></td>
</tr>
<tr>
<td>Psep = 62.520 lbf (Joint Separation Load)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Applied Tensile Load on Bolt)</th>
<th>Max. Load on Bolt with Preload and Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>P = 52.100 lbf</td>
<td></td>
</tr>
<tr>
<td>V = 71.700 lbf (Applied Shear on Bolt)</td>
<td></td>
</tr>
<tr>
<td>M = 0.000 in lbf (Applied Bending on Bolt)</td>
<td></td>
</tr>
</tbody>
</table>

Max. Load on Bolt With Preload WithOut Factor of Safety

Pbapp = 1159 lbf

Max. Load on Bolt With Preload WithOut Factor of Safety

Pb = 1172 lbf (Ultimate)

Pby = 1162 lbf (Yield)
**Bolt Allowables**

- $P_A = 3018\text{ lbf} = (Bolt\ \text{Ultimate\ Tensile\ Strength)}$
- $VAu = 1649\text{ lbf} = (Bolt\ \text{Shear\ Strength)}$
- $P_{As} = 3337\text{ lbf} = (Thread\ \text{Pullout\ Strength)}$
- $MAu = 63\text{ in-lbf} = (Bolt\ \text{Bending\ Strength)}$

**General Checks**

- $length\_check = "Bolt\ length\ is\ sufficient\ and\ insert\ fully\ engaged"$
- $cone\_check = "Joint\ pressure\ cone\ does\ not\ extend\ pass\ flange\ edge"
- $preload\_check = "WARNING:\ Nominal\ preload\ < 50%\ of\ bolt\ yield\ strength"
- $washer\_check = "Washer(s)\ under\ head\ do\ not\ extend\ past\ flange"
- $insert\_check = "NOTE:\ Insert\ extends\ past\ flange\ two--check\ dimensions"

**Note:** This is because flange 2, the Ballistic Cover, is a half inch sandwich composite (.05 AL skin, .41 AL honeycomb core) but only the .05 AL inner skin resists pullout of the Self-Clinching Standoff.

**Margin of Safety for Standoff Pull-Thru**

- $Insert = "PEM\ SOS-032-16-Passivated, .1900-32, .495L, 303\ Stainless\ Steel, Thru-Hole Threaded Standoff"

**Note:**
- For 0.060 inch thick AL 5052-H34 sheet, Pull-Thru Allowable = 464 lbf.
- For sheet thickness < 0.060 inch, must use 80%.
- Reference: Footnote (2), page SO-11, PEM Bulletin SO 1206

\[
\text{PullThru}_5052H34_060 = 464\text{ lbf} = (AL\ 5052-H34, 0.060\ Inch\ Thick\ Sheet) \\
\text{PullThru}_5052H34_050 = 371.200\text{ lbf} = (AL\ 5052-H34, 0.050\ Inch\ Thick\ Sheet) \\
\text{Fsu}_6061T6 = 27\text{ ksi} = (Shear\ Ultimate\ for\ 6061-T6) \\
\text{Fsu}_5052H34 = 20\text{ ksi} = (Shear\ Ultimate\ for\ 5052-H34) \\
\text{PullThru}_6061T6_050 = \frac{\text{Fsu}_6061T6}{\text{Fsu}_5052H34} \cdot \text{PullThru}_5052H34_050 \\
\text{PullThru}_6061T6_050 = 501.120\text{ lbf} = (AL\ 6061-T6, 0.050\ Inch\ Thick\ Sheet) \\
\text{MS}_\text{PullThru}_6061T6_050 = \frac{\text{PullThru}_6061T6_050}{\text{P}\cdot\text{SFu}\cdot\text{FF}} - 1
\]
Summary of Margins for Bolt

MS\(_1\) = 7.33 \hspace{2cm} \ldots \text{Joint Separation} \hspace{2cm} MS\(_6\) = 26.84 \hspace{2cm} \ldots \text{Direct Thread Shear Ultimate}

MS\(_2\) = 24.19 \hspace{2cm} \ldots \text{Direct Tension Ultimate} \hspace{2cm} MS\(_7\) = 1.85 \hspace{2cm} \ldots \text{Total Thread Shear Ultimate}

MS\(_3\) = 29.22 \hspace{2cm} \ldots \text{Direct Tension Yield} \hspace{2cm} MS\(_8\) = 9 \hspace{2cm} \ldots \text{Shear Ultimate}

MS\(_4\) = 1.58 \hspace{2cm} \ldots \text{Total Tension Ultimate} \hspace{2cm} MS\(_9\) = 100 \hspace{2cm} \ldots \text{Bending Ultimate}

MS\(_5\) = 0.95 \hspace{2cm} \ldots \text{Total Tension Yield} \hspace{2cm} MS\(_{10}\) = 1.55 \hspace{2cm} \ldots \text{Combined Shear, Tension and Bending Ultimate}

Smallest Margin of Safety for Bolt and Failure Mode

MS\(_5\) = 0.95 \hspace{2cm} \ldots \text{Total Tension Yield}

Note: The default MS\(_7\), Total Thread Shear Ultimate, calculation used by this Bolt Analysis Template, Rev. D, is not valid for this analysis because this insert/standoff is installed by pressing (embedding) the standoff's hex head flush in the AL Sheet Inner Skin. This insert is NOT threaded into the flange as the default calculation assumes.
Fail-Safe Analysis

Fail-Safe Loads

\[ P_{FS} := 55.717 \text{ lbf} \] (Applied Tensile)
\[ V_{FS} := 77.195 \text{ lbf} \] (Applied Shear)
\[ M_{FS} := 0.0 \text{ in-lbf} \] (Applied Bending)

Failure Factors of Safety

\[ SF_{u,FS} := 1.0 \] (Ultimate)
\[ SF_{sep,FS} := 1.0 \] (Joint Separation)

\[ P_{sep,FS} = 55.717 \text{ lbf} \] (Joint Separation Load)
\[ P_{b,FS} = 1159.6 \text{ lbf} \] (Max. Ultimate Load on Bolt)

Fail-Safe Margin of Safety for Standoff Pull-Thru

\[ MS_{FS, PullThru, 6061T6, 050} := \frac{P_{PullThru, 6061T6, 050}}{P_{FS} \cdot SF_{u,FS} \cdot FF} - 1 \]
\[ MS_{FS, PullThru, 6061T6, 050} = 6.821 \] ... Standoff Pull-Thru Ultimate

Summary of Fail-Safe Margins for Bolt

\[ MS_{FS1} = 8.35 \] ... Joint Separation
\[ MS_{FS2} = 46.1 \] ... Direct Tension Ultimate
\[ MS_{FS3} = 1.6 \] ... Total Tension Ultimate
\[ MS_{FS4} = 51.07 \] ... Direct Thread Shear Ultimate
\[ MS_{FS5} = 1.88 \] ... Total Thread Shear Ultimate
\[ MS_{FS6} = 17.58 \] ... Shear Ultimate
\[ MS_{FS7} = 10.00 \] ... Bending Ultimate
\[ MS_{FS8} = 1.60 \] ... Combined Shear, Tension, and Bending Ultimate

Smallest Fail-Safe Margin of Safety for Bolt and Failure Mode

\[ MS_{FS8} = 1.60 \] ... Combined Shear, Tension, and Bending Ultimate

Note: The default MS_{FS5}, Total Thread Shear Ultimate, calculation used by this Bolt Analysis Template, Rev. D, is not valid for this analysis because this insert/standoff is installed by pressing (embedding) the standoff’s hex head flush in the AL Sheet Inner Skin. This insert is NOT threaded into the flange as the default calculation assumes.
Bolt Hole Analysis

Recall Loads From Bolt Calculation

Safety Factors
- SFu = 2.00 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

Input Loads
- V = 71.7 lbf (Shear Load)
- P = 52.1 lbf (Axial Load)

Bolt Calc Results
- Pb = 1172 lbf (Max Bolt Load)

Dimensions
- L = 0.625 in (Length of Bolt)
- twh = 0.229 in (Thickness of Washer)

Recall Bolt Hole Dimensions
- tf₁ := tf₁ = 0.120 in (Entire Thickness of Flange 1)
- tf₂ := tf₂ = 0.050 in (Entire Thickness of Flange 2)
- edge₁ := edge₁ = 0.500 in (Edge Distance for Hole in Flange 1)
- edge₂ := edge₂ = 0.500 in (Edge Distance for Hole in Flange 2)
- D = 0.190 in (Diameter of Bolt)
- D_shank = 0.184 in (Min. Shank Diameter of Bolt)
- D_hole = 0.213 in (Diameter of Hole)

Shear Tear-Out Check

Shear Area of the Mating Components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[
A_{\text{shpl}} = \left( 2 \cdot \text{tf} \cdot \frac{1}{2} \cdot \text{D}_{\text{hole}} \right) \left( \text{Plate1} \right) \left( \text{Plate2} \right)
\]

Allowables for Flanges that Fastener Goes Through

- Fsu₁ := Tф₁E = 38 ksi (Ultimate Shear Allowable for Flange 1)
- Fsu₂ := Tф₂E = 27 ksi (Ultimate Shear Allowable for Flange 2)

\[
P_{\text{su}} := \left( A_{\text{shpl}} \cdot F_{\text{su}} \right)
\]

\[
P_{\text{su}} = \begin{cases} 
3517 \text{ lbf} & \text{Plate1} \\
1041 \text{ lbf} & \text{Plate2} 
\end{cases}
\]

(Shear Ultimate Allowable)

Margin of Safety for Shear Tear-Out

\[
M_{\text{su}} := \left( \frac{P_{\text{su}}}{V \cdot SFu \cdot FF} - 1 \right) \left( \text{Plate1} \right) \left( \text{Plate2} \right)
\]

\[
M_{\text{su}} = \begin{cases} 
20.33 & \text{Plate1} \\
5.31 & \text{Plate2} 
\end{cases}
\]

\[
M_{\text{bh₁}} := \min \left( M_{\text{su}} \right)
\]

\[
M_{\text{bh₁}} = 5.314
\]

... Shear Tear-Out

Typical shear tear-out failure
Bearing Check

Recall Bolt Hole Dimensions

- \( t_f_1 = 0.120 \text{ in} \) (Thickness of Flange 1)
- \( t_f_2 = 0.050 \text{ in} \) (Thickness of Flange 2)
- \( \text{edge}_1 = 0.500 \text{ in} \) (Edge Distance for thru Hole in Flange 1)
- \( \text{edge}_2 = 0.500 \text{ in} \) (Edge Distance for tapped Hole in Flange 2)

\[
(\text{Bearing Areas})
\]

\[
A_{br} := \frac{(t_f-\min(D, D_{shank}))}{2}\left(\frac{A_{br}^1}{\text{Plate1}} \frac{A_{br}^2}{\text{Plate2}}\right)
\]

\[
e_{D} := \frac{\text{edge}}{D_{hole}}
\]

Bearing Allowables for Flanges that Fastener Goes Through

<table>
<thead>
<tr>
<th>Flange 1</th>
<th>Flange 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru ((e/D=1.5))</td>
<td>Fbru15 := Ti1E·103ksi</td>
</tr>
<tr>
<td>Fbru ((e/D=2.0))</td>
<td>Fbru20 := Ti1E·132ksi</td>
</tr>
<tr>
<td>Fbry ((e/D=1.5))</td>
<td>Fbry15 := Ti1E·81ksi</td>
</tr>
<tr>
<td>Fbry ((e/D=2.0))</td>
<td>Fbry20 := Ti1E·97ksi</td>
</tr>
</tbody>
</table>

Modified Bearing Strength

\[
Fbru_m := \begin{cases} 
\text{if } e_D > 2.0, Fbru_{20}, \frac{e_D - 1.5}{2.0 - 1.5} (Fbru_{20} - Fbru_{15}), & \text{Fbru}_{15} \left(\text{e}_D < 0.5\right) \\
\text{if } e_D > 2.0, Fbru_{20}, \left(\text{e}_D > 0.5\right), & \text{Fbru}_{15} + e_D - 1.5 \\
\frac{e_D - 1.5}{2.0 - 1.5}, & \text{Fbru}_{20} - \text{Fbru}_{15} \\
\end{cases}
\]

\[
Fbry_m := \begin{cases} 
\text{if } e_D > 2.0, Fbry_{20}, \frac{e_D - 1.5}{2.0 - 1.5} (Fbry_{20} - Fbry_{15}), & \text{Fbry}_{15} \left(\text{e}_D < 0.5\right) \\
\text{if } e_D > 2.0, Fbry_{20}, \left(\text{e}_D > 0.5\right), & \text{Fbry}_{15} + e_D - 1.5 \\
\frac{e_D - 1.5}{2.0 - 1.5}, & \text{Fbry}_{20} - \text{Fbry}_{15} \\
\end{cases}
\]

- \( Fbru_m \left(\text{Ultimate}\right) = \frac{129.36}{86.24} \text{ ksi} \) (Plate1) (Plate2)
- \( Fbry_m \left(\text{Yield}\right) = \frac{95.06}{56.84} \text{ ksi} \) (Plate1) (Plate2)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Gas Supply - Standoff Bracket A to TRD Gas Ballistic Cover

\[
P_{bru} := \left( \frac{A_{bru}}{F_{bru,m}} \right) \quad P_{bru} = \left( \frac{2856}{793} \right) \text{lbf} \quad (Bearing \ Ultimate \ Allowable)
\]

\[
P_{bry} := \left( \frac{A_{bry}}{F_{bry,m}} \right) \quad P_{bry} = \left( \frac{2099}{523} \right) \text{lbf} \quad (Bearing \ Yield \ Allowable)
\]

**Margin of Safety for Bearing Failure**

\[
MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right) \quad MS_{bru} = \left( \frac{16.320}{3.811} \right) \quad \text{Plate1}
\]

\[
MS_{bh2} := \min(\{MS_{bru}\}) \quad MS_{bh2} = 3.811 \quad \text{... Bearing Ultimate Strength}
\]

\[
MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right) \quad MS_{bry} = \left( \frac{19.36}{4.07} \right) \quad \text{Plate1}
\]

\[
MS_{bh3} := \min(\{MS_{bry}\}) \quad MS_{bh3} = 4.074 \quad \text{... Bearing Yield Strength}
\]
Bolt := "NAS 1351N3LB10, .1900-32, .625L, HRES A286, Self Locking, Passivate, 160ksi"
Washer := "NAS 1149E0332R, .438 OD, .203 ID, .032 THK, Countersunk, CRES A286, 160ksi, Passivate"
Insert := "PEM SOS-032-16-Passivated, .1900-32, .495L, 303 Stainless Steel, Thru-Hole Threaded Standoff"

Flange_1 := "Standoff Bracket B"
Part_Number_1 := "SDG39137918-001"
Material_1 := "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 1.00 Thk, A"
edge1 := 0.500 in  (Minimum Edge Distance of Flange 1)

Flange_2 := "TRD Gas Ballistic Cover - Inner Skin"
Part_Number_2 := "SLG39137916-502"
Material_2 := "AL ALY 6061-T6, SAE-AMS-4027, Sheet, 0.050 Thk, A"
edge2 := 0.500 in  (Minimum Edge Distance of Flange 2)

Methodology

The TRD Gas Ballistic Cover, SLG39137916-701, is attached to Box S with (3) Standoff Bracket A, SDG39137917-001, and (1) Standoff Bracket B, SDG39137918-301. All 4 brackets are AL ALY 7075-T7351. Each Standoff Bracket attaches to the Ballistic Cover by (2) NAS 1351N3LB10 fasteners with NAS 1587A3C washers, going into SOS-032-16 Self Clinching Standoffs in the TRD Gas Ballistic Cover.

A stand-alone FEM of the TRD Gas Ballistic Cover and Standoff Brackets was created. It was constrained at the 4 attachment points to Box S. Twenty-four g-load combinations, using the 40 (g) Load Factor from Table 4-4: Launch/Landing Design Limit Load Factors for Small Secondary Structures, JSC-28792, Rev. E, were analyzed.

The attachments between the Standoff Brackets and the TRD Gas Ballistic Cover are represented by Spider RBE3's (with the center dependent node given 6 dof T1 T2 T3 R1 R2 R3, and the outer independent nodes given T1 T2 T3) in the fastner holes of each flange, connected by CBush elements. The fastener loads between the Standoff Brackets and Cover are recovered as CBush Forces.

The largest absolute CBush Axial (P) load and the largest absolute CBush Total Shear (V) load, are enveloped across all 4 Standoff Brackets, for all 24 load cases, and then used to calculate the Margins of Safety for the joints. Since each Bracket attaches to the Cover with two fasteners, for Fail-Safe Analysis, the worst case Axial and Total Shear loads were doubled and then used to calculate the Fail-Safe Margins of Safety for the joints.
Allowables

Factors of Safety (reference)

\[ SF_u = 2.00 \]  
\[ SF_y = 1.25 \]  
\[ FF = 1.15 \]  
\[ SF_{sep} = 1.20 \]

\( SF_u \) := Ultimate Factor of Safety  
\( SF_y \) := Yield Factor of Safety  
\( FF \) := Fitting Factor  
\( SF_{sep} \) := Joint Separation

Temperature Data (reference)

\[ \text{Temp}_{\text{initial}} = 70 \text{ deg} \]  
\[ \text{Temp}_{\text{max}} = 140 \text{ deg} \]  
\[ \text{Temp}_{\text{min}} = -76 \text{ deg} \]

Note: These are maximum temperatures that hardware sees. If maximum load occurs at a different temperature, this will be conservative.

Bolt Data (Bolt = "NAS 1351N3LB10, .1900-32, .625L, HRES A286, Self Locking, Passivate, 160ksi")

\[ D = 0.1900 \text{ in} \]  
\[ N_t = 32 \frac{1}{\text{in}} \]  
\[ D_{\text{shank}} = 0.1840 \text{ in} \]  
\[ L = 0.625 \text{ in} \]  
\[ L_t = 0.625 \text{ in} \]  
\[ d_w = 0.303 \text{ in} \]  
\[ b_h = 0.185 \text{ in} \]

Note: If there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area.

Thread data lookup table is hidden
This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

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Bolt Data (Bolt = "NAS 1351N3LB10, .1900-32, .625L, HRES A286, Self Locking, Passivate, 160ksi")

\[ T_{SU_{\text{bolt}}} = 0.98 \]  
\[ T_{SY_{\text{bolt}}} = 0.98 \]  
\[ F_{tu_{\text{bolt}}} = 160000 \text{ psi} \]  
\[ F_{ty_{\text{bolt}}} = 120000 \text{ psi} \]  
\[ F_{su_{\text{bolt}}} = 0.6 \times F_{tu_{\text{bolt}}} \]  
\[ T_{E_{\text{bolt}}} = 0.98 \]  
\[ E_{\text{bolt}} = \left(29.1 \times 10^6\right) \text{ psi} \]

(Temperature Correction Factor for Bolt Strength)  
(Bolt Ultimate Tensile Allowable Stress)  
(Bolt Ultimate Shear Allowable Stress)  
(Temperature Correction Factor for Bolt Modulus)  
(Modulus of Elasticity of Bolt)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert  
TRD Gas Supply - Standoff Bracket B to TRD Gas Ballistic Cover

(Thermal Coefficients for Bolt)

\[ \beta_{\text{bolt\_hot}} := 9.1 \times 10^6 \frac{\text{in}}{\text{deg}} \]
\[ \beta_{\text{bolt\_cold}} := 8.5 \times 10^6 \frac{\text{in}}{\text{deg}} \]

Washer Data (Washer = "NAS 1149E0332R, .438 OD, .203 ID, .032 THK, Countersunk, CRES A286, 160ksi, Passivate")

Thickness of Washers

\[ tw := 0.032 \text{ in} \]
\[ L_{\text{unthreaded}} := 0.197 \text{ in} \]
\[ twh := tw + L_{\text{unthreaded}} \]
\[ twh = 0.229 \text{ in} \]  
(Head)

Diameter of Washer Under Head

\[ D_{\text{woh}} := 0.275 \text{ in} \]  
(Outer - Limited to Minimum External Diameter of Standoff)

\[ D_{\text{wih}} := 0.203 \text{ in} \]  
(Inner)

Modulus of Elasticity

\[ E_{\text{washerh}} := 29.1 \times 10^6 \text{ psi} \]  
(Head)

Temperature Correction Factor for Modulus

\[ T_{E_{\text{washerh}}} := 0.98 \]  
(Head)  
[same as bolt]

Insert Data (Insert = "PEM SOS-032-16-Passivated, .1900-32, .495L, 303 Stainless Steel, Thru-Hole Threaded Standoff")

\[ L_{\text{ins}} := 0.298 \text{ in} \]  
(USING THREADED LENGTH OF STANDOFF, L - D)

\[ F_{\text{min}} := 0.275 \text{ in} \]  
(Min. External Diameter of Insert)

\[ l_r := 0.020 \text{ in} \]  
(Depth of Recess for Insert)

\[ T_{S_{\text{ins}}} := 0.98 \]  
(Temperature Correction Factor for Insert Strength)

\[ F_{\text{tu\_ins}} := 73000 \text{ psi} \]  
(Ultimate Tensile Allowable Stress)

\[ F_{\text{su\_ins}} := 0.6 \times F_{\text{tu\_ins}} \]  
(Ultimate Shear Allowable Stress)

Note: CONDITION/TEMPER UNKNOWN. Could be Annealed, 1/4 1/2 3/4 or Full Hard. So, assuming the weakest, Annealed.
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Flange_1 = "Standoff Bracket B"
Material_1 = "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 1.00 Thk, A"

Flange_2 = "TRD Gas Ballistic Cover - Inner Skin"
Material_2 = "AL ALY 6061-T6, SAE-AMS-4027, Sheet, 0.050 Thk, A"

D_hole := 0.213 in (Diameter of Thru Hole in Flange 2)

Thickness of Flanges

\[
\begin{align*}
tf1 & := 0.120 \text{ in} \\
tf2 & := 0.050 \text{ in}
\end{align*}
\]

Compressive Modulus of Elasticity

\[
\begin{align*}
E_{flange1} & := (10.6 \times 10^6 \text{ psi}) \\
E_{flange2} & := (10.1 \times 10^6 \text{ psi})
\end{align*}
\]

Temperature Correction Factor (Modulus)

\[
\begin{align*}
Tf1E & := 0.98 \\
Tf2E & := 0.98
\end{align*}
\]

Coefficient of thermal expansion for Flanges

\[
\begin{align*}
\beta_{flange1\_hot} & := 12.5 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \\
\beta_{flange1\_cold} & := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \\
\beta_{flange2\_hot} & := 12.8 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \\
\beta_{flange2\_cold} & := 12.1 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}}
\end{align*}
\]

\[
\begin{align*}
F_{su\_f2} & := 27000 \text{ psi} \quad \text{(Shear Strength of Flange 2, with Temperature Reduction)} \\
Tf2s & := 0.96 \quad \text{(If Unavailable, Use Temperature Reduction Factor for Ftu)}
\end{align*}
\]
Applied Loads (reference)

P := 52.1 lbf (Tensile)  

V := 71.7 lbf (Shear)  

M := 0.0 in lbf (Bending)  

Torque/Preload

Tmax := 25.6 in lbf (Maximum Torque)  

Tmin := 21.8 in lbf (Minimum Torque)  

n := 0.5 (Loading Plane Factor)  

Joint is lubed/dry  

u := 0.25 (Preload Uncertainty - 0.25 lubed/0.35 dry)  

k := 0.15 (Torque Coefficient - 0.15 lubed/0.20 dry)  

Stiffness and Margin calculations are hidden

This file uses calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness.mcd

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Bolt Load

= 0.436 (Bolt/Joint Stiffness Factor)  

Pthr_pos = 22.8 lbf (Preload Due to Temperature)  

PLDmax = 1146 lbf (Max. Preload)  

Pthr_neg = -49.1 lbf (Min. Preload)  

PLDnom = 898 lbf (Nom. Preload)  

u = 0.25 (Uncertainty Factor)  

PLDratio = 0.397 (Preload to Yield Ratio nom.)  

k = 0.150 (Torque Coefficient)  

Psep = 62.520 lbf (Joint Separation Load)  

n = 0.500 (Loading Plane Factor)  

Max. Load on Bolt with Preload and Factor of Safety

Max. Load on Bolt With Preload Without Factor of Safety

Last Saved 2/24/2009 3:22 PM
# Bolt Allowables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{At} ) (Bolt Ultimate Tensile Strength)</td>
<td>3018 lbf</td>
</tr>
<tr>
<td>( P_{Au} ) (Bolt Shear Strength)</td>
<td>1649 lbf</td>
</tr>
<tr>
<td>( P_{As} ) (Thread Pullout Strength)</td>
<td>3337 lbf</td>
</tr>
<tr>
<td>( M_{Au} ) (Bolt Bending Strength)</td>
<td>63 in-lbf</td>
</tr>
</tbody>
</table>

# General Checks

- **length_check** = "Bolt length is sufficient and insert fully engaged"
- **cone_check** = "Joint pressure cone does not extend pass flange edge"
- **preload_check** = "WARNING: Nominal preload < 50% of bolt yield strength"
- **washer_check** = "Washer(s) under head do not extend past flange"
- **insert_check** = "NOTE: Insert extends past flange two--check dimensions"

# Margin of Safety for Standoff Pull-Thru

Insert = "PEM SOS-032-16-Passivated, .1900-32, .495L, 303 Stainless Steel, Thru-Hole Threaded Standoff"

- **PullThru_5052H34_060** = 464 lbf (AL 5052-H34, 0.060 Inch Thick Sheet)
- **PullThru_5052H34_050** = 371.200 lbf (AL 5052-H34, 0.050 Inch Thick Sheet)
- **Fsu_6061T6** = 27 ksi (Shear Ultimate for 6061-T6)
- **Fsu_5052H34** = 20 ksi (Shear Ultimate for 5052-H34)


\[
MS_{PullThru_6061T6_050} := \frac{PullThru_6061T6_050}{P \cdot SFu \cdot FF} - 1
\]
Summary of Margins for Bolt

- MS₁ = 7.33 \text{ ...Joint Separation}
- MS₂ = 24.19 \text{ ...Direct Tension Ultimate}
- MS₃ = 29.22 \text{ ...Direct Tension Yield}
- MS₄ = 1.58 \text{ ...Total Tension Ultimate}
- MS₅ = 0.95 \text{ ...Total Tension Yield}
- MS₆ = 26.84 \text{ ...Direct Thread Shear Ultimate}
- MS₇ = 1.85 \text{ ...Total Thread Shear Ultimate}
- MS₈ = 9 \text{ ...Shear Ultimate}
- MS₉ = 100 \text{ ...Bending Ultimate}
- MS₁₀ = 1.55 \text{ ...Combined Shear, Tension and Bending Ultimate}

Smallest Margin of Safety for Bolt and Failure Mode

- MS₅ = 0.95 \text{ ...Total Tension Yield}

Note: The default MS7, Total Thread Shear Ultimate, calculation used by this Bolt Analysis Template, Rev. D, is not valid for this analysis because this insert/standoff is installed by pressing (embedding) the standoff’s hex head flush in the AL Sheet Inner Skin. This insert is NOT threaded into the flange as the default calculation assumes.
Fail-Safe Analysis

Fail-Safe Loads

(See A28.7.1.15.1 One Splice Plate Removed, Landing & Liftoff)

**CBSH: ABS Axial Force - Standoff Brackets**

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>AXIAL</th>
<th>SHEAR</th>
<th>MX</th>
<th>MY</th>
<th>MZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000006</td>
<td>2030</td>
<td>-5.571735E+01</td>
<td>1.274937E+01</td>
<td>-3.635549E-01</td>
<td>3.725737E-02</td>
<td>7.099232E+03</td>
</tr>
</tbody>
</table>

**CBSH: MAG Shear Force - Standoff Brackets**

<table>
<thead>
<tr>
<th>ID</th>
<th>SUBCASE</th>
<th>AXIAL</th>
<th>SHEAR</th>
<th>MX</th>
<th>MY</th>
<th>MZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000005</td>
<td>2030</td>
<td>-3.173613E+01</td>
<td>7.719511E+01</td>
<td>1.765853E+01</td>
<td>-1.349644E+01</td>
<td>3.9308835E+03</td>
</tr>
</tbody>
</table>

**Fail-Safe Factors of Safety**

SFu_FS := 1.0 (Ultimate)
SFsep_FS := 1.0 (Joint Separation)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated
This file calculations shown in \\escfil02\i11\mathcad\8307_bolts\Rev_D\bolt_insert_stiffness__FS.mcd

**Bolt Fail-Safe Load Data**

Psep_FS := 55.717 lbf (Joint Separation Load)
Pb_FS = 1159.6 lbf (Max. Ultimate Load on Bolt)

**Fail-Safe Margin of Safety for Standoff Pull-Thru**

MS_FS_PullThru_6061T6_050 := \( \frac{PullThru_6061T6_050}{P_FS \cdot SFu_FS \cdot FF} - 1 \)

MS_FS_PullThru_6061T6_050 = 6.821 ... Standoff Pull-Thru Ultimate

**Summary of Fail-Safe Margins for Bolt**

<table>
<thead>
<tr>
<th>MS_FS</th>
<th>...Joint Separation</th>
<th>MS_FS</th>
<th>...Total Thread Shear Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.35</td>
<td></td>
<td>1.88</td>
<td></td>
</tr>
<tr>
<td>46.1</td>
<td>...Direct Tension Ultimate</td>
<td>17.58</td>
<td>...Shear Ultimate</td>
</tr>
<tr>
<td>1.6</td>
<td>...Total Tension Ultimate</td>
<td>10.00</td>
<td>...Bending Ultimate</td>
</tr>
<tr>
<td>51.07</td>
<td>...Direct Thread Shear Ultimate</td>
<td>1.60</td>
<td>...Combined Shear, Tension, and Bending Ultimate</td>
</tr>
</tbody>
</table>

**Smallest Fail-Safe Margin of Safety for Bolt and Failure Mode**

MS_FS := 1.60 ...Combined Shear, Tension, and Bending Ultimate

Note: The default MS_FS5, Total Thread Shear Ultimate, calculation used by this Bolt Analysis Tempate, Rev. D, is not valid for this analysis because this insert/standoff is installed by pressing (embedding) the standoff’s hex head flush in the AL Sheet Inner Skin. This insert is NOT threaded into the flange as the default calculation assumes.
**Bolt Hole Analysis**

**Recall Loads From Bolt Calculation**

**Safety Factors**
- SFu = 2.00 (Ultimate)
- SFy = 1.250 (Yield)
- FF = 1.150 (Fitting Factor)

**Input Loads**
- V = 71.7 lbf (Shear Load)
- P = 52.1 lbf (Axial Load)

**Bolt Calc Results**
- Pb = 1172 lbf (Max Bolt Load)

**Dimensions**
- L = 0.625 in (Length of Bolt)
- twh = 0.229 in (Thickness of Washer)

**Recall Bolt Hole Dimensions**
- tf1 := tf1 = 0.120 in (Entire Thickness of Flange 1)
- tf2 := tf2 = 0.050 in (Entire Thickness of Flange 2)
- edge1 := edge1 = 0.500 in (Edge Distance for Hole in Flange 1)
- edge2 := edge2 = 0.500 in (Edge Distance for Hole in Flange 2)
- D = 0.190 in (Diameter of Bolt)
- D_shank = 0.184 in (Min. Shank Diameter of Bolt)
- D_hole = 0.213 in (Diameter of Hole)

**Shear Tear-Out Check**

**Shear Area of the Mating Components**

\[ A_{shrpl} = \left( 2 \cdot \text{tf} \cdot \frac{\text{edge}}{2} - \frac{D_{\text{hole}}}{2} \right) \times \left( \frac{\text{Plate1}}{\text{Plate2}} \right) \]

\[ A_{shrpl} = \left( \frac{0.094}{0.039} \right) \text{ in}^2 \]

**Allowables for Flanges that Fastener Goes Through**
- Fsu1 := T11E = 38 ksi (Ultimate Shear Allowable for Flange 1)
- Fsu2 := T12E = 27 ksi (Ultimate Shear Allowable for Flange 2)

\[ P_{su} := \left( A_{shrpl} \times \text{Fsu} \right) \]

\[ P_{su} = \left( \frac{3517}{1041} \right) \text{ lbf} \]

**Margin of Safety for Shear Tear-Out**

\[ MS_{su} := \left( \frac{P_{su}}{V \times \text{SFu} \times \text{FF}} - 1 \right) \times \left( \frac{\text{Plate1}}{\text{Plate2}} \right) \]

\[ MS_{su} = \left( \frac{20.33}{5.31} \right) \]

**Minimum Margin of Safety**

**MSbh1 := min(MSsu) = 5.314**

... Shear Tear-Out
Bearing Check

Recall Bolt Hole Dimensions

\[
\begin{align*}
tf_1 &= 0.120 \text{ in} & \text{(Thickness of Flange 1)} \\
ft_2 &= 0.050 \text{ in} & \text{(Thickness of Flange 2)} \\
edge_1 &= 0.500 \text{ in} & \text{(Edge Distance for thru Hole in Flange 1)} \\
edge_2 &= 0.500 \text{ in} & \text{(Edge Distance for tapped Hole in Flange 2)}
\end{align*}
\]

\[
A_{br} := \frac{(tf - \min(D, D_{shank}))}{(Plate1 \div Plate2)} \quad A_{br} = \begin{pmatrix} 0.022 \\ 0.009 \end{pmatrix} \text{ in}^2 \quad \text{(Bearing Areas)}
\]

\[
e_D := \frac{\text{edge}}{D_{hole}} \quad e_D = \begin{pmatrix} 2.347 \\ 2.347 \end{pmatrix} \quad \text{(e/D for Flanges)}
\]

Bearing Allowables for Flanges that Fastener Goes Through

<table>
<thead>
<tr>
<th>Flange 1</th>
<th>Flange 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru (e/D=1.5)</td>
<td>Fbru151 := T11E-103ksi</td>
</tr>
<tr>
<td>Fbru (e/D=2.0)</td>
<td>Fbru201 := T11E-132ksi</td>
</tr>
<tr>
<td>Fbry (e/D=1.5)</td>
<td>Fbry151 := T11E-81ksi</td>
</tr>
<tr>
<td>Fbry (e/D=2.0)</td>
<td>Fbry201 := T11E-97ksi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flange 1</th>
<th>Flange 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru151 := T11E-103ksi</td>
<td>Fbru151 = 100.94 ksi</td>
</tr>
<tr>
<td>Fbru201 := T11E-132ksi</td>
<td>Fbru152 := T12E-67ksi</td>
</tr>
<tr>
<td>Fbry151 := T11E-81ksi</td>
<td>Fbry151 = 79.38 ksi</td>
</tr>
<tr>
<td>Fbry201 := T11E-97ksi</td>
<td>Fbry201 = 95.060 ksi</td>
</tr>
</tbody>
</table>

Modified Bearing Strength

\[
\begin{align*}
\text{Fbru}_m &= \frac{e_D}{2.0} \times \text{Fbru151}, \text{if } \begin{cases} \text{e_D} > 2.0 \text{ ksi}, \text{Fbru201} \text{, if } \begin{cases} \text{e_D} > 1.5 \text{ ksi}, \text{Fbru151} + \frac{e_D}{2.0} - 1.5 \text{ ksi} \end{cases} \end{cases} \\
\text{Fbru}_m &= \frac{e_D}{2.0} \times \text{Fbru152} \text{, if } \begin{cases} \text{e_D} > 2.0 \text{ ksi}, \text{Fbru202} \text{, if } \begin{cases} \text{e_D} > 2.0 \text{ ksi}, \text{Fbru201} + \frac{e_D}{2.0} - 1.5 \text{ ksi} \end{cases} \end{cases} \\
\text{Fbry}_m &= \frac{e_D}{2.0} \times \text{Fbry151} \text{, if } \begin{cases} \text{e_D} > 2.0 \text{ ksi}, \text{Fbry201} \text{, if } \begin{cases} \text{e_D} > 1.5 \text{ ksi}, \text{Fbry151} + \frac{e_D}{2.0} - 1.5 \text{ ksi} \end{cases} \end{cases} \\
\text{Fbry}_m &= \frac{e_D}{2.0} \times \text{Fbry152} \text{, if } \begin{cases} \text{e_D} > 2.0 \text{ ksi}, \text{Fbry202} \text{, if } \begin{cases} \text{e_D} > 2.0 \text{ ksi}, \text{Fbry201} + \frac{e_D}{2.0} - 1.5 \text{ ksi} \end{cases} \end{cases}
\end{align*}
\]

\[
\begin{align*}
\text{Fbru}_m &= \begin{pmatrix} 129.36 \\ 86.24 \end{pmatrix} \text{ ksi} \quad \text{(Ultimate)} \\
\text{Fbry}_m &= \begin{pmatrix} 95.06 \\ 56.84 \end{pmatrix} \text{ ksi} \quad \text{(Yield)}
\end{align*}
\]
P_{bru} := \left( \frac{A_{bru} \cdot F_{bru \_m}}{A_{bru} \cdot F_{bru \_m}} \right) lbf
P_{bru} = \left( \frac{2856}{793} \right) lbf \quad (Bearing \ \text{Ultimate Allowable})

P_{bry} := \left( \frac{A_{bry} \cdot F_{bry \_m}}{A_{bry} \cdot F_{bry \_m}} \right) lbf
P_{bry} = \left( \frac{2099}{523} \right) lbf \quad (Bearing \ \text{Yield Allowable})

\textbf{Margin of Safety for Bearing Failure}

MS_{bru} := \left( \frac{P_{bru}}{V \cdot SF \_u \cdot FF} - 1 \right)
MS_{bru} = \left( \frac{16.320}{3.811} \right) \quad (Plate 1)

MS_{bh2} := \min(MS_{bru})
MS_{bh2} = 3.811 \quad \text{... Bearing Ultimate Strength}

MS_{bry} := \left( \frac{P_{bry}}{V \cdot SF \_y \cdot FF} - 1 \right)
MS_{bry} = \left( \frac{19.36}{4.07} \right) \quad (Plate 1)

MS_{bh3} := \min(MS_{bry})
MS_{bh3} = 4.074 \quad \text{... Bearing Yield Strength}
Bolt := "NAS1351N3-6, 0.190-32, 0.375L, HRES A286, 160ksi"
Washer := "NAS1149E0332R, 0.438 OD, 0.203 ID, 0.032 THK, A286"
Insert := "NASM21209F1-10, 0.190-32, 0.190L (1.0xDia), CRES"

Flange_1 := "Standoff Bracket A"
Part_Number_1 := "SDG39137917-001"
Material_1 := "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 0.80 Thk, A"
edge1 := 0.285-in \textit{(Minimum Edge Distance of Flange 1)}

Flange_2 := "Box S (base plate)"
Part_Number_2 := "unknown"
Material_2 := "AL ALY 7050-T7451"
edge2 := 1.315-in \textit{(Minimum Edge Distance of Flange 2)}

\section*{Methodology}

The TRD Gas Ballistic Cover, SLG39137916-701, is attached to Box S with (3) Standoff Bracket A, SDG39137917-001, and (1) Standoff Bracket B, SDG39137918-301. All 4 brackets are AL ALY 7075-T7351. Each Standoff Bracket attaches to the Ballistic Cover by (2) NAS 1351N3LB10 fasteners with NAS1149E0332R washers, going into SOS-032-16 Self Clinching Standoffs in the TRD Gas Ballistic Cover.

A stand-alone FEM of the TRD Gas Ballistic Cover and Standoff Brackets was created. It was constrained at the 4 attachment points to Box S. Twenty-four g-load combinations, using the 40 (g) Load Factor from Table 4-4: Launch/Landing Design Limit Load Factors for Small Secondary Structures, JSC-28792, Rev. E, were analyzed.

The attachments between the Standoff Brackets and the TRD Gas Ballistic Cover are represented by Spider RBE3's (with the center dependent node given 6 dof T1 T2 T3 R1 R2 R3, and the outer independent nodes given T1 T2 T3) in the fastener holes of each flange, connected by CBush elements. The fastener loads between the Standoff Brackets and Cover are recovered as CBush Forces.

The largest absolute CBush Axial (P) load and the largest absolute CBush Total Shear (V) load, are enveloped across all 4 Standoff Brackets, for all 24 load cases, and then used to calculate the Margins of Safety for the joints. Since each Bracket attaches to the Cover with two fasteners, for Fail-Safe Analysis, the worst case Axial and Total Shear loads were doubled and then used to calculate the Fail-Safe Margins of Safety for the joints.
Allowables

Factors of Safety (reference)

- SFu := 2.00  (Ultimate Factor of Safety)
- SFy := 1.25  (Yield Factor of Safety)
- FF := 1.15   (Fitting Factor)
- SFsep := 1.20  (Joint Separation)

Temperature Data (reference)

- Temp_initial := 70 deg  (Assembly)
- Temp_max := 140 deg  (Maximum)
- Temp_min := -76 deg  (Minimum)

Note: These are maximum temperatures that hardware sees. If maximum load occurs at a different temperature, this will be conservative.

Bolt Data (Bolt = "NAS1351N3-6, 0.190-32, 0.375L, HRES A286, 160ksi")

- D := 0.1900 in  (Nominal Diameter of Bolt)
- Nt := 32 \frac{1}{in}  (Number of Threads/Inch)
- D_{shank} := 0.1840 in  (Shank Diameter of Bolt)
- L := 0.375 in  (Total Length of Bolt)
- Lt := 0.375 in  (Threaded Length - bolt is fully threaded, input Lt = L)
- dw := 0.303 in  (Bolt Head Dia. Across Flats - dia of pressure boss if it exists, otherwise dia of head)
- bh := 0.185 in  (Bolt Head Height - head height is 0 if bolt is flat head)

Note: If there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area.

Bolt Data (Bolt = "NAS1351N3-6, 0.190-32, 0.375L, HRES A286, 160ksi")

- TSu_bolt := 0.98  (Temperature Correction Factor for Bolt Strength)
- TSy_bolt := 0.98
- Ftu_bolt := 160000 psi  (Bolt Ultimate Tensile Allowable Stress)
- Fty_bolt := 120000 psi
- Fsu_bolt := 0.6 \cdot Ftu_bolt  (Bolt Ultimate Shear Allowable Stress)
- TE_bolt := 0.98  (Temperature Correction Factor for Bolt Modulus)
- E_bolt := \left(29.1 \cdot 10^6\right) psi  (Modulus of Elasticity of Bolt)

Thread data lookup table is hidden
This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Fri Apr 27 14:11:39 2007
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Gas Supply - Standoff Bracket A to Box S (base plate)

\[ \beta_{\text{bolt\_hot}} = 9.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \beta_{\text{bolt\_cold}} = 8.5 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
*(Thermal Coefficients for Bolt)*

**Washer Data** *(Washer = "NAS1149E0332R, 0.438 OD, 0.203 ID, 0.032 THK, A286")*

<table>
<thead>
<tr>
<th>Thickness of Washers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\text{wh}} ) := 0.032 in (Head)</td>
</tr>
</tbody>
</table>

*Note: This is the total washer thickness, if there are more than one.*

<table>
<thead>
<tr>
<th>Diameter of Washer Under Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{\text{woh}} := 0.438 in ) (Outer)</td>
</tr>
<tr>
<td>( D_{\text{wih}} := 0.203 in ) (Inner)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{washerh}} := 29.1 \times 10^6 \text{ psi} ) (Head)</td>
</tr>
</tbody>
</table>

*Temperature Correction Factor for Modulus*

<table>
<thead>
<tr>
<th>Temperature Correction Factor for Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>( TE_{\text{washerh}} := 0.98 ) (Head) [same as bolt]</td>
</tr>
</tbody>
</table>

**Insert Data** *(Insert = "NASM21209F1-10, 0.190-32, 0.190L (1.0xDia), CRES")*

<table>
<thead>
<tr>
<th>Length of Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{\text{ins}} := 0.190 \text{ in} ) (Length of Insert)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Min. External Diameter of Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{min}} := 0.236 \text{ in} ) (Min. External Diameter of Insert)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth of Recess for Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_{r} := 0.020 \text{ in} ) (Depth of Recess for Insert)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature Correction Factor for Insert Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>( TS_{\text{ins}} := 0.98 ) (Temperature Correction Factor for Insert Strength)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate Tensile Allowable Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{tu_ins}} := 150000 \text{ psi} ) (Ultimate Tensile Allowable Stress)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate Shear Allowable Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{su_ins}} := 0.6 \times F_{\text{tu_ins}} ) (Ultimate Shear Allowable Stress)</td>
</tr>
</tbody>
</table>

*Note: See Procurement Specification NASM8846 3.2.2 Tensile Strength.*
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Flange_1 = "Standoff Bracket A"
Material_1 = "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 0.80 Thk, A"

Flange_2 = "Box S (base plate)"
Material_2 = "AL ALY 7050-T7451"

**D_hole** := 0.190 in  (Diameter of Thru Hole in Flange 2)

<table>
<thead>
<tr>
<th>Thickness of Flanges</th>
</tr>
</thead>
<tbody>
<tr>
<td>tf1 := 0.100 in</td>
</tr>
<tr>
<td>tf2 := 0.2362 in</td>
</tr>
</tbody>
</table>

(6mm)

**Compressive Modulus of Elasticity**

| E_flange1 := (10.6 \times 10^6 \text{ psi}) |
| E_flange2 := (10.6 \times 10^6 \text{ psi}) |

**Temperature Correction Factor (Modulus)**

| T1&E := 0.98 |
| T2&E := 0.98 |

**Coefficient of thermal expansion for Flanges**

| \( \beta_{\text{flange1, hot}} := 12.5 \times 10^{-6} \text{ in/in deg} \) |
| \( \beta_{\text{flange2, hot}} := 12.5 \times 10^{-6} \text{ in/in deg} \) |

| \( \beta_{\text{flange1, cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \) |
| \( \beta_{\text{flange2, cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \) |

| Fsu_f2 := 43000 psi |

(If Unavailable, Use Temperature Reduction Factor for Ftu)
**Applied Loads (reference)**

- **P := 16.160 lbf** (Applied Tensile Load on Bolt)
- **V := 28.165 lbf** (Applied Shear on Bolt)
- **M := 0.000 in-lbf** (Applied Bending on Bolt)

- **PLDmax = 1858 lbf** (Max. Preload)
- **PLDmin = 648 lbf** (Min. Preload)
- **PLDnom = 1425 lbf** (Nom. Preload)
- **Psep = 19.392 lbf** (Joint Separation Load)

**Torque/Preload**

- **Tmax := 40.6 in-lbf** (Maximum Torque)
- **Tmin := 34.5 in-lbf** (Minimum Torque)
- **n := 0.5** (Loading Plane Factor)

- **u := 0.25** (Preload Uncertainty - 0.25 lubed)
- **k := 0.15** (Torque Coefficient - 0.15 lubed)

**Stiffness and Margin calculations are hidden**

*This file uses calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness.mcd*

**Bolt Load**

- **P = 16.160 lbf** (Applied Tensile Load on Bolt)
- **V = 28.165 lbf** (Applied Shear on Bolt)
- **M = 0.000 in-lbf** (Applied Bending on Bolt)

- **PLDapp = 1862 lbf** (Ultimate)
- **Pby = 1863 lbf** (Yield)

- **Max. Load on Bolt With Preload With Out Factor of Safety**

Last Saved 7/7/2009 3:59 PM
Bolt Allowables

\[ PA_t = 3018 \text{ lbf} \]  (Bolt Ultimate Tensile Strength) \[ VAu = 1649 \text{ lbf} \]  (Bolt Shear Strength)

\[ PAs = 2756 \text{ lbf} \]  (Thread Pullout Strength) \[ MAu = 63 \text{ in-lbf} \]  (Bolt Bending Strength)

General Checks

- length_check = "Bolt length is sufficient and insert fully engaged"
- cone_check = "Joint pressure cone does not extend past flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washer(s) under head do not extend past flange"
- insert_check = "Flange two is thick enough for insert"

Summary of Margins for Bolt

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( MS_1 )</td>
<td>36.48</td>
</tr>
<tr>
<td>( MS_2 )</td>
<td>80.2</td>
</tr>
<tr>
<td>( MS_3 )</td>
<td>96.45</td>
</tr>
<tr>
<td>( MS_4 )</td>
<td>0.62</td>
</tr>
<tr>
<td>( MS_5 )</td>
<td>0.22</td>
</tr>
<tr>
<td>( MS_6 )</td>
<td>73.15</td>
</tr>
<tr>
<td>( MS_7 )</td>
<td>0.48</td>
</tr>
<tr>
<td>( MS_8 )</td>
<td>24.46</td>
</tr>
<tr>
<td>( MS_9 )</td>
<td>100</td>
</tr>
<tr>
<td>( MS_{10} )</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Smallest Margin of Safety for Bolt and Failure Mode

\[ MS_{bolt} = 0.22 \]  Failure Mode = "Total Tension Yield"
Fail-Safe Analysis

**Applied Fail-Safe Loads**

\[
\begin{align*}
P_{FS} &= 22.100 \text{ lbf} & \text{(Tensile)} \\
V_{FS} &= 32.204 \text{ lbf} & \text{(Shear)} \\
M_{FS} &= 0.0 \text{ in lbf} & \text{(Bending)}
\end{align*}
\]

**Fail-Safe Factors of Safety**

\[
\begin{align*}
SF_{u,FS} &= 1.0 & \text{(Ultimate)} \\
SF_{sep,FS} &= 1.0 & \text{(Joint Separation)}
\end{align*}
\]

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated
This file calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness__FS.mcd

**Bolt Fail-Safe Load Data**

\[
\begin{align*}
P_{sep,FS} &= 22.100 \text{ lbf} & \text{(Joint Separation Load)} \\
P_{b,FS} &= 1863.6 \text{ lbf} & \text{(Max. Ultimate Load on Bolt)}
\end{align*}
\]

**Summary of Fail-Safe Margins for Bolt**

\[
\begin{align*}
MS_{FS1} &= 31.89 & \text{...Joint Separation} \\
MS_{FS2} &= 117.76 & \text{...Direct Tension Ultimate} \\
MS_{FS3} &= 0.62 & \text{...Total Tension Ultimate} \\
MS_{FS4} &= 107.44 & \text{...Direct Thread shear Ultimate} \\
MS_{FS5} &= 0.48 & \text{...Total Thread shear Ultimate} \\
MS_{FS6} &= 43.54 & \text{...Shear Ultimate} \\
MS_{FS7} &= 10.00 & \text{...Bending Ultimate} \\
MS_{FS8} &= 0.62 & \text{...Combined Shear, Tension and Bending Ultimate}
\end{align*}
\]

Smallest Fail-Safe Margin of Safety for Bolt and Failure Mode

\[
\begin{align*}
MS_{bolt,FS} &= 0.48 \\
\text{Failure Mode FS} &= "\text{Total Thread Shear Ultimate (Flange)}"
\end{align*}
\]
Bolt Hole Analysis

Recall Loads From Bolt Calculation

<table>
<thead>
<tr>
<th>Safety Factors</th>
<th>SFu = 2.00 (Ultimate)</th>
<th>SFy = 1.250 (Yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF = 1.150</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Input Loads

- V = 28.2 lbf (Shear Load)
- P = 16.2 lbf (Axial Load)

Bolt Calc Results

- Pb = 1866 lbf (Max Bolt Load)

Dimensions

- L = 0.375 in (Length of Bolt)
- twh = 0.032 in (Thickness of Washer)

Recall Bolt Hole Dimensions

- tf1 := tf1 = 0.100 in
- tf2 := tf2 = 0.236 in
- edge1 := edge1 = 0.285 in
- edge2 := edge2 = 1.315 in
- D = 0.190 in
- D_shank = 0.184 in
- D_hole = 0.190 in

Shear Tear-Out Check

Shear Area of the Mating Components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{shrpl} = \left( \frac{2 \times tf \times edge - \frac{1}{2} D_{\text{hole}}}{\text{Plate1}} - \frac{1}{\text{Plate2}} \right) \]

\[ A_{shrpl} = \left( \frac{0.038}{0.576} \right) \text{in}^2 \]

Allowables for Flanges that Fastener Goes Through

- Fsu1 := Tf1E = 38 ksi
- Fsu1 = 37.240 ksi (Ultimate Shear Allowable for Flange 1)
- Fsu2 := Tf2E = 43 ksi
- Fsu2 = 42.140 ksi (Ultimate Shear Allowable for Flange 2)
- Psu := \( F_{su} \times A_{shrpl} \)
- Psu = \( \frac{1415}{24286} \) lbf (Shear Ultimate Allowable)

Margin of Safety for Shear Tear-Out

\[ MS_{su} = \left( \frac{P_{su}}{V \times SFu \times FF} - 1 \right) \]

\[ MS_{su} = \left( \frac{20.85}{373.91} \right) \]

\[ MS_{bh1} := \min (MS_{su}) \]

\[ MS_{bh1} = 20.845 \quad \text{... Shear Tear-Out} \]
Bearing Check

Recall Bolt Hole Dimensions

\[ t_1 = 0.100 \text{ in} \quad \text{(Thickness of Flange 1)} \]

\[ t_2 = 0.236 \text{ in} \quad \text{(Thickness of Flange 2)} \]

\[ \text{edge}_1 = 0.285 \text{ in} \quad \text{(Edge Distance for thru Hole in Flange 1)} \]

\[ \text{edge}_2 = 1.315 \text{ in} \quad \text{(Edge Distance for tapped Hole in Flange 2)} \]

Typical Bearing Failure

\[ e_\text{D} := \left( \frac{\text{edge}}{D_{\text{hole}}} \right) \]

\[ e_D \left( \frac{1.500}{6.921} \right) \quad \text{(e/D for Flanges)} \]

Bearing Allowables for Flanges that Fastener Goes Through

<table>
<thead>
<tr>
<th>Flange 1</th>
<th>Flange 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru (e/D=1.5)</td>
<td>Fbru15 := T11E·103 ksi</td>
</tr>
<tr>
<td>Fbru (e/D=2.0)</td>
<td>Fbru20 := T11E·132 ksi</td>
</tr>
<tr>
<td>Fbry (e/D=1.5)</td>
<td>Fbry15 := T11E·81 ksi</td>
</tr>
<tr>
<td>Fbry (e/D=2.0)</td>
<td>Fbry20 := T11E·97 ksi</td>
</tr>
</tbody>
</table>

Modified Bearing Strength

\[ \text{Fbru}_m := \begin{cases} 
\frac{e_D - 1.5}{2.0 - 1.5} & \text{if } e_D > 2.0, \ Fbru_1, \text{if } \left[ \begin{array}{c}
(e_D > 1.5) \ (e_D < 2.0), \ Fbru_1 + \\
\end{array} \right] 
\end{cases} \]

\[ \text{Fbry}_m := \begin{cases} 
\frac{e_D - 1.5}{2.0 - 1.5} & \text{if } e_D > 2.0, \ Fbry_1, \text{if } \left[ \begin{array}{c}
(e_D > 1.5) \ (e_D < 2.0), \ Fbry_1 + \\
\end{array} \right] 
\end{cases} \]

Ultimate Bearing Strength:

\[ \text{Fbru} = \begin{cases} 
100.94 \text{ ksi} & \text{Plate 1} \\
137.2 \text{ ksi} & \text{Plate 2} 
\end{cases} \]

Yield Bearing Strength:

\[ \text{Fbry} = \begin{cases} 
79.38 \text{ ksi} & \text{Plate 1} \\
98.98 \text{ ksi} & \text{Plate 2} 
\end{cases} \]
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Gas Supply - Standoff Bracket A to Box S (base plate)

\[ P_{bru} := \left( \frac{A_{bru}}{F_{bru}} \right) \]
\[ P_{bru} = \left( \frac{1857}{5963} \right) \text{lbf} \quad (\text{Bearing Ultimate Allowable}) \]

\[ P_{bry} := \left( \frac{A_{bry}}{F_{bry}} \right) \]
\[ P_{bry} = \left( \frac{1461}{4302} \right) \text{lbf} \quad (\text{Bearing Yield Allowable}) \]

**Margin of Safety for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} - 1 \right) \]
\[ MS_{bru} = \left( \frac{27.671}{91.048} \right) \quad \text{(Plate1)} \quad \text{(Plate2)} \]

\[ MS_{bry} := \min(\{MS_{bru}\}) \]
\[ MS_{bh2} = 27.671 \quad \ldots \text{Bearing Ultimate Strength} \]

\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} - 1 \right) \]
\[ MS_{bry} = \left( \frac{35.08}{105.25} \right) \quad \text{(Plate1)} \quad \text{(Plate2)} \]

\[ MS_{bh3} := \min(\{MS_{bry}\}) \]
\[ MS_{bh3} = 35.075 \quad \ldots \text{Bearing Yield Strength} \]
**Methodology**

The TRD Gas Ballistic Cover, SLG39137916-701, is attached to Box S with (3) Standoff Bracket A, SDG39137917-001, and (1) Standoff Bracket B, SDG39137918-301. All 4 brackets are AL ALY 7050-T7451. Each Standoff Bracket attaches to the Ballistic Cover by (2) NAS1351N3LB10 fasteners with NAS1149E0332R washers, going into SOS-032-16 Self Clinching Standoffs in the TRD Gas Ballistic Cover.

A stand-alone FEM of the TRD Gas Ballistic Cover and Standoff Brackets was created. It was constrained at the 4 attachment points to Box S. Twenty-four g-load combinations, using the 40 (g) Load Factor from Table 4-4: Launch/Landing Design Limit Load Factors for Small Secondary Structures, JSC-28792, Rev. E, were analyzed.

The attachments between the Standoff Brackets and the TRD Gas Ballistic Cover are represented by Spider RBE3's (with the center dependent node given 6 dof T1 T2 T3 R1 R2 R3, and the outer independent nodes given T1 T2 T3) in the fastner holes of each flange, connected by CBush elements. The fastener loads between the Standoff Brackets and Cover are recovered as CBush Forces.

The largest absolute CBush Axial (P) load and the largest absolute CBush Total Shear (V) load, are enveloped across all 4 Standoff Brackets, for all 24 load cases, and then used to calculate the Margins of Safety for the joints. Since each Bracket attaches to the Cover with two fasteners, for Fail-Safe Analysis, the worst case Axial and Total Shear loads were doubled and then used to calculate the Fail-Safe Margins of Safety for the joints.
Allowables

Factors of Safety (reference)

\[ SF_u := 2.00 \] (Ultimate Factor of Safety)
\[ SF_y := 1.25 \] (Yield Factor of Safety)
\[ FF := 1.15 \] (Fitting Factor)
\[ SF_{sep} := 1.20 \] (Joint Separation)

Temperature Data (reference)

\[ \text{Temp}_{\text{initial}} := 70 \, \text{deg} \] (Assembly)
\[ \text{Temp}_{\text{max}} := 140 \, \text{deg} \] (Maximum)
\[ \text{Temp}_{\text{min}} := -76 \, \text{deg} \] (Minimum)

Note: These are maximum temperatures that hardware sees. If maximum load occurs at a different temperature, this will be conservative.

Bolt Data (Bolt = "NAS1351N3-10, .1900-32, .625L, HRES A286, 160ksi")

\[ D := .1900 \, \text{in} \] (Nominal Diameter of Bolt)
\[ N_t := 32 \, \text{in}^{-1} \] (Number of Threads/Inch)
\[ D_{\text{shank}} := .1840 \, \text{in} \] (Shank Diameter of Bolt)
\[ L := 0.625 \, \text{in} \] (Total Length of Bolt)
\[ L_t := 0.625 \, \text{in} \] (Threaded Length - bolt is fully threaded, input \( L_t = L \))
\[ d_w := 0.303 \, \text{in} \] (Bolt Head Dia. Across Flats - dia of pressure boss if it exists, otherwise dia of head)
\[ b_h := 0.185 \, \text{in} \] (Bolt Head Height - head height is 0 if bolt is flat head)

Thread data lookup table is hidden
This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Fri Apr 27 14:11:39 2007

Bolt Data (Bolt = "NAS1351N3-10, .1900-32, .625L, HRES A286, 160ksi")

\[ T_{Su, \text{bolt}} := 0.98 \] (Temperature Correction Factor for Bolt Strength)
\[ T_{Sy, \text{bolt}} := 0.98 \]
\[ F_{tu, \text{bolt}} := 160000 \, \text{psi} \] (Bolt Ultimate Tensile Allowable Stress)
\[ F_{ty, \text{bolt}} := 120000 \, \text{psi} \]
\[ F_{su, \text{bolt}} := 0.6 \times F_{tu, \text{bolt}} \] (Bolt Ultimate Shear Allowable Stress)
\[ T_{E, \text{bolt}} := 0.98 \] (Temperature Correction Factor for Bolt Modulus)
\[ E_{\text{bolt}} := (29.1 \times 10^6 \, \text{psi}) \] (Modulus of Elasticity of Bolt)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Gas Supply - Box S (base plate) to Standoff Bracket B

\[
\beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \text{ in} / \text{deg} \quad \beta_{\text{bolt\_cold}} := 8.5 \times 10^{-6} \text{ in} / \text{deg}
\]

(Thermal Coefficients for Bolt)

**Washer Data** (Washer = "NAS1149E0332R, 0.438 OD, 0.203 ID, 0.032 THK, A286")

**Thickness of Washers**
\[
t_{\text{wh}} := 0.064 \text{ in} \quad \text{(Head)}
\]

Note: This is the total washer thickness, if there are more than one.

**Diameter of Washer Under Head**
\[
D_{\text{woh}} := 0.438 \text{ in} \quad \text{(Outer)}
D_{\text{wih}} := 0.203 \text{ in} \quad \text{(Inner)}
\]

Note: If there is no washer, tw's, Dwo's, and Dwi's should be zero.

**Modulus of Elasticity**
\[
E_{\text{washerh}} := 29.1 \times 10^6 \text{ psi} \quad \text{(Head)}
\]

Temperature Correction Factor for Modulus
\[
T_{E_{\text{washerh}}} := 0.98 \quad \text{(Head)} \quad \text{[same as bolt]}
\]

**Insert Data** (Insert = "NASM21209F1-15L, .1900-32, .285L (1.5xDia), CRES")

**Length of Insert**
\[
L_{\text{ins}} := 0.285 \text{ in} \quad \text{(Length of Insert)}
\]

**Min. External Diameter of Insert**
\[
F_{\text{min}} := 0.236 \text{ in} \quad \text{(Min. External Diameter of Insert)}
\]

**Depth of Recess for Insert**
\[
I_{r} := 0.020 \text{ in} \quad \text{(Depth of Recess for Insert)}
\]

**Temperature Correction Factor for Insert Strength**
\[
T_{S_{\text{ins}}} := 0.98 \quad \text{(Temperature Correction Factor for Insert Strength)}
\]

**Ultimate Tensile Allowable Stress**
\[
F_{\text{tu\_ins}} := 150000 \text{ psi} \quad \text{(Ultimate Tensile Allowable Stress)}
\]

**Ultimate Shear Allowable Stress**
\[
F_{\text{su\_ins}} := 0.6 \times F_{\text{tu\_ins}} \quad \text{(Ultimate Shear Allowable Stress)}
\]

Note: See Procurement Specification NASM8846 3.2.2 Tensile Strength.
Flange data (Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties)

Flange_1 = "Box S (base plate)"
Material_1 = "AL ALY 7050-T7451"

Flange_2 = "Standoff Bracket B"
Material_2 = "AL ALY 7075-T7351, AMS-QQ-Q-250/12, Plate, 1.00 Thk, A"

D_hole := 0.190 in (Diameter of Thru Hole in Flange 2)

Thickness of Flanges

\[ t_1 := 0.2362 \text{ in} \quad (6mm) \]
\[ t_2 := 0.50 \text{ in} \]

Compressive Modulus of Elasticity

\[ E_{\text{flange1}} := \left(10.6 \times 10^6 \text{ psi}\right) \]
\[ E_{\text{flange2}} := \left(10.6 \times 10^6 \text{ psi}\right) \]

Temperature Correction Factor (Modulus)

\[ T_{f1E} := 0.98 \]
\[ T_{f2E} := 0.98 \]

Coefficient of thermal expansion for Flanges

\[ \beta_{\text{flange1_hot}} := 12.5 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange1_cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange2_hot}} := 12.5 \times 10^{-6} \text{ in/in deg} \]
\[ \beta_{\text{flange2_cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \]

\[ F_{su_{f2}} := 38000 \text{ psi} \] (Shear Strength of Flange 2, with Temperature Reduction)
\[ T_{f2s} := 0.96 \] (If Unavailable, Use Temperature Reduction Factor for Flu)
Applied Loads (reference)

\[ P := 16.160 \text{ lbf} \] (Applied Tensile)

\[ V := 28.165 \text{ lbf} \] (Applied Shear)

\[ M := 0.0 \text{ in lbf} \] (Applied Bending)

Torque/Preload

\[ T_{\text{max}} := 40.6 \text{ in lbf} \] (Maximum Torque)

\[ T_{\text{min}} := 34.5 \text{ in lbf} \] (Minimum Torque)

\[ n := 0.5 \] (Loading Plane Factor)

Joint is lubed

\[ u := 0.25 \] (Preload Uncertainty - 0.25 lubed)

\[ k := 0.15 \] (Torque Coefficient - 0.15 lubed)

Stiffness and Margin calculations are hidden
This file uses calculations shown in \escfil02\\i11_mathcad\\8307_bolts\\Rev_D\\bolt_insert_stiffness.mcd

Bolt Load

\[ = 0.391 \] (Bolt/Joint Stiffness Factor)

\[ P_{\text{th}} = 110.6 \text{ lbf} \] (Preload Due to Temperature)

\[ P_{\text{ld}} = 1891 \text{ lbf} \] (Max. Preload)

\[ P_{\text{min}} = 575 \text{ lbf} \] (Min. Preload)

\[ P_{\text{nom}} = 1425 \text{ lbf} \] (Nom. Preload)

\[ u = 0.250 \] (Uncertainty Factor)

\[ k = 0.150 \] (Torque Coefficient)

\[ P_{\text{sep}} = 19.392 \text{ lbf} \] (Joint Separation Load)

\[ n = 0.500 \] (Loading Plane Factor)

\[ P = 16.160 \text{ lbf} \] (Applied Tensile Load on Bolt)

\[ V = 28.165 \text{ lbf} \] (Applied Shear on Bolt)

\[ M = 0.000 \text{ in lbf} \] (Applied Bending on Bolt)

Max. Load on Bolt with Preload and Factor of Safety

\[ P_{\text{ub}} = 1899 \text{ lbf} \] (Ultimate)

\[ P_{\text{by}} = 1896 \text{ lbf} \] (Yield)

Max. Load on Bolt With Preload WithOut Factor of Safety

\[ P_{\text{app}} = 1895 \text{ lbf} \]
Bolt Allowables

\[ P_{At} = 3018 \text{ lbf} \quad (\text{Bolt Ultimate Tensile Strength}) \quad V_{Au} = 1649 \text{ lbf} \quad (\text{Bolt Shear Strength}) \]

\[ P_{As} = 3854 \text{ lbf} \quad (\text{Thread Pullout Strength}) \quad M_{Au} = 63 \text{ in lbf} \quad (\text{Bolt Bending Strength}) \]

General Checks

- length_check = "Bolt length is sufficient and insert fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washer(s) under head do not extend past flange"
- insert_check = "Flange two is thick enough for insert"

Summary of Margins for Bolt

| MS1 = 31.02 | \( \text{...Joint Separation} \) | MS6 = 102.7 | \( \text{...Direct Thread Shear Ultimate} \) |
| MS2 = 80.2 | \( \text{...Direct Tension Ultimate} \) | MS7 = 1.03 | \( \text{...Total Thread Shear Ultimate} \) |
| MS3 = 96.45 | \( \text{...Direct Tension Yield} \) | MS8 = 24.46 | \( \text{...Shear Ultimate} \) |
| MS4 = 0.59 | \( \text{...Total Tension Ultimate} \) | MS9 = 100 | \( \text{...Bending Ultimate} \) |
| MS5 = 0.19 | \( \text{...Total Tension Yield} \) | MS10 = 0.59 | \( \text{...Combined Shear, Tension and Bending Ultimate} \) |

Smallest Margin of Safety for Bolt and Failure Mode

\[ MS_{\text{bolt}} = 0.19 \quad \text{Failure Mode} = "\text{Total Tension Yield}" \]
Fail-Safe Analysis

**Applied Fail-Safe Loads**

(See A28.7.1.15.2 One Standoff Bracket to Box S Removed, Landing & Liftoff)

\[ P_{FS} := 22.100 \text{ lbf} \]  
(Tensile)

\[ V_{FS} := 32.204 \text{ lbf} \]  
(Shear)

\[ M_{FS} := 0.0 \text{ in} \times \text{lbf} \]  
(Bending)

**Fail-Safe Factors of Safety**

\[ SF_{u,FS} := 1.0 \]  
(Ultimate)

\[ SF_{sep,FS} := 1.0 \]  
(Joint Separation)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated
This file calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_insert_stiffness__FS.mcd

**Bolt Fail-Safe Load Data**

\[ P_{sep,FS} = 22.100 \text{ lbf} \]  
(Joint Separation Load)

\[ P_{b,FS} = 1896.3 \text{ lbf} \]  
(Max. Ultimate Load on Bolt)

**Summary of Fail-Safe Margins for Bolt**

\[ MS_{FS1} = 27.09 \]  
(Joint Separation)

\[ MS_{FS2} = 117.76 \]  
(Direct Tension Ultimate)

\[ MS_{FS3} = 0.59 \]  
(Total Tension Ultimate)

\[ MS_{FS4} = 150.65 \]  
(Direct Thread shear Ultimate)

\[ MS_{FS5} = 1.03 \]  
(Total Thread shear Ultimate)

\[ MS_{FS6} = 43.54 \]  
(Shear Ultimate)

\[ MS_{FS7} = 10.00 \]  
(Bending Ultimate)

\[ MS_{FS8} = 0.59 \]  
(Combined Shear, Tension and Bending Ultimate)

**Smallest Fail-Safe Margin of Safety for Bolt and Failure Mode**

\[ MS_{bolt,FS} = 0.59 \]  
Failure Mode FS = "Combined Shear Tension Bending Ultimate"

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5.10.3-112
Bolt Hole Analysis

Recall Loads From Bolt Calculation

Safety Factors
\[ S_{FU} = 2.00 \quad \text{(Ultimate)} \]
\[ S_{FY} = 1.250 \quad \text{(Yield)} \]
\[ F_F = 1.150 \quad \text{(Fitting Factor)} \]

Input Loads
\[ V = 28.2 \, \text{lbf} \quad \text{(Shear Load)} \]
\[ P = 16.2 \, \text{lbf} \quad \text{(Axial Load)} \]

Bolt Calc Results
\[ P_b = 1899 \, \text{lbf} \quad \text{(Max Bolt Load)} \]

Dimensions
\[ L = 0.625 \, \text{in} \quad \text{(Length of Bolt)} \]
\[ t_{wh} = 0.064 \, \text{in} \quad \text{(Thickness of Washer)} \]

Recall Bolt Hole Dimensions
\[ t_f := t_f^1 = 0.236 \, \text{in} \quad \text{(Entire Thickness of Flange 1)} \]
\[ t_f := t_f^2 = 0.500 \, \text{in} \quad \text{(Entire Thickness of Flange 2)} \]
\[ \text{edge}_1 := \text{edge}_1^1 = 0.382 \, \text{in} \quad \text{(Edge Distance for Hole in Flange 1)} \]
\[ \text{edge}_2 := \text{edge}_2^2 = 0.285 \, \text{in} \quad \text{(Edge Distance for Hole in Flange 2)} \]
\[ D = 0.190 \, \text{in} \quad \text{(Diameter of Bolt)} \]
\[ D_{shank} = 0.184 \, \text{in} \quad \text{(Min. Shank Diameter of Bolt)} \]
\[ D_{hole} = 0.190 \, \text{in} \quad \text{(Diameter of Hole)} \]

Shear Tear-Out Check

Shear Area of the Mating Components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)
\[ A_{shrpl} = \frac{2 \cdot t_f \cdot \text{edge} - \frac{1}{2} D_{\text{hole}}}{2} \]
\[ \left( \begin{array}{c} \text{Plate1} \\ \text{Plate2} \end{array} \right) \]
\[ \begin{array}{c} A_{shrpl} = 0.136 \\ 0.190 \end{array} \, \text{in}^2 \]

Allowables for Flanges that Fastener Goes Through
\[ F_{su1} := T_{f1E} \cdot 43 \, \text{ksi} \quad \text{(Ultimate Shear Allowable for Flange 1)} \]
\[ F_{su2} := T_{f2E} \cdot 38 \, \text{ksi} \quad \text{(Ultimate Shear Allowable for Flange 2)} \]
\[ P_{su} := \left( A_{shrpl} \cdot F_{su} \right) \quad \text{(Shear Ultimate Allowable)} \]

Margin of Safety for Shear Tear-Out
\[ MS_{su} := \frac{P_{su}}{V \cdot S_{FU} \cdot F_F - 1} \]
\[ \left( \begin{array}{c} \text{Plate1} \\ \text{Plate2} \end{array} \right) \]
\[ MS_{su} = \frac{87.2}{108.23} \]
\[ MS_{bh1} := \min (MS_{su}) \]
\[ MS_{bh1} = 87.196 \quad \text{(Shear Tear-Out)} \]
Bearing Check

Recall Bolt Hole Dimensions

\[ t_1 = 0.236 \text{in} \]  
\[ t_2 = 0.500 \text{in} \]

(Thickness of Flange 1)

(Thickness of Flange 2)

\[ \text{edge}_1 = 0.382 \text{in} \]

(Edge Distance for thru Hole in Flange 1)

(Edge Distance for tapped Hole in Flange 2)

\[ e_D = \frac{\text{edge}_2}{D_{\text{hole}}} \]

(Angle for Flanges)

Bearing Allowables for Flanges that Fastener Goes Through

<table>
<thead>
<tr>
<th>Flange 1</th>
<th>Flange 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru (e/D=1.5)</td>
<td>Fbru151 := T11E \cdot 107\text{ksi}</td>
</tr>
<tr>
<td>Fbru (e/D=2.0)</td>
<td>Fbru201 := T11E \cdot 140\text{ksi}</td>
</tr>
<tr>
<td>Fbry (e/D=1.5)</td>
<td>Fbry151 := T11E \cdot 86\text{ksi}</td>
</tr>
<tr>
<td>Fbry (e/D=2.0)</td>
<td>Fbry201 := T11E \cdot 101\text{ksi}</td>
</tr>
</tbody>
</table>

Modified Bearing Strength

\[ Fbru_m := \begin{cases} 
\frac{e_D - 1.5}{2.0 - 1.5} (Fbru_{151} - Fbru_{151}) & \text{if } e_D > 2.0, Fbru_{201}, \frac{e_D - 1.5}{2.0 - 1.5} (Fbru_{201} - Fbru_{151}) & \text{if } e_D < 2.0, Fbru_{151} \\
\frac{e_D - 1.5}{2.0 - 1.5} (Fbru_{201} - Fbru_{151}) & \text{if } e_D > 1.5, Fbru_{201}, Fbru_{201} \end{cases} \]

\[ Fbry_m := \begin{cases} 
\frac{e_D - 1.5}{2.0 - 1.5} (Fbry_{151} - Fbry_{151}) & \text{if } e_D > 2.0, Fbry_{201}, \frac{e_D - 1.5}{2.0 - 1.5} (Fbry_{201} - Fbry_{151}) & \text{if } e_D < 2.0, Fbry_{151} \\
\frac{e_D - 1.5}{2.0 - 1.5} (Fbry_{201} - Fbry_{151}) & \text{if } e_D > 1.5, Fbry_{201}, Fbry_{201} \end{cases} \]

Fbru_m := \begin{cases} 
Fbry_m := \begin{cases} 
137.2 \text{ksi} & (Ultimate) \\
100.94 \text{ksi} & \text{Plate 1} \\
100.94 \text{ksi} & \text{Plate 2} \end{cases} \\
100.94 \text{ksi} & \text{Plate 2} \end{cases} 

(Plate 1)

(Plate 2)
Debris Shield Fastener Joint Analysis for Bolt/Washer with Insert
TRD Gas Supply - Box S (base plate) to Standoff Bracket B

\[ P_{bru} := \left( A_{bru} \times F_{bru_m} \right) \]
\[ P_{bru} = \left( \frac{5963}{9286} \right) \text{ lbf} \quad \text{(Bearing Ultimate Allowable)} \]

\[ P_{bry} := \left( A_{bry} \times F_{bry_m} \right) \]
\[ P_{bry} = \left( \frac{4302}{7303} \right) \text{ lbf} \quad \text{(Bearing Yield Allowable)} \]

**Margin of Safety for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot SFu \cdot FF} \right) - 1 \]
\[ MS_{bru} = \left( \frac{91.048}{142.355} \right) \quad \text{Plate1} \]
\[ MS_{bru} = \left( \frac{91.048}{142.355} \right) \quad \text{Plate2} \]

\[ MS_{bh2} := \min \left( MS_{bru} \right) \]
\[ MS_{bh2} = 91.048 \quad \text{... Bearing Ultimate Strength} \]

\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot SFy \cdot FF} \right) - 1 \]
\[ MS_{bry} = \left( \frac{105.25}{179.38} \right) \quad \text{Plate1} \]
\[ MS_{bry} = \left( \frac{105.25}{179.38} \right) \quad \text{Plate2} \]

\[ MS_{bh3} := \min \left( MS_{bry} \right) \]
\[ MS_{bh3} = 105.25 \quad \text{... Bearing Yield Strength} \]
Rivet Analysis

Rivet := "NAS 1398BFC6-3, Rivet Blind, Protruding Head, Locked Spindle, .190 Dia, .126 Grip, .350 L, AL)"

Flange_1 := "Outer Skin Splice Plates"
Part_Number_1 := "SDG39137927/8/9"
Material_1 := "AL ALY 6061-T651, AMS-QQ-A-250/11"

D_hole := 0.191 in

\[ c_1 := \frac{D_{\text{hole}}}{2} \]

(\( c_1 \): edge to hole center)

edge_1 := 0.215 in  Minimum edge distance of flange one

Flange_2 := "TRD Gas Ballistic Cover - Outer Skin"
Part_Number_2 := "SLG39137916-503"
Material_2 := "AL ALY 6061-T6, SAE-AMS-4027"

D_hole := 0.191 in

\[ c_2 := \frac{D_{\text{hole}}}{2} \]

(\( c_2 \): edge to hole center)

edge_2 := 0.215 in  Minimum edge distance of flange two

Methodology

The TRD Gas Ballistic Cover Outer Skin has 8 Angle Brackets SDG39137927, SDG39137928, SDG39137929, which support the Outer Skin where it is folded. All 8 Angle Brackets are .120 thick AL 6061-T651; use NAS 1398BFC6-3 rivets which go through 0.191 holes.

Each rivet was modeled in NASTRAN as two spider RBE2s connected by a CBUSH. 64 Lift Off and 64 Landing load conditions were analyzed using the Integrated Loads FEM.

The worst case Axial (P) and Total Shear (V) loads from the CBUSH's were enveloped for all the rivets, for all 8 Angle Brackets, for all 128 load cases. The worst case P and the worst case V were used together to calculate the tensile and shear margins of safety.

For Fail-Safe Analysis, the worst worst case P and V from the fail-safe NASTRAN runs were used together to calculate the tensile and shear fail-safe margins of safety.

Allowables

**Rivet Strengths (Spindle AL ALY 7075, QQ-A-430)**

\[ F_{\text{su}} := 640 \text{ lbf} \]  (Minimum Shear Strength)  (Per Document NAS1400, Table III)

\[ F_{\text{tu}} := 540 \text{ lbf} \]  (Minimum Tensile Strength)  (Per Document NAS1400, Table IV)

**Factors of Safety (reference)**

\[ FS_{\text{u}} := 2.00 \]  (Ultimate Factor of Safety)

\[ FS_{\text{y}} := 1.25 \]  (Yield Factor of Safety)

\[ FF := 1.15 \]  (Fitting Factor of Safety)
Temperature Data (reference)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp_initial</td>
<td>70 deg</td>
<td>(Assembly)</td>
</tr>
<tr>
<td>Temp_max</td>
<td>140 deg</td>
<td>(Maximum)</td>
</tr>
<tr>
<td>Temp_min</td>
<td>-76 deg</td>
<td>(Minimum)</td>
</tr>
</tbody>
</table>

Note: these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative.

Temperature Reduction Factors

Note: For the Debris Shield, the temperature extremes are -76°F to 140°F. These temperature reduction factors are conservative for liftoff/landing conditions.

\[
\beta_u = 0.99 \quad \text{(Ultimate Temperature Reduction Factor)} \quad \text{(Ref. MMPDS-03, Figure 3.2.3.1.4)}
\]

\[
\beta_y = 0.99
\]

Allowable Strengths With Temperature Reduction Factor

\[
F_{sug} := \beta_u F_{su} \quad F_{sug} = 634 \text{ lbf} \quad \text{(Shear Strength Allowable)}
\]

\[
F_{tug} := \beta_u F_{tu} \quad F_{tug} = 535 \text{ lbf} \quad \text{(Tensile Strength Allowable)}
\]

Loads (reference)

Landing

(Relation: Rivet Hole Loads, "Splice Plates.xmcdz", pp. 5.10.3-56)

Rivet hole loads

\[
\text{MaxShear}_j := \sqrt{(Fx)^2 + (Fy)^2} \quad \text{max}(\text{MaxShear}) = 23.41 \text{ lbf} \quad \text{min}(\text{MaxShear}) = 0.04 \text{ lbf}
\]

\[
\text{MaxTension}_j := \sqrt{(Fz)^2} \quad \text{max}(\text{MaxTension}) = 14.659 \text{ lbf} \quad \text{min}(\text{MaxTension}) = 0 \text{ lbf}
\]

Liftoff

Rivet hole loads

\[
\text{MaxShear}_j := \sqrt{(Fx)^2 + (Fy)^2} \quad \text{max}(\text{MaxShear}) = 10.548 \text{ lbf} \quad \text{min}(\text{MaxShear}) = 0.03 \text{ lbf}
\]

\[
\text{MaxTension}_j := \sqrt{(Fz)^2} \quad \text{max}(\text{MaxTension}) = 7.363 \text{ lbf} \quad \text{min}(\text{MaxTension}) = 0.001 \text{ lbf}
\]
Debris Shield Fastener/Joint Analysis for Blind Rivet, Protruding Head, Locked Spindle TRD Gas Supply - Splice Brackets Rivet Analysis

| P := 14.7 lbf | (Applied Tensile Load) | (Worst Case Combination) |
| V := 23.4 lbf | (Applied Shear Load)    |
| M := 0 in-lbf | (Applied Bending Moment) |

**Margin of Safety**

\[ MS_{\text{ult}} := \frac{F_{\text{tug}}}{F_{\text{Su}}F_{\text{F}}P} - 1 \]
\[ MS_{\text{ult}} = 14.81 \] \[ \ldots \text{Tensile Ultimate Margin of Safety} \]

\[ MS_{\text{shear}} := \frac{F_{\text{sug}}}{F_{\text{Su}}F_{\text{F}}V} - 1 \]
\[ MS_{\text{shear}} = 10.77 \] \[ \ldots \text{Shear Ultimate Margin of Safety} \]

**Fail-Safe Analysis**

**Fail-Safe Factors of Safety**

\[ F_{\text{Su}}_{\text{FS}} := 1.00 \] \[ \text{(Ultimate)} \]

**Fail-Safe Loads**

(Reference: Landing, Rivet Hole Loads, "Splice Plates.xmcdz", pp. 5.10.3-62)

\[ P_{\text{FS}} := 17.412 \text{ lbf} \] \[ \text{(Applied Tensile Load)} \]
\[ V_{\text{FS}} := 28.074 \text{ lbf} \] \[ \text{(Applied Shear Load)} \]
\[ M_{\text{FS}} := 0.0 \text{ in-lbf} \] \[ \text{(Applied Bending Moment)} \]

**Fail-Safe Margin of Safety**

\[ MS_{\text{FSult}} := \frac{F_{\text{tug}}}{F_{\text{Su}}_{\text{FS}}F_{\text{F}}P_{\text{FS}}} - 1 \]
\[ MS_{\text{FSult}} = 25.7 \] \[ \ldots \text{Fail-Safe Tensile Ultimate Margin of Safety} \]

\[ MS_{\text{FSshear}} := \frac{F_{\text{sug}}}{F_{\text{Su}}_{\text{FS}}F_{\text{F}}V_{\text{FS}}} - 1 \]
\[ MS_{\text{FSshear}} = 18.63 \] \[ \ldots \text{Fail-Safe Shear Ultimate Margin of Safety} \]
Rivet Hole Analysis

Safety Factors

\[ FS_u = 2.00 \]  (Ultimate)

\[ FS_y = 1.250 \]  (Yield)

\[ FF = 1.150 \]  (Fitting Factor)

Input Loads

\[ V = 23.4 \text{lbf} \]  (Shear Load)

\[ P = 14.7 \text{lbf} \]  (Axial Load)

Dimensions

\[ L := 0.350 \text{ in} \]  (Length Max)

\[ twh := 0.00 \text{ in} \]  (Thickness of Washer)

Bolt Hole Dimensions

\[ tf_1 := 0.125 \text{ in} \]  (Entire Thickness of Flange 1)

\[ tf_2 := 0.040 \text{ in} \]  (Entire Thickness of Flange 2)

\[ edge_1 = 0.215 \text{ in} \]  (Edge Distance for Hole in Flange 1)

\[ edge_2 = 0.215 \text{ in} \]  (Edge Distance for Hole in Flange 2)

\[ D := 0.190 \text{ in} \]  (Diameter of Bolt)

\[ D_{\text{ Shank}} := 0.187 \text{ in} \]  (Min. Shank Diameter of Bolt)

\[ D_{\text{ Hole}} = 0.191 \text{ in} \]  (Diameter of Hole)

Shear Tear-Out Check

Shear Area of the Mating Components (Ref. Analysis & Design of Flight Vehicle Structures, Bruhn, Pg. D1.5)

\[ A_{\text{ shrpl}} := \left[ 2 \cdot tf \cdot \left( \frac{1}{2} \cdot D_{\text{ Hole}} \right) \right] \]  (Plate1)

\[ A_{\text{ shrpl}} := \left( \frac{0.030}{0.010} \right) \text{ in}^{2} \cdot 2.000 \]  (Plate2)

Allowables for Flanges that Fastener Goes Through

\[ F_{\text{ su1}} := Tf_1E \cdot 27 \cdot \text{ksi} \]  (Ultimate Shear Allowable for Flange 1)

\[ F_{\text{ su1}} = 26.730 \text{ksi} \]

\[ F_{\text{ su2}} := Tf_2E \cdot 27 \cdot \text{ksi} \]  (Ultimate Shear Allowable for Flange 2)

\[ F_{\text{ su2}} = 26.730 \text{ksi} \]

\[ P_{\text{ su}} := \left( A_{\text{ shrpl}} \cdot F_{\text{ su}} \right) \]  (Shear Ultimate Allowable)

\[ P_{\text{ su}} = \left( \frac{795}{254} \right) \text{lbf} \]
Margin of Safety for Shear Tear-Out

\[ \text{MS}_{su} := \left( \frac{P_{su}}{V \cdot F_{Su} \cdot FF} \right) - 1 \]

\[ \text{MS}_{bh1} := \min(\text{MS}_{su}) \]

\[ \text{MS}_{bh1} = 3.728 \]

... Shear Tear-Out

Bearing Check

Recall Bolt Hole Dimensions

- \( tf_1 = 0.125 \text{ in} \) (Thickness of Flange 1)
- \( tf_2 = 0.040 \text{ in} \) (Thickness of Flange 2)
- \( \text{edge}_1 = 0.215 \text{ in} \) (Edge Distance for thru Hole in Flange 1)
- \( \text{edge}_2 = 0.215 \text{ in} \) (Edge Distance for tapped Hole in Flange 2)

\[ A_{br} := \left( \frac{tf \cdot \min(D, D_{shank})}{(\text{Plate1})} \right) \]

\[ A_{br} = \begin{pmatrix} 0.023 \\ 0.007 \end{pmatrix} \text{in}^2 \]

(Bearing Areas)

\[ e_D := \frac{\text{edge}}{D_{hole}} \]

\[ e_D = \begin{pmatrix} 1.123 \\ 1.123 \end{pmatrix} \]

(e/D for Flanges)

Bearing Allowables for Flanges that Fastener Goes Through

<table>
<thead>
<tr>
<th></th>
<th>Flange 1</th>
<th>Flange 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fbru  ((e/D=1.5))</td>
<td>Fbru151 := T11E·67ksi</td>
<td>Fbru151 := T12E·67ksi</td>
</tr>
<tr>
<td></td>
<td>Fbru151 = 66.33ksi</td>
<td>Fbru152 := T12E·67ksi</td>
</tr>
<tr>
<td></td>
<td>Fbru152 = 66.33ksi</td>
<td>Fbru152 = 66.33ksi</td>
</tr>
<tr>
<td>Fbru  ((e/D=2.0))</td>
<td>Fbru201 := T11E·88ksi</td>
<td>Fbru201 := T11E·88ksi</td>
</tr>
<tr>
<td></td>
<td>Fbru201 = 87.12ksi</td>
<td>Fbru201 = 87.12ksi</td>
</tr>
<tr>
<td>Fbry  ((e/D=1.5))</td>
<td>Fbry151 := T11E·50ksi</td>
<td>Fbry151 := T11E·50ksi</td>
</tr>
<tr>
<td></td>
<td>Fbry151 = 49.5ksi</td>
<td>Fbry152 := T11E·50ksi</td>
</tr>
<tr>
<td></td>
<td>Fbry152 = 49.5ksi</td>
<td>Fbry152 = 49.5ksi</td>
</tr>
<tr>
<td>Fbry  ((e/D=2.0))</td>
<td>Fbry201 := T11E·58ksi</td>
<td>Fbry201 := T11E·58ksi</td>
</tr>
<tr>
<td></td>
<td>Fbry201 = 57.420ksi</td>
<td>Fbry201 = 57.420ksi</td>
</tr>
<tr>
<td></td>
<td>Fbry202 := T11E·58ksi</td>
<td>Fbry202 := T11E·58ksi</td>
</tr>
<tr>
<td></td>
<td>Fbry202 = 57.420ksi</td>
<td>Fbry202 = 57.420ksi</td>
</tr>
</tbody>
</table>
**Modified Bearing Strength**

\[ F_{bru_m} := \begin{cases} F_{bru1} & \text{if } e_D > 2.0, F_{bru2} & \text{if } (e_D > 1.5) \land (e_D < 2.0), F_{bru1} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bru2} - F_{bru1}) \end{cases} \]

\[ F_{bry_m} := \begin{cases} F_{bry1} & \text{if } e_D > 2.0, F_{bry2} & \text{if } (e_D > 1.5) \land (e_D < 2.0), F_{bry1} + \frac{e_D - 1.5}{2.0 - 1.5} (F_{bry2} - F_{bry1}) \end{cases} \]

\[ F_{bru} = \frac{41.326}{41.326} \text{ ksi (Ultimate)} \]

\[ F_{bry} = \frac{30.84}{30.84} \text{ ksi (Yield)} \]

\[ P_{bru} := \frac{A_{br}}{F_{bru}} \quad P_{bru} = \frac{966}{309} \text{ lbf (Bearing Ultimate Allowable)} \]

\[ P_{bry} := \frac{A_{br}}{F_{bry}} \quad P_{bry} = \frac{721}{231} \text{ lbf (Bearing Yield Allowable)} \]

**Margin of Safety for Bearing Failure**

\[ MS_{bru} := \left( \frac{P_{bru}}{V \cdot FS_y \cdot FF} - 1 \right) \quad MS_{bru} = \left( \frac{16.949}{4.744} \right) \text{ (Plate1)} \]

\[ MS_{bry} := \min\left( MS_{bru} \right) \quad MS_{bry} = 4.744 \quad ... \text{ Bearing Ultimate Strength} \]

\[ MS_{bry} := \left( \frac{P_{bry}}{V \cdot FS_y \cdot FF} - 1 \right) \quad MS_{bry} = \left( \frac{20.43}{5.86} \right) \text{ (Plate1)} \]

\[ MS_{bry} := \min\left( MS_{bry} \right) \quad MS_{bry} = 5.858 \quad ... \text{ Bearing Yield Strength} \]
5.11 STS and ISS Integration Hardware Bolt Analysis
Section 5.11  

STS and ISS Integration Hardware Bolt Analysis

The STS and ISS Integration Hardware Bolt Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.11.2</td>
<td>PVGF to PVGF Bracket</td>
</tr>
<tr>
<td>5.11.2</td>
<td>PVGF to PVGF Bracket Fail Safe</td>
</tr>
<tr>
<td>5.11.3</td>
<td>PVGF Bracket to Upper Trunnion Bridge Beam</td>
</tr>
<tr>
<td>5.11.3</td>
<td>PVGF Bracket to Upper Trunnion Bridge Beam Fail Safe</td>
</tr>
<tr>
<td>5.11.4</td>
<td>FRGF to FRGF Bracket</td>
</tr>
<tr>
<td>5.11.4</td>
<td>FRGF to FRGF Bracket Fail Safe</td>
</tr>
<tr>
<td>5.11.5</td>
<td>FRGF Bracket to Upper Trunnion Bridge Beam</td>
</tr>
<tr>
<td>5.11.5</td>
<td>FRGF Bracket to Upper Trunnion Bridge Beam Fail Safe</td>
</tr>
<tr>
<td>5.11.6</td>
<td>ROEU Fastener Analysis</td>
</tr>
<tr>
<td>5.11.6.1</td>
<td>ROEU Arm Flange to Sill Joint</td>
</tr>
<tr>
<td>5.11.6.1</td>
<td>ROEU Arm Flange to Sill Joint (Fail-Safe)</td>
</tr>
<tr>
<td>5.11.6.2</td>
<td>ROEU Bearing Failure Analysis</td>
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<tr>
<td>5.11.6.3</td>
<td>ROEU PDA Bracket, Pin, and Lug Analysis</td>
</tr>
<tr>
<td>5.11.6.4</td>
<td>ROEU Assembly Harness Bracket and Bolt Analysis</td>
</tr>
<tr>
<td>5.11.9</td>
<td>Scuff Plate to Sill Joint Bolt Analysis</td>
</tr>
<tr>
<td>5.11.9</td>
<td>Scuff Plate to Sill Joint Bolt Analysis Fail Safe</td>
</tr>
<tr>
<td>5.11.11</td>
<td>Interface Panel A to USS-02 Trunnion Bridge Beam</td>
</tr>
<tr>
<td>5.11.11</td>
<td>Interface Panel A to USS-02 Trunnion Bridge Beam Fail-Safe</td>
</tr>
</tbody>
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5.11.1 Intentionally Left Blank
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<tr>
<th>Prepared By</th>
<th>Name</th>
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<tr>
<td></td>
<td>G. Reyes</td>
<td>07/20/08</td>
<td>Sec5-11-1.mcd</td>
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<tr>
<td>Checked By</td>
<td>C. Bala</td>
<td></td>
<td>Drawing No.</td>
</tr>
</tbody>
</table>

**Title**

AMS-02

**Intentionally Left Blank**
5.11.2 PVGF to PVGF Bracket
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Section 5.11.2

PVGF Bracket to PVGF Bolt Analysis

CHECK BOLTS (EWB0420-6-17 0.375"-24 x 1.7195 L Material-A-286), Nut Plate MS21060L6, Washer 200003-XX CRES 15-5PH (Along with thermal washer)

Analysis: The fasteners connecting the PVGF bracket to the PVGF will be analyzed. The tension and shear on the bolts will be calculated. This analysis only includes the 6 fasteners shown in the figure below.

Bolt Geometry

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
0.375 & \quad 24
\end{align*}
\]

\[\text{bolt} := \begin{bmatrix}
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375 \\
0.375
\end{bmatrix} \quad \text{24}
\]

\[i := 1 \ldots \text{rows(bolt)}
\]

\[N_i := \text{bolt, } i, \frac{1}{2} \text{ in} \quad \text{pitch of bolt}
\]

\[D_i := \text{bolt, } i, \text{1 in} \quad \text{bolt diameter}
\]

\[
\begin{align*}
\text{Tensile Area of bolt} & \quad A_{ti} := \beta \left( \frac{D_i - 0.9743}{N_i} \right)^2 \\
\text{Shear Area of bolt} & \quad A_{si} := \beta \left( \frac{D_i - 1.299038}{N_i} \right)^2
\end{align*}
\]
Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-2.5</td>
<td>4.33</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>-4.33</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>-4.33</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-2.5</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
\begin{align*}
x_{\text{force}} & := 0.0\text{in} & y_{\text{force}} & := 0.0\text{in} & z_{\text{force}} & := 0.0\text{in} \\
\text{cgload} & := \begin{bmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{bmatrix} & \text{cgload} & := \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\end{align*}
\]
Center of gravity of bolt group

\[
\begin{align*}
\text{x}_{\text{cg}} := & \frac{\sum x_i}{\text{rows}(x)} & \text{x}_{\text{cg}} = 0 \text{ in} \\
\text{y}_{\text{cg}} := & \frac{\sum y_i}{\text{rows}(y)} & \text{y}_{\text{cg}} = 0 \text{ in} \\
\text{z}_{\text{cg}} := & \frac{\sum z_i}{\text{rows}(z)} & \text{z}_{\text{cg}} = 0 \text{ in}
\end{align*}
\]

\[
\text{c}_{\text{gbolt}} := \begin{pmatrix} \text{x}_{\text{cg}} \\ \text{y}_{\text{cg}} \\ \text{z}_{\text{cg}} \end{pmatrix}
\]

\[
\text{c}_{\text{gbolt}} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

Load Vector

\[
\text{r}_{\text{load}} := \text{c}_{\text{gload}} - \text{c}_{\text{gbolt}}
\]

\[
\text{r}_{\text{load}} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\text{r}_i := \sqrt{\left( x_i - \text{x}_{\text{cg}} \right)^2 + \left( y_i - \text{y}_{\text{cg}} \right)^2}
\]

\[
\text{r} = \begin{pmatrix} 5.000 \\ 5.000 \\ 5.000 \\ 5.000 \end{pmatrix} \text{ in}
\]

Reading database file

The following file reads in all the loads:

```plaintext
data := READPRN("centerloads-pv.txt")
num_bolts := rows(bolt)  j := 1 . rows(data)
```

* Note that "centerloads-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files.
Loads from loads model

Shear in X axis \( F_x \) := \( data_{j,3} \) lbf

Moment about X axis \( M_x \) := \( data_{j,6} \) in-lbf

Shear in Y axis \( F_y \) := \( data_{j,4} \) lbf

Moment about Y axis \( M_y \) := \( data_{j,8} \) in-lbf

Axial Load \( F_z \) := \( data_{j,5} \) lbf

Torsion \( M_z \) := \( data_{j,7} \) in-lbf

Extrapolation of Moments:

Distance from RBE \( dist \) := 1.0 in

Extrapolation of My Moment:

\( M_y \) := \( M_y \) + \( F_x \) \( \cdot \) \( dist \)

Extrapolation of Mx Moment:

\( M_x \) := \( M_x \) + \( F_y \) \( \cdot \) \( dist \)

Element Identification \( ID \) := \( data_{j,1} \)

\( ID \) := \( ID \) \( \cdot \) 1000 + 1 \( \) Counter for number of bolts in pattern

Load Case Number \( LC \) := \( data_{j,2} \)

Applied Bending Moment at Bolts \( M_j \) := 0 in-lbf

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\( ID := \) stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5)

\( LC := \) stack(LC, LC, LC, LC, LC, LC)
Moment Distribution

\[ M_{tot}^{(j)} := \begin{pmatrix} M_{x_j} \\ M_{y_j} \\ M_{z_j} \end{pmatrix} + \mathbf{r}_{load} \times \begin{pmatrix} F_{x_j} \\ F_{y_j} \\ F_{z_j} \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{x_{boltcg}} := M_{tot1,j} \quad M_{y_{boltcg}} := M_{tot2,j} \quad M_{z_{boltcg}} := M_{tot3,j} \]

Tension on bolts

\[ F_{direct,i,j} := \begin{cases} 0 \cdot \text{lbf} & \text{if } F_{z_j} \leq 0 \text{lbf} \\ \frac{F_{z_j}}{\text{num_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ F_{mz,i,j} := 0 \cdot \text{lbf} \quad \text{if } (y_i - \text{ycg}) = 0 \cdot \text{in} \]
\[ \frac{[M_{x_{boltcg}}.(y_i - \text{ycg})].At_i}{\sum (y_i - \text{ycg})^2 \cdot At_i} \]

\[ F_{my,i,j} := 0 \cdot \text{lbf} \quad \text{if } (x_i - \text{xcg}) = 0 \cdot \text{in} \]
\[ \frac{[M_{y_{boltcg}}.(x_i - \text{xcg})].At_i}{\sum (x_i - \text{xcg})^2 \cdot At_i} \]

\[ F_{t,i,j} := F_{direct,i,j} + F_{mz,i,j} + F_{my,i,j} \quad \text{Total Tensile load} \]

Shear on bolts

Direct shear Loads \[ F_{sd,i,j} := \sqrt{\left(\frac{F_{y_j}}{\text{num_bolts}}\right)^2 + \left(\frac{F_{x_j}}{\text{num_bolts}}\right)^2} \]

Secondary shear on bolts \[ F_{s,i,j} := \frac{[M_{z_{boltcg}}].r \cdot As_i}{\sum [r_i^2 \cdot (As_i)]} \quad \text{Total shear load} \]
\[ F_{stot,i,j} := F_{s,i,j} + F_{sd,i,j} \]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P := \text{stack}\left[\begin{array}{c}
F_t^T(1),
F_t^T(2),
F_t^T(3),
F_t^T(4),
F_t^T(5),
F_t^T(6),
\end{array}\right]
\]

\[
V := \text{stack}\left[\begin{array}{c}
F_{stot}^T(1),
F_{stot}^T(2),
F_{stot}^T(3),
F_{stot}^T(4),
F_{stot}^T(5),
F_{stot}^T(6),
\end{array}\right]
\]

\[
M := \text{stack}(M, M, M, M, M)
\]

The "Output" file outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

\[
\text{Output} := \text{augment}\left(\begin{array}{c}
\text{ID}, \text{LC}, \frac{P}{\text{lbf}}, \frac{V}{\text{lbf}}, \frac{M}{\text{in-lbf}}
\end{array}\right)
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \(\text{rows}(\text{Output}) = 396\)

\[
\text{WRITEPRN("centerboltloads-pv.txt") := Output}
\]
CHECK BOLTS (EWB0420-6-17 0.375"-24 x 1.7195 L Material-A-286), Nut Plate MS21060L6, Washer 200003-XX CRES 15-5PH (Along with thermal washer)

```math
\[
\text{data} := \text{READPRN}("\text{centerboltloads-pv.txt}\")
\]

\[s := 1..\text{rows(data)}\]

Flange 1: PVGF
Part number: Drawing not provided
Material: Titanium (Assume Ti-6Al-4V)

Flange 2: PVGF Bracket
Part number: SDG39135860
Material: Al Alloy 7075-T7351

```

**Loads**

Applied tensile load

\[P := \text{data}_{s,3}\text{lbf} \quad ID := \text{data}_{s,1}\]

Applied shear load

\[V := \text{data}_{s,4}\text{lbf} \quad LC := \text{data}_{s,2}\]

Applied bending moment

\[M := \text{data}_{s,5}\text{in}\cdot\text{lbf}\]

**Factors of Safety**

Ultimate

\[\text{SFu} := 2.0\]

Yield

\[\text{SFy} := 1.25\]

Assembly

\[\text{Temp\_initial} := 70\text{-deg}\]

Joint Separation

\[\text{SFsep} := 1.2\]

Fitting factor

\[\text{FF} := 1.15\]

Maximum

\[\text{Temp\_max} := 225\text{-deg}\]

Minimum

\[\text{Temp\_min} := -65\text{-deg}\]

**Bolt and Nut Data**

Nominal diameter of bolt

\[D := 0.375\text{in}\]

Number of threads/inch

\[Nt := 24\frac{1}{\text{in}}\]

Total length of bolt

\[L := 1.7195\text{in}\]

Height of nut

\[H := 0.344\text{in}\]

Threaded length

\[Lt := 0.657\text{in}\]

(If bolt is fully threaded, input Lt = L)

**This file uses the calculations shown in \escfil02\2i11\mathcad\08307\bolts\thread\thread_data.mcd**

**Washer Data**

Thicknes of washers

\[tw := 0.1\text{in}\]

Outer Diameter of washer

\[Dw := 1.25\text{in}\]

Inner Diameter of washer

\[Dwi := 0.391\text{in}\]

Bolt head dia. across flats

\[dw := 0.0\text{in}\]

(used only if there is no washer)

Note: If there is no washer tw, Dw and Dwi should be zero
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate. \( T_{Su\_bolt} := 0.96 \)  
Bolt ultimate tensile allowable stress \( F_{tu\_bolt} := 200000 \text{ psi} \)  
Bolt ultimate shear allowable stress \( F_{su\_bolt} := 0.6 \times F_{tu\_bolt} \)  
Bolt yield Tensile allowable stress \( F_{ty\_bolt} := 180000 \text{ psi} \)  
Temperature correction factor for bolt modulus \( T_{E\_bolt} := 0.96 \)  
Modulus of elasticity of bolt \( E_{\text{bolt}} := \left( 29.1 \times 10^6 \text{ psi} \right) \)  
Thermal coefficient for bolt \( u_{\text{bolt\_hot}} := 9.2 \times 10^{-6} \text{ in/deg} \)

Nut

Temperature correction factor for nut strength \( T_{S\_nut} := 0.96 \)  
Ultimate tensile allowable stress \( F_{tu\_nut} := 125000 \text{ psi} \)  
Ultimate Shear allowable stress \( F_{su\_nut} := 0.6 \times F_{tu\_nut} \)  
Ultimate axial strength of nut \( P_{tu\_nut} := 11450 \text{ lbf} \)  
(Ref. MS21060)

Washer

Temperature correction factor for washer modulus \( T_{E\_washer} := 1.0 \)  
Modulus of elasticity of washer: \( E_{\text{washer}} := \left( 28.5 \times 10^6 \text{ psi} \right) \)

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.  
Temperature correction factor for flange 1 \( T_{f1E} := 0.94 \text{ (modulus)} \)  
Temperature correction factor for flange 2 \( T_{f2E} := 0.95 \)  
Modulus of elasticity for the parts in the joint \( E_{\text{flange1}} := \left( 16.0 \times 10^6 \text{ psi} \right) \)  
\( E_{\text{flange2}} := \left( 10.3 \times 10^6 \text{ psi} \right) \)  
Coefficient of thermal expansion for flanges \( u_{\text{flange1\_hot}} := 5.05 \times 10^{-6} \text{ in/deg} \)  
\( u_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \text{ in/deg} \)  
\( u_{\text{flange1\_cold}} := 4.7 \times 10^{-6} \text{ in/deg} \)  
\( u_{\text{flange2\_cold}} := 12.05 \times 10^{-6} \text{ in/deg} \)

Torque/Preload data

Maximum torque (49% of Yield) \( T_{max} := 435 \text{ in-lbf} \)  
Loading plane factor \( n := 0.5 \)  
Minimum torque (85% of Max Torque) \( T_{min} := 370 \text{ in-lbf} \)  
Preload Uncertainty \( := 0.25 \)  
Torque coefficient \( k := 0.15 \)
AMS-02 PVGF Bracket - Bolt Analysis

This file uses the calculations shown in \\escf\02\2i11\mathcad\08307_bolts\multi_bolt_stiffness_nut_RevC

<table>
<thead>
<tr>
<th>Bolt Load data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
</tr>
<tr>
<td>Max. preload</td>
</tr>
<tr>
<td>Min. preload</td>
</tr>
<tr>
<td>Joint separation load</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
</tr>
<tr>
<td>Max. load on the bolt(yield)</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
</tr>
</tbody>
</table>

Length_check = "Bolt length is sufficient"

<table>
<thead>
<tr>
<th>Summary of Margins for bolt:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

MSbolt := \min(MS)

| MSbolt = 0.03 |

Failure_Mode = "Combined Shear Tension Bending Ultimate"

| MS_min_ID = 19511004 | Element Identification (19511) and Bolt Number (4) for Minimum Margin |
| MS_min_LC = 5036 | Load Case Number for Minimum Margin |
| MS_min_P = 1861.5 | Applied Tensile Load for Minimum Margin |
| MS_min_V = 0 | Applied Shear Load for Minimum Margin |
| MS_min_M = 0 | Applied Bending Moment for Minimum Margin |
Bolt Fail Safe Analysis for PVGF Bracket to PVGF

Since bolt number 4 has the lowest margin of safety, it is assumed that this bolt will be the first bolt to fail. There are now 5, EWB0420 0.375"-24 fasteners, holding the PVGF to the PVGF bracket.

**Bolt Geometry**

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
\begin{cases}
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
0.375 & 24 \\
\end{cases}
\end{align*}
\]

\[\text{bolt2} := \begin{bmatrix} 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \\ 0.375 & 24 \end{bmatrix} \]

\[s := 1..\text{rows(bolt2)}\]

\[N2_s := \text{bolt2}_{s,2} \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt}\]

\[D2_s := \text{bolt2}_{s,1} \cdot \text{in} \quad \text{bolt diameter}\]

\[\text{At2}_s := \beta \cdot \left( \frac{D2_s - 0.9743 \cdot \frac{1}{N2_s}}{2} \right)^2 \quad \text{Tensile Area of bolt}\]

\[\text{As2}_s := \beta \cdot \left( \frac{D2_s - 1.299038 \cdot \frac{1}{N2_s}}{2} \right)^2 \quad \text{Shear Area of bolt}\]
Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-2.5</td>
<td>4.33</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>4.33</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>-4.33</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-2.5</td>
<td>-4.33</td>
<td>0</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[
xforce2 := 0.0\text{in} \quad yforce2 := 0.0\text{in} \quad zforce2 := 0.0\text{in}
\]

\[
cgload2 := \begin{pmatrix} xforce2 \\ yforce2 \\ zforce2 \end{pmatrix} \quad \text{cgload2} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}
\]
Center of gravity of bolt group

\[
\begin{align*}
\text{xcg2} &:= \frac{s}{\text{rows(x2)}} \quad \text{xcg2} = -1 \text{ in} \\
\text{ycg2} &:= \frac{s}{\text{rows(y2)}} \quad \text{ycg2} = 0 \text{ in} \\
\text{zcg2} &:= \frac{s}{\text{rows(z2)}} \quad \text{zcg2} = 0 \text{ in}
\end{align*}
\]

\[
\begin{align*}
\text{cgbolt2} &:= \begin{pmatrix}
\text{xcg2} \\
\text{ycg2} \\
\text{zcg2}
\end{pmatrix} \\
\text{cgbolt2} &:= \begin{pmatrix}
-1 \\
0 \\
0
\end{pmatrix} \text{ in}
\end{align*}
\]

Load Vector

\[
\begin{align*}
\text{r}_{\text{load2}} &:= \text{cgload2} - \text{cgbolt2} \\
\text{r}_{\text{load2}} &:= \begin{pmatrix}
1 \\
0 \\
0
\end{pmatrix} \text{ in}
\end{align*}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\begin{align*}
\text{r}_{s} &:= \sqrt{(x_{s} - \text{xcg2})^2 + (y_{s} - \text{ycg2})^2} \\
\text{r}_{s} &:= \begin{pmatrix}
4.000 \\
4.582 \\
5.568 \\
5.568 \\
4.582
\end{pmatrix} \text{ in}
\end{align*}
\]

Reading database file

The following file reads in all the loads:

\[
\begin{align*}
\text{data} &:= \text{READPRN("centerloads-fail-pv.txt")} \\
\text{num_bolts2} &:= \text{rows(bolt2)} \\
\text{q} &:= 1 \ldots \text{rows(data)}
\end{align*}
\]

* Note that "centerloads-fail-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files.
Loads from loads model

Shear in X axis \( F_{x2} := \text{data}_{q3}, \text{lbf} \)  
Shear in Y axis \( F_{y2} := \text{data}_{q4}, \text{lbf} \)  
Axial Load \( F_{z2} := \text{data}_{q5}, \text{lbf} \)  

Moment about Z axis \( M_{x2} := \text{data}_{q6}, \text{in-lbf} \)  
Moment about Y axis \( M_{y2} := \text{data}_{q8}, \text{in-lbf} \)

Extrapolation of Moments:

Distance from RBE \( \text{dist2} := 1.0 \text{-in} \)

Extrapolation of My Moment: \( M_{y2} := M_{y2} + F_{y2} \cdot \text{dist2} \)

Extrapolation of Mx Moment: \( M_{x2} := M_{x2} + F_{x2} \cdot \text{dist} \)

Element Identification \( \text{ID}_{2} := \text{data}_{q1} \) \( \text{ID}_{2} := \text{ID}_{2} \cdot 1000 + \text{Counter for number of bolts in pattern} \)

Load Case Number \( \text{LC}_{2} := \text{data}_{q2} \)

Applied Bending Moment at Bolts \( M_{2} := 0 \text{-in-lbf} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\( \text{ID2} := \text{stack} \left( \text{ID2}, \text{ID2} + 1, \text{ID2} + 2, \text{ID2} + 4, \text{ID2} + 5 \right) \)

\( \text{LC2} := \text{stack} \left( \text{LC2}, \text{LC2}, \text{LC2}, \text{LC2}, \text{LC2} \right) \)
Moment Distribution

\[ M_{tot2}(q) := \begin{pmatrix} Mx_{q} \\ My_{q} \\ Mz_{q} \end{pmatrix} + n_{load2} \times \begin{pmatrix} Fx_{q} \\ Fy_{q} \\ Fz_{q} \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ Mx_{boltcg2} := M_{tot1, q} \]
\[ My_{boltcg2} := M_{tot2, q} \]
\[ Mz_{boltcg2} := M_{tot3, q} \]

Tension on bolts

\[ F_{direct2, s, q} := \begin{cases} 0 \cdot \text{lbf} & \text{if } Fz_{q} \leq 0 \text{lbf} \\ \frac{Fz_{q}}{num\_bolts2} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ Fmz_{s, q} := \frac{0 \cdot \text{lbf}}{\text{if } (y_{s} - y_{cg2}) = 0 \text{ in}} \]
\[ \frac{[Mx_{boltcg2} \cdot (y_{s} - y_{cg2})] At_{s}} {\sum_{s} [(y_{s} - y_{cg2})^2 At_{s}]} \]

\[ F_{t2, s, q} := F_{direct2, s, q} + Fmz_{s, q} + Fmy_{s, q} \]

Total Tensile load

Shear on bolts

Direct shear Loads

\[ Fsd_{s, q} := \sqrt{(Fy_{q})^2 + (Fx_{q})^2} \]

\[ \text{num\_bolts2} \]

Secondary shear on bolts

\[ Fs_{s, q} := \frac{Mz_{boltcg2} \cdot r_{s}^2 \cdot As_{s}} {\sum_{s} [r_{s}^2 (As_{s})]} \]

Total shear load

5.11.2-16

ESCG-4450-05-AMS-0039
The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P_2 := \text{stack}
\left[
(F_{T2}^T)^{(1)}, \ (F_{T2}^T)^{(2)}, \ (F_{T2}^T)^{(3)}, \ (F_{T2}^T)^{(4)}, \ (F_{T2}^T)^{(5)}
\right]
\]

\[
V_2 := \text{stack}
\left[
(F_{stot2}^T)^{(1)}, \ (F_{stot2}^T)^{(2)}, \ (F_{stot2}^T)^{(3)}, \ (F_{stot2}^T)^{(4)}, \ (F_{stot2}^T)^{(5)}
\right]
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). The array is then written to a text file.

Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output2" Array: \( \text{rows(Output2)} = 330 \)
Fail-safe Analysis

data_fs := READPRN("centerboltloads-fail-pv.txt")
s := 1..rows(data_fs)

### Fail-safe Loads

- **Applied tensile load**
  \[
  P_{FS} := \text{data}_{fs,s}, 3 \text{ lbf}
  \]
- **Applied shear load**
  \[
  V_{FS} := \text{data}_{fs,s}, 4 \text{ lbf}
  \]
- **Applied bending moment**
  \[
  M_{FS} := \text{data}_{fs,s}, 5 \text{ in-lbf}
  \]

### Fail-safe Factors of Safety

- **Ultimate**
  \[
  SF_u_{FS} := 1.0
  \]
- **Joint Separation**
  \[
  SF_{sep_{FS}} := 1.0
  \]

This file uses the calculations shown in /escfii02/2111_mathcad/8307_bolts\multi_bolt_stiffness_nut_{FS}_RevC

---

**Bolt Fail-safe Load data**

- **Joint separation load**
  \[
  \text{max}(P_{sep_{FS}}) = 2497 \text{ lbf}
  \]
- **Max. load on the bolt(ultimate)**
  \[
  \text{max}(P_{b_{FS}}) = 10562.1 \text{ lbf}
  \]

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>MS_{min_{FS}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1, 1 = 0.300</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>2, 1 = 2.828</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>3, 1 = 0.041</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>4, 1 = 5.89</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>8, 1 = 0.0407</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[
MS_{bolt_{FS}} := \min(\text{MS}_{FS})
\]

\[
MS_{bolt_{FS}} = 0.041
\]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

- **Element Identification (19511) and Bolt Number (1) for Minimum Margin**
  \[
  MS_{min_{ID}} = 19511001
  \]
- **Load Case Number for Minimum Margin**
  \[
  MS_{min_{LC}} = 5034
  \]
- **Applied Tensile Load for Minimum Margin**
  \[
  MS_{min_{P}} = 2497
  \]
- **Applied Shear Load for Minimum Margin**
  \[
  MS_{min_{V}} = 0
  \]
- **Applied Bending Moment for Minimum Margin**
  \[
  MS_{min_{M}} = 0
  \]
5.11.3 PVGF Bracket to Upper Trunnion Bridge Beam
Section 5.11.3

PVGF Bracket to Upper Trunnion Bridge Beam Bolt Analysis

CHECK BOLTS (NAS1351N4H14 0.25"-28 x 0.875L Material-A-286), Insert MS51831CA202L, Washer NAS1149E0463R

Analysis: The fasteners connecting the PVGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. This analysis only includes the 11 fasteners shown in the figure below.

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[
\begin{align*}
\text{loads} & := \text{READPRN("11fst-pv.txt")} \\
i & := 1..\text{rows(loads)} \quad \text{rows(loads)} = 726 \quad j := 2..\text{cols(loads)} \quad \text{cols(loads)} = 10 \\
\text{ID} & := \text{loads}^{(1)} \quad \text{Fx} := \text{loads}^{(3)} \cdot \text{lbf} \quad \text{Fz} := \text{loads}^{(5)} \cdot \text{lbf} \\
\text{LC} & := \text{loads}^{(2)} \quad \text{Fy} := \text{loads}^{(4)} \cdot \text{lbf} \quad \text{My} := \text{loads}^{(7)} \cdot \text{in-lbf} \\
\text{ID} & := \text{loads}^{(1)} \quad \text{Fx} := \text{loads}^{(3)} \cdot \text{lbf} \quad \text{My} := \text{loads}^{(7)} \cdot \text{in-lbf} \\
\text{ID} & := \text{loads}^{(1)} \quad \text{Fz} := \text{loads}^{(5)} \cdot \text{lbf} \quad \text{Mz} := \text{loads}^{(8)} \cdot \text{in-lbf} \\
\end{align*}
\]

* Note that "12fst.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\begin{align*}
\text{Ft}_i & := \left| \text{Fz}_i \right| \quad \text{max(Ft)} = 1023.5 \text{ lbf} \quad \text{Tensile Load} \\
\text{Fv}_i & := \sqrt{\left( \text{Fy}_i \right)^2 + \left( \text{Fx}_i \right)^2} \quad \text{max(Fv)} = 499.5 \text{ lbf} \quad \text{Shear Load}
\end{align*}
\]
AMS-02 PVGF Bracket - Bolt Analysis

CHECK BOLTS (NAS1351N4H14 0.25"-28 x 0.875L Material-A-286), Insert MS51831CA202L, Washer NAS1149E0463R

Flange 1: Upper Trunnion Bridge Beam
Part number: SDG39135728
Material: Al Alloy 7075-T73511 Extrusion

Flange 2: PVGF Bracket
Part number: SDG39135860
Material: Al Alloy 7075-T7351

Loads
Applied tensile load \( P = 1023.5 \text{ lbf} \)
Applied shear load \( V = 499.5 \text{ lbf} \)
Applied bending moment \( M = 0 \text{ in-lbf} \)

Factors of Safety
Ultimate \( SF_u = 2.0 \)
Yield \( SF_y = 1.25 \)
Joint Separation \( SF_{sep} = 1.2 \)
Fitting factor \( FF = 1.15 \)

Temperature data
Assembly \( Temp_{initial} = 70 \text{ deg} \)
Maximum \( Temp_{max} = 225 \text{ deg} \)
Minimum \( Temp_{min} = -65 \text{ deg} \)

Bolt and Insert Data
Nominal diameter of bolt \( D = 0.250 \text{ in} \)
Number of threads/inch \( N_t = \frac{28}{1} \text{ in} \)
Total length of bolt \( L = 0.875 \text{ in} \)
Length of insert \( L_{ins} = 0.375 \text{ in} \)
Threaded length \( L_t = 0.875 \text{ in} \)
Min. external diameter of insert \( F_{min} = 0.375 \text{ in} \)
Depth of recess for insert \( l_r = 0.02 \text{ in} \)
(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Washer Data
Thickness of washer \( t_w = 0.063 \text{ in} \)
Outer Diameter of washer \( D_w = 0.50 \text{ in} \)
Inner Diameter of washer \( D_{wi} = 0.265 \text{ in} \)
Bolt head dia. across flats \( d_w = 0.365 \text{ in} \)

Flange data
Thickness of flange 1 \( t_f1 = 0.25 \text{ in} \)
Thickness of flange 2 \( t_f2 = 0.375 \text{ in} \)
Diameter of hole \( D_{hole} = 0.288 \text{ in} \)

Note: If there is no washer, \( t_w, D_w, \) and \( D_{wi} \) should be zero.

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ESCG-4005-05-AMS-0039
Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate
TSu_bolt := 0.96  yield  TSy_bolt := 0.96

Bolt ultimate tensile allowable stress
Ftu_bolt := 160000·psi

Bolt ultimate shear allowable stress
Fsu_bolt := 0.6·Ftu_bolt

Bolt yield tensile allowable
Fty_bolt := 120000·psi

Temperature correction factor for bolt modulus
TE_bolt := 0.96

\[
\beta_{\text{bolt, hot}} := 9.2 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]

\[
\beta_{\text{bolt, cold}} := 8.55 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]

Modulus of elasticity of bolt
\[
E_{\text{bolt}} := (29.1\times10^6 \cdot \text{psi})
\]

Insert
Temperature correction factor for insert strength
TS_ins := 0.96

Ultimate tensile allowable stress
Ftu_ins := 140000·psi

Ultimate shear allowable stress
Fsu_ins := 0.6·Ftu_ins

Washer
Temperature correction factor for washer modulus
TE_washer := 0.96

Modulus of elasticity of washer
\[
E_{\text{washer}} := (29.1\times10^6 \cdot \text{psi})
\]

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
TF1E := 0.96 (modulus)  TF2s := 0.87 (strength)

Temperature correction factor for flange 2
TF2E := 0.95 (modulus)  Fsu_f2 := 39000·psi

Modulus of elasticity for the parts in the joint
\[
E_{\text{flange 1}} := (10.4\times10^6 \cdot \text{psi})
\]
\[
E_{\text{flange 2}} := (10.3\times10^6 \cdot \text{psi})
\]

Coefficient of thermal expansion for flanges
\[
\beta_{\text{flange 1, hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]
\[
\beta_{\text{flange 2, hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]
\[
\beta_{\text{flange 1, cold}} := 12.05 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]
\[
\beta_{\text{flange 2, cold}} := 12.05 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]

Torque/Preload data

Maximum torque (61% of Yield)
\[
T_{\text{max}} := 100\, \text{in-lbf}
\]

Loading plane factor:
\[
n := 0.5
\]

Minimum torque (92% of Max Torque)
\[
T_{\text{min}} := 92\, \text{in-lbf}
\]

Preload Uncertainty:
\[
u := 0.25
\]

Torque coefficient:
\[
k := 0.15
\]
Bolt Load data

Bolt/joint stiffness factor \( = 0.286 \)  
Preload due to temperature \( \text{Pth}_{\text{pos}} = 486.4 \text{ lbf} \)

Max. preload \( \text{P}_{\text{LD, max}} = 3819.7 \text{ lbf} \)

Min. preload \( \text{P}_{\text{LD, min}} = 1261.5 \text{ lbf} \)

Joint separation load \( \text{P}_{\text{sep}} = 1.228 \times 10^3 \text{ lbf} \)

Max. load on the bolt (ultimate) \( \text{P}_{\text{b}} = 4156.8 \text{ lbf} \)

Max. load on the bolt (yield) \( \text{P}_{\text{by}} = 4030.4 \text{ lbf} \)

Bolt ultimate tensile strength \( \text{P}_{\text{At}} = 5419.4 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS</th>
<th>Factor</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1</td>
<td>0.04</td>
<td>Direct Thread shear Ultimate</td>
<td>( \text{MS}_{6} = 2.18 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>2</td>
<td>1.3</td>
<td>Total Thread shear Ultimate</td>
<td>( \text{MS}_{7} = 0.8 )</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>3</td>
<td>1.76</td>
<td>Shear Ultimate</td>
<td>( \text{MS}_{8} = 1.61 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>4</td>
<td>0.3</td>
<td>Bending Ultimate</td>
<td>( \text{MS}_{9} = 10 )</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>5</td>
<td>0.008</td>
<td>Combined shear, tension and bending ultimate</td>
<td>( \text{MS}_{10} = 0.233 )</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\( \text{MS}_{\text{bolt}} = \min(\text{MS}) \)

\( \text{MS}_{\text{bolt}} = 0.008 \)  

Failure Mode = "Total Tension Yield"
Fail-safe Analysis

Read in the external datum from NASPOST results:

\[
\text{loadfs} := \text{READPRN("11fst-fail-pv.txt")}
\]

\[
\begin{align*}
\text{pf} & := 1..\text{rows(loadfs)} & \text{rows(loadfs)} = 660 & \text{yf} := 2..\text{cols(loadfs)} & \text{cols(loadfs)} = 10 \\
\text{ID} & := \text{loadfs}^{1} & \text{Fx} := \text{loadfs}^{3}\cdot\text{lbf} & \text{Fz} := \text{loadfs}^{5}\cdot\text{lbf} & \text{My} := \text{loadfs}^{7}\cdot\text{in-lbf} \\
\text{LC} & := \text{loadfs}^{2} & \text{Fy} := \text{loadfs}^{4}\cdot\text{lbf} & \text{Mx} := \text{loadfs}^{6}\cdot\text{in-lbf} & \text{Mz} := \text{loadfs}^{8}\cdot\text{in-lbf}
\end{align*}
\]

* Note that "11fst-fail-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\begin{align*}
\text{Ft}_{pf} & := \left| Fz_{pf} \right| & \text{max(Ft)} = 1254.7 \text{ lbf} & \text{Tensile Load} \\
\text{Fv}_{pf} & := \sqrt{\left( Fy_{pf} \right)^{2} + \left( Fx_{pf} \right)^{2}} & \text{max(Fv)} = 532.37 \text{ lbf} & \text{Shear Load}
\end{align*}
\]

**Fail-safe Loads**

- **Applied tensile load**
  \[ P_{FS} := 1595.26 \text{ lbf} \]
  \[ \text{Ultimate} \]
  \[ SF_{u,FS} := 1.0 \]

- **Applied shear load**
  \[ V_{FS} := 499.24 \text{ lbf} \]
  \[ \text{Joint Separation} \]
  \[ SF_{sep,FS} := 1.0 \]

- **Applied bending moment**
  \[ M_{FS} := 0 \text{ in-lbf} \]

This file uses the calculations shown in \escfil02\2111_mathcad\8307_bolts\bolt_stiffness_insert_FS_RevC

---

**Bolt Fail-safe Load data**

- **Joint separation load**
  \[ P_{sep,FS} = 1595.26 \text{ lbf} \]

- **Max. load on the bolt(ultimate)**
  \[ P_{b,FS} = 4082.4 \text{ lbf} \]

**Summary of fail-safe Margins for bolt:**

- **Joint separation**
  \[ MS_{FS,1} = -0.2 \]
  \[ \text{Total Thread shear Ultimate} \]
  \[ MS_{FS,5} = 0.84 \]

- **Direct Tension Ultimate**
  \[ MS_{FS,2} = 1.95 \]
  \[ \text{Shear Ultimate} \]
  \[ MS_{FS,6} = 4.23 \]

- **Total Tension Ultimate**
  \[ MS_{FS,3} = 0.33 \]
  \[ \text{Bending Ultimate} \]
  \[ MS_{FS,7} = 10 \]

- **Direct Thread shear Ultimate**
  \[ MS_{FS,4} = 3.09 \]
  \[ \text{Combined shear, tension and bending ultimate} \]
  \[ MS_{FS,8} = 0.32 \]

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ MS_{bolt,FS} := \min(\text{MS}_{FS}) \]

\[ MS_{bolt,FS} = -0.2 \]

Failure Mode FS = "Joint Separation"

Joint separation is acceptable for fail-safe analysis.
CHECK BOLTS (NAS1351N4H16 0.25"-28 x 1.0 L Material-A-286), Nut NAS1291C4, Washer NAS1149E0463R

Analysis: The fasteners connecting the PVGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. This analysis only includes the 2 fasteners shown in the figure below.

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[
\text{loads := READPRN("5fst-pv.txt")}
\]

\[
i := 1 \ldots \text{rows(loads)} \quad \text{rows(loads)} = 330 \quad j := 2 \ldots \text{cols(loads)} \quad \text{cols(loads)} = 10
\]

\[
\text{ID := loads(1)} \quad \text{Fx := loads(3)}.\text{lbf} \quad \text{Fz := loads(5)}.\text{lbf} \quad \text{My := loads(7)}.\text{in}.\text{lbf}
\]

\[
\text{LC := loads(2)} \quad \text{Fy := loads(4)}.\text{lbf} \quad \text{Mx := loads(6)}.\text{in}.\text{lbf} \quad \text{Mz := loads(8)}.\text{in}.\text{lbf}
\]

* Note that "5fst-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\text{Ft}_i := \left| Fx_i \right| \\
\text{max(Ft) = 559.64 lbf} \quad \text{Tensile Load}
\]

\[
\text{Fv}_i := \sqrt{\left( Fy_i \right)^2 + \left( Fx_i \right)^2} \\
\text{max(Fv) = 525.94 lbf} \quad \text{Shear Load}
\]
CHECK BOLTS (NAS1351N4H16 0.25”-28 x 1.0 L Material-A-286), Nut NAS1291C4M, Washer NAS1149E0463R

Flange 1: PVGF Bracket
Part number: SDG39135860
Material: Al Alloy 7075-T7351

Flange 2: Upper Trunnion Bridge Beam
Part number: SDG39135728
Material: Al Alloy 7075-T73511 Extrusion

Loads
Applied tensile load \( P := 559.64 \text{ lbf} \)
Applied shear load \( V := 525.94 \text{ lbf} \)
Applied bending moment \( M := 0 \text{ in-lbf} \)

Factors of Safety
Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)
Assembly
Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)
Maximum
Minimum

Temperature data
Temp_initial := 70-deg
Temp_max := 225-deg
Temp_min := -65-deg

Bolt and Nut Data
Nominal diameter of bolt \( D := 0.25 \text{ in} \)
Number of threads/inch \( N_t := 28 \frac{1}{16} \text{ in} \)
Total length of bolt \( L := 1.0 \text{ in} \)
Height of nut \( H := 0.204 \text{ in} \)
Threaded length \( L_t := 1.0 \text{ in} \)
(If bolt is fully threaded, input \( L_t = L \))

Washer Data
Thickness of washers \( tw := 0.063 \text{ in} \)
Outer Diameter of washer \( D_w := 0.50 \text{ in} \)
Inner Diameter of washer \( D_{wi} := 0.265 \text{ in} \)
Bolt head dia. across flats \( d_w := 0.365 \text{ in} \)
(used only if there is no washer)

Flange data
Thickness of flange 1 \( t_{f1} := 0.325 \text{ in} \)
Thickness of flange 2 \( t_{f2} := 0.25 \text{ in} \)
Diameter of hole \( D_{hole} := 0.288 \text{ in} \)

Note: If there is no washer \( tw \), \( D_w \) and \( D_{wi} \) should be zero
Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate.

\[ T_{Su\_bolt} := 0.96 \quad \text{Yield} \quad T_{Sy\_bolt} := 0.96 \]

Bolt ultimate tensile allowable stress
\[ F_{tu\_bolt} := 160000 \text{ psi} \]
Bolt ultimate shear allowable stress
\[ F_{su\_bolt} := 0.6 \times F_{tu\_bolt} \]
Bolt yield Tensile allowable stress
\[ F_{ty\_bolt} := 120000 \text{ psi} \]
Temperature correction factor for bolt modulus \[ T_{E\_bolt} := 0.96 \]

Modulus of elasticity of bolt
\[ E_{\text{bolt}} := \left(29.1 \times 10^6 \text{ psi}\right) \]

Theoretical coefficient for bolt
\[ \beta_{\text{bolt\_hot}} := 9.2 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

Nut
Temperature correction factor for nut strength \[ T_{S\_nut} := 0.96 \]

Ultimate tensile allowable stress \[ F_{tu\_nut} := 160000 \text{ psi} \]

Ultimate shear allowable stress:
\[ F_{su\_nut} := 0.6 \times F_{tu\_nut} \]
Ultimate axial strength of nut
\[ P_{tu\_nut} := 4580 \text{ lbf} \] (Ref. NAS1291)

Washer
Temperature correction factor for washer modulus \[ T_{E\_washer} := 0.96 \]

Modulus of elasticity of washer:
\[ E_{\text{washer}} := \left(29.1 \times 10^6 \text{ psi}\right) \]

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.
Temperature correction factor for flange 1 \[ T_{E1} := 0.95 \text{(modulus)} \]
Temperature correction factor for flange 2 \[ T_{E2} := 0.96 \]
Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{\text{flange2}} := \left(10.4 \times 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges
\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
\[ \beta_{\text{flange1\_cold}} := 12.05 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{\text{flange2\_cold}} := 12.05 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

Torque/Preload data
Maximum torque (63% of Yield)
\[ T_{\text{max}} := 103 \text{ in-lbf} \]
Minimum torque (85% of Max Torque)
\[ T_{\text{min}} := 88 \text{ in-lbf} \]
Torque coefficient
\[ k := 0.15 \]
Loading plane factor \[ n := 0.5 \]
Preload Uncertainty \[ u := 0.25 \]
Bolt Load data

Bolt/joint stiffness factor \( = 0.275 \) Preload due to temperature \( P_{thr\_pos} = 359.6 \text{lbf} \)
Max. preload \( \text{PLD}_{\text{max}} = 3792.9 \text{lbf} \) Pthr_neg = −304.5 lbf
Min. preload \( \text{PLD}_{\text{min}} = 1283.8 \text{lbf} \) Uncertainty factor \( u = 0.25 \)
Joint separation load \( P_{\text{sep}} = 671.568 \text{lbf} \) Torque coefficient \( k = 0.15 \)
Max. load on the bolt(ultimate) \( P_b = 3969.6 \text{lbf} \) Loading plane factor \( n = 0.5 \)
Max. load on the bolt(yield) \( P_{by} = 3903.4 \text{lbf} \) Thread pullout strength required to develop full strength of bolt \( P_{As} = 6503.3 \text{lbf} \)
Bolt ultimate tensile strength \( P_{At} = 4396.8 \text{lbf} \) Nut ultimate tensile strength \( P_{tu\_nut} = 4396.8 \text{lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_1 = 0.93</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_2 = 2.42</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_3 = 4.05</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_4 = 0.11</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_5 = 0.04</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{\text{bolt}} := \min(\text{MS}) \]

\[ \text{MS}_{\text{bolt}} = 0.04 \]

Failure Mode = “Total Tension Yield”
Fail-safe Analysis

Read in the external datum from NASPOST results:

\[
\text{loadfs} := \text{READPRN}("5fst-fail-pv.txt")
\]

\[
pf := 1.0 \quad \text{rows(loadfs)} = 264 \quad \text{yf} := 2.0 \quad \text{cols(loadfs)} = 10
\]

\[
\text{ID} := \text{loadfs}(1) \quad \text{Fx} := \text{loadfs}(3) \quad \text{lbf} \quad \text{Fz} := \text{loadfs}(6) \quad \text{lbf} \quad \text{My} := \text{loadfs}(7) \quad \text{in-lbf}
\]

\[
\text{LC} := \text{loadfs}(2) \quad \text{Fy} := \text{loadfs}(4) \quad \text{lbf} \quad \text{Mx} := \text{loadfs}(8) \quad \text{in-lbf} \quad \text{Mz} := \text{loadfs}(9) \quad \text{in-lbf}
\]

* Note that "5fst-fail-pv.txt" is generated from NASPOST results (.LIS file) by just removing all words and comments.

\[
\text{Ft}_{pf} := \left| \frac{\text{Fz}}{\text{pf}} \right| \quad \text{max(Ft)} = 670.86 \text{lbf} \quad \text{Tensile Load}
\]

\[
\text{Fv}_{pf} := \sqrt{\left( \frac{\text{Fy}}{\text{pf}} \right)^2 + \left( \frac{\text{Fx}}{\text{pf}} \right)^2} \quad \text{max(Fv)} = 578.91 \text{lbf} \quad \text{Shear Load}
\]

### Fail-safe Loads

- **Applied tensile load**
  
  \[
  \text{P}_{FS} := 670.5 \text{lbf}
  \]

- **Applied shear load**
  
  \[
  \text{V}_{FS} := 578.83 \text{lbf}
  \]

- **Applied bending moment**
  
  \[
  \text{M}_{FS} := 0 \text{in-lbf}
  \]

### Fail-safe Factors of Safety

- **Joint separation**
  
  \[
  \text{SF}_{sep_{FS}} := 1.0
  \]

- **Ultimate**
  
  \[
  \text{SF}_{u_{FS}} := 1.0
  \]

- **Joint Separation**
  
  \[
  \text{SF}_{sep_{FS}} := 1.0
  \]

- **Joint Separation**
  
  \[
  \text{SF}_{sep_{FS}} := 1.0
  \]

### Bolt Fail-safe Load data

**Joint separation load**

\[
\text{P}_{sep_{FS}} := 670.5 \text{lbf}
\]

**Max. load on the bolt (ultimate)**

\[
\text{Pb}_{FS} := 3898.8 \text{lbf}
\]

### Summary of fail-safe Margins for bolt:

- **Joint separation**
  
  \[
  \text{MS}_{FS_1} := 0.93
  \]

- **Direct Tension Ultimate**
  
  \[
  \text{MS}_{FS_2} := 4.7
  \]

- **Total Tension Ultimate**
  
  \[
  \text{MS}_{FS_3} := 0.13
  \]

- **Direct Thread shear Ultimate**
  
  \[
  \text{MS}_{FS_4} := 7.43
  \]

### Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MSbolt}_{FS} := \min(\text{MS}_{FS})
\]

\[
\text{MSbolt}_{FS} = 0.12 \quad \text{Failure Mode}_{FS} = "\text{Combined Shear Tension Bending Ultimate}"\]
CHECK BOLTS (NAS1351N4H16 0.25”-28 x 1.0L Material-A-286), Insert MS21209 F4-15, Material-A-286, Washer NAS1149E0463R

**Analysis**: The fasteners connecting the PVGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. These bolts are shared with the radiator bracket. This analysis only includes the 6 fasteners shown in the figure below.

**Loads**: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

```plaintext
loads := READPRN("6fst-pv.txt")
```

\[
\text{p} := 1 \ldots \text{rows}(\text{loads}) \quad \text{rows}(\text{loads}) = 396
\]

\[
y := 2 \ldots \text{cols}(\text{loads}) \quad \text{cols}(\text{loads}) = 10
\]

\[
\text{ID} := \text{loads}^{(1)} \quad \text{Fx} := \text{loads}^{(3)} \cdot \text{lbf} \quad \text{Fz} := \text{loads}^{(5)} \cdot \text{lbf} \quad \text{My} := \text{loads}^{(7)} \cdot \text{in-lbf}
\]

\[
\text{LC} := \text{loads}^{(2)} \quad \text{Fy} := \text{loads}^{(4)} \cdot \text{lbf} \quad \text{Mx} := \text{loads}^{(6)} \cdot \text{in-lbf} \quad \text{Mz} := \text{loads}^{(8)} \cdot \text{in-lbf}
\]

* Note that "6fst-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\text{Ft} := \begin{vmatrix} \text{Fz} \\ \text{Fx} \end{vmatrix} \quad \max(\text{Ft}) = 557.76 \text{ lbf} \quad \text{Tensile Load}
\]

\[
\text{Fv} := \sqrt{\left(\frac{\text{Fy}}{\text{p}}\right)^2 + \left(\frac{\text{Fx}}{\text{p}}\right)^2} \quad \max(\text{Fv}) = 534.12 \text{ lbf} \quad \text{Shear Load}
\]
CHECK BOLTS (NAS1351N4H16 0.25"-28 x 1.0L Material-A-286), Insert MS21209 F4-15, Material-A-286, Washer NAS1149E0463R

Flange 1: PVGF Bracket
Part number: SDG39135860
Material: Al Alloy 7075-T7351

Flange 2: Upper Trunnion Bridge Beam
Part number: SDG39135728
Material: Al Alloy 7075-T7351 Extrusion

Flange 3: Radiator Top Bracket
Material: Al Alloy 7075-T7352 Hand Forging

Loads

Applied tensile load \( P := 557.76 \text{ lbf} \)

Applied shear load \( V := 534.12 \text{ lbf} \)

Applied bending moment \( M := 0 \text{ in.-lbf} \)

Factors of Safety

Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)

Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)

Temperature data

Assembly \( \text{Temp}_{\text{initial}} := 70 \text{ deg} \)

Maximum \( \text{Temp}_{\text{max}} := 225 \text{ deg} \)

Minimum \( \text{Temp}_{\text{min}} := -65 \text{ deg} \)

Bolt and Insert Data

Nominal diameter of bolt \( D := 0.25 \text{ in} \)
Number of threads/inch \( N_t := 28 \cdot \frac{1}{\text{in}} \)

Total length of bolt \( L := 1.0 \text{ in} \)
Length of insert \( L_{\text{ins}} := 0.375 \text{ in} \)

Threaded length \( L_t := 1.0 \text{ in} \)
Min. external diameter of insert \( F_{\text{min}} := 0.306 \text{ in} \)

(If bolt is fully threaded, input \( L_t = L \))
Depth of recess for insert \( l_r := 0.02 \text{ in} \)

Washer Data

Thickness of washer \( t_w := 0.063 \text{ in} \)

Outer Diameter of washer \( D_w := 0.50 \text{ in} \)

Flange data

Thickness of flange 1 \( t_{f1} := 0.325 \text{ in} \)
Thickness of flange 2 \( t_{f2} := 0.25 \text{ in} \)
Thickness of flange 3 \( t_{f3} := 0.375 \text{in} \) (length of insert)

Reference:\\Esch\0\211_mathcad\08307_bolts\thread_data.mcd

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AMS-02 PVGF Bracket - Bolt Analysis

Inner Diameter of washer \( D_{wi} := 0.265 \text{ in} \)

Diameter of hole \( D_{hole} := 0.288 \text{ in} \)

Bolt head dia. across flats \( d_{w} := 0.365 \text{ in} \)

Note: If there is no washer, \( t_{w} \), \( D_{w} \), and \( D_{wi} \) should be zero.

**Material Property Data**

**Bolt**

Temperature correction factor for bolt strength ultimate \( T_{SU_{-}}bolts := 0.96 \) \( \text{ yield } \) \( T_{SY_{-}}bolts := 0.96 \)

Bolt ultimate tensile allowable stress \( F_{TU_{-}}bolts := 160000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{SU_{-}}bolts := 0.6F_{TU_{-}}bolts \)

Bolt yield tensile allowable \( F_{TY_{-}}bolts := 120000 \text{ psi} \)

Temperature correction factor for bolt modulus \( T_{E_{-}}bolts := 0.96 \) \( \beta_{bolts} := 9.2\cdot10^{-6} \frac{\text{in}}{\text{in}}\frac{1}{\text{deg}} \)

Modulus of elasticity of bolt \( E_{bolts} := \left(29.1\cdot10^6 \text{ psi}\right) \)

**Insert**

Temperature correction factor for insert strength \( T_{S_{-}}ins := 0.96 \)

Ultimate tensile allowable stress \( F_{TU_{-}}ins := 150000 \text{ psi} \) (Ref. MS21209)

Ultimate shear allowable stress \( F_{SU_{-}}ins := 0.6F_{TU_{-}}ins \)

**Washer**

Temperature correction factor for washer modulus \( T_{E_{-}}washer := 0.96 \)

Modulus of elasticity of washer \( E_{washer} := \left(29.1\cdot10^6 \text{ psi}\right) \)
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1
\[ T_{f1E} := 0.95 \text{ (modulus)} \]
\[ T_{f1S} := 0.96 \text{ (strength)} \]

Temperature correction factor for flange 2
\[ T_{f2E} := 0.96 \text{ (modulus)} \]
\[ F_{s_u3} := 35000 \text{ psi} \]

Temperature correction factor for flange 3
\[ T_{f3E} := 0.96 \text{ (modulus)} \]
\[ T_{f3S} := 0.96 \text{ (strength)} \]

Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := \left(10.3 \cdot 10^6 \text{ psi}\right) \]
\[ E_{\text{flange2}} := \left(10.4 \cdot 10^6 \text{ psi}\right) \]
\[ E_{\text{flange3}} := \left(10.2 \cdot 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges
\[ \beta_{\text{flange1_hot}} := 12.8 \cdot 10^{-6} \text{ in} / \text{in} / \text{deg} \]
\[ \beta_{\text{flange2_hot}} := 12.8 \cdot 10^{-6} \text{ in} / \text{in} / \text{deg} \]
\[ \beta_{\text{flange1_cold}} := 12.05 \cdot 10^{-6} \text{ in} / \text{in} / \text{deg} \]
\[ \beta_{\text{flange2_cold}} := 12.05 \cdot 10^{-6} \text{ in} / \text{in} / \text{deg} \]
\[ \beta_{\text{flange3_hot}} := 12.8 \cdot 10^{-6} \text{ in} / \text{in} / \text{deg} \]
\[ \beta_{\text{flange3_cold}} := 12.05 \cdot 10^{-6} \text{ in} / \text{in} / \text{deg} \]

Torque/Preload data

Torque coefficient
\[ k := 0.15 \]

Preload Percentage:
\[ \text{Per}\_\text{Preload} := 0.63 \]

Tensile Area:
\[ At := 0.0364 \text{in}^2 \]

Fp\_Preload := Per\_Preload\_At\_Fty\_bolt

Maximum torque
\[ T_{\text{max}} := \text{Fp\_Preload} \cdot k \cdot D \]

Minimum torque
\[ T_{\text{min}} := 0.85 \cdot T_{\text{max}} \]

Maximum torque
\[ T_{\text{max}} = 103.2 \text{ in-lbf} \]

Loading plane factor:
\[ n := 0.5 \]

Minimum torque
\[ T_{\text{min}} = 87.7 \text{ in-lbf} \]

Preload Uncertainty:
\[ u := 0.25 \]
Bolt Load data

Bolt/joint stiffness factor \( = 0.7453 \)

Preload due to temperature

Max. preload \( \text{PLD}_{\text{max}} = 3598.1 \text{ lbf} \)

Min. preload \( \text{PLD}_{\text{min}} = 1448.2 \text{ lbf} \)

Joint separation load \( \text{P}_{\text{sep}} = 669.312 \text{ lbf} \)

Max. load on the bolt(ultimate) \( \text{P}_{\text{b}} = 4076.2 \text{ lbf} \)

Max. load on the bolt(yield) \( \text{P}_{\text{by}} = 3896.9 \text{ lbf} \)

Bolt ultimate tensile strength \( \text{P}_{\text{At}} = 5419.4 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

- Joint separation \( \text{MS}_1 = 2 \) Direct Thread shear Ultimate \( \text{MS}_6 = 3.72 \)
- Direct Tension Ultimate \( \text{MS}_2 = 3.22 \) Total Thread shear Ultimate \( \text{MS}_7 = 0.49 \)
- Direct Tension Yield \( \text{MS}_3 = 4.07 \) Shear Ultimate \( \text{MS}_8 = 1.44 \)
- Total Tension Ultimate \( \text{MS}_4 = 0.33 \) Bending Ultimate \( \text{MS}_9 = 10 \)
- Total Tension Yield \( \text{MS}_5 = 0.043 \) Combined shear, tension and bending ultimate \( \text{MS}_{10} = 0.24 \)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[
\text{MS}_{\text{bolt}} := \min(\text{MS})
\]

\[\text{MS}_{\text{bolt}} = 0.043 \]

Failure Mode = "Total Tension Yield"
Fail-safe Analysis

Read in the external datum from NASPOST results:

\[ \text{loadfs} := \text{READPRN}("6fst-fail-pv.txt") \]
\[ \text{pf} := 1., \text{rows(loadfs)} \quad \text{rows(loadfs)} = 330 \quad \text{yf} := 2., \text{cols(loadfs)} \quad \text{cols(loadfs)} = 10 \]
\[ \text{ID} := \text{loadfs}, 1 \quad \text{Fx} := \text{loadfs}, 3 \quad \text{lbf} \quad \text{Fz} := \text{loadfs}, 5 \quad \text{lbf} \quad \text{My} := \text{loadfs}, 7 \quad \text{in-lbf} \]
\[ \text{LC} := \text{loadfs}, 2 \quad \text{Fx} := \text{loadfs}, 4 \quad \text{lbf} \quad \text{Mx} := \text{loadfs}, 6 \quad \text{in-lbf} \quad \text{Mz} := \text{loadfs}, 8 \quad \text{in-lbf} \]

* Note that "6fst-fail-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[ \text{Ft}_{\text{pf}} := \left| \text{Fz}_{\text{pf}} \right| \quad \max(\text{Ft}) = 663.85\text{-lbf} \quad \text{Tensile Load} \]
\[ \text{Fv}_{\text{pf}} := \sqrt{\left( \text{Fy}_{\text{pf}} \right)^2 + \left( \text{Fx}_{\text{pf}} \right)^2} \quad \max(\text{Fv}) = 579.78\text{-lbf} \quad \text{Shear Load} \]

**Fail-safe Loads**

- Applied tensile load \( P_{\text{FS}} := 685.61\text{-lbf} \)
- Applied shear load \( V_{\text{FS}} := 606.32\text{-lbf} \)
- Applied bending moment \( M_{\text{FS}} := 0\text{-in-lbf} \)

**Fail-safe Factors of Safety**

- Ultimate \( SFu_{\text{FS}} := 1.0 \)
- Joint Separation \( SF_{\text{sep,FS}} := 1.0 \)

Reference:\\Eschil02\i11_mathcad\08307_bolts\bolt_stiffness_insert_FS_RevC.mcd

**Bolt Fail-safe Load data**

- Joint separation load \( P_{\text{sep,FS}} = 685.61\text{-lbf} \)
- Max. load on the bolt(ultimate) \( P_{\text{b,FS}} = 3892\text{-lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Condition</th>
<th>MS_{\text{FS}}</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_{\text{FS}}_1 = 1.93</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_{\text{FS}}_2 = 5.87</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_{\text{FS}}_3 = 0.39</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_{\text{FS}}_4 = 6.68</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ \text{MS_{bolt,FS}} := \min(\text{MS}_{\text{FS}}) \]
\[ \text{MS_{bolt,FS}} = 0.37 \quad \text{Failure Mode}_{\text{FS}} = "\text{Combined Shear Tension Bending Ultimate}" \]
CHECK BOLTS (NAS1351N4H16 0.25”-28 x 1.0L Material-A-286), Insert MS21209 F4-10, Material-A-286, Washer NAS1149E0463R

**Analysis**: The fasteners connecting the PVGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. These bolts are shared with the tracker bracket. This analysis only includes the 3 fasteners shown in the figure below.

**Loads**: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

```
loads := READPRN("5fst-pv.txt")
p := 1..rows(loads) rows(loads) = 300 y := 2..cols(loads) cols(loads) = 10
ID := loads(1) Fx := loads(3)·lbf Fz := loads(5)·lbf My := loads(7)·in-lbf
LC := loads(2) Fy := loads(4)·lbf Mx := loads(6)·in-lbf Mz := loads(8)·in-lbf
```

* Note that "5fst-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
F_t \left( \frac{F_z}{p} \right) \text{ max}(F_t) = 559.64 \text{ lbf} \quad \text{Tensile Load}
\]

\[
F_v \left( \frac{F_y}{p} \right)^2 + \left( \frac{F_x}{p} \right)^2 \text{ max}(F_v) = 525.94 \text{ lbf} \quad \text{Shear Load}
\]
CHECK BOLTS (NAS1351N4H16 0.25"-28 x 1.0L Material-A-286), Insert MS21209 F4-10, Material-A-286, Washer NAS1149E0463R

Flange 1: PVGF Bracket
Part number: SDG39135860
Material: Al Alloy 7075-T7351

Flange 2: Upper Trunnion Bridge Beam
Part number: SDG39135728
Material: Al Alloy 7075-T73511 Extrusion

Flange 3: Tracker Bracket
Material: Al Alloy 7075-T7351

 Loads

Applied tensile load \( P := 559.64 \text{ lbf} \)

Applied shear load \( V := 525.94 \text{ lbf} \)

Applied bending moment \( M := 0 \text{ in \cdot lbf} \)

 Factors of Safety

Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)
Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)

 Temperature data

Assembly \( \text{Temp}_{\text{initial}} := 70 \text{ deg} \)
Maximum \( \text{Temp}_{\text{max}} := 225 \text{ deg} \)
Minimum \( \text{Temp}_{\text{min}} := -65 \text{ deg} \)

 Bolt and Insert Data

Nominal diameter of bolt \( D := 0.25 \text{ in} \)
Total length of bolt \( L := 1.0 \text{ in} \)
Threaded length \( L_t := 1.0 \text{ in} \)
(If bolt is fully threaded, input \( L_t = L \))
Number of threads/inch \( N_t := 28 \frac{1}{\text{in}} \)
Length of insert \( L_{\text{ins}} := 0.25 \text{ in} \)
Min. external diameter of insert \( F_{\text{min}} := 0.306 \text{ in} \)
Depth of recess for insert \( l_r := 0.02 \text{ in} \)

 Washer Data

Thickness of washer \( t_w := 0.063 \text{ in} \)
Outer Diameter of washer \( D_w := 0.50 \text{ in} \)

 Flange data

Thickness of flange 1 \( t_{f1} := 0.325 \text{ in} \)
Thickness of flange 2 \( t_{f2} := 0.25 \text{ in} \)
Thickness of flange 3 \( t_{f3} := 0.25 \text{ in} \) (length of insert)
### Material Property Data

#### Bolt

- **Temperature correction factor for bolt strength ultimate**
  \[
  \text{TS}_\text{bolt} := 0.96 \quad \text{yield} \quad \text{TS}_{\text{y}}\text{bolt} := 0.96
  \]

- **Bolt ultimate tensile allowable stress**
  \[
  F_{\text{tu}}\text{bolt} := 160000\text{ psi}
  \]

- **Bolt ultimate shear allowable stress**
  \[
  F_{\text{su}}\text{bolt} := 0.6F_{\text{tu}}\text{bolt}
  \]

- **Bolt yield tensile allowable**
  \[
  F_{\text{ty}}\text{bolt} := 120000\text{ psi}
  \]

- **Temperature correction factor for bolt modulus**
  \[
  \text{TE}_{\text{bolt}} := 0.96
  \]

- **Modulus of elasticity of bolt**
  \[
  E_{\text{bolt}} := \left(29.1\cdot10^6\text{ psi}\right)
  \]

**Thermal coefficient for bolt**:
\[
\beta_{\text{bolt\_hot}} := 9.2\cdot10^{-6}\frac{\text{in}}{\text{in} \cdot \text{deg}}
\]

#### Insert

- **Temperature correction factor for insert strength**
  \[
  \text{TS}_{\text{ins}} := 0.96
  \]

- **Ultimate tensile allowable stress**
  \[
  F_{\text{tu}}\text{ins} := 150000\text{ psi}
  \quad \text{(Ref. MS21209)}
  \]

- **Ultimate shear allowable stress**
  \[
  F_{\text{su}}\text{ins} := 0.6F_{\text{tu}}\text{ins}
  \]

#### Washer

- **Temperature correction factor for washer modulus**
  \[
  \text{TE}_{\text{washer}} := 0.96
  \]

- **Modulus of elasticity of washer**
  \[
  E_{\text{washer}} := \left(29.1\cdot10^6\text{ psi}\right)
  \]
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

\[ T_{f1E} = 0.95 \text{(modulus)} \quad T_{f1S} = 0.96 \text{(strength)} \]

Temperature correction factor for flange 2

\[ T_{f2E} = 0.96 \text{(modulus)} \quad F_{su3} = 38000 \text{ psi} \]

Temperature correction factor for flange 3

\[ T_{f3E} = 0.96 \text{(modulus)} \quad T_{f3S} = 0.96 \text{(strength)} \]

Modulus of elasticity for the parts in the joint

\[ E_{\text{flange1}} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{\text{flange2}} := \left(10.4 \times 10^6 \text{ psi}\right) \]

\[ E_{\text{flange3}} := \left(10.3 \times 10^6 \text{ psi}\right) \]

Coefficient of thermal expansion for flanges

\[ \beta_{\text{flange1\_hot}} := 12.8 \times 10^{-6} \text{\frac{in}{deg}} \quad \beta_{\text{flange2\_hot}} := 12.8 \times 10^{-6} \text{\frac{in}{deg}} \]

\[ \beta_{\text{flange1\_cold}} := 12.05 \times 10^{-6} \text{\frac{in}{deg}} \quad \beta_{\text{flange2\_cold}} := 12.05 \times 10^{-6} \text{\frac{in}{deg}} \]

\[ \beta_{\text{flange3\_hot}} := 12.8 \times 10^{-6} \text{\frac{in}{deg}} \quad \beta_{\text{flange3\_cold}} := 12.05 \times 10^{-6} \text{\frac{in}{deg}} \]

Torque/Preload data

Torque coefficient

\[ k := 0.15 \]

Preload Percentage:

\[ \text{Per\_Preload} := 0.63 \]

Tensile Area:

\[ A_t := 0.0364 \text{in}^2 \]

\[ F_{p\_\text{Preload}} := \text{Per\_Preload} \times \text{At} \times F_{t\_\text{bolt}} \]

Maximum torque

\[ T_{\text{max}} := F_{p\_\text{Preload}} \times k \times D \]

Minimum torque

\[ T_{\text{min}} := 0.85 \times T_{\text{max}} \]

Maximum torque

\[ T_{\text{max}} = 103.2 \text{ in-lbf} \]

Loading plane factor:

\[ n := 0.5 \]

Minimum torque

\[ T_{\text{min}} = 87.7 \text{ in-lbf} \]

Preload Uncertainty:

\[ u := 0.25 \]
### Bolt Load data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt/joint stiffness factor</td>
<td>$= 0.7285$</td>
</tr>
<tr>
<td>Preload due to temperature</td>
<td></td>
</tr>
<tr>
<td>Max. preload</td>
<td>$PLD_{\text{max}} = 3601$-lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>$PLD_{\text{min}} = 1445.8$-lbf</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>$P_{\text{sep}} = 671.568$-lbf</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
<td>$P_b = 4069.8$-lbf</td>
</tr>
<tr>
<td>Loading plane factor</td>
<td></td>
</tr>
<tr>
<td>Max. load on the bolt(yield)</td>
<td>$P_{\text{by}} = 3894$-lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$P_{\text{At}} = 5419.4$-lbf</td>
</tr>
</tbody>
</table>

Preload due to temperature $P_{\text{thr}_{\text{pos}}} = 161.1594$-lbf
Preload due to temperature $P_{\text{thr}_{\text{neg}}} = -136.5$-lbf

Uncertainty factor $u = 0.25$
Torque coefficient $k = 0.15$
Loading plane factor $n = 0.5$

Thread shear pullout load of bolt or insert $P_{\text{ths}} = 10527$-lbf
Thread shear pullout load in parent metal $P_{\text{pths}} = 4383.7$-lbf

Length_check = "Bolt length is sufficient"

### Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$M_{S1} = 1.94$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$M_{S6} = 2.41$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$M_{S2} = 3.21$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$M_{S3} = 4.05$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$M_{S4} = 0.33$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$M_{S5} = 0.044$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$M_{S7} = 0.08$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$M_{S8} = 1.48$</td>
</tr>
<tr>
<td></td>
<td>$M_{S9} = 10$</td>
</tr>
<tr>
<td></td>
<td>$M_{S10} = 0.245$</td>
</tr>
</tbody>
</table>

### Determination of the smallest margin of safety for the bolt, and the failure mode:

$$M_{\text{Sbolt}} := \min(MS)$$

$M_{\text{Sbolt}} = 0.044$

Failure Mode = "Total Tension Yield"
Fail-safe Analysis

Read in the external datum from NASPOST results:

\[
\text{loadfs} := \text{READPRN}("5fst-fail-pv.txt")
\]
\[
\text{pf} := 1., \text{rows(loadfs)} \quad \text{rows(loadfs)} = 264 \quad \text{yf} := 2., \text{cols(loadfs)} \quad \text{cols(loadfs)} = 10
\]
\[
\text{ID} := \text{loadfs}(1), \quad \text{Fx} := \text{loadfs}(3) \text{-lbf} \quad \text{Fz} := \text{loadfs}(5) \text{-lbf} \quad \text{My} := \text{loadfs}(7) \text{-in-lbf}
\]
\[
\text{LC} := \text{loadfs}(2), \quad \text{Fy} := \text{loadfs}(4) \text{-lbf} \quad \text{Mx} := \text{loadfs}(6) \text{-in-lbf} \quad \text{Mz} := \text{loadfs}(8) \text{-in-lbf}
\]

* Note that "5fst-fail-pv.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\text{Ft}_{\text{pf}} := \left| \text{Fz}_{\text{pf}} \right| \quad \text{max(Ft)} = 670.86 \text{-lbf} \quad \text{Tensile Load}
\]
\[
\text{Fv}_{\text{pf}} := \sqrt{\left(\text{Fy}_{\text{pf}}\right)^2 + \left(\text{Fx}_{\text{pf}}\right)^2} \quad \text{max(Fv)} = 578.91 \text{-lbf} \quad \text{Shear Load}
\]

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Applied tensile load</th>
<th>P_FS := 685.61-lbf</th>
<th>Ultimate</th>
<th>SFu_FS := 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear load</td>
<td>V_FS := 606.32-lbf</td>
<td>Joint Separation</td>
<td>SFsep_FS := 1.0</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_FS := 0-in-lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference:\\Eschi02\211_mathcad\08307_bolts\bolt_stiffness_insert_FS_RevC.mcd

**Bolt Fail-safe Load data**

Joint separation load \( P_{\text{sep-FS}} = 685.61 \text{-lbf} \)

Max. load on the bolt(ultimate) \( P_{\text{b-FS}} = 3888.1 \text{-lbf} \)

**Summary of fail-safe Margins for bolt:**

| Joint separation | MS_FS_1 = 1.88 | Total Thread shear Ultimate | MS_FS_5 = 0.13 |
| Direct Tension Ultimate | MS_FS_2 = 5.87 | Shear Ultimate | MS_FS_6 = 3.3 |
| Total Tension Ultimate | MS_FS_3 = 0.39 | Bending Ultimate | MS_FS_7 = 10 |
| Direct Thread shear Ultimate | MS_FS_4 = 4.56 | Combined shear, tension and bending ultimate | MS_FS_8 = 0.37 |

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MSbolt}_{\text{FS}} := \min(\text{MS}_{\text{FS}})
\]
\[
\text{MSbolt}_{\text{FS}} = 0.13 \quad \text{Failure\_Mode\_FS} = "\text{Total Thread Shear Ultimate}" \]
5.11.4 FRGF to FRGF Bracket
Section 5.11.4

FRGF Bracket to FRGF Bolt Analysis

CHECK BOLTS (EWB0420-6-27 0.375"-24 x 2.3445 L Material-A-286), Nut Plate MS21060L6, Washer 200003-XX CRES 15-5PH (Along with thermal washer)

Analysis: The fasteners connecting the FRGF bracket to the FRGF will be analyzed. The tension and shear on the bolts will be calculated. This analysis only includes the 6 fasteners shown in the figure below.

Bolt Geometry

<table>
<thead>
<tr>
<th>Size</th>
<th>Thread/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
<tr>
<td>0.375</td>
<td>24</td>
</tr>
</tbody>
</table>

\[
i := 1 \ldots \text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{i,2} \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{i,1} \frac{\text{in}}{\text{in}} \quad \text{bolt diameter}
\]

\[
A_{ti} := \beta \left( \frac{D_i - 0.9743 \frac{1}{N_i}}{2} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
A_{si} := \beta \left( \frac{D_i - 1.299038 \frac{1}{N_i}}{2} \right)^2 \quad \text{Shear Area of bolt}
\]
AMS-02 FRGF Bracket - Bolt Analysis

Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-5.0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-2.5</td>
<td>4.33</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>5.0</td>
<td>4.33</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2.5</td>
<td>-4.33</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>-2.5</td>
<td>-4.33</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

\[ \begin{align*} x_{\text{force}} &:= 0.0 \text{in} \\ y_{\text{force}} &:= 0.0 \text{in} \\ z_{\text{force}} &:= 0.0 \text{in} \end{align*} \]

\[ \begin{pmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{pmatrix} \]

\[ \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \]
**Center of gravity of bolt group**

\[
\begin{align*}
\sum_{i} x_i & = x_{cg} = 0 \text{ in} \\
\sum_{i} y_i & = y_{cg} = 0 \text{ in} \\
\sum_{i} z_i & = z_{cg} = 0 \text{ in}
\end{align*}
\]

\[
c_{gbolt} := \begin{pmatrix} x_{cg} \\ y_{cg} \\ z_{cg} \end{pmatrix} \quad c_{gbolt} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

**Load Vector**

\[
r_{load} := c_{gload} - c_{gbolt} \quad r_{load} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in}
\]

**Distance from CG of Bolts to Individual Bolts for shear calculations**

\[
r_i := \sqrt{(z_i - z_{cg})^2 + (y_i - y_{cg})^2} \quad r = \begin{pmatrix} 5.000 \\ 5.000 \\ 5.000 \\ 5.000 \end{pmatrix} \text{ in}
\]

**Reading database file**

The following file reads in all the loads:

\[
data := \text{READPRN("centerloads.txt")}
\]

\[
um_{bolts} := \text{rows(bolt)} \quad j := 1 \ldots \text{rows(data)}
\]

* Note that "centerloads.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files.
Loads from loads model

Axial Load \( F_x \) := data \( j \).3-lbf  
Shear in Y axis \( F_y \) := data \( j \).4-lbf  
Shear in Z axis \( F_z \) := data \( j \).5-lbf  

Torsion \( M_x \) := data \( j \).6-in-lbf  
Moment about Y axis \( M_y \) := data \( j \).7-in-lbf  
Moment about Z axis \( M_z \) := data \( j \).8-in-lbf  

Extrapolation of Moments:

Distance from RBE \( \text{dist} := 3.8197 \text{ in} \)

Extrapolation of My Moment: \( M_y := M_y + F_y \cdot \text{dist} \)

Extrapolation of Mx Moment: \( M_z := M_z + F_y \cdot \text{dist} \)

Element Identification \( \text{ID} \) \( j \) := data \( j \).1  
Load Case Number \( \text{LC} \) \( j \) := data \( j \).2  

Counter for number of bolts in pattern \( \text{ID} := \text{ID} \cdot 1000 + 1 \)

Applied Bending Moment at Bolts \( M_j := 0 \cdot \text{in-lbf} \)

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\( \text{ID} := \text{stack(ID, ID + 1, ID + 2, ID + 3, ID + 4, ID + 5)} \)

\( \text{LC} := \text{stack(LC, LC, LC, LC, LC, LC)} \)
**Moment Distribution**

\[
M_{\text{tot}}^{(j)} := \begin{pmatrix} M_{x,j} \\ M_{y,j} \\ M_{z,j} \end{pmatrix} + \text{r}_{\text{load}} \times \begin{pmatrix} F_{x,j} \\ F_{y,j} \\ F_{z,j} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x,\text{boltcg}} := M_{\text{tot1},j} \quad My_{\text{boltcg}} := M_{\text{tot2},j} \quad Mz_{\text{boltcg}} := M_{\text{tot3},j}
\]

**Tension on bolts**

\[
\text{F}_{\text{direct},i,j} := \begin{cases} 0 \text{-lbf} & \text{if } F_{x,j} \leq 0 \text{lbf} \\ \frac{F_{x,j}}{\text{num_bolts}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation - (The if statement checks for compression)

\[
\text{F}_{\text{mz},i,j} := \begin{cases} 0 \text{-lbf} & \text{if } (y_{i} - y_{\text{cg}}) \neq 0 \text{-in} \\ \left[ M_{x,\text{boltcg},i} (y_{i} - y_{\text{cg}}) \right] \frac{1}{\text{At}_{i}} + \sum_{i} \left( (y_{i} - y_{\text{cg}})^2 \cdot \text{At}_{i} \right) & \text{otherwise} \end{cases}
\]

\[
\text{F}_{\text{my},i,j} := \begin{cases} 0 \text{-lbf} & \text{if } (z_{i} - z_{\text{cg}}) \neq 0 \text{-in} \\ \left[ M_{x,\text{boltcg},i} (z_{i} - z_{\text{cg}}) \right] \frac{1}{\text{At}_{i}} + \sum_{i} \left( (z_{i} - z_{\text{cg}})^2 \cdot \text{At}_{i} \right) & \text{otherwise} \end{cases}
\]

\[
\text{F}_{t,i,j} := \text{F}_{\text{direct},i,j} + \text{F}_{\text{mz},i,j} + \text{F}_{\text{my},i,j} \quad \text{Total Tensile load}
\]

**Shear on bolts**

Direct shear Loads

\[
\text{F}_{\text{sd},i,j} := \sqrt{\left( F_{y,j} \right)^2 + \left( F_{z,j} \right)^2} \quad \text{num_bolts}
\]

Secondary shear on bolts

\[
\text{F}_{s,i,j} := \frac{\left| M_{x,\text{boltcg},i} \right| \cdot r_{i} \cdot \text{As}_{i}}{\sum_{i} \left( r_{i}^2 \cdot \text{As}_{i} \right)} \quad \text{Total shear load}
\]

\[
\text{F}_{\text{stot},i,j} := \text{F}_{s,i,j} + \text{F}_{\text{sd},i,j}
\]
The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P := \text{stack}\begin{bmatrix}
F_t^T(1), & F_t^T(2), & F_t^T(3), & F_t^T(4), & F_t^T(5), & F_t^T(6)
\end{bmatrix}
\]

\[
V := \text{stack}\begin{bmatrix}
F_{stot}^T(1), & F_{stot}^T(2), & F_{stot}^T(3), & F_{stot}^T(4), & F_{stot}^T(5), & F_{stot}^T(6)
\end{bmatrix}
\]

\[
M := \text{stack}(M, M, M, M, M)
\]

The "Output" file outputs an array from left to right starting with the element identification (ID), load case number (LC), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M). The array is then written to a text file.

\[
\text{Output} := \text{augment}\begin{bmatrix}
\text{ID}, & \text{LC}, & \frac{P}{\text{lbf}}, & \frac{V}{\text{lbf}}, & \frac{M}{\text{in-lbf}}
\end{bmatrix}
\]

(Note: Since the ID and LC numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)

Size of the "Output" Array: \(\text{rows}(\text{Output}) = 192\)
CHECK BOLTS (EWB0420-6-27 0.375"-24 x 2.3445 L Material-A-286), Nut Plate MS21060L6, Washer 200003-XX CRES 15-5PH (Along with thermal washer)

data := READPRN("centerboltloads.txt")

s := 1..rows(data)

Flange 1: FRGF
Part number: Drawing not provided
Material: Titanium (Assume Ti-6Al-4V)

Flange 2: FRGF Bracket
Part number: SDG39135861
Material: Al Alloy 7050-T7451

Loads

Applied tensile load  $P_s := \text{data}_{s,3}$ lbf  ID := data$_{s,1}$
Applied shear load  $V_s := \text{data}_{s,4}$ lbf  LC := data$_{s,2}$
Applied bending moment  $M_s := \text{data}_{s,5}$ in-lbf

Factors of Safety

Ultimate  SF$_{u}$ := 2.0  Yield  SF$_{y}$ := 1.25  Assembly
Joint Separation  SF$_{sep}$ := 1.2  Fitting factor  FF := 1.15  Maximum

Bolt and Nut Data
Nominal diameter of bolt  D := 0.375-in
Total length of bolt  L := 2.3445-in
Threaded length  Lt := 0.657-in

(If bolt is fully threaded, input Lt = L)

This file uses the calculations shown in \escfil02\2i11\mathcad\08307_bolts\thread_data.mcd

Washer Data
Thickness of washers  tw := 0.08-in
Outer Diameter of washer  Dw := 0.98in
Inner Diameter of washer  Dwi := 0.377-in
Bolt head dia. across flats  dw := 0.0-in (used only if there is no washer)

Flange data
Thickness of flange 1  tf1 := 1.357-in
Thickness of flange 2  tf2 := 0.375in
Diameter of hole  D$_\text{hole}$ := 0.377-in

Note: If there is no washer tw, Dw and Dwi should be zero
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate. \( T_{SU_{\text{bolt}}} = 0.95 \)  
Yield \( T_{SY_{\text{bolt}}} = 0.95 \)

Bolt ultimate tensile allowable stress \( F_{TU_{\text{bolt}}} = 200000 \, \text{psi} \)

Bolt ultimate shear allowable stress \( F_{SU_{\text{bolt}}} = 0.6 \times F_{TU_{\text{bolt}}} \)

Bolt yield Tensile allowable stress \( F_{TY_{\text{bolt}}} = 180000 \, \text{psi} \)

Temperature correction factor for bolt modulus \( T_{E_{\text{bolt}}} = 0.96 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} = \left(29.1 \times 10^6 \, \text{psi}\right) \)

Thermal coefficient for bolt \( u_{\text{bolt}_{\text{hot}}} = 9.2 \times 10^{-6} \, \text{in/in/deg} \)

Nut

Temperature correction factor for nut strength \( T_{S_{\text{nut}}} = 0.95 \)

Ultimate tensile allowable stress \( F_{TU_{\text{nut}}} = 125000 \, \text{psi} \)

Ultimate Shear allowable stress: \( F_{SU_{\text{nut}}} = 0.6 \times F_{TU_{\text{nut}}} \)

Ultimate axial strength of nut \( P_{TU_{\text{nut}}} = 11450 \, \text{lbf} \) (Ref. MS21060)

Washer

Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} = 1.0 \)

Modulus of elasticity of washer: \( E_{\text{washer}} = \left(28.5 \times 10^6 \, \text{psi}\right) \)

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners,  
Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{F1E} = 0.94 \) (modulus)

Temperature correction factor for flange 2 \( T_{F2E} = 0.93 \)

Modulus of elasticity for the parts in the joint \( E_{\text{flange1}} = \left(16.0 \times 10^6 \, \text{psi}\right) \) \( E_{\text{flange2}} = \left(10.3 \times 10^6 \, \text{psi}\right) \)

Coefficient of thermal expansion for flanges \( u_{\text{flange1}_{\text{hot}}} = 5.05 \times 10^{-6} \, \text{in/in/deg} \) \( u_{\text{flange2}_{\text{hot}}} = 12.9 \times 10^{-6} \, \text{in/in/deg} \)

\[ u_{\text{flange1}_{\text{cold}}} = 4.7 \times 10^{-6} \, \text{in/in/deg} \]

\[ u_{\text{flange2}_{\text{cold}}} = 12.05 \times 10^{-6} \, \text{in/in/deg} \]

Torque/Preload data

Maximum torque (49% of Yield) \( T_{\text{max}} = 435 \, \text{in-lbf} \)

Loading plane factor \( n = 0.5 \)

Minimum torque (85% of Max Torque) \( T_{\text{min}} = 370 \, \text{in-lbf} \)

Preload Uncertainty \( = 0.25 \)

Torque coefficient \( k = 0.15 \)
This file uses the calculations shown in \escf\02\2i11\mathcad\08307\bolts\multi\_bolt\_stiffness\_nut\_RevC

**Bolt Load data**

- Bolt/joint stiffness factor $= 0.145$
- Preload due to temperature $P_{\text{thr\_pos}} = 809.7 \text{lbf}$
- Max. preload $P_{\text{Lmax}} = 10476.3 \text{lbf}$
- Min. preload $P_{\text{Lmin}} = 3299 \text{lbf}$
- Uncertainty factor $= 0.25$
- Joint separation load $\max(P_{\text{sep}}) = 1636.305 \text{lbf}$
- Torque coefficient $k = 0.15$
- Max. load on the bolt (ultimate) $\max(P_b) = 10704.2 \text{lbf}$
- Loading plane factor $n = 0.5$
- Max. load on the bolt (yield) $\max(P_{by}) = 10618.7 \text{lbf}$
- Thread pullout strength required to develop full strength of bolt $P_{As} = 19591.7 \text{lbf}$
- Bolt ultimate tensile strength $P_{At} = 10877.5 \text{lbf}$
- Nut ultimate tensile strength $P_{tu\_nut} = 10877.5 \text{lbf}$

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Margin</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_{min1,1} = 0.890$</td>
<td>$0.145$</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_{min2,1} = 2.468$</td>
<td>$0.15$</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_{min3,1} = 6.496$</td>
<td>$0.5$</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_{min4,1} = 0.016$</td>
<td>$0.5$</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_{min5,1} = 0.384$</td>
<td>$0.5$</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

$MS_{bolt} := \min(MS)$

$MS_{bolt} = 0.02$

Failure Mode = "Combined Shear Tension Bending Ultimate"

- $MS_{min\_ID} = 10001006$ Element Identification (10001) and Bolt Number (6) for Minimum Margin
- $MS_{min\_LC} = 5002$ Load Case Number for Minimum Margin
- $MS_{min\_P} = 1363.6$ Applied Tensile Load for Minimum Margin
- $MS_{min\_V} = 215.4$ Applied Shear Load for Minimum Margin
- $MS_{min\_M} = 0$ Applied Bending Moment for Minimum Margin

5.11.4-10 ESCG-4450-05-AMS-0039
Bolt Fail Safe Analysis for FRGF Bracket to FRGF

Since bolt number 6 has the lowest margin of safety, it is assumed that this bolt will be first bolt to fail. There are now 5, EWB0420 0.375"-24 fasteners, holding the FRGF to the FRGF bracket.

**Bolt Geometry**

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.375 & \quad 24 \\
0.375 & \quad 24 \\
\end{align*}
\]

\[
\text{bolt2} := \begin{pmatrix}
0.375 \\
0.375 \\
0.375 \\
0.375 \\
\end{pmatrix}
\]

\[
s := 1..\text{rows(bolt2)}
\]

\[
N_2^s := \text{bolt2}_s \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt}
\]

\[
D_2^s := \text{bolt2}_s \cdot 1 \cdot \text{in} \quad \text{bolt diameter}
\]

\[
\text{At}_2^s := \beta \left( \frac{D_2^s - 0.9743 \cdot \frac{1}{N_2^s}}{2} \right)^2 \quad \text{Tensile Area of bolt}
\]

\[
\text{As}_2^s := \beta \left( \frac{D_2^s - 1.299038 \cdot \frac{1}{N_2^s}}{2} \right)^2 \quad \text{Shear Area of bolt}
\]
AMS-02 FRGF Bracket - Bolt Analysis

Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-2.5</td>
<td>4.33</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2.5</td>
<td>-4.33</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Location of applied forces and moments

xforce2 := 0.0in  yforce2 := 0.0in  zforce2 := 0.0in

cgload2 := \begin{pmatrix} xforce2 \\ yforce2 \\ zforce2 \end{pmatrix}

5.11.4-12
Center of gravity of bolt group

\[
\begin{align*}
    x_{cg2} &= \frac{\sum x^2_s}{\text{rows}(x^2)} \\
    y_{cg2} &= \frac{\sum y^2_s}{\text{rows}(y^2)} \\
    z_{cg2} &= \frac{\sum z^2_s}{\text{rows}(z^2)} \\
\end{align*}
\]

\[
\begin{align*}
    x_{cg2} &= 0 \text{ in} \\
    y_{cg2} &= 0.5 \text{ in} \\
    z_{cg2} &= 0.866 \text{ in} \\
\end{align*}
\]

\[
\begin{align*}
    c_{gbolt2}^g &= \left( \begin{array}{c}
        x_{cg2} \\
        y_{cg2} \\
        z_{cg2}
    \end{array} \right) \\
    c_{gbolt2} &= \left( \begin{array}{c}
        0 \\
        0.5 \\
        0.866
    \end{array} \right) \text{ in}
\end{align*}
\]

Load Vector

\[
\begin{align*}
    r_{load2}^g &= c_{gload2}^g - c_{gbolt2} \\
    r_{load2} &= \left( \begin{array}{c}
        0 \\
        -0.5 \\
        -0.866
    \end{array} \right) \text{ in}
\end{align*}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\begin{align*}
    r_s^2 &= \sqrt{(x_s - x_{cg2})^2 + (y_s - y_{cg2})^2} \\
    r_s^2 &= \left( \begin{array}{c}
        5.568 \\
        4.582 \\
        4.000 \\
        4.583 \\
        5.568
    \end{array} \right) \text{ in}
\end{align*}
\]

Reading database file

The following file reads in all the loads:

\[
\begin{align*}
    \text{data} &= \text{READPRN}("centerloads-fail.txt") \\
    \text{num_bolts2} &= \text{rows}(\text{bolt2}) \\
    \text{q} &= 1..\text{rows}(\text{data})
\end{align*}
\]

* Note that "centerloads-fail.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments. This file is archived along with the other analysis files.
Loads from loads model

Axial Load \( F_x \) := data \(_q\) \( \cdot \) lbf

Shear in Y axis \( F_y \) := data \(_q\) \( \cdot \) lbf

Shear in Z axis \( F_z \) := data \(_q\) \( \cdot \) lbf

Torsion \( M_x \) := data \(_q\) \( \cdot \) in-lbf

Moment about Y axis \( M_y \) := data \(_q\) \( \cdot \) in-lbf

Moment about Z axis \( M_z \) := data \(_q\) \( \cdot \) in-lbf

Extrapolation of Moments:

Distance from RBE \( \text{dist} \) := 3.8197-in

Extrapolation of My Moment: \( M_y \) := \( M_y \) \( \cdot \) \( F_z \) \( \cdot \) \( \text{dist} \)

Extrapolation of Mx Moment: \( M_x \) := \( M_x \) \( \cdot \) \( F_z \) \( \cdot \) \( \text{dist} \)

Element Identification \( \text{ID}_2 \) := data \(_q\) \( \cdot \) \( 1 \)

Load Case Number \( \text{LC}_2 \) := data \(_q\) \( \cdot \) \( 2 \)

Applied Bending Moment at Bolts \( M_2 \) := 0-in-lbf

Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the LC numbers in the second column.

\[ \text{ID}_2 := \text{stack}(\text{ID}_2, \text{ID}_2 + 1, \text{ID}_2 + 2, \text{ID}_2 + 3, \text{ID}_2 + 4) \]

\[ \text{LC}_2 := \text{stack}(\text{LC}_2, \text{LC}_2, \text{LC}_2, \text{LC}_2, \text{LC}_2) \]
Moment Distribution

\[ M_{\text{tot}}(q) := \begin{pmatrix} M_x(q) \\ M_y(q) \\ M_z(q) \end{pmatrix} + r_{\text{load}} \times \begin{pmatrix} F_x(q) \\ F_y(q) \\ F_z(q) \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ M_{\text{bolt cg}}(q) := M_{\text{tot} 1}(q) \quad M_{\text{my bolt cg}}(q) := M_{\text{tot} 2}(q) \quad M_{\text{mz bolt cg}}(q) := M_{\text{tot} 3}(q) \]

Tension on bolts

\[ F_{\text{direct}}(s, q) := \begin{cases} 0 \text{-lbf} & \text{if } F_x(q) \leq 0 \text{lbf} \\ \frac{F_x(q)}{\text{num_bolts}} & \text{otherwise} \end{cases} \]

Direct tensile load calculation - (The if statement checks for compression)

\[ F_{\text{mz}}(s, q) := 0 \text{-lbf} \quad \text{if } (y_s - y_{cg}) = 0 \text{-in} \]

\[ F_{\text{my}}(s, q) := 0 \text{-lbf} \quad \text{if } (z_s - z_{cg}) = 0 \text{-in} \]

\[ \sum_s \left[ (y_s - y_{cg})^2 \cdot A_{t_s} ight] \]

\[ \sum_s \left[ (z_s - z_{cg})^2 \cdot A_{t_s} \right] \]

\[ F_{\text{t}}(s, q) := F_{\text{direct}}(s, q) + F_{\text{mz}}(s, q) + F_{\text{my}}(s, q) \quad \text{Total Tensile load} \]

Shear on bolts

Direct shear Loads

\[ F_{\text{sd}}(s, q) := \sqrt{\left( \frac{F_y(q)}{\text{num_bolts}} \right)^2 + \left( \frac{F_z(q)}{\text{num_bolts}} \right)^2} \]

Secondary shear on bolts

\[ F_s(s, q) := \frac{M_{\text{bolt cg}}(q) \cdot r_s \cdot A_{s}}{\sum_s \left[ \left( r_s \right)^2 \cdot \left( A_{s} \right) \right]} \quad \text{Total shear load} \]

\[ F_{\text{tot}}(s, q) := F_s(s, q) + F_{\text{sd}}(s, q) \]
The stack commands below are used to stack applied axial load \( P_2 \), applied shear load \( V_2 \), and applied moment \( M_2 \) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above.

\[
P_2 := \text{stack}
\left[
\left(F_{t2}^T\right)_{1}, \left(F_{t2}^T\right)_{2}, \left(F_{t2}^T\right)_{3}, \left(F_{t2}^T\right)_{4}, \left(F_{t2}^T\right)_{5}\right]
\]

\[
V_2 := \text{stack}
\left[
\left(F_{stot2}^T\right)_{1}, \left(F_{stot2}^T\right)_{2}, \left(F_{stot2}^T\right)_{3}, \left(F_{stot2}^T\right)_{4}, \left(F_{stot2}^T\right)_{5}\right]
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt \( P_2 \), applied shear on the bolt \( V_2 \), and applied moment on the bolt \( M_2 \). The array is then written to a text file.

\[
\text{Output2} := \text{augment}
\left[
\begin{array}{ccc}
\text{ID2}, \text{LC2}, & P_2 \text{ lbf}, & V_2 \text{ lbf}, & M_2 \text{ in-lbf}
\end{array}
\right]
\]

(Note: Since the ID and LC numbers are dimensionless, the \( P \), \( V \), and \( M \) values are divided by their units in order to make the array dimensionless.)

\[
\text{Size of the "Output2" Array}: \quad \text{rows(Output2)} = 160
\]

WRITEPRN("centerboltloads-fail.txt") := Output2
Fail-safe Analysis

data_fs := READPRN("centerboltloads-fail.txt")
s := 1..rows(data_fs)

Fail-safe Loads

<table>
<thead>
<tr>
<th>Applied Load Type</th>
<th>Applied Load</th>
<th>Fs Fs</th>
<th>Fs Fs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Load</td>
<td>P_FS := data_fs s,3 lbf</td>
<td>ID_FS := data_fs s,1</td>
<td></td>
</tr>
<tr>
<td>Shear Load</td>
<td>V_FS := data_fs s,4 lbf</td>
<td>LC_FS := data_fs s,2</td>
<td></td>
</tr>
<tr>
<td>Bending Moment</td>
<td>M_FS := data_fs s,5 in-lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu_FS := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep_FS := 1.0</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in \escfii02\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC

Bolt Fail-safe Load data

- Joint separation load: max(Psep_FS) = 1467.016 lbf
- Max. load on the bolt(ultimate): max(Pb_FS) = 10598.9 lbf

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_minFS_{1,1} = 1.109</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_minFS_{2,1} = 5.448</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_minFS_{3,1} = 0.026</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_minFS_{4,1} = 10</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MSbolt_FS := min(MS_FS)

MSbolt_FS = 0.026

Failure_Mode_FS = "Combined Shear Tension Bending Ultimate"

Element Identification (10001) and Bolt Number (1) for Minimum Margin
Load Case Number for Minimum Margin
Applied Tensile Load for Minimum Margin
Applied Shear Load for Minimum Margin
Applied Bending Moment for Minimum Margin
5.11.5 FRGF Bracket to Upper Trunnion Bridge Beam
Section 5.11.5
FRGF Bracket to Upper Trunnion Bridge Beam Bolt Analysis

CHECK BOLTS (NAS1351N4H14 0.25"-28 x 0.875L Material-A-286), Nut NAS1291C4, Washer NAS1149E0463R

Analysis: The fasteners connecting the FRGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. This analysis only includes the 12 fasteners shown in the figure below.

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

loads := READPRN("12fst.txt")

\[
\begin{align*}
\text{id} & := 1..\text{rows}(\text{loads}) & \text{rows}(\text{loads}) = 384 \\
\text{id} & := 2..\text{cols}(\text{loads}) & \text{cols}(\text{loads}) = 10 \\
\text{id} & := \text{loads}(\text{id}) & \text{Fx} := \text{loads}(\text{id})\cdot\text{lb} \\
\text{id} & := \text{loads}(\text{id}) & \text{Fz} := \text{loads}(\text{id})\cdot\text{lb} \\
\text{id} & := \text{loads}(\text{id}) & \text{My} := \text{loads}(\text{id})\cdot\text{in}\cdot\text{lb} \\
\text{id} & := \text{loads}(\text{id}) & \text{Mx} := \text{loads}(\text{id})\cdot\text{in}\cdot\text{lb} \\
\text{id} & := \text{loads}(\text{id}) & \text{Mz} := \text{loads}(\text{id})\cdot\text{in}\cdot\text{lb} \\
\end{align*}
\]

* Note that "12fst.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\begin{align*}
\text{Fx}_i := \text{Fx}_i & \quad\text{max}(\text{Fx}) = 436.26\text{ lb} \\
\text{Fv}_i := \sqrt{\left(\text{Fx}_i\right)^2 + \left(\text{Fz}_i\right)^2} & \quad\text{max}(\text{Fv}) = 252.8\text{ lb}
\end{align*}
\]

Tensile Load

Shear Load
CHECK BOLTS (NAS1351N4H14 0.25”-28 x 0.875L Material-A-286), Nut NAS1291C4M, Washer NAS1149E0463R

Flange 1: FRGF Bracket  
Part number: SDG39135861  
Material: Al Alloy 7050-T7451

Flange 2: Upper Trunnion Bridge Beam  
Part number: SDG39135728  
Material: Al Alloy 7075-T73511 Extrusion

**Loads**
- Applied tensile load \( P := 436.26 \text{lbf} \)
- Applied shear load \( V := 252.8 \text{lbf} \)
- Applied bending moment \( M := 0 \text{in-lbf} \)

**Factors of Safety**
- Ultimate \( SF_u := 2.0 \)
- Yield \( SF_y := 1.25 \)
- Joint Separation \( SF_{sep} := 1.2 \)
- Fitting factor \( FF := 1.15 \)

**Temperature data**
- Assembly \( \text{Temp\_initial} := 70\text{-deg} \)
- Maximum \( \text{Temp\_max} := 260\text{-deg} \)
- Minimum \( \text{Temp\_min} := -75\text{-deg} \)

**Bolt and Nut Data**
- Nominal diameter of bolt \( D := .25\text{\text{-in}} \)
- Total length of bolt \( L := 0.875\text{\text{-in}} \)
- Threaded length \( L_t := 0.875\text{\text{-in}} \)

(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \"escfil02/2i11_mathcad\8307_bolts\thread_data.mcd\"

**Washer Data**
- Thickness of washers \( tw := 0.063\text{\text{-in}} \)
- Outer Diameter of washer \( D_w := 0.50\text{in} \)
- Inner Diameter of washer \( D_{wi} := 0.265\text{\text{-in}} \)
- Bolt head dia. across flats \( dw := 0.365\text{\text{-in}} \)

Note: If there is no washer \( tw \), \( D_w \) and \( D_{wi} \) should be zero

**Flange data**
- Thickness of flange 1 \( t_{f1} := 0.25\text{\text{-in}} \)
- Thickness of flange 2 \( t_{f2} := 0.25\text{\text{-in}} \)
- Diameter of hole \( D_{\text{hole}} := 0.288\text{\text{-in}} \)
Material Property Data

Bolt
Temperature correction factor for bolt strength ultimate. \( T_{Su\_bolt} := 0.95 \)

Bolt ultimate tensile allowable stress \( F_{tu\_bolt} := 160000\text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su\_bolt} := 0.6F_{tu\_bolt} \)

Bolt yield Tensile allowable stress \( F_{ty\_bolt} := 120000\text{ psi} \)

Temperature correction factor for bolt modulus \( TE_{bolt} := 0.96 \)

Modulus of elasticity of bolt \( E_{bolt} := (29.1 \times 10^6 \text{ psi}) \)

Thermal coefficient for bolt \( \beta_{\text{bolt\_hot}} := 9.2 \times 10^{-6} \text{ in/in\_deg} \)

Nut
Temperature correction factor for nut strength \( TS_{nut} := 0.95 \)

Ultimate tensile allowable stress \( F_{tu\_nut} := 160000\text{ psi} \)

Ultimate Shear allowable stress: \( F_{su\_nut} := 0.6F_{tu\_nut} \)

Ultimate axial strength of nut \( P_{tu\_nut} := 4580\text{ lbf} \) (Ref. NAS1291)

Washer
Temperature correction factor for washer modulus \( TE_{washer} := 0.96 \)

Modulus of elasticity of washer: \( E_{washer} := (29.1 \times 10^6 \text{ psi}) \)

Flanges
Stiffness of the joint depends upon number of members in the grip of the fasteners.

Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( TF1E := 0.93 \) (modulus)

Temperature correction factor for flange 2 \( TF2E := 0.93 \)

Modulus of elasticity for the parts in the joint \( E_{flange1} := (10.3 \times 10^6 \text{ psi}) \)

\( E_{flange2} := (10.4 \times 10^6 \text{ psi}) \)

Coefficient of thermal expansion for flanges

\( \beta_{\text{flange1\_hot}} := 12.9 \times 10^{-6} \text{ in/in\_deg} \)

\( \beta_{\text{flange2\_hot}} := 12.9 \times 10^{-6} \text{ in/in\_deg} \)

\( \beta_{\text{flange1\_cold}} := 12.05 \times 10^{-6} \text{ in/in\_deg} \)

\( \beta_{\text{flange2\_cold}} := 12.05 \times 10^{-6} \text{ in/in\_deg} \)

Torque/Preload data

Maximum torque (63% of Yield) \( T_{\text{max}} := 103\text{-in-lbf} \)

Loading plane factor \( n := 0.5 \)

Minimum torque (85% of Max Torque) \( T_{\text{min}} := 88\text{in-lbf} \)

Preload Uncertainty \( u := 0.25 \)

Torque coefficient \( k := 0.15 \)

\[ 5.11.5-5 \quad \text{ESCG-4005-05-AMS-0039} \]
Bolt Load data

- Bolt/joint stiffness factor: \(0.29\)
- Preload due to temperature: \(P_{thr\_pos} = 436.7 \text{lbf}\)
- Max. preload: \(P_{LD_{max}} = 3870.1 \text{lbf}\)
- Min. preload: \(P_{LD_{min}} = 1273.1 \text{lbf}\)
- Joint separation load: \(P_{sep} = 523.512 \text{lbf}\)
- Max. load on the bolt (ultimate): \(P_{b} = 4015.7 \text{lbf}\)
- Max. load on the bolt (yield): \(P_{by} = 3961.1 \text{lbf}\)
- Bolt ultimate tensile strength: \(P_{At} = 4351 \text{lbf}\)
- Nut ultimate tensile strength: \(P_{tu\_nut} = 4351 \text{lbf}\)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

- Joint separation: \(MS_1 = 1.47\)
- Direct Tension Ultimate: \(MS_2 = 3.34\)
- Direct Tension Yield: \(MS_3 = 5.41\)
- Total Tension Ultimate: \(MS_4 = 0.08\)
- Total Tension Yield: \(MS_5 = 0.02\)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[
MS_{bolt} := \min(MS)
\]

\[
MS_{bolt} = 0.02 \quad \text{Failure Mode = “Total Tension Yield”}
\]
Fail-safe Analysis

Read in the external datum from NASPOST results:

\[
\text{loadfs} := \text{READPRN(“12fst-fail.txt”)}
\]

\[
p_f := 1..\text{rows(loadfs)} \quad \text{rows(loadfs)} = 352 \quad y_f := 2..\text{cols(loadfs)} \quad \text{cols(loadfs)} = 10
\]

\[
\text{ID} := \text{loadfs}^{(1)} \quad \text{Fx} := \text{loadfs}^{(3)} \cdot \text{lbf} \quad \text{Fz} := \text{loadfs}^{(8)} \cdot \text{lbf} \quad \text{My} := \text{loadfs}^{(7)} \cdot \text{in-lbf}
\]

\[
\text{LC} := \text{loadfs}^{(2)} \quad \text{Fy} := \text{loadfs}^{(4)} \cdot \text{lbf} \quad \text{Mx} := \text{loadfs}^{(6)} \cdot \text{in-lbf} \quad \text{Mz} := \text{loadfs}^{(8)} \cdot \text{in-lbf}
\]

* Note that "12fst-fail.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\text{Ft} \quad p_f := \left| \frac{\text{Fx}}{p_f} \right| \quad \text{max(Ft)} = 571.08 \text{ lbf} \quad \text{Tensile Load}
\]

\[
\text{Fv} \quad p_f := \sqrt{\left(\frac{\text{Fy}}{p_f}\right)^2 + \left(\frac{\text{Fz}}{p_f}\right)^2} \quad \text{max(Fv)} = 362.28 \text{ lbf} \quad \text{Shear Load}
\]

**Fail-safe Loads**

**Fail-safe Factors of Safety**

- **Applied tensile load**
  \[
  \text{P}_{FS} := 571.08\text{-lbf} \quad \text{SF}_{u,FS} := 1.0
  \]

- **Applied shear load**
  \[
  \text{V}_{FS} := 362.28\text{-lbf} \quad \text{SF}_{sep,FS} := 1.0
  \]

- **Applied bending moment**
  \[
  \text{M}_{FS} := 0\cdot\text{in-lbf}
  \]

**This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\bolt_stiffness_nut_FS_RevC**

**Bolt Fail-safe Load data**

- **Joint separation load**
  \[
  \text{P}_{sep,FS} = 571.08\text{ lbf}
  \]

- **Max. load on the bolt(ultimate)**
  \[
  \text{P}_{b,FS} = 3965.4\text{ lbf}
  \]

**Summary of fail-safe Margins for bolt:**

- **Joint separation**
  \[
  \text{MS}_{FS_1} = 1.27 \quad \text{Total Thread shear Ultimate} \quad \text{MS}_{FS_5} = 0.62
  \]

- **Direct Tension Ultimate**
  \[
  \text{MS}_{FS_2} = 5.63 \quad \text{Shear Ultimate} \quad \text{MS}_{FS_6} = 6.13
  \]

- **Total Tension Ultimate**
  \[
  \text{MS}_{FS_3} = 0.1 \quad \text{Bending Ultimate} \quad \text{MS}_{FS_7} = 10
  \]

- **Direct Thread shear Ultimate**
  \[
  \text{MS}_{FS_4} = 8.8 \quad \text{Combined shear, tension and bending ultimate} \quad \text{MS}_{FS_8} = 0.1
  \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MS}_{bolt,FS} := \min(\text{MS}_{FS})
\]

\[
\text{MS}_{bolt,FS} = 0.1 \quad \text{Failure Mode}_{FS} = "\text{Combined Shear Tension Bending Ultimate}"
\]
CHECK BOLTS (NAS1351N4H14 0.25”-28 x 0.875L Material-A-286), Nut NAS1291C4, Washer NAS1149E0463R

**Analysis**: The fasteners connecting the FRGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. This analysis only includes the 2 fasteners shown in the figure below.

**Loads**: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[
\text{loads} := \text{READPRN}("5fst.txt")
\]

\[
i := 1..\text{rows}(\text{loads}) \quad \text{rows}(\text{loads}) = 160 \quad j := 2..\text{cols}(\text{loads}) \quad \text{cols}(\text{loads}) = 10
\]

\[
\text{ID} := \text{loads}^{(1)} \quad \text{Fx} := \text{loads}^{(3)} \text{lbf} \quad \text{Fz} := \text{loads}^{(5)} \text{lbf} \quad \text{My} := \text{loads}^{(7)} \text{in}\cdot\text{lbf}
\]

\[
\text{LC} := \text{loads}^{(2)} \quad \text{Fy} := \text{loads}^{(4)} \text{lbf} \quad \text{Mx} := \text{loads}^{(6)} \text{in}\cdot\text{lbf} \quad \text{Mz} := \text{loads}^{(8)} \text{in}\cdot\text{lbf}
\]

* Note that "5fst.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\text{Ft}_i := |\text{Fx}_i| \quad \max(\text{Ft}) = 271.65 \text{ lbf} \quad \text{Tensile Load}
\]

\[
\text{Fv}_i := \sqrt{(\text{Fy}_i)^2 + (\text{Fz}_i)^2} \quad \max(\text{Fv}) = 174.03 \text{ lbf} \quad \text{Shear Load}
\]
CHECK BOLTS (NAS1351N4H14 0.25"-28 x 0.875L Material-A-286), Nut NAS1291C4M, Washer NAS1149E0463R

Flange 1: FRGF Bracket
Part number: SDG39135861
Material: Al Alloy 7050-T7451

Flange 2: Upper Trunnion Bridge Beam
Part number: SDG39135728
Material: Al Alloy 7075-T73511 Extrusion

Loads
Applied tensile load \( P = 271.65 \text{lbf} \)
Applied shear load \( V = 174.03 \text{lbf} \)
Applied bending moment \( M = 0 \text{in-lbf} \)

Factors of Safety
Ultimate \( SF_u = 2.0 \)
Yield \( SF_y = 1.25 \)
Assembly
Joint Separation \( SF_{sep} = 1.2 \)
Fitting factor \( FF = 1.15 \)
Temperature data
Temp_initial := 70-deg
Temp_max := 260-deg
Temp_min := -75-deg

Bolt and Nut Data
Nominal diameter of bolt \( D = 0.25 \text{ in} \)
Number of threads/inch \( N_t = 28 \frac{1}{8} \text{ in} \)
Total length of bolt \( L = 0.875 \text{ in} \)
Height of nut \( H = 0.204 \text{ in} \)
Threaded length \( L_t = 0.875 \text{ in} \)

(If bolt is fully threaded, input \( L_t = L \))

This file uses the calculations shown in \( \backslash \text{escfil02} \backslash \text{2i11\_mathcad} \backslash \text{8307\_bolts\_thread\_data.mcd} \)

\( \text{Tue Feb 15 10:54:02 AM 2005} \)

Washer Data
Thickness of washers \( tw = 0.063 \text{ in} \)
Outer Diameter of washer \( D_w = 0.50 \text{ in} \)
Inner Diameter of washer \( D_{wi} = 0.265 \text{ in} \)
Bolt head dia. across flats \( d_w = 0.365 \text{ in} \)
Note: If there is no washer \( tw \), \( D_w \) and \( D_{wi} \) should be zero

Flange data
Thickness of flange 1 \( t_{f1} = 0.25 \text{ in} \)
Thickness of flange 2 \( t_{f2} = 0.25 \text{ in} \)
Diameter of hole \( D_{\text{hole}} = 0.288 \text{ in} \)
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate. \( T_{SU_{\text{bolt}}} := 0.95 \)  
Yield \( T_{SY_{\text{bolt}}} := 0.95 \)

Bolt ultimate tensile allowable stress \( F_{UT_{\text{bolt}}} := 160000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{SU_{\text{bolt}}} := 0.6 F_{UT_{\text{bolt}}} \)

Bolt yield Tensile allowable stress \( F_{YT_{\text{bolt}}} := 120000 \text{ psi} \)

Temperature correction factor for bolt modulus \( TE_{\text{bolt}} := 0.96 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \cdot 10^6 \text{ psi}\right) \)

Thermal coefficient for bolt \( \beta_{\text{bolt hot}} := 9.2 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \)

Nut

Temperature correction factor for nut strength \( TS_{\text{nut}} := 0.95 \)  
\( \beta_{\text{bolt cold}} := 8.55 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \)

Ultimate tensile allowable stress \( F_{UT_{\text{nut}}} := 160000 \text{ psi} \)

Ultimate Shear allowable stress: \( F_{SU_{\text{nut}}} := 0.6 F_{UT_{\text{nut}}} \)

Ultimate axial strength of nut \( P_{TU_{\text{nut}}} := 4580 \text{ lbf} \)  
(Ref. NAS1291)

Washer

Temperature correction factor for washer modulus \( TE_{\text{washer}} := 0.96 \)

Modulus of elasticity of washer: \( E_{\text{washer}} := \left(29.1 \cdot 10^6 \text{ psi}\right) \)

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners,  
Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( TF1E := 0.93 \text{ (modulus)} \)

Temperature correction factor for flange 2 \( TF2E := 0.93 \)

Modulus of elasticity for the parts in the joint \( E_{\text{flange1}} := \left(10.3 \cdot 10^6 \text{ psi}\right) \)  
\( E_{\text{flange2}} := \left(10.4 \cdot 10^6 \text{ psi}\right) \)

Coefficient of thermal expansion for flanges \( \beta_{\text{flange1 hot}} := 12.9 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \)  
\( \beta_{\text{flange2 hot}} := 12.9 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \)

\( \beta_{\text{flange1 cold}} := 12.05 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \)  
\( \beta_{\text{flange2 cold}} := 12.05 \cdot 10^{-6} \frac{\text{in}}{\text{in deg}} \)

Torque/Preload data

Maximum torque (63% of Yield) \( T_{max} := 103 \text{ in-lbf} \)

Minimum torque (85% of Max Torque) \( T_{min} := 88 \text{ in-lbf} \)

Torque coefficient \( k := 0.15 \)  
Preload Uncertainty \( u := 0.25 \)
This file uses the calculations shown in \escfii02\2i11_mathcad\8307_bolts\bolt_stiffness_nut_RevC

**Bolt Load data**

- Bolt/joint stiffness factor = 0.29
- Preload due to temperature \( P_{thre}^{pos} = 436.7 \text{ lbf} \)
- Max. preload \( PL_{Dmax} = 3870.1 \text{ lbf} \)
- Pthre_{neg} = −315.3 lbf
- Min. preload \( PL_{Dmin} = 1273.1 \text{ lbf} \)
- Uncertainty factor \( u = 0.25 \)
- Joint separation load \( P_{sep} = 325.98 \text{ lbf} \)
- Torque coefficient \( k = 0.15 \)
- Max. load on the bolt(ultimate) \( P_b = 3960.8 \text{ lbf} \)
- Loading plane factor \( n = 0.5 \)
- Max. load on the bolt(yield) \( P_{by} = 3926.7 \text{ lbf} \)
- Thread pullout strength required to develop full strength of bolt \( P_{As} = 6435.6 \text{ lbf} \)
- Bolt ultimate tensile strength \( P_{At} = 4351 \text{ lbf} \)
- Nut ultimate tensile strength \( P_{tu_nut} = 4351 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

**Summary of Margins for bolt:**

- Joint separation \( MS_1 = 2.97 \)
- Direct Thread shear Ultimate \( MS_6 = 9.3 \)
- Direct Tension Ultimate \( MS_7 = 0.62 \)
- Total Thread shear Ultimate \( MS_8 = 6.42 \)
- Direct Tension Yield \( MS_3 = 9.3 \)
- Shear Ultimate \( MS_9 = 10 \)
- Total Tension Ultimate \( MS_4 = 0.1 \)
- Bending Ultimate \( MS_9 = 10 \)
- Total Tension Yield \( MS_5 = 0.02 \)
- Combined shear, tension and bending ultimate \( MS_10 = 0.1 \)

**Determination of the smallest margin of safety for the bolt, and the failure mode:**

\[
MS_{bolt} := \min(\text{MS})
\]

\[
MS_{bolt} = 0.02 \quad \text{Failure Mode = “Total Tension Yield”}
\]
Fail-safe Analysis

Read in the external datum from NASPOST results:

\[
\begin{align*}
\text{loadfs} & := \text{READPRN}("5fst-fail.txt") \\
\text{pf} & := 1..\text{rows(loadfs)} \quad \text{rows(loadfs)} = 128 \quad \text{yf} := 2..\text{cols(loadfs)} \quad \text{cols(loadfs)} = 10 \\
\text{ID} & := \text{loadfs}[1] \quad \text{Fx} := \text{loadfs}[3] \cdot \text{lbf} \quad \text{Fz} := \text{loadfs}[8] \cdot \text{lbf} \quad \text{My} := \text{loadfs}[7] \cdot \text{in-lbf} \\
\text{LC} & := \text{loadfs}[2] \quad \text{Fy} := \text{loadfs}[4] \cdot \text{lbf} \quad \text{Mx} := \text{loadfs}[6] \cdot \text{in-lbf} \quad \text{Mz} := \text{loadfs}[8] \cdot \text{in-lbf}
\end{align*}
\]

* Note that "5fst-fail.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\begin{align*}
\text{Ft}_{\text{pf}} & := \frac{\text{Fx}_{\text{pf}}}{\text{max}(\text{Ft}) = 334.69 \text{lbf}} \quad \text{Tensile Load} \\
\text{Fv}_{\text{pf}} & := \sqrt{\left(\frac{\text{Fy}_{\text{pf}}}{\text{max}(\text{Fv}) = 222.67 \text{lbf}}\right)^2 + \left(\frac{\text{Fz}_{\text{pf}}}{\text{max}(\text{Fz})}ight)^2} \quad \text{Shear Load}
\end{align*}
\]

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P(_{FS}) := 334.69 lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V(_{FS}) := 222.67 lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M(_{FS}) := 0 in-lbf</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu(_{FS}) := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep(_{FS}) := 1.0</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS(_{FS}) := 10</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfil02\2i11_mathcad\8307_bolts\bolt_stiffness_nut_FS_RevC`

---

**Bolt Fail-safe Load data**

Joint separation load \( P_{\text{sep,FS}} = 334.69 \text{lbf} \)

Max. load on the bolt (ultimate) \( P_{\text{b,FS}} = 3925.9 \text{lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS(_{FS_1}) = 2.87</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS(_{FS_2}) = 10.3</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS(_{FS_3}) = 0.11</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS(_{FS_4}) = 15.72</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS(_{FS_8}) = 0.11</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ MS_{\text{bolt,FS}} := \min(\text{MS}_{FS}) \]

\[ MS_{\text{bolt,FS}} = 0.11 \quad \text{Failure Mode}_{FS} = "\text{Combined Shear Tension Bending Ultimate}" \]
**CHECK BOLTS (NAS1351N4H16 0.25"-28 x 1.0L Material-A-286), Insert MS21209 F4-15, Material-A-286, Washer NAS1149E0463R**

**Analysis**: The fasteners connecting the FRGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. These bolts are shared with the radiator bracket. This analysis only includes the 7 fasteners shown in the figure below.

**Loads**: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

```
loads := READPRN("7fst.txt")
p := 1..rows(loads)    rows(loads) = 224    y := 2..cols(loads)    cols(loads) = 10

ID := loads(1)      Fx := loads(3) lbf    Fz := loads(5) lbf    My := loads(7) in-lbf
LC := loads(2)      Fy := loads(4) lbf    Mx := loads(6) in-lbf    Mz := loads(8) in-lbf
```

* Note that "7fst.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
F_t := \left| \frac{F_x}{p} \right| \quad \text{max}(F_t) = 216.68 \text{ lbf} \quad \text{Tensile Load}
\]

\[
F_v := \sqrt{\left(\frac{F_y}{p}\right)^2 + \left(\frac{F_z}{p}\right)^2} \quad \text{max}(F_v) = 174.1 \text{ lbf} \quad \text{Shear Load}
\]
AMS-02 FRGF Bracket - Bolt Analysis

CHECK BOLTS (NAS1351N4H16 0.25”-28 x 1.0L Material-A-286), Insert MS21209 F4-15, Material-A-286, Washer NAS1149E0463R

Bolt 1

<table>
<thead>
<tr>
<th>Flange 1: FRGF Bracket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part number: SDG39135861</td>
</tr>
<tr>
<td>Material: Al Alloy 7050-T7451</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flange 2: Upper Trunnion Bridge Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part number: SDG39135728</td>
</tr>
<tr>
<td>Material: Al Alloy 7075-T73511 Extrusion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flange 3: Radiator Top Bracket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part number:</td>
</tr>
<tr>
<td>Material: Al Alloy 7075-T7352 Hand Forging</td>
</tr>
</tbody>
</table>

**Loads**

- **Applied tensile load**  \( P := 216.68 \text{ lbf} \)
- **Applied shear load**  \( V := 174.1 \text{ lbf} \)
- **Applied bending moment**  \( M := 0 \text{ in-lbf} \)

**Factors of Safety**

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>( SF_u := 2.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>( SF_y := 1.25 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint Separation</th>
<th>( SF_{sep} := 1.2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting factor</td>
<td>( FF := 1.15 )</td>
</tr>
</tbody>
</table>

**Temperature data**

- **Assembly**  \( \text{Temp}_{\text{initial}} := 70 \text{-deg} \)
- **Maximum**  \( \text{Temp}_{\text{max}} := 260 \text{-deg} \)
- **Minimum**  \( \text{Temp}_{\text{min}} := -75 \text{-deg} \)

**Bolt and Insert Data**

- **Nominal diameter of bolt**  \( D := 0.25 \text{-in} \)
- **Number of threads/inch**  \( N_t := 28 \frac{1}{\text{in}} \)
- **Total length of bolt**  \( L := 1.0 \text{-in} \)
- **Length of insert**  \( L_{\text{ins}} := 0.375 \text{-in} \)
- **Threaded length**  \( L_t := 1.0 \text{-in} \)
- **Min. external diameter of insert**  \( F_{\text{min}} := 0.306 \text{-in} \)
- **Depth of recess for insert**  \( l_r := 0.02 \text{-in} \)

(If bolt is fully threaded, input \( L_t = L \))

**Washer Data**

- **Thickness of washer**  \( t_w := 0.063 \text{-in} \)
- **Outer Diameter of washer**  \( D_w := 0.50 \text{in} \)

**Flange data**

- **Thickness of flange 1**  \( t_{f1} := 0.25 \text{-in} \)
- **Thickness of flange 2**  \( t_{f2} := 0.25 \text{-in} \)
- **Thickness of flange 3**  \( t_{f3} := 0.375 \text{-in} \)  (length of insert)
Inner Diameter of washer \( D_{wi} := 0.265 \text{ in} \)  
Diameter of hole \( D_{\text{hole}} := 0.288 \text{ in} \) 
Bolt head dia. across flats \( d_w := 0.365 \text{ in} \) 
Note: If there is no washer, \( t_w, D_{w}, \) and \( D_{wi} \) should be zero.

**Material Property Data**

**Bolt**

Temperature correction factor for bolt strength ultimate \( T_{Su_{\text{bolt}}} := 0.95 \)  
Yield \( T_{Sy_{\text{bolt}}} := 0.95 \) 
Bolt ultimate tensile allowable stress \( F_{tu_{\text{bolt}}} := 160000 \text{ psi} \) 
Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 F_{tu_{\text{bolt}}} \) 
Bolt yield tensile allowable \( F_{ty_{\text{bolt}}} := 120000 \text{ psi} \) 
Temperature correction factor for bolt modulus \( T_{E_{\text{bolt}}} := 0.96 \)  
\( \beta_{\text{bolt\_hot}} := 9.2 \times 10^{-6} \text{ in} \text{ in}^{-1} \text{ deg}^{-1} \) 
Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \times 10^6 \text{ psi}\right) \)

**Insert**

Temperature correction factor for insert strength \( T_{S_{\text{ins}}} := 0.95 \) 
Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} := 150000 \text{ psi} \)  
(Ref. MS21209) 
Ultimate shear allowable stress \( F_{su_{\text{ins}}} := 0.6 F_{tu_{\text{ins}}} \)

**Washer**

Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} := 0.96 \) 
Modulus of elasticity of washer \( E_{\text{washer}} := \left(29.1 \times 10^6 \text{ psi}\right) \)
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1  \( T_{f1}E := 0.93 \) (modulus)  \( T_{f1}s := 0.93 \) (strength)

Temperature correction factor for flange 2  \( T_{f2}E := 0.93 \) (modulus)  \( F_{su3} := 35000 \text{ psi} \)

Temperature correction factor for flange 3  \( T_{f3}E := 0.93 \) (modulus)  \( T_{f3}s := 0.93 \) (strength)

Modulus of elasticity for the parts in the joint  
\[
E_{\text{flange}1} := \left(10.3 \cdot 10^6 \text{ psi}\right) \\
E_{\text{flange}2} := \left(10.4 \cdot 10^6 \text{ psi}\right) \\
E_{\text{flange}3} := \left(10.2 \cdot 10^6 \text{ psi}\right)
\]

Coefficient of thermal expansion for flanges  
\[
\beta_{\text{flange}1\_hot} := 12.9 \cdot 10^{-6} \text{ in/in/deg} \\
\beta_{\text{flange}2\_hot} := 12.9 \cdot 10^{-6} \text{ in/in/deg} \\
\beta_{\text{flange}1\_cold} := 12.05 \cdot 10^{-6} \text{ in/in/deg} \\
\beta_{\text{flange}2\_cold} := 12.05 \cdot 10^{-6} \text{ in/in/deg} \\
\beta_{\text{flange}3\_hot} := 12.9 \cdot 10^{-6} \text{ in/in/deg} \\
\beta_{\text{flange}3\_cold} := 12.05 \cdot 10^{-6} \text{ in/in/deg}
\]

**Torque/Preload data**

Torque coefficient  \( k := 0.15 \)

Preload Percentage:  \( \text{Per\_Preload} := 0.63 \)

Tensile Area:  \( A_t := 0.0364 \text{in}^2 \)

\[ F_{p\_\text{Preload}} := \text{Per\_Preload\_At\_Fty\_bolt} \]

Maximum torque  \( T_{\text{max}} := F_{p\_\text{Preload}} \cdot k \cdot D \)

Minimum torque  \( T_{\text{min}} := 0.85 \cdot T_{\text{max}} \)

Maximum torque  \( T_{\text{max}} = 103.2 \text{ in-lbf} \)

Loading plane factor:  \( n := 0.5 \)

Minimum torque  \( T_{\text{min}} = 87.7 \text{ in-lbf} \)

Preload Uncertainty:  \( u := 0.25 \)
Bolt Load data

Bolt/joint stiffness factor $= 0.749$

Preload due to temperature $P_{thr\_pos} = 202.041\ lbf$

Max. preload $PLD_{max} = 3641.8\ lbf$

$P_{thr\_neg} = -145.9\ lbf$

Min. preload $PLD_{min} = 1436.5\ lbf$

Uncertainty factor $u = 0.25$

Joint separation load $P_{sep} = 260.016\ lbf$

Torque coefficient $k = 0.15$

Max. load on the bolt (ultimate) $P_b = 3828.5\ lbf$

Loading plane factor $n = 0.5$

Max. load on the bolt (yield) $P_{by} = 3758.5\ lbf$

Thread shear pullout load of bolt or insert $P_{ths} = 12701.8\ lbf$

Bolt ultimate tensile strength $P_{At} = 5363\ lbf$

Thread shear pullout load in parent metal $P_{pths} = 5867.1\ lbf$

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Description</th>
<th>MS</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_1 = 6.68$</td>
<td>Direct Thread shear Ultimate $MS_6 = 10.77$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_2 = 9.76$</td>
<td>Total Thread shear Ultimate $MS_7 = 0.53$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_3 = 11.91$</td>
<td>Shear Ultimate $MS_8 = 6.42$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_4 = 0.4$</td>
<td>Bending Ultimate $MS_9 = 10$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_5 = 0.07$</td>
<td>Combined shear, tension and bending ultimate $MS_{10} = 0.396$</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[
MS_{bolt} := \min(\{MS\})
\]

MS_{bolt} = 0.07 Failure_Mode = "Total Tension Yield"
Fail-safe Analysis

Read in the external datum from NASPOST results:

loadfs := READPRN("7fst-fail.txt")

pf := 1 .. rows(loadfs) rows(loadfs) = 192 yf := 2 .. cols(loadfs) cols(loadfs) = 10

ID := loadfs(1) Fx := loadfs(3) lbf Fz := loadfs(5) lbf My := loadfs(7) in-lbf

LC := loadfs(2) Fy := loadfs(4) lbf Mx := loadfs(6) in-lbf Mz := loadfs(8) in-lbf

* Note that "7fst-fail.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
F_{t_{pf}} := \left| \frac{F_x}{p_f} \right| \quad \text{max}(F_t) = 315.17 \text{ lbf} \quad \text{Tensile Load}
\]

\[
F_{v_{pf}} := \sqrt{\left( \frac{F_y}{p_f} \right)^2 + \left( \frac{F_z}{p_f} \right)^2} \quad \text{max}(F_v) = 194.37 \text{ lbf} \quad \text{Shear Load}
\]

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Applied tensile load</th>
<th>P_FS := 315.17-lbf</th>
<th>Ultimate</th>
<th>SFu_FS := 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear load</td>
<td>V_FS := 194.37-lbf</td>
<td>Joint Separation</td>
<td>SFsep_FS := 1.0</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_FS := 0-in-lbf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>PFS bolt</th>
<th>MS_FS = 5.34</th>
<th>Total Thread shear Ultimate</th>
<th>MS_FS = 0.55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_FS = 13.8</td>
<td>Shear Ultimate</td>
<td>MS_FS = 12.28</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_FS = 0.42</td>
<td>Bending Ultimate</td>
<td>MS_FS = 10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_FS = 15.19</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_FS = 0.42</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MSbolt_FS := min(MS_FS)}
\]

MBolt_FS = 0.42 Failure_Mode_FS = "Combined Shear Tension Bending Ultimate"

Reference:\\Eschil02\\2111_mathcad\\08307_bolts\\bolt_stiffness_insert_FS_RevC.mcd

**Bolt Fail-safe Load data**

Joint separation load \( P_{sep \_FS} = 315.17 \text{ lbf} \)

Max. load on the bolt(ultimate) \( P_{b \_FS} = 3777.6 \text{ lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>MS_FS = 5.34</th>
<th>Total Thread shear Ultimate</th>
<th>MS_FS = 0.55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_FS = 13.8</td>
<td>Shear Ultimate</td>
<td>MS_FS = 12.28</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_FS = 0.42</td>
<td>Bending Ultimate</td>
<td>MS_FS = 10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_FS = 15.19</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_FS = 0.42</td>
</tr>
</tbody>
</table>

5.11.5-18

ESC-4005-05-AMS-0039
CHECK BOLTS (NAS1351N4H14 0.25”-28 x 0.875L Material-A-286), Insert MS21209 F4-10, Material-A-286, Washer NAS1149E0463R

Analysis: The fasteners connecting the FRGF bracket to the Upper Trunnion Bridge Beam will be analyzed. The tension and shear on the bolts will be calculated. These bolts are shared with the tracker bracket. This analysis only includes the 3 fasteners shown in the figure below.

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

```
loads := READPRN("5fst.txt")
p := 1..rows(loads) rows(loads) = 160 y := 2..cols(loads) cols(loads) = 10
ID := loads(1) Fx := loads(3)·lbf Fz := loads(5)·lbf My := loads(7)·in·lbf
LC := loads(2) Fy := loads(4)·lbf Mx := loads(6)·in·lbf Mz := loads(8)·in·lbf
```

* Note that "5fst.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
F_t := \begin{bmatrix} Fx \\ p \end{bmatrix} \quad \text{max}(F_t) = 271.65\text{ lbf}
\]

\[
F_v := \sqrt{(F_y)^2 + (F_z)^2} \quad \text{max}(F_v) = 174.03\text{ lbf}
\]

Tensile Load

Shear Load
CHECK BOLTS (NAS1351N4H14 0.25”-28 x 0.875L Material-A-286), Insert MS21209 F4-10, Material-A-286, Washer NAS1149E0463R

Bolt 1

Flange 1: FRGF Bracket
Part number: SDG39135861
Material: Al Alloy 7050-T7451

Flange 2: Upper Trunnion Bridge Beam
Part number: SDG39135728
Material: Al Alloy 7075-T73511 Extrusion

Flange 3: Tracker Bracket
Part number:
Material: Al Alloy 7075-T7351

Loads
Applied tensile load \( P := 271.65 \text{ lbf} \)
Applied shear load \( V := 174.03 \text{ lbf} \)
Applied bending moment \( M := 0 \text{ in} \cdot \text{lbf} \)

Factors of Safety
Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)
Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)

Temperature data
Assembly \( Temp_{initial} := 70 \text{ deg} \)
Maximum \( Temp_{max} := 260 \text{ deg} \)
Minimum \( Temp_{min} := -75 \text{ deg} \)

Bolt and Insert Data
Nominal diameter of bolt \( D := 0.25 \text{ in} \)
Total length of bolt \( L := 0.875 \text{ in} \)
Threaded length \( L_t := 0.875 \text{ in} \)
(If bolt is fully threaded, input \( L_t = L \))

Number of threads/inch \( N_t := 28 \cdot \frac{1}{\text{in}} \)
Length of insert \( L_{ins} := 0.25 \text{ in} \)
Min. external diameter of insert \( F_{min} := 0.306 \text{ in} \)
Depth of recess for insert \( l_r := 0.02 \text{ in} \)

Washer Data
Thickness of washer \( tw := 0.063 \text{ in} \)
Outer Diameter of washer \( D_w := 0.50 \text{ in} \)

Flange data
Thickness of flange 1 \( tf_1 := 0.25 \text{ in} \)
Thickness of flange 2 \( tf_2 := 0.25 \text{ in} \)
Thickness of flange 3 \( tf_3 := 0.25 \text{ in} \) (length of insert)
Inner Diameter of washer \( D_{wi} := 0.265 \text{ in} \)  
Diameter of hole \( D_{hole} := 0.288 \text{ in} \)  
Bolt head dia. across flats \( d_{w} := 0.365 \text{ in} \)  
Note: If there is no washer, \( t_{w}, D_{w}, \) and \( D_{wi} \) should be zero.

**Material Property Data**

**Bolt**

Temperature correction factor for bolt strength ultimate \( T_{Su,bolt} := 0.95 \)  
Bolt ultimate tensile allowable stress \( F_{tu,bolt} := 160000 \text{ psi} \)  
Bolt ultimate shear allowable stress \( F_{su,bolt} := 0.6 \cdot F_{tu,bolt} \)  
Bolt yield tensile allowable \( F_{ty,bolt} := 120000 \text{ psi} \)  
Temperature correction factor for bolt modulus \( T_{E,bolt} := 0.96 \)  

\[ \beta_{bolt, hot} := 9.2 \cdot 10^{-6} \frac{\text{in}}{\text{ps}^{2}} \]  
Modulus of elasticity of bolt \( E_{bolt} := (29.1 \cdot 10^{6} \text{ psi}) \)  

**Insert**

Temperature correction factor for insert strength \( T_{S,ins} := 0.95 \)  
Ultimate tensile allowable stress \( F_{tu,ins} := 150000 \text{ psi} \)  
(Ref. MS21209)  
Ultimate shear allowable stress \( F_{su,ins} := 0.6 \cdot F_{tu,ins} \)  

**Washer**

Temperature correction factor for washer modulus \( T_{E, washer} := 0.96 \)  
Modulus of elasticity of washer \( E_{washer} := (29.1 \cdot 10^{6} \text{ psi}) \)
Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1

Temperature correction factor for flange 2

Temperature correction factor for flange 3

Modulus of elasticity for the parts in the joint

Coefficient of thermal expansion for flanges

Torque/Preload data

Torque coefficient

Preload Percentage:

Tensile Area:

Maximum torque

Minimum torque

Maximum torque

Minimum torque

Loading plane factor:

Preload Uncertainty:
Bolt Load data

Bolt/joint stiffness factor $= 0.735$  
Preload due to temperature $P_{thr\_pos} = 199.7031\text{ lbf}$

Max. preload $PLD_{max} = 3639.5\text{ lbf}$  
Uncertainty factor $u = 0.25$

Min. preload $PLD_{min} = 1438.1\text{ lbf}$  
Torque coefficient $k = 0.15$

Joint separation load $P_{sep} = 325.98\text{ lbf}$  
Loading plane factor $n = 0.5$

Max. load on the bolt(ultimate) $P_b = 3869.1\text{ lbf}$  
Thread shear pullout load of bolt or insert $P_{ths} = 8894.3\text{ lbf}$

Max. load on the bolt(yield) $P_{by} = 3783\text{ lbf}$  
Thread shear pullout load in parent metal $P_{pths} = 4246.7\text{ lbf}$

Bolt ultimate tensile strength $P_{At} = 5363\text{ lbf}$

Length_check = "Bolt length is sufficient"

Summary ofMargins for bolt:

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>MS$_1$ = 5.07</th>
<th>Direct Thread shear Ultimate</th>
<th>MS$_6$ = 5.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS$_2$ = 7.58</td>
<td>Total Thread shear Ultimate</td>
<td>MS$_7$ = 0.1</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS$_3$ = 9.3</td>
<td>Shear Ultimate</td>
<td>MS$_8$ = 6.42</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS$_4$ = 0.39</td>
<td>Bending Ultimate</td>
<td>MS$_9$ = 10</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS$_5$ = 0.063</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS$_{10}$ = 0.382</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

$$MS_{bolt} := \text{min}(MS)$$

$$MS_{bolt} = 0.063 \quad \text{Failure Mode} = "\text{Total Tension Yield}"$$
Fail-safe Analysis

Read in the external datum from NASPOST results:

loadfs := READPRN("5fst-fail.txt")

pf := 1., rows(loadfs) rows(loadfs) = 128  
yf := 2., cols(loadfs) cols(loadfs) = 10

ID := loadfs<1>  Fx := loadfs<3> lbf  
Fz := loadfs<5> lbf  My := loadfs<7> in-lbf

LC := loadfs<2>  Fy := loadfs<4> lbf  
Mx := loadfs<6> in-lbf  Mz := loadfs<8> in-lbf

* Note that "5fst-fail.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[ F_{\text{pf}} := \frac{|F_x|}{F_{\text{pf}}} \quad \text{max}(F_t) = 334.69\text{ lbf} \]  
Tensile Load

\[ F_{\text{pf}} := \sqrt{(F_y/F_{\text{pf}})^2 + (F_z/F_{\text{pf}})^2} \quad \text{max}(F_v) = 222.67\text{ lbf} \]  
Shear Load

Fail-safe Loads  
Applied tensile load \( P_{\text{FS}} := 334.69\text{ lbf} \)  
Ultimate  \( SF_{\text{u,FS}} := 1.0 \)

Applied shear load \( V_{\text{FS}} := 222.67\text{ lbf} \)  
Joint Separation  \( SF_{\text{sep,FS}} := 1.0 \)

Applied bending moment \( M_{\text{FS}} := 0.\text{ in-lbf} \)

Bolt Fail-safe Load data

Joint separation load \( P_{\text{sep,FS}} = 334.69\text{ lbf} \)

Max. load on the bolt(ultimate) \( P_{\text{b,FS}} = 3781\text{ lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Load Case</th>
<th>( \text{MS}_{\text{FS}} )</th>
<th>Ultimate Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( \text{MS}_{\text{FS}}_1 = 4.91 )</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( \text{MS}_{\text{FS}}_2 = 12.93 )</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( \text{MS}_{\text{FS}}_3 = 0.42 )</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( \text{MS}_{\text{FS}}_4 = 10.03 )</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

\[ \text{MS}_{\text{bolt,FS}} := \min(\text{MS}_{\text{FS}}) \]
\[ \text{MS}_{\text{bolt,FS}} = 0.12 \]

Failure Mode = "Total Thread Shear Ultimate"

Reference:\\Eschil02\\2111_mathcad\\08307_bolts\\bolt_flexural_insert_FS_RevC.mcd
5.11.6 ROEU Fastener Analysis
Section 5.11.6  ROEU Fastener Analysis

The ROEU Fastener Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.11.6.1</td>
<td>ROEU Arm Flange to Sill Joint</td>
</tr>
<tr>
<td>5.11.6.1</td>
<td>ROEU Arm Flange to Sill Joint (Fail-Safe)</td>
</tr>
<tr>
<td>5.11.6.2</td>
<td>ROEU Bearing Failure Analysis</td>
</tr>
<tr>
<td>5.11.6.3</td>
<td>ROEU PDA Bracket, Pin, and Lug Analysis</td>
</tr>
<tr>
<td>5.11.6.4</td>
<td>ROEU Assembly Harness Bracket and Bolt Analysis</td>
</tr>
</tbody>
</table>
5.11.6.1 ROEU Arm Flange to Sill Joint
Section 5.11.6.1 ROEU/USS Interface
Foldable ROEU Assembly to Sill Joint Bolt Analysis - Part no.: SEG39137677

The parts comprising the Foldable ROEU Assembly are the ROEU Clevis Assembly, PDA Mounting Bracket, and Clamp and Harness Brackets. Eight (8) fasteners attach the ROEU Clevis Assembly to the Sill Joint of the USS. These fasteners, NAS1351N4-20 bolts (160 ksi ultimate), 0.2500-28 UNJF are the subject of the following analysis. The drawing number for the ROEU Clevis Assembly is SEG39137676.

\[
\begin{align*}
\text{bolt} &:= \begin{bmatrix}
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 
\end{bmatrix} \\
\text{thread/in} &:= \begin{bmatrix}
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 
\end{bmatrix}
\end{align*}
\]

\[
i := 1.. \text{rows(bolt)}
\]

\[
N_i := \text{bolt}_{i,2} \times \frac{1}{\text{in}}
\]

\[
\text{pitch of bolt}
\]

\[
D_i := \text{bolt}_{i,1} \times \text{in}
\]

\[
\text{bolt diameter}
\]

\[
A_{ti} := \beta \left( \frac{D_i - 0.9743 \times \frac{1}{N_i}}{2} \right)^2
\]

\[
A_{si} := \beta \left( \frac{D_i - 1.299038 \times \frac{1}{N_i}}{2} \right)^2
\]

Tensile Area of bolt

Shear Area of bolt
Location of the Centroid of the Fastener Group

ROEU Clevis Flange Bolt Pattern

Note: The reference y-axis and z-axis locations were conveniently chosen such that the fasteners are contained within the first quadrant of the coordinate system. The x-direction is into the plate and perpendicular to the shear plane. Hole location dimensions were obtained from drawing no. SEG39137676.

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0.0)</td>
<td>(0.000)</td>
<td>(0.000)</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>2.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>3.000</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>(0.0)</td>
<td>7.875</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>1.000</td>
<td>7.875</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>2.000</td>
<td>7.875</td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>3.000</td>
<td>7.875</td>
</tr>
</tbody>
</table>
Center of gravity of bolt group

\[ \text{xcg} := \frac{\sum x_i}{\text{rows}(x)} \quad \text{ycg} := \frac{\sum y_i}{\text{rows}(y)} \quad \text{zcg} := \frac{\sum z_i}{\text{rows}(z)} \]

\[ \text{xcg} = 0\text{ in} \quad \text{ycg} = 1.5\text{ in} \quad \text{zcg} = 3.938\text{ in} \]

\[ \text{cgbolt} := \begin{pmatrix} \text{xcg} \\ \text{ycg} \\ \text{zcg} \end{pmatrix} \]

\[ \text{cgbolt} = \begin{pmatrix} 0 \\ 1.5 \\ 3.938 \end{pmatrix} \text{ in} \]

Distance from CG of Bolts to individual bolts for shear calculations:

\[ r_i := \sqrt{\left( z_i - \text{zcg} \right)^2 + \left( y_i - \text{ycg} \right)^2} \]

\[ r = \begin{pmatrix} 4.214 \\ 3.969 \\ 3.969 \\ 4.214 \\ 4.214 \\ 3.969 \\ 3.969 \\ 4.214 \end{pmatrix} \text{ in} \]

Location of applied forces and moments

The load cases are comprised of launch and abort landing load cases. Loads were obtained from a modified 2-06 loads model. The data recovered are the MPC forces for node 9900, which represents the end of the CBUSH connected to the beam. These loads are at the center of gravity of the bolt pattern. Post processing was performed in NASPOST for forces and moments in the x, y, and z directions. These loads are read into an array and distributed to the 8 bolts of the ROEU clevis flange. The loads information was obtained from the loads group.

Load Vector - xforce, yforce, and zforce represents the components of the position vector measured from the cg of the bolt pattern to the point of application of the forces and moments recovery point of the finite element model.

\[ x_{\text{force}} := 0.0\text{ in} \quad y_{\text{force}} := 0.0\text{ in} \quad z_{\text{force}} := 0.0\text{ in} \]

\[ r_{\text{load}} := \begin{pmatrix} x_{\text{force}} \\ y_{\text{force}} \\ z_{\text{force}} \end{pmatrix} \quad r_{\text{load}} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in} \]
Reading NASPOST file for loads

data := READPRN("ROEU_uss_interface_naspost3.txt")
j := 1..rows(data)

num_bolts := rows(bolt)

* Note: the "ROEU_uss_interface_naspost3.txt" data file was generated from the NASPOST result (.LIS file) by removing all words and comments. This file is archived along with the other analysis files.

Loads from 2-06 loads model, launch, on-orbit, and abort landing case

Element Identification   ID := data, , 1   rows(ID) = 128
Load Case Number         LC := data, , 2   rows(LC) = 128
Axial Load               Fx := data, , 3-lbf Torsion
Shear in Y axis          Fy := data, , 4-lbf Moment about Y axis
Shear in Z axis          Fz := data, , 5-lbf Moment about Z axis

Applied Bending Moment at Bolts   M := 0-in-lbf

Rotation of Coordinate System of Loads For Alignment With Coordinate System of Bolt Pattern in Clevis Flange

The loads are recovered in the global coordinate system at the cg of the bolt pattern where the local coordinate system, Xcg, Ycg, Zcg is created. The forces and moments are transformed to the local coordinate system at the cg of the bolt pattern. Two global coordinate system rotations are required, a 5.35 degree rotation about the X axis and a 180 degree rotation about the Z axis.

\[ u := 5.35\text{-deg} \hspace{1cm} := 180\text{-deg} \]

\[ \text{Transform} := \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(u) & -\sin(u) \\ 0 & \sin(u) & \cos(u) \end{pmatrix} \begin{pmatrix} \cos(u) & -\sin(u) & 0 \\ \sin(u) & \cos(u) & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ \text{Transform} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -0.996 & -0.093 \\ 0 & -0.093 & 0.996 \end{pmatrix} \]
Analysis of Bolts Attaching ROEU Arm Flange to Sill Joint

\[ \text{F}_{\text{local}} := \begin{bmatrix} F_{x_j}^T \; F_{y_j}^T \; F_{z_j}^T \end{bmatrix} \quad \text{M}_{\text{local}} := \begin{bmatrix} M_{x_j}^T \; M_{y_j}^T \; M_{z_j}^T \end{bmatrix} \]

\[ F_{x_j} := \left( \text{F}_{\text{local}} \right)^{(1)} \quad F_{y_j} := \left( \text{F}_{\text{local}} \right)^{(2)} \quad F_{z_j} := \left( \text{F}_{\text{local}} \right)^{(3)} \]

\[ M_{x_j} := \left( \text{M}_{\text{local}} \right)^{(1)} \quad M_{y_j} := \left( \text{M}_{\text{local}} \right)^{(2)} \quad M_{z_j} := \left( \text{M}_{\text{local}} \right)^{(3)} \]

Coordinate Systems For Transformation
Format of Output File

The stack commands below are used to stack the element identifications (ID) and load cases (LC) in ascending order per bolt. The element ID number is located in the first column and the load case numbers, LC, in the second column. For the element identification number, 9900, the bolt number within the bolt pattern is added to the end of each element identification (times 1000). For example, the element identification number 9900 will have bolt numbers 1 thru 8 attached to the end for all 128 load cases. This brings the total number of load cases to 1024 (1 joint x 8 bolts x 128 load cases = 1024). See the array example on the next page.

\[ \text{ID}_j := \text{ID}_j \times 1000 + 1 \]  
Counter for number of bolts in pattern

\[ \text{ID}_2 := \text{stack}(\text{ID}_1, \text{ID}_2, \text{ID}_3, \text{ID}_4, \text{ID}_5, \text{ID}_6, \text{ID}_7) \]

\[ \text{LC}_2 := \text{stack}(\text{LC}_1, \text{LC}_2, \text{LC}_3, \text{LC}_4, \text{LC}_5, \text{LC}_6, \text{LC}_7) \]

Moment Distribution

\[ \mathbf{M}_{\text{tot}}^j := \begin{pmatrix} \mathbf{M}_x^j \\ \mathbf{M}_y^j \\ \mathbf{M}_z^j \end{pmatrix} + \mathbf{t}_{\text{load}} \times \begin{pmatrix} \mathbf{F}_x^j \\ \mathbf{F}_y^j \\ \mathbf{F}_z^j \end{pmatrix} \]

Use the cross-product to determine the additional moments acting on the fasteners.

\[ \mathbf{M}_x_{\text{boltcg}}^j := \mathbf{M}_{\text{tot1}}^j \]
\[ \mathbf{M}_y_{\text{boltcg}}^j := \mathbf{M}_{\text{tot2}}^j \]
\[ \mathbf{M}_z_{\text{boltcg}}^j := \mathbf{M}_{\text{tot3}}^j \]

Tension on bolts

Direct tensile load calculation:

\[ \mathbf{F}_{\text{direct}}^j := \left| \frac{\mathbf{F}_x^j}{\text{num_bolts}} \right| \]
Analysis of Bolts Attaching ROEU Arm Flange to Sill Joint

\[
F_{mz,ij} := \begin{cases} 
0 \text{ lbf} & \text{if } (y_i - yc_g) = 0 \text{ in} \\
[Mz_{boltc_g} (y_i - yc_g)] At_i \\
\sum_i [(y_i - yc_g)^2 \cdot At_i] 
\end{cases}
\]

\[
F_{my,ij} := \begin{cases} 
0 \text{ lbf} & \text{if } (z_i - zc_g) = 0 \text{ in} \\
[M_y_{boltc_g} (z_i - zc_g)] At_i \\
\sum_i [(z_i - zc_g)^2 \cdot At_i] 
\end{cases}
\]

Total Tensile load:
\[
F_{t,i,j} := F_{direct, i,j} + F_{mz, i,j} + F_{my, i,j}
\]

Shear on bolts

Secondary shear on bolts:
\[
F_{s,i,j} := \frac{[Mx_{boltc_g}] r_i \cdot As_i}{\sum_i (r_i)^2 \cdot (As_i)}
\]

Direct shear on bolts:
\[
F_{sd,i,j} := \sqrt{\left(\frac{Fz_j}{2}\right)^2 + \left(\frac{Fy_j}{2}\right)^2}
\]

Total shear load:
\[
F_{stot,i,j} := F_{sd, i,j} + F_{s, i,j}
\]

Fsd_{1, 1} = 28.264 lbf

The stack commands below are used to stack applied axial load (P1), applied shear load (V1), and applied moment (M1) in ascending order per bolt. These loads are put into an array with the element/bolt number and load case number from above. See the "Output" file below.

\[
P_1 := \begin{bmatrix} (Ft^T)^{1}, (Ft^T)^{2}, (Ft^T)^{3}, (Ft^T)^{4}, (Ft^T)^{5}, (Ft^T)^{6}, (Ft^T)^{7}, (Ft^T)^{8} \end{bmatrix}
\]

\[
V_1 := \begin{bmatrix} (Fstot^T)^{1}, (Fstot^T)^{2}, (Fstot^T)^{3}, (Fstot^T)^{4}, (Fstot^T)^{5}, (Fstot^T)^{6}, (Fstot^T)^{7}, (Fstot^T)^{8} \end{bmatrix}
\]
\[ M_1 := \text{stack}(M, M, M, M, M, M) \]

The "Output" file below outputs an array from left to right starting with the element identification (ID), Load case number (LC), applied load on the bolt (P1), applied shear on the bolt (V1), and applied moment on the bolt (M1). See the output array example below. The array is then written to a text file.

Output := augment \( \left( \text{ID2, LC2, } \frac{\text{P1}}{\text{lbf}}, \frac{\text{V1}}{\text{lbf}}, \frac{\text{M1}}{\text{in-lbf}} \right) \) (Note: Since the ID and LC numbers are dimensionless, the P1, V1, and M1 values are divided by their units in order to make the array dimensionless.)

\[
\begin{array}{cccc}
\text{ID} & \text{LC} & \text{P1} & \text{V1} \\
9900001 & 1001 & -141.6 & 39.794 \\
9900001 & 1002 & -273.9 & 44.675 \\
\ldots & \ldots & \ldots & \ldots \\
9900001 & 2064 & 294.7 & 94.445 \\
9900002 & 1001 & -100.2 & 39.125 \\
9900002 & 1002 & -136.3 & 43.883 \\
\ldots & \ldots & \ldots & \ldots \\
9900002 & 2064 & 278.2 & 92.972 \\
\ldots & \ldots & \ldots & \ldots \\
\ldots & \ldots & \ldots & \ldots \\
9900008 & 1001 & 200.9 & 39.794 \\
9900008 & 1002 & 356.9 & 44.675 \\
\ldots & \ldots & \ldots & \ldots \\
9900008 & 2064 & 270.0 & 94.445 \\
\end{array}
\]

Size of the "Output" Array: \( \text{rows}(\text{Output}) = 1024 \)

(8 bolts x 128 load cases) x 1 joint = 1024 load cases

Example of Output Array

WRITEPRN("output_forces_ROEU_uss.txt" ) := Output
CHECK BOLTS (NAS1351N4-20 0.25"-28 UNJF-3A x 1.25" L, Material-A-286), Nut NAS1291C4M, Nut Washer NAS1149E0432R, Bolt Head Washer NAS1587-4C

The array from the text file above is read:

\[ s := 1 \text{ rows}(\text{Output}) \quad \text{rows}(\text{Output}) = 1024 \quad \text{cols}(\text{Output}) = 5 \]

Flange 1: Clevis Plate
Part number: SEG39137676
Material: Al Alloy 7050-T7451 BMS-7-323C

Flange 2: USS-02 Sill Joint Assembly
Part number: SDG39135730-301
Material: Al Alloy 7050-T7451 AMS 4050

Loads

- Node ID: \( s \) := Output\(_s,1\)
- Applied tensile load: \( P_s := \text{Output}\(_s,3\), \text{lbf}\)
- Applied shear load: \( V_s := \text{Output}\(_s,4\), \text{lbf}\)
- Applied bending moment: \( M_s := \text{Output}\(_s,5\), \text{in-lbf}\)

Factors of Safety

- Ultimate SFu := 2.0
- Yield SFy := 1.25

Temperature data

- Assembly Temp\(_\text{initial}\) := 70-deg
- Maximum Temp\(_\text{max}\) := 120-deg
- Minimum Temp\(_\text{min}\) := 40-deg

Bolt and Nut Data

- Nominal diameter of bolt D := .250-in
- Number of threads/inch Nt := 28 \( \frac{1}{\text{in}} \)
- Total length of bolt L := 1.25-in
- Height of nut H := 0.204-in
- Threaded length Lt := 1.00-in

(If bolt is fully threaded, input Lt = L)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd
Analysis of Bolts Attaching ROEU Arm Flange to Sill Joint

**Washer Data**

- Thickness of washers: $t_w := 0.110\text{ in}$
- Outer Diameter of washer: $D_w := 0.531\text{ in}$
- Inner Diameter of washer: $D_{wi} := 0.252\text{ in}$

**Flange data**

- Thickness of flange 1: $t_{f1} := 0.375\text{ in}$ (SEG39137676)
- Thickness of flange 2: $t_{f2} := 0.375\text{ in}$ (SDG39135730)
- Diameter of hole: $D_{hole} := 0.272\text{ in}$ (SEG39137676)

Bolt head dia. across flats: $d_w := 0.490\text{ in}$ (used only if there is no washer)

Note: If there is no washer $t_w$, $D_w$ and $D_{wi}$ should be zero

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength ultimate: $T_{Su\_bolt} := 0.98$
- Bolt ultimate tensile allowable stress: $F_{tu\_bolt} := 160000\text{ psi}$ (Ref. MMPDS, fig. 6.2.1.1.1)
- Bolt ultimate shear allowable stress: $F_{su\_bolt} := 0.6F_{tu\_bolt}$
- Bolt yield Tensile allowable stress: $F_{ty\_bolt} := 120000\text{ psi}$
- Temperature correction factor for bolt modulus: $T_{E\_bolt} := 0.98$ (Ref. MMPDS, fig. 6.2.1.1.4(a))
- Modulus of elasticity of bolt: $E_{\_bolt} := \left(29.1\cdot10^6\text{ psi}\right)$ (Ref. MMPDS, table 6.2.1.0(b))
- Thermal coefficient for bolt: $=_{\_bolt\_hot} := 9.1\cdot10^{-6}\frac{\text{in}}{\text{deg}}$ $=_{\_bolt\_cold} := 8.9\cdot10^{-6}\frac{\text{in}}{\text{deg}}$

**Nut**

- Temperature correction factor for nut strength: $T_{S\_nut} := 0.98$
- Ultimate tensile allowable stress: $F_{tu\_nut} := 125000\text{ psi}$ (Ref. NAS1291, A-286)
- Ultimate Shear allowable stress: $F_{su\_nut} := 0.6F_{tu\_nut}$
Ultimate axial strength of nut $P_{tu \_ nut} := 4580 \text{ lbf}$ (Ref. NAS1291, A-286)

**Washer**

Temperature correction factor for washer modulus $T_{E\_ washer} := 0.98$ (Ref. MMPDS, fig. 6.2.1.1.1)

Modulus of elasticity of washer: $E_{\_ washer} := \left(29.1 \times 10^6 \text{ psi}\right)$ (Ref. MMPDS, table 6.2.1.0(b))

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 $T_{f1\_ E} := 0.98$ (modulus)

Temperature correction factor for flange 2 $T_{f2\_ E} := 0.98$

Modulus of elasticity for the parts in the joint $E_{\_ flange1} := \left(10.3 \times 10^6 \text{ psi}\right)$ $E_{\_ flange2} := \left(10.3 \times 10^6 \text{ psi}\right)$

(Ref. for flange 1: MMPDS, table 3.7.6.0(b3))

(Ref. for flange 2 Ref. MMPDS, table 3.7.4.0(b1))

Coefficient of thermal expansion for flanges $\gamma_{\_ flange1\_ hot} := 12.5 \times 10^{-6} \frac{\text{in}}{\text{deg}}$ $\gamma_{\_ flange2\_ hot} := 12.5 \times 10^{-6} \frac{\text{in}}{\text{deg}}$

$\gamma_{\_ flange1\_ cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}}$ $\gamma_{\_ flange2\_ cold} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}}$

(Ref. MMPDS, figure 3.7.6.0 and Appendix C9)

**Torque/Preload data**

Maximum torque (60% of yield) $T_{max} := 97.3 \text{ in-lbf}$ Loading plane factor $n := 0.5$

Minimum torque (95% of $T_{max}$) $T_{min} := 82.7 \text{ in-lbf}$ Preload Uncertainty $y := 0.25$

Torque coefficient $k := 0.15$

This file uses the calculations shown in \\escfio2\211_mathcad\8307_bolts\multi_bolt_stiffness_nut_RevC
Bolt Load data

Bolt/joint stiffness factor, $= 0.237$

Preload due to temperature

$P_{thr\_pos} = 123.9\text{ lbf}$

Max. preload

$P_{ld\text{max}} = 3367.3\text{ lbf}$

Uncertainty factor

$y = 0.25$

Max. load on the bolt (ultimate)

$P_{b\text{ult}} = 3515.7\text{ lbf}$

$P_{As} = 6638.8\text{ lbf}$

Max. load on the bolt (yield)

$P_{by\text{ult}} = 3460\text{ lbf}$

Nut ultimate tensile strength

$P_{tu\_nut} = 4488.4\text{ lbf}$

Joint separation load

$P_{sep\text{max}} = 653.247\text{ lbf}$

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_{min_1,1} = 1.147$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$MS_{min_6,1} = 4.302$</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>$MS_{min_7,1} = 0.888$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$MS_{min_3,1} = 4.302$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_{min_9,1} = 10$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_{min_10,1} = 0.276$</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

$MS_{bolt} = \min(\text{MS})$

Minimum Margin of Safety

$Failure\_Mode = "Total\ Tension\ Yield"$

Element Identification (9900001) and Bolt Number (1) for Minimum Margin

Load Case Number for Minimum Margin

Applied Tensile Load for Minimum Margin
Fail-Safe Analysis For ROEU Assembly to Sill Joint Bolts

Fail-Safe analysis assumes the bolt with the lowest margin of safety will be the first to fail. The 7 remaining fasteners are required to maintain positive margins of safety for joint stability. Bolt no. 1 has the lowest margin and hence it is removed. (Ref. page 5.11.6.1-13)

\[
\begin{align*}
MS_{\text{min}_V} &= 80.5 & \text{Applied Shear Load for Minimum Margin} \\
MS_{\text{min}_M} &= 0 & \text{Applied Bending Moment for Minimum Margin}
\end{align*}
\]

\[
\begin{align*}
thread/in \\
\begin{pmatrix}
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28
\end{pmatrix}
\end{align*}
\]

\[
bolt2 := \begin{pmatrix}
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28 \\
0.2500 & 28
\end{pmatrix}
\]

\[
s := 1..\text{rows}(bolt2)
\]

\[
pitch of bolt \quad N2_s := bolt2_{s,2} \cdot \frac{1}{\text{in}}
\]

\[
bolt diameter \quad D2_s := bolt2_{s,1} \cdot \text{in}
\]

\[
\begin{align*}
\text{Tensile Area of bolt} & \quad \text{Shear Area of bolt} \\
\begin{align*}
At2_s & := \beta \left( \frac{D2_s - 0.9743 \cdot \frac{1}{N2_s}}{2} \right)^2 \\
As2_s & := \beta \left( \frac{D2_s - 1.299038 \cdot \frac{1}{N2_s}}{2} \right)^2
\end{align*}
\end{align*}
\]

\[
\begin{align*}
\text{Bolt no.} & \quad x \ co-ord & \quad y \ co-ord & \quad z \ co-ord \\
2 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
1.000 \\
2.000 \\
3.000 \\
7.875 \\
7.875
\end{pmatrix} \\
3 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
0.000 \\
0.000 \\
0.000 \\
7.875 \\
7.875
\end{pmatrix} \\
4 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
0.000 \\
0.000 \\
0.000 \\
7.875 \\
7.875
\end{pmatrix} \\
5 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
0.000 \\
0.000 \\
0.000 \\
7.875 \\
7.875
\end{pmatrix} \\
6 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
0.000 \\
0.000 \\
0.000 \\
7.875 \\
7.875
\end{pmatrix} \\
7 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
0.000 \\
0.000 \\
0.000 \\
7.875 \\
7.875
\end{pmatrix} \\
8 & \quad \begin{pmatrix}
0.0 \\
0.0 \\
0.0 \\
0.0 \\
0.0
\end{pmatrix} & \quad \begin{pmatrix}
0.000 \\
0.000 \\
0.000 \\
7.875 \\
7.875
\end{pmatrix}
\end{align*}
\]
**Location of applied forces and moments**

The center of gravity of the load (shown as cgload2) is the center of gravity of the bolt pattern for the 8 bolt configuration and was calculated on page 5.11.6.1-4. Since the x direction is into the plate the loads are shared equally between the bolts in the y and z directions. However, due to a failure in bolt 1, the y and z directions in the bolt pattern are unsymmetric and have offsets from the center of gravity of the load.

\[
\begin{align*}
\text{xforce}2 & := 0 \text{in} & \text{yforce}2 & := 1.50 \text{in} & \text{zforce}2 & := 3.937 \text{in} \\
cgload2 & := \begin{pmatrix} \text{xforce}2 \\ \text{yforce}2 \\ \text{zforce}2 \end{pmatrix} & \text{cgload2} & = \begin{pmatrix} 0 \\ 1.5 \\ 3.937 \end{pmatrix} \text{in}
\end{align*}
\]

**Center of gravity of bolt group**

\[
\begin{align*}
x_{cg2} & := \frac{\sum_{s} \text{x}s}{\text{rows}(\text{x}2)} & y_{cg2} & := \frac{\sum_{s} \text{y}s}{\text{rows}(\text{y}2)} & z_{cg2} & := \frac{\sum_{s} \text{z}s}{\text{rows}(\text{z}2)}
\end{align*}
\]

\[
\begin{align*}
x_{cg2} & = 0 \text{in} & y_{cg2} & = 1.714 \text{in} & z_{cg2} & = 4.5 \text{in}
\end{align*}
\]

\[
\begin{align*}
c_{cg bolt 2} & := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} & c_{cg bolt 2} & = \begin{pmatrix} 0 \\ 1.714 \\ 4.5 \end{pmatrix} \text{in}
\end{align*}
\]

**Load Vector**

\[
\begin{align*}
r_{\text{load}2} & := \text{cgload2} - \text{cg bolt 2} \\
r_{\text{load}2} & = \begin{pmatrix} 0 \\ -0.214 \\ -0.563 \end{pmatrix} \text{in}
\end{align*}
\]
Distance from CG of Bolts to individual bolts for shear calculations:

\[
r_2^s = \sqrt{(r_2^s - z_{cg})^2 + (y_2^s - y_{cg})^2}
\]

\[
r_2^s = \begin{bmatrix}
4.556 \\
4.509 \\
4.680 \\
3.785 \\
3.450 \\
3.387 \\
3.612
\end{bmatrix} \text{ in}
\]

Reading database file for bolted joint, fail-safe case

data := READPRN("ROEU_uss_interface_naspost3.txt")
ID2 := 0
LC2 := 0

q := 1..rows(data)  num_bolts2 := rows(bolt2)

Loads from 2-06 loads model

Axial Load  \( F_x^q := \text{data}_{q3} \text{lbf} \)

Shear in Y axis  \( F_y^q := \text{data}_{q4} \text{lbf} \)

Shear in Z axis  \( F_z^q := \text{data}_{q5} \text{lbf} \)

Element Identification  \( \text{ID}_2^q := \text{data}_{q1} \)

Load Case Number  \( \text{LC}_2^q := \text{data}_{q2} \)

Applied Bending Moment at Bolts  \( M_2^q := 0 \text{ in-lbf} \)

Format of Output File

The stack command below is used to stack the element identifications (ID2) and load cases (LC2) in ascending order per bolt. See the array example above for explanation. Note: bolt number 1 is not included.

\[
\text{ID} := \text{stack(ID2 + 1, ID2 + 2, ID2 + 3, ID2 + 4, ID2 + 5, ID2 + 6, ID2 + 7)}
\]

\[
\text{LC} := \text{stack(LC2, LC2, LC2, LC2, LC2, LC2, LC2)}
\]
** Loads Transformation **

\[
\begin{align*}
F_{\text{local}}_q ^T & := \begin{bmatrix} F_{x2q} \\ F_{y2q} \\ F_{z2q} \end{bmatrix} \cdot \text{Transform} \\
M_{\text{local}}_q ^T & := \begin{bmatrix} M_{x2q} \\ M_{y2q} \\ M_{z2q} \end{bmatrix} \cdot \text{Transform}
\end{align*}
\]

\[
\begin{align*}
F_{x2q} & := \left( F_{\text{local}}_q ^T \right)_1 \\
F_{y2q} & := \left( F_{\text{local}}_q ^T \right)_2 \\
F_{z2q} & := \left( F_{\text{local}}_q ^T \right)_3 \\
M_{x2q} & := \left( M_{\text{local}}_q ^T \right)_1 \\
M_{y2q} & := \left( M_{\text{local}}_q ^T \right)_2 \\
M_{z2q} & := \left( M_{\text{local}}_q ^T \right)_3
\end{align*}
\]

** Moment Distribution **

\[
M_{\text{tot}}_q ^T := \begin{bmatrix} M_{x2q} \\ M_{y2q} \\ M_{z2q} \end{bmatrix} + \eta_{\text{load}} \times \begin{bmatrix} F_{x2q} \\ F_{y2q} \\ F_{z2q} \end{bmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
\begin{align*}
M_{\text{bolt}}_q & := M_{\text{tot}}_1, q \\
M_{\text{bolt}}_2 & := M_{\text{tot}}_2, q \\
M_{\text{bolt}}_3 & := M_{\text{tot}}_3, q
\end{align*}
\]

** Tension on bolts **

Direct tensile load calculation:

\[
F_{\text{direct}}_s,q := \frac{F_{x2q}}{\text{num_bolts2}}
\]

\[
\begin{align*}
F_{mz2}_s,q & := 0 \text{-lbf if } (y^2_s - y_{cg}^2) = 0 \text{-in} \\
& = \left[ M_{\text{bolt}}_q \left( y^2_s - y_{cg}^2 \right) \right] A_{t2_s} \\
& \quad \sum_s \left[ (y^2_s - y_{cg}^2)^2 \cdot A_{t2_s} \right] \\
F_{my2}_s,q & := 0 \text{-lbf if } (z^2_s - z_{cg}^2) = 0 \text{-in} \\
& = \left[ M_{\text{bolt}}_q \left( z^2_s - z_{cg}^2 \right) \right] \cdot A_{t2_s} \\
& \quad \sum_s \left[ (z^2_s - z_{cg}^2)^2 \cdot A_{t2_s} \right]
\end{align*}
\]
Analysis of Bolts Attaching ROEU Arm Flange to Sill Joint

Total Tensile load

\[
F_t^{s, q} := F_{\text{direct}}^{s, q} + F_{\text{mz}}^{s, q} + F_{\text{my}}^{s, q}
\]

Shear on bolts

Secondary shear on bolts

\[
F_s^{s, q} := \sum_s \left[ \frac{M_{\text{bolt} \text{c}}^{s, q}}{r_s} \cdot A_{s}^{2} \right]
\]

Direct shear on bolts

\[
F_{sd}^{s, q} := \frac{\sqrt{(F_z^{s, q})^2 + (F_y^{s, q})^2}}{\text{num}_b\text{olts}^2}
\]

Total shear load

\[
F_{\text{stot}}^{s, q} := F_{sd}^{s, q} + F_{s}^{s, q}
\]

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are placed in an array with the element/bolt number and load case number from above. See the "Output2" file below. Notice how there are only 7 bolts, since bolt number 1 is excluded.

\[
P_2 := \text{stack}(F_{t}^{T}{}^{(1)}, F_{t}^{T}{}^{(2)}, F_{t}^{T}{}^{(3)}, F_{t}^{T}{}^{(4)}, F_{t}^{T}{}^{(5)}, F_{t}^{T}{}^{(6)}, F_{t}^{T}{}^{(7)})
\]

\[
V_2 := \text{stack}(F_{\text{stot}}^{T}{}^{(1)}, F_{\text{stot}}^{T}{}^{(2)}, F_{\text{stot}}^{T}{}^{(3)}, F_{\text{stot}}^{T}{}^{(4)}, F_{\text{stot}}^{T}{}^{(5)}, F_{\text{stot}}^{T}{}^{(6)}, F_{\text{stot}}^{T}{}^{(7)})
\]

\[
M_2 := \text{stack}(M_2, M_2, M_2, M_2, M_2, M_2, M_2)
\]

The "Output2" file below outputs an array from left to right starting with the element identification (ID2), load case number (LC2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2). See the output array example above. The array is written to a text file.

\[
\text{WRITEPRN}(\text{"output_forces_ROEU_failsafe.txt"}) := \text{Output2}
\]

Size of the "Output2" Array: \( \text{rows(Output2)} = 896 \quad \text{cols(Output2)} = 5 \)

(7 bolts x 128 load cases) x 1 joint = 896 load cases
Bolt Fail-safe Results

The array from the text file above is read:

```math
\text{data}_fs := \text{READPRN}(\text{"output_forces_ROEU_failsafe.txt"})
\text{s} := 1..\text{rows(data}_fs\text{)}\quad \text{rows(data}_fs\text{)} = 896\quad \text{cols(data}_fs\text{)} = 5
```

**Fail-safe Loads**

Node ID  
\text{ID}_FS := \text{data}_fs\text{, 1}

Load Case  
\text{LC}_FS := \text{data}_fs\text{, 2}

Applied tensile load  
\text{P}_FS := \text{data}_fs\text{, 3 lbf}

Applied shear load  
\text{V}_FS := \text{data}_fs\text{, 4 lbf}

Applied bending moment  
\text{M}_FS := \text{data}_fs\text{, 5 in-lbf}

**Factors of Safety**

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>SFu_FS := 1.0</th>
<th>Yield</th>
<th>SFy := 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Separation</td>
<td>SFsep_FS := 1.0</td>
<td>Fitting factor</td>
<td>FF := 1.15</td>
</tr>
</tbody>
</table>

**Temperature data**

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Temp_initial := 70\text{-deg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>Temp_max := 120\text{-deg}</td>
</tr>
<tr>
<td>Minimum</td>
<td>Temp_min := 40\text{-deg}</td>
</tr>
</tbody>
</table>

This file uses the calculations shown in `\escfil02\2111_mathcad\8307_bolts\multi_bolt_stiffness_nut_FS_RevC`

**Bolt Fail-safe Load data**

Joint separation load  
\text{max(Psep}_FS\text{)} = 690.819\text{-lbf}

Max. load on the bolt(ultimate)  
\text{max(Pb}_FS\text{)} = 3461.5\text{-lbf}

\text{rows(Output)} = 896

5.11.6.1-19 ESCG-4005-05-AMS-0039
Summary of fail-safe Margins for bolt:

Joint separation  \( MS_{\text{min}FS,1,1} = 1.030 \)  Total Thread shear Ultimate  \( MS_{\text{min}FS,5,1} = 0.918 \)

Direct Tension Ultimate  \( MS_{\text{min}FS,2,1} = 4.650 \)  Shear Ultimate  \( MS_{\text{min}FS,6,1} = 40.78 \)

Total Tension Ultimate  \( MS_{\text{min}FS,3,1} = 0.2967 \)  Bending Ultimate  \( MS_{\text{min}FS,7,1} = 10 \)

Direct Thread shear Ultimate  \( MS_{\text{min}FS,4,1} = 7.36 \)  Combined shear, tension and bending ultimate  \( MS_{\text{min}FS,8,1} = 0.2967 \)

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt FS}} := \min(\text{MS}_{\text{FS}}) \]

\[ MS_{\text{bolt FS}} = 0.297 \]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"

\[ MS_{\text{min ID}} = 9900005 \]  Element Identification (9900005) and Bolt Number (5) for Minimum Margin

\[ MS_{\text{min LC}} = 1017 \]  Load Case Number for Minimum Margin

\[ MS_{\text{min P}} = 690.8 \]  Applied Tensile Load for Minimum Margin

\[ MS_{\text{min V}} = 23.7 \]  Applied Shear Load for Minimum Margin

\[ MS_{\text{min M}} = 0 \]  Applied Bending Moment for Minimum Margin
5.11.6.2 ROEU Bearing Failure Analysis
Section 5.11.6.2 ROEU/USS Interface

Foldable ROEU Clevis

Part No.: SEG39137677

Stress Check at Bolt Hole for ROEU Clevis Assembly

The total shear load applied to the bolts is used to determine the bering stress and shear tear-out of the clevis flange. The drawing number for the ROEU Clevis Assembly is SEG39137676. See page 5.11.6.1-2 for diagram of ROEU Assembly. The internal forces, \( P, V, \) and \( M \) were determined in section 5.11.6.

Clevis Flange Geometry:

- **Hole Diameter**
  \[ d := 0.250 \text{ in} \]
- **Plate Thickness**
  \[ t_p := 0.375 \text{ in} \]
- **Bearing Area**
  \[ A_b := d \cdot t_p \]
- **Edge Distance**
  \[ e := 0.360 \text{ in} \]

\[ \frac{e}{d} = 1.440 \]

\[ A_b = 0.094 \text{ in}^2 \]

Material Property Data for SDG39137676-001, 7050-T7451, AMS 4050, Plate, 4-5in, A (Ref.: Table 3.7.4.0(b1) MMPDS-03)

- **Bearing Allowables**
  - **Ultimate, \( e/d = 1.5 \)**
    \[ F_{bru_1} := 107000 \text{ psi} \]
  - **Ultimate, \( e/d = 2.0 \)**
    \[ F_{bru_2} := 138000 \text{ psi} \]
  - **Yield, \( e/d = 1.5 \)**
    \[ F_{bry_1} := 90000 \text{ psi} \]
  - **Yield, \( e/d = 2.0 \)**
    \[ F_{bry_2} := 105000 \text{ psi} \]

- **Shear Allowable**
  \[ F_{su} := 43000 \text{ psi} \]
Select Bearing Allowables Based on e/d Ratio:

\[
F_{brult} := \begin{cases} 
\frac{F_{bru1}}{1.5 - .5 \left( \frac{e}{d} - .5 \right)} & \text{if } \frac{.5}{d} \leq \frac{e}{d} < 1.499 \\
F_{bru1} & \text{if } 1.499 < \frac{e}{d} < 2.0 \\
F_{bru2} & \text{if } \frac{e}{d} \geq 2.0 \\
0 \text{ psi} & \text{otherwise}
\end{cases}
\]

\[
F_{brult} = 100580 \text{ psi}
\]

\[
F_{bryld} := \begin{cases} 
\frac{F_{bry1}}{1.5 - .5 \left( \frac{e}{d} - .5 \right)} & \text{if } \frac{.5}{d} \leq \frac{e}{d} < 1.499 \\
F_{bry1} & \text{if } 1.499 < \frac{e}{d} < 2.0 \\
F_{bry2} & \text{if } \frac{e}{d} \geq 2.0 \\
0 \text{ psi} & \text{otherwise}
\end{cases}
\]

\[
F_{bryld} = 84600 \text{ psi}
\]

Factors of Safety

- Ultimate: \( SF_u := 2.0 \)
- Yield: \( SF_y := 1.25 \)

Fitting Factor: \( FF := 1.15 \)

Temperature Data

- Assembly: Temp_initial := 70 deg
- Maximum: Temp_max := 120 deg
- Minimum: Temp_min := 40 deg

Temperature Correction Factor for Flange Ultimate Bearing Strength

Ref. MMPDS-03, For 7050 Temperature Correction Factors for Bearing are N/A, so Using Temperature Correction Factors for Ftu and Fty.

\( TS_u := 0.95 \)
\( TS_y := 0.98 \)
Reading Output Forces Obtained at Centroid of Bolt Pattern

data := READPRN("output_forces_ROEU_us.txt")

Maximum Axial Load in Data:

Axial := data\(^2\) lbf
P\(_\text{max}\) := max(Axial) P\(_\text{min}\) := min(Axial)

min(Axial) = \(-528.327\) lbf
data\(_{0,0}\) = 9.900 \times 10^6
P\(_\text{max}\) = 544.372 lbf
P\(_\text{min}\) = \(-528.327\) lbf

Maximum Shear Load in Data:

Shear := data\(^3\) lbf
V\(_\text{max}\) := max(Shear) V\(_\text{min}\) := min(Shear)

V\(_\text{max}\) = 97.790 lbf
V\(_\text{min}\) = 8.296 lbf

Maximum Load Per Bolt:

P\(_z\) := V\(_\text{max}\)
P\(_z\) = 97.790 lbf

Maximum Bearing Stress:

\(\beta_b\) := \(\frac{P_z}{\text{FF}}\) \(\frac{\text{FF}}{\text{Ab}}\)
\(\beta_b\) = 1199.554 psi

\(F_{\text{bru}}\) := Fbrult\cdot TSu
\(F_{\text{bru}}\) = 9.555 \times 10^4 psi

Margin of Safety:

\(\text{MS}_{\text{br}}\) := \(\frac{F_{\text{bru}}}{\beta_b \cdot \text{SFu}} - 1\)

\(\text{MS}_{\text{br}}\) = 38.828 ... Bearing MS
**Shear Tear Out**

*Shear Out Area:*

\[ A_s := 2 \left( e - \frac{d}{2} \right) \cdot t_p \]

\[ A_s = 0.176 \text{in}^2 \]

*Allowable Shear Strength:*

\[ F_{su} = 4.300 \times 10^4 \text{psi} \]

*Maximum Shear Tear Out Stress:*

\[ \tau_s := \frac{P_F}{A_s} \]

\[ \tau_s = 638.061 \text{psi} \]

*Margin of Safety:*

\[ M_{s_{\text{shear}}} := \frac{F_{su}}{\tau_s \cdot F_u} - 1 \]

\[ M_{s_{\text{shear}}} = 32.696 \]

... *Shear Tear Out MS*
5.11.6.3  ROEU PDA Bracket, Pin, and Lug Analysis
Section 5.11.6.3 ROEU PDA Bracket, Pin, and Lug Analysis
Part no.: SEG39137678 & SEG39137676

INTRODUCTION:
The ROEU clevis is attached to the PDA bracket lug with two removable pins and a cap screw. The two pins, one on each side of the cap screw prevent rotation of the PDA bracket lug in the x-z plane. The pins and the cap screw are in double shear. Analysis of the cap screw assumes the pins are in place with maximum loads applied in the x, y and z directions. The removable pins are of the same size and type, but different in design and tolerance limits from the center cap screw. Reference: Astronautic Structures Manual, NASA - TM - X - 73305, Vol. 1, section B 2. See drawing no. SDG39137676, SEG39137677, and SDG39137678.

LOADS: (Ref. section 5.11.6.1-5 ROEU Assembly Bolt Analysis)
The load cases are comprised of launch and abort landing load cases. Loads were obtained from a modified 2-06 loads model. The data recovered are the MPC forces for node 9900, which represents the end of the CBUSH connected to the beam. These loads are recovered at the center of gravity of the bolt pattern in the clevis flange. Post processing was performed in NASPOST for forces and moments in the x, y, and z directions.

ANALYSIS METHOD:
The loads obtained from the loads model are applied using classical hand calculation methods. Forces in the x and z directions and moments about the x, y, and z axes distribute direct shearing forces to the fasteners. The difference in sizes of the fasteners is based on the dimensional tolerances given in the specifications. The loads are distributed proportionately to the fasteners based on these differences such that the minimum margins of safety are produced. Moments Mx, My and Mz are expressed as couple forces and are added to the shearing forces Fz andFx. These forces represent the axial and transverse loads for tear-out and lug analysis.

FACTORS OF SAFETY:
The factors of safety utilized are 2.0 for ultimate and 1.25 for yield. The temperature exposure range is 40 degrees F. to 120 degrees F.
Figure 1: ROEU Clevis Assembly and PDA Mounting Bracket

Figure 2: Clevis and Bracket Attachment
Geometry (See figures above): The PDA mounting bracket represents the lug. Lug dimensions are:

(Reference: SEG39137678)

- Lug thickness: \( t_2 = 0.985\text{-in} \)
- Lug edge distance: \( e_{\text{lug}} = 0.751\text{-in} \)
- Width of lug: \( W_{\text{lug}} = 5.50\text{-in} \)
- Lug hole Diameter: \( D_{\text{lug}} = .525\text{-in} \)
Analysis of Clevis Assembly And PDA Mounting Bracket

Clevis thickness: \( t_1 := 0.500\text{-in} \)

**Center Cap Screw: NAS1351N8-44**

- Bolt ultimate tensile allowable stress: \( F_{tu\_bolt} := 160000\text{-psi} \) (Ref. NAS1351N)
- Bolt ultimate shear allowable stress: \( F_{su\_bolt} := 0.6 \times F_{tu\_bolt} \)
- Bolt yield Tensile allowable stress: \( F_{ty\_bolt} := 120000\text{-psi} \)
- Cap screw maximum shank diameter: \( d_{max} := 0.500\text{-in} \)
- Cap screw minimum shank diameter: \( d_{min} := 0.4919\text{-in} \)

**Double Acting Space Pin: 56789R8-15DL10C6**

- Space pin maximum diameter: \( p_{in\_max} := 0.4985\text{-in} \) Minimum double shear value: 28622 lbf
- Space pin minimum diameter: \( p_{in\_min} := 0.4970\text{-in} \)

**Material Properties of ROEU Clevis, SDG39137676, and PDA Bracket, SDG39137678 7050-T7451, AMS 4050, Plate, 4.0-5.0 inch, A.** (Ref: MMPDS-03, Table 3.7.4.0(b1))

- Tensile allowable, Ultimate, ST: \( F_{tu} := 67000\text{-psi} \)
- Yield, ST: \( F_{ty} := 57000\text{-psi} \)
- Shear allowable: \( F_{su} := 43000\text{-psi} \)

**Bearing allowables**

- Ultimate, \( e/d = 1.5 \): \( F_{bru1} := 107000\text{-psi} \) \( F_{bry1} := 90000\text{-psi} \)
- Ultimate, \( e/d = 2.0 \): \( F_{bru2} := 138000\text{-psi} \) \( F_{bry2} := 105000\text{-psi} \)

**Factors of Safety**

- Ultimate: \( SF_{u} := 2.0 \) \( SF_{y} := 1.25 \)
- Assembly Temperature data (Ref: AMS-02 Launch and Abort Landing Temperatures)
  - Initial: \( Temp_{\text{initial}} := 70\text{-deg} \)
  - Maximum: \( Temp_{\text{max}} := 120\text{-deg} \)
  - Minimum: \( Temp_{\text{min}} := 40\text{-deg} \)
- Fitting factor: \( FF := 1.15 \)

**Ultimate and Yield Thermal Degradation Factors:**

- \( T_{sub} := 0.95 \) \( T_{sb} := 0.98 \) (Ref. MMPDS-03, Fig. 3.7.4.2.1(a)&(b). Bearing Temperature Degradation Factors Not Available So Using Factors for \( F_{tu} \) & \( F_{ty} \)).
F_{bru} = 101650\text{-}psi \quad F_{bry} = 88200\text{-}psi

Tsu := 0.95 \quad Tsy := 0.98 \quad (\text{Ref. MMPDS-03, Figs. 3.7.4.2.1(a)&(b)})

F_{tu} := Tsu \cdot F_{tu} \quad F_{ty} := Tsy \cdot F_{ty} \quad F_{su} := Tsu \cdot F_{su}

F_{tu} = 63650\text{-}psi \quad F_{ty} = 55860\text{-}psi \quad F_{su} = 40850.000\text{-}psi

**Reading NASPOST file for loads**

data := READPRN("ROEU_uss_interface_naspost3.txt")

j := 1 .. rows(data)

* Note: the "ROEU_uss_interface_naspost3.txt" data file was generated from the NASPOST result (.LIS file) by removing all words and comments. This file is archived along with the other analysis files.

**Loads from 2-06 loads model, launch, on-orbit, and abort landing case**

The center of gravity of the load is the center of gravity of the bolt pattern (cgbolt) for the 8 bolt configuration in the clevis flange and was calculated on page 5.11.6.1-4. The load vector, rload, is the position vector measured from the center of gravity of the bolt pattern to the point of application of the forces and moments which determine the shear and bearing loads.

<table>
<thead>
<tr>
<th>Element Identification</th>
<th>ID _j := data_j,1</th>
<th>Shear in Y axis</th>
<th>Fy _j := data_j,4 lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Case Number</td>
<td>LC _j := data_j,2</td>
<td>Shear in Z axis</td>
<td>Fz _j := data_j,5 lbf</td>
</tr>
<tr>
<td>Axial Load</td>
<td>Fx _j := data_j,3 lbf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torsion</td>
<td>Mx _j := data_j,6 \text{in-lbf}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moment about Y axis</td>
<td>My _j := data_j,7 \text{in-lbf}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moment about Z axis</td>
<td>Mz _j := data_j,8 \text{in-lbf}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Rotation of Coordinate System of Loads**

For Alignment With Coordinate System at Fastener Centerline

The loads are recovered in the global coordinate system at the cg of the bolt pattern (see section 5.11.6.1-4). The forces and moments are transformed to the local coordinate system at the centerline of the fasteners by a 180 degree ccw rotation about the global Z axis.

5.11.6.3-6
Lug Analysis of PDA Mounting Bracket

\[ \beta := 180\text{ deg} \]

\[
F_{\text{transform}} := \begin{pmatrix}
\cos(\beta) & -\sin(\beta) & 0 \\
\sin(\beta) & \cos(\beta) & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[ F_{\text{transform}} = \begin{pmatrix}
-1.000 & 0.000 & 0.000 \\
0.000 & -1.000 & 0.000 \\
0.000 & 0.000 & 1.000
\end{pmatrix}
\]

\[
F_{\text{local}} := (\text{augment}(F_x, F_y, F_z)) \cdot F_{\text{transform}}
\]

\[
F_x := F_{\text{local}}(1) \quad F_y := F_{\text{local}}(2) \quad F_z := F_{\text{local}}(3)
\]

\[
M_{\text{local}} := (\text{augment}(M_x, M_y, M_z)) \cdot F_{\text{transform}}
\]

\[
M_x := M_{\text{local}}(1) \quad M_y := M_{\text{local}}(2) \quad M_z := M_{\text{local}}(3)
\]

Fig. 6 Location of the Centroid of the Fastener Group
Relationship of Centroid of Cross Sections to Centroid of Bolt Pattern (clevis flange not shown for clarity and dimensions shown are at clevis flange)

Fig. 7 cg of bolt pattern located 0.117 in. right and 1.345 in. above the lower left corner of the clevis.

**Moment Distribution**

Vector from Centerline of fasteners to centroid of bolt pattern at clevis flange:

Centroid of lug in local coordinate system:

$$ c_{lug} := \begin{pmatrix} -9.069 \\ -0.8905 \\ -0.155 \end{pmatrix} \text{ in} $$

Centroid of bolt pattern:

$$ r_{cs} := \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ in} $$

$$ r_{load} := c_{lug} - r_{cs} $$

$$ r_{load} = \begin{pmatrix} -9.069 \\ -0.8905 \\ -0.155 \end{pmatrix} \text{ in} $$
Use the cross-product to determine the additional moments acting on the cap screw and pins.

$$M_{\text{tot}}^j := \begin{pmatrix} M_{x_j} \\ M_{y_j} \\ M_{z_j} \end{pmatrix} + \text{load} \times \begin{pmatrix} F_{x_j} \\ F_{y_j} \\ F_{z_j} \end{pmatrix}$$

$$M_{\text{bolt}_1} := M_{\text{tot1},j} \quad M_{\text{bolt}_2} := M_{\text{tot2},j} \quad M_{\text{bolt}_3} := M_{\text{tot3},j}$$
Lug Analysis of PDA Mounting Bracket

\[
\begin{align*}
M_x_{\text{max}} &= \max \left(\left| M_x_{\text{bolt}} \right| \right) \\
M_y_{\text{max}} &= \max \left(\left| M_y_{\text{bolt}} \right| \right) \\
M_z_{\text{max}} &= \max \left(\left| M_z_{\text{bolt}} \right| \right) \\
M_x_{\text{max}} &= 396.893 \text{ in-lbf} \\
M_y_{\text{max}} &= 3174 \text{ in-lbf} \\
M_z_{\text{max}} &= 1042.452 \text{ in-lbf} \\
F_x_{\text{max}} &= \max \left(\left| F_x \right| \right) \\
F_y_{\text{max}} &= \max \left(\left| F_y \right| \right) \\
F_z_{\text{max}} &= \max \left(\left| F_z \right| \right) \\
F_x_{\text{max}} &= 332.048 \text{ lbf} \\
F_y_{\text{max}} &= 164.014 \text{ lbf} \\
F_z_{\text{max}} &= 551.520 \text{ lbf}
\end{align*}
\]

**Shape Ratios:**

\[
\begin{align*}
\frac{e_{\text{lug}}}{D_{\text{lug}}} &= 1.430 \\
H &= 2.015 \text{ in} \\
d_1 &= 1.515 \text{ in} \\
d_2 &= 2.00 \text{ in}
\end{align*}
\]

Shear in the pins and the screw is produced by \( F_x, F_z, M_x, M_y, \) and \( M_z \) and the maximum loads are used conservatively.

\[
\begin{align*}
P_{x1} &= \frac{M_z_{\text{max}}}{d_1} \\
P_x &= \left( \frac{F_{x_{\text{max}}}}{2} \right) + P_{x1} \\
P_x &= 854.111 \text{ lbf} \\
P_{z1} &= \frac{M_x_{\text{max}}}{d_1} \\
P_{z2} &= \frac{M_y_{\text{max}}}{2d_2} \\
P_z &= P_{z1} + P_{z2} + \left( \frac{F_{z_{\text{max}}}}{2} \right) \\
P_z &= 1331.328 \text{ lbf}
\end{align*}
\]

Distribution of the shearing force based on single shear strength of screw and pin:

\[
\begin{align*}
\text{Psu}_{\text{pin}} &= \frac{28622}{2} \text{ lbf} \\
\text{Psu}_{\text{pin}} &= 14311 \text{ lbf} \\
\text{Psu}_{\text{screw}} &= 25600 \text{ lbf} \\
\text{sum}_{\text{Psu}} &= 2 \cdot \text{Psu}_{\text{pin}} + \text{Psu}_{\text{screw}} \quad \text{Sum of the allowables for 2 pins and 1 screw}
\end{align*}
\]

\[
\begin{align*}
px_{\text{pin}} &= \frac{P_x \cdot \text{Psu}_{\text{pin}}}{\text{sum}_{\text{Psu}}} \\
px_{\text{screw}} &= \frac{P_x \cdot \text{Psu}_{\text{screw}}}{\text{sum}_{\text{Psu}}} \\
px_{\text{pin}} &= 225.428 \text{ lbf} \\
px_{\text{screw}} &= 403.254 \text{ lbf}
\end{align*}
\]

\[
\begin{align*}
pz_{\text{pin}} &= \frac{P_z \cdot \text{Psu}_{\text{pin}}}{\text{sum}_{\text{Psu}}} \\
pz_{\text{screw}} &= \frac{P_z \cdot \text{Psu}_{\text{screw}}}{\text{sum}_{\text{Psu}}}
\end{align*}
\]

5.11.6.3-10
\( p_z\_pin = 351.382\text{ lbf} \quad p_z\_screw = 628.564\text{ lbf} \)

**Shear Tearout Analysis of Clevis**

Clevis dimensions:

\[
t_1 := 0.500\text{ in}
\]

Clevis edge distance: \( e := 0.751\text{ in} \)

Maximum lug hole diameter: \( D_{\text{lug}} = 0.525\text{ in} \)

Shear Tear-out area:

\[
A_{s1} := 2\left(e - \frac{D_{\text{lug}}}{2}\cos(u)\right)t_1
\]

Allowable shear stress of clevis (7050-T7451):

\[
F_{su} = 40850.000\text{ psi} \quad \text{(Ref: page 5.11.6.3-6)}
\]

\[
P_{u1} := F_{su}A_{s1} \quad P_{u1} = 22464\text{ lbf}
\]

\[
MS_{1\text{tearout}} := \frac{P_{u1}}{SF_u FF P_x} - 1
\]

\( MS_{1\text{tearout}} = 10.435 \)

**Shear Tearout Analysis of Center Lug**

Allowable shear stress of center lug (7075-T7351)

\[
F_{su} = 40850.000\text{ psi}
\]

\[
A_{s2} := 2\left(e - \frac{D_{\text{lug}}}{2}\cos(u)\right)t_2
\]

\[
P_{u2} := F_{su}A_{s2} \quad P_{u2} = 44254\text{ lbf}
\]

\[
Ps_2 := \frac{(F_{x_{max}} + P_{x_1})P_{su\_pin}}{\sum_{P_{su}}}
\]

\[
MS_{2\text{tearout}} := \frac{P_{u2}}{SF_u FF Ps_2} - 1
\]

\( MS_{2\text{tearout}} = 70.462 \)

(Ref: Bruhn, fig. D1.9, page D1.5)
PDA Mounting Bracket Assembly Lug Analysis

$$\frac{e_{\text{lug}}}{D_{\text{lug}}} = 1.430 \quad \frac{D_{\text{lug}}}{t_2} = 0.533$$  Parameters for determining $K_{\text{br}}$

$$K_{\text{br}} := 1.4 \quad \text{(Ref: Astronautics Structures Manual, Vol. 1, p. 221, Fig. B 2.1.0-3, extrapolated value)}$$

$$P_{\text{bru}} := K_{\text{br}} \cdot F_{\text{tu}} \cdot A_{\text{br}} \quad P_{\text{bru}} = 48506\text{-lbf}$$  (Ultimate Bearing Load)

Width of Equivalent lug:  $W_{\text{eq}} := 1.5\text{-in}$  
(Ref: The equivalent lug width is based on "W" in Astronautics Structures Manual, Vol. 1, p. 221 Fig. B 2.1.0-4)

$$\frac{W_{\text{eq}}}{D_{\text{lug}}} = 2.857$$  Parameter for determining $K_{\text{t}}$

$$K_{\text{t}} := 0.81 \quad \text{(Ref: Astronautics Structures Manual, Vol. 1, p. 223, Fig. B 2.1.0-4, Curve 4)}$$

$$A_{\text{t}} := (W_{\text{eq}} - D_{\text{lug}}) t_2 \quad P_{\text{tu}} := K_{\text{t}} \cdot F_{\text{tu}} \cdot A_{\text{t}} \quad P_{\text{tu}} = 52120\text{-lbf}$$  (Ultimate Tensile load)

$$\frac{e_{\text{lug}}}{D_{\text{lug}}} = 1.430$$  Parameter for determining $K_{\text{bry}}$

$$K_{\text{bry}} := 1.4 \quad \text{(Ref: Astronautics Structures Manual, p. 226, Vol. 1, Fig. B 2.1.0-5)}$$

$$P_{\text{bry}} := K_{\text{bry}} \cdot A_{\text{br}} \cdot F_{\text{ty}} \quad P_{\text{bry}} = 40441\text{-lbf}$$  (Yield Bearing Load)

**Compute Ultimate and Yield Load Ratios (actual/allowable)**

Use the smaller of $P_{\text{tu}}$ and $P_{\text{bru}}$ for ultimate:

$$P_{\text{axial}} := \left(\frac{F_{x_{\text{max}}} + P_{x_1}}{\text{sum}_{\text{Psu}}}\right) \cdot \text{Psu}_{\text{screw}} \quad P_{\text{axial}} = 481.639\text{-lbf}$$

$$R_{\text{bru}} := \begin{cases} \frac{SF_u\cdot P_{\text{axial}}}{P_{\text{tu}}} & \text{if } P_{\text{tu}} < P_{\text{bru}} \\ \frac{SF_u\cdot P_{\text{axial}}}{P_{\text{tu}}} & \text{otherwise} \end{cases}$$

$$R_{\text{bru}} = 0.018$$
Calculate the weighted average:

\[ A_{av} = \frac{6}{\frac{1}{A_1} + \frac{1}{A_2} + \frac{1}{A_3} + \frac{1}{A_4}} \]

\[ A_{av} = 1.002 \text{ in}^2 \]

Bearing area is: \[ A_{br} = 0.517 \text{ in}^2 \] Ref: Page 5.11.6.3-10

Shape Parameter: \[ \frac{A_{av}}{A_{br}} = 1.938 \]

Ultimate and yield transverse bearing load parameters are:

\[ K_{tbru} := 0.35 \quad K_{tbry} := 1.3 \quad (Reference: NASA Astronautics Structures Manual, Vol. 1, Section B 2, p.21, Fig. B 2.2.0-4 Curve 10.) \]

\[ P_{tbru} := K_{tbru} F_{tu} A_{br} \quad P_{tbru} = 11520 \text{ lbf} \quad \text{(Ultimate transverse bearing load)} \]

\[ P_{tbry} := K_{tbry} F_{ty} A_{br} \quad P_{tbry} = 37553 \text{ lbf} \quad \text{(Yield transverse bearing load)} \]
Compute Ultimate and Yield Load Ratios

\[
P_{\text{transverse}} = \frac{(F_{z_{\text{max}}} + P_{z1} + P_{z2}) \cdot P_{\text{screw}}}{\text{sum}_{\text{Psu}}} \quad P_{\text{transverse}} = 758.76\text{-lbf}
\]

Ultimate:

\[
R_{tbru} = \frac{SF_u \cdot P_{\text{transverse}}}{P_{\text{bru}}} \quad R_{tbru} = 0.132
\]

\[
R_{tbry} = \frac{SF_y \cdot P_{\text{transverse}}}{P_{\text{bry}}} \quad R_{tbry} = 0.025
\]

Calculate Combined Margins of Safety: (Reference: Astronautics Structures Manual, Section B2.3.0)

\[
MS_{\text{ult}} := \frac{1}{\left( R_{bru}^{1.6} + R_{tbru}^{1.6} \right)^{.625}} - 1
\]

\[
MS_{\text{yld}} := \frac{1}{\left( R_{bry}^{1.6} + R_{tbry}^{1.6} \right)^{.625}} - 1
\]

\[
MS_{\text{ult}} = 6.394 \quad \text{...Margin of Safety on Combined Ultimate}
\]

\[
MS_{\text{yld}} = 30.673 \quad \text{...Margin of Safety on Combined Yield}
\]

**Shear and Bending Strength of Center Cap Screw, NAS1351N8-44**

The center cap screw is made of heat-resistant steel. The cap screw is in double shear. From the National Aerospace Standard, single shear strength of 0.500 inch diameter heat resistant steel bolt is 25600 lb.

\[
P_{\text{su}} := 25600\text{-lbf} \quad \text{Single shear allowable (Ref: NAS 1351)}
\]

The axial load is in the X-direction:

\[
px_{\text{screw}} = 403.254\text{-lbf}
\]

The transverse load is in the z direction:

\[
pz_{\text{screw}} = 629\text{-lbf}
\]

Maximum load:

\[
P_{\text{resultant}} := \sqrt{px_{\text{screw}}^2 + pz_{\text{screw}}^2} \quad P_{\text{resultant}} = 746.797\text{-lbf}
\]
**Maximum Cap Screw Bending Moment**

Gap:

Depth of lugs: \( d_{lug} := 2.015 \text{ in} \)

\[ g_p := \frac{d_{lug} - 2 \cdot t_1 - t_2}{2} \]

\( g_p = 0.015 \text{ in} \)

Moment arm (Ref: Astronautics Structures Manual, Vol. 1, Section B 2.1.0):

Reference values:

\[ e = 0.751 \text{ in} \]

\[ D_{lug} = 0.525 \text{ in} \]

\[ P_{tu} = 52119.551 \text{ lbf} \]

\[ P_{bru} = 48506.325 \text{ lbf} \]

\[ r := \left[ \left( \frac{e}{D_{lug}} \right) - \frac{1}{2} \right] \frac{D_{lug}}{t_2} \]

\( r = 0.496 \)

\[ P_{u_{min}} := \begin{cases} P_{tu} & \text{if } P_{tu} < P_{bru} \\ \frac{P_{bru}}{A_{bru} F_{tu}} & \text{otherwise} \end{cases} \]

\( P_{u_{min}} = 1.474 \)

\( \gamma := 0.72 \quad \text{Ref: Astronautics Structures Manual, Vol. 1, Fig. B 2.1.0-6:} \)

The bending moment arm, \( b \), on the center pin is obtained from Astronautic Structures Manual, Vol. 1, Section B 2.1.0, page 220:

\[ b := \left( \frac{t_1}{2} \right) + g_p + \frac{t_2}{4} \]

\( b = 0.442 \text{ in} \)

**Cap screw bending moment:**

\[ M_{screw} := 0.5 \cdot P_{\text{resultant}} \cdot b \]

\[ M_{screw} = 165.154 \text{ in-lbf} \]

**Section Properties**

Minimum cross section of the cap screw is a circle of diameter, \( d_{min} \):

\[ \text{Area} := \frac{d_{min}^2}{4} \]

\( \text{Area} = 0.190 \text{ in}^2 \)
Distance from centroid to outer fiber: 
\[ z_c = \frac{d_{\text{min}}}{2} \quad z_c = 0.246 \text{ in} \]

Moments of inertia about centroid: 
\[ I_y := \left( \frac{\pi}{64} \right) d_{\text{min}}^4 \quad I_y = 0.003 \text{ in}^4 \]

Stresses on cross section: 
Bending stress: 
\[ y_b := \frac{M_{\text{screw}} z_c}{I_y} \quad y_b = 14134 \text{ psi} \]

Find Modulus of Rupture of screw to check bending
Assume D/t = 2 for a solid pin:

**Material properties of Cap Screw:**

Temperature correction factor: 
\[ cpin = 0.98 \quad \text{(Ref. MMPDS)} \]

\[ F_{\text{tu}}_{\text{capscrew}} := 160000 \cdot cpin \cdot \text{psi} \quad F_{\text{tu}}_{\text{capscrew}} = 156800 \text{ psi} \]

\[ Frup := 260000 \cdot cpin \cdot \text{psi} \quad \text{(Ref: Bruhn, C4.16, figure C4.11)} \]

\[ Frup = 254800 \text{ psi} \]

**Margins of Safety:**

Bending Stress: 
\[ M_{\text{bnd}} := \frac{Frup}{F_{\text{tu}}_{\text{capscrew}} y_b} - 1 \quad M_{\text{bnd}} = 8.014 \]

Shear stress: 
\[ \tau := \frac{4P_{\text{resultant}}}{3 \cdot \text{Area}} \quad \text{(Ref: Bruhn, p. A14.4, table A14.2)} \]

\[ \tau = 5240 \text{ psi} \]

\[ F_{\text{su}}_{\text{capscrew}} := 0.6 \cdot F_{\text{tu}}_{\text{capscrew}} \]

\[ F_{\text{su}}_{\text{capscrew}} = 94080 \text{ psi} \]

**Margins of Safety:**

Margin of Safety: 
\[ M_{\text{shr}} := \frac{F_{\text{su}}_{\text{capscrew}}}{F_{\text{tu}}_{\text{capscrew}}} - 1 \]

\[ M_{\text{shr}} = 7.978 \]
Shear and Bending Strength of Double Acting Space Pin, 56789R8-15DL10C6

The center spacepin is made of steel. The pin is in double shear.

\[ P_{su} := 28622 \text{ lbf} \quad \text{Double shear allowable (Ref: Avibank Mfg., Inc. Drawing no. 56789)} \]

The axial load is in the X - direction: \( p_{x\_pin} = 225.428 \text{ lbf} \)

The transverse load is in the z direction: \( p_{z\_pin} = 351 \text{ lbf} \)

Maximum load: \( P_{\text{resultant}} := \sqrt{p_{x\_pin}^2 + p_{z\_pin}^2} \quad P_{\text{resultant}} = 417.477 \text{ lbf} \)

**Maximum Pin Bending Moment**

Gap:

Depth of lugs: \( d_{lug} := 2.015 \text{ in} \quad g_p := \frac{d_{lug} - 2 \cdot t_1 - t_2}{2} \quad g_p = 0.015 \text{ in} \)

Moment arm (Ref: Astronautics Structures Manual, Vol. 1, Section B 2.1.0):

Reference values: \( e = 0.751 \text{ in} \quad d_{pinhole} := 0.510 \text{ in} \quad P_{tu} = 52119.551 \text{ lbf} \quad P_{bru} = 48506.325 \text{ lbf} \)

\[ r_2 := \left[ \left( \frac{e}{d_{pinhole}} \right) - \frac{1}{2} \right] \cdot \frac{d_{pinhole}}{t_2} \quad r_2 = 0.504 \quad A_{br2} := d_{pinhole} \cdot t_2 \]

\[ P_{u\_min} := \begin{cases} \frac{P_{tu}}{A_{br2} \cdot F_{tu}} & \text{if } P_{tu} < P_{bru} \\ \frac{P_{bru} \cdot F_{tu}}{A_{br2}} & \text{otherwise} \end{cases} \]

\[ P_{u\_min} = 1.517 \quad 2 := 0.74 \]

The bending moment arm, \( b \), on the center pin is obtained from Astronautic Structures Manual, Vol. 1, Section B 2.1.0, page 220:
Pin bending moment: \[ M_{\text{pin}} = 0.5 \cdot P_{\text{resultant}} \cdot b_2 \quad M_{\text{pin}} = 93.353 \text{ in-lbf} \]

**Section Properties**

Minimum cross section of the pin is a circle of diameter, \( d_{2\text{min}} \):

\[
b_2 = \left( \frac{t_1}{2} \right) + g_p + 2 \cdot \frac{t_2}{4} \\
b_2 = 0.447 \text{ in}
\]

\[
b_{\text{pin}} := \frac{d_{2\text{min}}}{2} = 0.4970 \text{ in}
\]

\[
Area_2 := \frac{d_{2\text{min}}^2}{4} = 0.194 \text{ in}^2
\]

Distance from centroid to outer fiber:

\[
z_c := \frac{d_{2\text{min}}}{2} = 0.248 \text{ in}
\]

Moments of inertia about centroid:

\[
I_{2y} := \frac{z_c^4}{64} \cdot d_{2\text{min}}^4 = 0.003 \text{ in}^4
\]

Stresses on cross section:

\[
y_{2b} := \frac{M_{\text{screw}}}{I_{2y}} = 13703 \text{ psi}
\]

Bending stress:

Find Modulus of Rupture of pin to check bending

Assume \( D/t = 2 \) for a solid pin:

**Material properties of Pin:**

Temperature correction factor: \( \text{cpin} = 0.98 \) (Ref. MMPDS)

\[
P_{su} = 28622 \text{ lbf} \quad (\text{Double shear allowable, reference: Avibank Mfg., Inc. drawing no. 56789})
\]

\[
P_{sus} := \frac{P_{su}}{2} \quad (\text{Single shear allowable})
\]

\[
F_{\text{supin}} := \frac{P_{sus}}{Area_2} \quad F_{\text{supin}} = 73768 \text{ psi} \quad \text{Allowable Shear Stress}
\]

\[
F_{\text{tupin}} := \text{cpin} \cdot \frac{F_{\text{supin}}}{0.6}
\]

\[
F_{\text{tupin}} = 120488 \text{ psi} \quad \text{Allowable Tensile Stress}
\]

5.11.6.3-18
Frup2 := 190000-cpin·psi \hspace{1cm} \text{(Ref: Bruhn, C4.16, figure C4.11)} \hspace{1cm} \text{Frup2 = 186200-psi}

\textbf{Margins of Safety:}

\textbf{Bending Stress} \hspace{1cm} MS_{2\text{bnd}} := \frac{\text{Frup2}}{\text{SFu} \cdot y_{2b}} - 1 \hspace{1cm} \text{MS}_{2\text{bnd}} = 5.794

\textbf{Shear stress} \hspace{1cm} \text{pin} := \frac{4\text{P_resultant}^2}{3 \cdot \text{Area}^2} \hspace{1cm} \text{(Ref: Bruhn, p. A14.4, table A14.2)}

\hspace{1cm} \text{pin} = 2869-\text{psi}

\text{MS}_{2\text{shr}} := \frac{\text{F}_{\text{supin}}}{\text{pin}} - 1 \hspace{1cm} \text{MS}_{2\text{shr}} = 24.710

\textbf{Bushing Yield Strength}

Material Properties of ROEU Assembly Bushing, SDG39137680, AL Bronze, AMS 4640 (Ref: AMS Analysis Files, Appendix C8, "Material Properties for Aluminum Bronze.")

\hspace{1cm} \text{T}_{\text{cub}} := 0.98 \hspace{1cm} \text{T}_{\text{cyb}} := 1.00 \hspace{1cm} \text{(Ref: AMS Analysis Files, Appendix C8, "Material Properties for Aluminum Bronze," email communication between ESCG Structural Analysis Section and ESCG Material Analysis Section)}

\hspace{1cm} \text{F}_{\text{ty}} := \text{T}_{\text{cyb}} \cdot \text{F}_{\text{tyb}} \hspace{1cm} \text{F}_{\text{ty}} = 65000-\text{psi}

\hspace{1cm} \text{F}_{\text{brub}} := \text{T}_{\text{cub}} \cdot \text{F}_{\text{brub1}} \hspace{1cm} \text{F}_{\text{brub}} = 112700-\text{psi}

\hspace{1cm} \text{Failure by Bearing of Bushing on Lug}

\hspace{1cm} \text{D}_{p} := 1.248-\text{in} \hspace{1cm} \text{A}_{\text{brb}} := \text{D}_{p} \cdot 12

\hspace{1cm} \text{P}_{\text{bryb}} := 1.85 \cdot \text{F}_{\text{ty}} \cdot \text{A}_{\text{brb}} \hspace{1cm} \text{P}_{\text{bryb}} = 147821-\text{lbf}

\text{5.11.6.3-19}
MS_3 := \frac{p_{bryb}}{p_{\text{resultant}}} - 1 \quad MS_3 = 196.940

Failure by Bearing of Bolt on Bushing
Bolt diameter: \quad d_{\text{min}} = 0.492 \text{ in}

P_{ubsh} := F_{brub} d_{\text{min}} t_2

MS_4 := \frac{P_{ubsh}}{p_{\text{resultant}}} - 1 \quad MS_4 = 72.120
5.11.6.4 ROEU Assembly Harness Bracket and Bolt Analysis
**INTRODUCTION:**

The harness bracket supports the cables attached to the PDA mounting bracket assembly. It is attached to the PDA mounting bracket by four bolts. An analysis of these bolts follows.

**LOADS:**

The bracket serving as a support for the cable harness transmits a 125 lb kick load to the PDA mounting bracket through four bolts.

**ANALYSIS METHOD:**

The bearing stress between the bolt and the harness bracket and the shear stress in the bolts are determined.

**FACTORS OF SAFETY:**

The factors of safety utilized are 2.0 for ultimate and 1.25 for yield. The temperature exposure range is 40 degrees F. to 120 degrees F.
**Material Properties of Harness Bracket, SDG39135865-001, 7050-T7451 8.75 x 7.50 x3.00 BMS-7-323C**

(Ref: MMPDS-03) Table 3.7.4.0(b1)) 7050 AMS 4050, Plate T7451,2-3in, A)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Ultimate ST:</td>
<td>Ftu := 68000 psi</td>
</tr>
<tr>
<td>edge distance:</td>
<td>e-hole := 0.38-in</td>
</tr>
<tr>
<td>Tensile Yield ST:</td>
<td>Fty := 59000 psi</td>
</tr>
<tr>
<td>hole diameter:</td>
<td>d-hole := .213-in</td>
</tr>
<tr>
<td>Shear Ultimate:</td>
<td>Fsu := 43000 psi</td>
</tr>
<tr>
<td>Bearing allowables</td>
<td>ed := e-hole / d-hole</td>
</tr>
<tr>
<td>Ultimate, e/d:</td>
<td>ed1 := 1.5-in</td>
</tr>
<tr>
<td>Fbrut1 := 108000 psi</td>
<td>Yield e/d = 1.5</td>
</tr>
<tr>
<td>Ultimate, e/d:</td>
<td>ed2 := 2.0-in</td>
</tr>
<tr>
<td>Fbrut2 := 141000 psi</td>
<td>Yield e/d = 2.0</td>
</tr>
</tbody>
</table>

\[
Fbrut := Fbrut1 + \frac{(Fbrut2 - Fbrut1)(ed - ed1)}{ed2 - ed1} \quad Fbrut = 126746 psi
\]

\[
Fbry := Fbry1 + \frac{(Fbry2 - Fbry1)(ed - ed1)}{ed2 - ed1} \quad Fbry = 97521 psi
\]

**Factors of Safety AMS-02 Launch and Abort Landing Factors of Safety**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu := 2.0</td>
</tr>
<tr>
<td>Fitting factor</td>
<td>FF := 1.15</td>
</tr>
<tr>
<td>Yield</td>
<td>SFy := 1.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature data (Ref: AMS-02 Launch and Abort Landing Temperatures)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
</tbody>
</table>

**Ultimate and Yield Thermal Degradation Factors:** (Ref. MMPDS, figs. 3.7.4.2.1).

| TSu := 0.95             | TSy := 0.98 |
| Fbrut := TSu * Fbrut    | Fbryt := TSy * Fbryt |
| Fbrut := 120409 psi     | Fbryt := 95571 psi |

| MSbrng := \frac{Fbrut}{SFu} \beta_{brng} - 1 |
| MSbrng = 9.981 |

**Bearing stress between bolt and bracket:**

\[
\beta_{brng} := \frac{125-lbf}{.12-in(.190-in)} \quad \beta_{brng} = 5482 psi
\]

5.11.6.4-3 ESCG-4005-05-AMS-0039
F = 125 lbf kick load (direction indicated yields most conservative result)

Taking moments about A:
\[ M = (5.72 \text{-in}) \times (125 \text{ lbf}) = 715 \text{ in-lbf} \]
\[ H = 1.75 \text{-in} \] (fastener spacing)

\[ F_T := \frac{M}{H} \quad F_T = 409 \text{ lbf} \quad (\text{Tension load}) \]
\[ V := 125 \text{ lbf} \quad (\text{Shear load}) \]

Load is distributed among four fasteners. Assume the entire load is carried by one fastener. This also covers the failsafe analysis.

CHECK BOLTS (NAS1351N3, 0.190-32, 0.625L, Material A-286), Nut NAS1291C3M, Washer NAS1149E 0463R

Flange 1 := "Harness Bracket"
Part number: SDG39135865
Material: AL 7050-T7451, BMS-7-323C (AMS 4050), 8.75 x 7.50 x 3.00

Flange 2 := "PDA Mounting Bracket"
Part number: SDG39137678-001
Material: AL 7050-T7451 BMS-7-323C (AMS 4050), 25.587 x 7.83 x 4.56

**Loads**

- **Applied tensile load**
  \[ P := 409 \text{ lbf} \]

- **Applied shear load**
  \[ V := 125 \text{ lbf} \]

- **Applied bending moment**
  \[ M := 0 \text{ in-lbf} \]
Factors of Safety

Ultimate \( SF_u := 2.0 \)  
Joint Separation \( SF_{sep} := 1.2 \)

Temperature data

Yield \( SF_y := 1.25 \)  
Assembly \( Temp_{initial} := 70\text{-deg} \)  
Maximum \( Temp_{max} := 120\text{-deg} \)  
Minimum \( Temp_{min} := 40\text{-deg} \)

Bolt and Nut Data

Nominal diameter of bolt \( D := 0.190\text{-in} \)  
Number of threads/inch \( N_t := \frac{1}{32}\text{-in} \)  
Total length of bolt \( L := 0.625\text{-in} \)  
Height of nut \( H := 0.154\text{-in} \)  
Threaded length \( L_t := 0.625\text{-in} \)

(If bolt is fully threaded, input \( L_t = L \))

Washer Data

Thickness of washers \( t_w := 0.032\text{-in} \)  
Outer Diameter of washer \( D_w := 0.438\text{-in} \)  
Inner Diameter of washer \( D_{wi} := 0.203\text{-in} \)  
Bolt head dia. across flats \( d_w := 0.3120\text{-in} \)  
Note: If there is no washer \( t_w \), \( D_w \) and \( D_{wi} \) should be zero

Flange Data

Thickness of flange 1 \( t_{f1} := 0.12\text{-in} \)  
Thickness of flange 2 \( t_{f2} := 0.12\text{in} \)  
Diameter of hole \( D_{hole} := 0.213\text{-in} \)

Bolt Material Property Data

Temperature correction factor for bolt strength ultimate \( TS_{u,\text{bolt}} := 0.98 \)  
Yield \( TS_{y,\text{bolt}} := 0.98 \)  
Bolt ultimate tensile allowable stress \( F_{tu,\text{bolt}} := 160000\text{-psi} \)  
Bolt ultimate shear allowable stress \( F_{su,\text{bolt}} := 0.6\text{-}F_{tu,\text{bolt}} \)  
Bolt yield Tensile allowable stress \( F_{ty,\text{bolt}} := 120000\text{-psi} \)  
Temperature correction factor for bolt modulus \( T_{E,\text{bolt}} := 0.94 \)
Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \cdot 10^6 \text{psi}\right) \)

**Thermal coefficient for bolt**

\( u_{\text{bolt}} := 9.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

**Nut Material Property Data**

**Temperature correction factor for nut strength**

\( TS_{\text{nut}} := 0.98 \)

**Ultimate tensile allowable stress**

\( F_{tu\_\text{nut}} := 160000 \text{psi} \)

**Ultimate Shear allowable stress**

\( F_{su\_\text{nut}} := 0.6 F_{tu\_\text{nut}} \)

**Ultimate axial strength of nut**

\( P_{tu\_\text{nut}} := 2460 \text{lb} \)

(Ref. NAS1291 page 2)

**Washer Material Property Data**

**Temperature correction factor for washer modulus**

\( TE_{\text{washer}} := 0.99 \)

**Modulus of elasticity of washer:**

\( E_{\text{washer}} := \left(29.1 \cdot 10^6 \text{psi}\right) \)

**Flanges Material Property Data**

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

**Temperature correction factor for flange 1**

\( TF1E := 0.98 \) (modulus)

**Temperature correction factor for flange 2**

\( TF2E := 0.98 \)

**Modulus of elasticity for the parts in the joint**

\( E_{\text{flange1}} := \left(10.5 \cdot 10^6 \text{psi}\right) \)

\( E_{\text{flange2}} := \left(10.5 \cdot 10^6 \text{psi}\right) \)

**Coefficient of thermal expansion for flanges**

\( u_{\text{flange1\_hot}} := 12.56 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

\( u_{\text{flange2\_hot}} := 12.56 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

\( u_{\text{flange1\_cold}} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

\( u_{\text{flange2\_cold}} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

**Torque/Preload Data**

**Maximum torque**

\( T_{\text{max}} := 40.6 \text{in-lbf} \)

**Loading plane factor**

\( n := 0.5 \)

**Minimum torque**

\( T_{\text{min}} := 34.5 \text{in-lbf} \)

**Preload Uncertainty**

\( := 0.25 \)

**Torque coefficient**

\( k := 0.15 \)

This file uses the calculations shown in `\escfil02\2i11\mathcad\8307_bolts\bolt_stiffness_nut_RevC`
Bolt Load data

Bolt/joint stiffness factor \( = : 0.244 \)  
Preload due to temperature  
\( P_{thr\_pos} = 61.9 \text{ lbf} \)

Max. preload \( PLD_{\text{max}} = 1842.6 \text{ lbf} \)
Min. preload \( PLD_{\text{min}} = 784.5 \text{ lbf} \)  
Uncertainty factor \( = 0.25 \)

Joint separation load \( P_{\text{sep}} = 490.8 \text{ lbf} \)  
Torque coefficient \( k = 0.15 \)

Max. load on the bolt(ultimate) \( P_b = 1950.5 \text{ lbf} \)  
Loading plane factor \( n = 0.5 \)

Max. load on the bolt(yield) \( P_{by} = 1910.1 \text{ lbf} \)  
Thread pullout strength required to develop full strength of bolt \( P_{\text{As}} = 3621.8 \text{ lbf} \)

Bolt ultimate tensile strength \( P_{At} = 2410.8 \text{ lbf} \)  
Nut ultimate tensile strength \( P_{\text{tu\_nut}} = 2410.8 \text{ lbf} \)

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>MS Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_1 = 0.57 )</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_2 = 1.56 )</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>( MS_3 = 2.85 )</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_4 = 0.24 )</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>( MS_5 = 0.19 )</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

\( MS_{\text{bolt}} := \min(\text{MS}) \)

\( MS_{\text{bolt}} = 0.19 \)  
Failure Mode = "Total Tension Yield"
5.11.7 Intentionally Left Blank
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5.11.8 Intentionally Left Blank
### Engineering and Science Contract Group

**Title**

AMS-02

<table>
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<th>Name</th>
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<td>C. Bala</td>
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</tbody>
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5.11.9 Scuff Plate to Sill Joint Bolt Analysis
Section 5.11.9: Scuff Plate to Sill Joint Bolt Analysis

Margin of Safety

Table 5.11.9-1: Fastener Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1954C5</td>
<td>Fasteners connecting Scuff Plate to Sill Joint</td>
<td>A286</td>
<td>Total Tension Yield</td>
<td>0.1 (y)</td>
<td>5.11.9-6</td>
</tr>
</tbody>
</table>

Table 5.11.9-2: Fail-Safe Fastener Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1954C5</td>
<td>Fasteners connecting Scuff Plate to Sill Joint</td>
<td>A286</td>
<td>Combined Shear Tension Bending Ultimate</td>
<td>0.12 (u)</td>
<td>5.11.9-7</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Load cases are defined in section 5.8. Fastener loads are listed in Appendix A18.
3. u = ultimate; y = yield
**CHECK BOLTS (NAS1954C5 0.25"-28 x 0.737" L, Material A286), Insert MS51831CA202L, Washer NAS1587-4C**

**Flange_1 := “Scuff Plate”**
- Part number: SDG39135867
- Material: Al Alloy 7050-T7451

**Flange_2 := “Sill Joint”**
- Part number: SDG39135730
- Material: Al Alloy 7050-T7451

Minimum edge distance of flange one:  edge1 := 0.87-in
flange two:  edge2 := 0.75-in

**Loads**
- Applied tensile load  \( P := 408.72 \text{lbf} \) (Refer to Appendix A18, pg A18-8)
- Max absolute FX = 628.97 lbf (Refer to Appendix A18, pg A18-8)
- Max absolute Fz = 770.01 lbf (Refer to Appendix A18, pg A18-7)

\[
\text{shear} := \sqrt{(628.97 \text{-lbf})^2 + (770.01 \text{-lbf})^2} \quad \text{shear} = 994.243 \text{lbf}
\]

- Applied shear load  \( V := 994.24 \text{lbf} \)
- Applied bending moment  \( M := 0 \text{in-lbf} \)

**Factors of Safety**
- Ultimate  \( SF_u := 2.0 \)
- Yield  \( SF_y := 1.25 \)
- Fitting factor  \( FF := 1.15 \)
- Joint Separation  \( SF_{sep} := 1.2 \)

**Temperature data**
- Assembly  \( Temp_{initial} := 70\degree \text{deg} \)
- Maximum  \( Temp_{max} := 150\degree \text{deg} \)
- Minimum  \( Temp_{min} := -47\degree \text{deg} \)

**Bolt Data**
- Nominal diameter of bolt  \( D := 0.25 \text{in} \)
- Number of threads/inch  \( N_t := \frac{28}{1} \text{in} \)
- Shank diameter of bolt  \( D_{shank} := 0.2485 \text{in} \)
- Total length of bolt  \( L := 0.737 \text{in} \)
- Threaded length  \( L_t := 0.425 \text{in} \) (If bolt is fully threaded, input \( L_t = L \))
- Bolt head dia. across flats  \( dw := 0.430 \text{in} \) (dia of pressure boss if it exists, otherwise dia of head)
- Bolt head height  \( bh := 0.125 \text{in} \) (head height is 0 if bolt is flat head)

**Note:** Figure is for reference only. Not to scale, and actual joint may differ. There may or may not be a washer(s).
Temperature correction factor for bolt strength ultimate.

Temperature correction factor for bolt modulus

Modulus of elasticity of bolt

Thermal coefficients for bolt

Washer Data

Diameter of washer under head, Outer:

Diameter of washer under head, Inner:

Note: If there are no washer tw's, Dw's and Dwi's should be zero

Insert Data

Length of insert

Min. external diameter of insert

Depth of recess for insert

Temperature correction factor for insert strength

Ultimate tensile allowable stress

Ultimate shear allowable stress
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties.

Thickness of flange 1: \( t_{f1} = 0.266\text{in} \)  
Thickness of flange 2: \( t_{f2} = 0.375\text{in} \)  
Diameter of thru hole \( D_{\text{hole}} = 0.375\text{in} \)

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint
- Flange 1: \( E_{\text{flange1}} = (10.3 \times 10^6 \text{psi}) \)
- Flange 2: \( E_{\text{flange2}} = (10.3 \times 10^6 \text{psi}) \)

Temperature correction factor (modulus) for flange 1: \( T_{f1E} = 0.98 \)  
Temperature correction factor (modulus) for flange 2: \( T_{f2E} = 0.98 \)

Coefficient of thermal expansion for flanges
- Flange 1 (hot): \( \beta_{\text{flange1 hotspot}} = 12.7 \times 10^{-6} \text{in/deg} \)
- Flange 1 (cold): \( \beta_{\text{flange1 coldest}} = 12.1 \times 10^{-6} \text{in/deg} \)
- Flange 2 (hot): \( \beta_{\text{flange2 hotspot}} = 12.7 \times 10^{-6} \text{in/deg} \)
- Flange 2 (cold): \( \beta_{\text{flange2 coldest}} = 12.1 \times 10^{-6} \text{in/deg} \)

Shear strength of flange two, with temperature reduction
- Flange 2: \( F_{su2} = 44000\text{psi} \)  
- Torque reduction factor: \( T_{f2s} = 0.98 \)

Torque/Preload data

Maximum torque \( T_{\text{max}} = 115\text{in-lbf} \)
Minimum torque \( T_{\text{min}} = 109\text{in-lbf} \)

Joint is lubed

Preload Uncertainty \( u = 0.25 \)
Torque coefficient \( k = 0.15 \)
Loading plane factor \( n = 0.5 \)

Stiffness and Margin calculations are hidden

This file uses calculations shown in \\escfl02\2111_mathcad\8307\bolts\Rev_E\bolt_insert_stiffness_RevE.xmcd

Bolt Load data

Bolt/joint stiffness factor \( = 0.841 \)

Max. preload \( PL_{\text{max}} = 3891\text{lbf} \)
Min. preload \( PL_{\text{min}} = 1906\text{lbf} \)
Nom. preload \( PL_{\text{nom}} = 3067\text{lbf} \)
Preload to yield ratio(nom.) \( PL_{\text{ratio}} = 0.657 \)
Joint separation load \( P_{\text{sep}} = 490.464\text{lbf} \)

Preload due to temperature
- Preload to yield ratio\( u = 0.25 \)
- Torque coefficient \( k = 0.15 \)
- Loading plane factor \( n = 0.5 \)
Bolt Load data (cont.)

Applied Tensile load on the bolt \( P = 408.72 \text{lbf} \)

Max. load on the bolt with preload and Factor of safety (ultimate) \( P_b = 4286 \text{lbf} \)

(yield) \( P_{by} = 4138 \text{lbf} \)

Applied shear on the bolt \( V = 994.24 \text{lbf} \)

Applied bending on the bolt \( M = 0 \text{in-lbf} \)

Max. load on the bolt with preload without factor of safety \( P_{bapp} = 4089 \text{lbf} \)

Bolt ultimate tensile strength \( P_{At} = 6224 \text{lbf} \)

Bolt shear strength \( V_{Au} = 3446 \text{lbf} \)

Bolt thread pullout strength \( P_{Asbolt} = 15503 \text{lbf} \)

Bolt bending strength \( M_{Au} = 173 \text{in-lbf} \)

Insert thread pullout strength \( P_{Asinsert} = 12058 \text{lbf} \)

Flange thread pullout strength \( P_{Asflange} = 9474.1 \text{lbf} \)

General Checks

length_check = "Bolt length is sufficient and insert fully engaged"

cone_check = "Joint Pressure Cone does not extend past flange"

preload_check = "Nominal preload >= 65% of bolt yield strength"

washer_check = "Washer(s) under head do not extend past flange"

insert_check = "NOTE: Insert extends past flange two--check dimensions"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th></th>
<th>( MS_1 = 4.83 )</th>
<th>Direct Thread shear Ultimate</th>
<th>( MS_6 = 9.08 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_2 = 5.62 )</td>
<td>Total Thread shear Ultimate</td>
<td>( MS_7 = 1.21 )</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>( MS_3 = 6.79 )</td>
<td>Shear Ultimate</td>
<td>( MS_8 = 0.51 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_4 = 0.45 )</td>
<td>Bending Ultimate</td>
<td>( MS_9 = 100 )</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>( MS_5 = 0.11 )</td>
<td>Combined shear, tension and bending ultimate</td>
<td>( MS_{10} = 0.12 )</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

\( MS_{bolt} = 0.11 \)  Failure_Mode = "Total Tension Yield"
### Fail-safe Analysis

(Conservatively, the loads were doubled to perform fail-safe analysis)

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P_{FS} := 817.44-lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V_{FS} := 1988.48-lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_{FS} := 0-in-lbf</td>
</tr>
</tbody>
</table>

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file calculations shown in escfi02\2i11_mathcad\8307_bolts\Rev_E\bolt_insert_stiffness_FS_RevE.xmlcd

### Bolt Fail-safe Load data

- Joint separation load \( P_{sep_{FS}} = 817.44 \text{ lbf} \)
- Max. load on the bolt (ultimate) \( P_{b_{FS}} = 4286.4 \text{ lbf} \)

### Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>( MS_{FS_i} ) Value</th>
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</thead>
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<tr>
<td>Joint separation</td>
<td>2.5</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>5.62</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.45</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>9.08</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>1.21</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>0.51</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>10</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt_{FS}} = 0.12 \]

Failure Mode FS = "Combined Shear Tension Bending Ultimate"
5.11.10 Intentionally Left Blank
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<th>Name</th>
<th>Date</th>
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<td>G. Reyes</td>
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| Title      | AMS-02 |

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5.11.11 Interface Panel A to USS-02 Trunnion Bridge Beam
Section 5.11.11: Interface Panel A to USS Trunnion Beam Bolt Analysis

Margin of Safety

Table 5.11.11-1: Minimum Margin of Safety

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1004-8A</td>
<td>Shared Fasteners</td>
<td>A286</td>
<td>Total Tension</td>
<td>0.14 (y)</td>
<td>5.11.11-13</td>
</tr>
<tr>
<td></td>
<td>connecting Lower Edge</td>
<td></td>
<td>Yield</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of IPA to Trunnion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. 64 launch load cases, 64 landing load cases and 3 kickload cases were applied to the IPA.
3. $y = \text{yield}$
<table>
<thead>
<tr>
<th>Prepared By</th>
<th>Name</th>
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<th>File Name</th>
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**Engineering and Science Contract Group**

*Structural Analysis Section*

**Title**
Bolt Analysis for Exterior Bolt through Base Panel & Stiffener to USS Beam

---

Base Panel and Stiffener (SDG39137685, SDG39137843) to USS Trunnion Beam (SDG39135735)

Washers( NAS1149E0463R, Material-A-286)

---

Fasteners connecting the upper edge of IPA to Trunnion Beam (NAS1004-6A, Qty 3)
Bolt Analysis for Exterior Bolt through Base Panel & Stiffener to USS Beam

Base Panel and Stiffener (SDG39137685, SDG39137843) to USS Trunnion Beam (SDG39135735)
Washers (NAS1149E0463R, Material-A-286)

Combined Flange 1: Base Panel & Stiffener
Part numbers: SDG39137685, 7843
Material: AL ALY 7075-T73

Flange 2: USS Beam
Part number: SDG39135735
Material: AL ALY 7075-T73511

Minimum edge distance of flange one: edge1 := 0.420 in
flange two: edge2 := 0.375 in

Loads
Applied tensile load P := 31.25 lbf
Applied shear load V := 752.275 lbf
Applied bending moment M := 0 in-lbf

Factors of Safety
Ultimate SFu := 2.0 Yield SFy := 1.25 Joint Separation SFsep := 1.2
Fitting factor FF := 1.15

Temperature data
Assembly Temp_initial := 70 deg
Maximum Temp_max := 220 deg
Minimum Temp_min := -180 deg

Bolt Data
Nominal diameter of bolt D := 0.25 in
Shank diameter of bolt D_shank := 0.2495 in
Total length of bolt L := 0.919 in
Threaded length Lt := 0.544 in (If bolt is fully threaded, input Lt = L)
Bolt head dia. across flats dw := 0.439 in (dia of pressure boss if it exists, otherwise dia of head)
Bolt head height bh := 0.156 in (head height is 0 if bolt is flat head)

Note: Figure is for reference only.
Not to scale, and actual joint may differ
Washer may be on nut side, head side, or both

5.11.11-4 ESCG-4005-05-AMS-0039
Thread data lookup table is hidden

This file uses the data shown in \escfil\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength ultimate. \( TS_{\text{bolt}} := 0.96 \)  
Yield \( TS_{\text{y,bolt}} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{\text{tu,bolt}} := 140000 \text{ psi} \)  
Yield \( F_{\text{ty,bolt}} := 95000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{\text{su,bolt}} := 0.6 F_{\text{tu,bolt}} \)

Temperature correction factor for bolt modulus \( TE_{\text{bolt}} := 0.96 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left( 29.1 \cdot 10^6 \right) \text{ psi} \)

\[ \beta_{\text{bolt,hot}} := 9.2 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{\text{bolt,cold}} := 8.0 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \]

Washer Data

Thickness of washers: head \( t_{\text{wh}} := 0.063 \text{ in} \)  
these are total washer thickness, if there are more than one  
nut \( t_{\text{wn}} := 0.063 \text{ in} \)

Diameter of washer under head, Outer: \( D_{\text{woh}} := 0.500 \text{ in} \)  
Inner: \( D_{\text{wih}} := 0.265 \text{ in} \)

Diameter of washer under nut, Outer: \( D_{\text{won}} := 0.500 \text{ in} \)  
Inner: \( D_{\text{win}} := 0.265 \text{ in} \)

\textbf{Note: If there are no washer tw's, Dw's and Dw's should be zero}

Modulus of elasticity, head: \( E_{\text{washerh}} := \left( 29.1 \cdot 10^6 \right) \text{ psi} \)  
Temperature correction factor for modulus, head: \( TE_{\text{washerh}} := 0.96 \)

Modulus of elasticity, nut: \( E_{\text{washern}} := \left( 29.1 \cdot 10^6 \right) \text{ psi} \)  
Temperature correction factor for modulus, nut: \( TE_{\text{washern}} := 0.96 \)

Nut Data

Height of nut \( H := 0.219 \text{ in} \)  
Nut dia. across flats \( D_{\text{n}} := 0.304 \text{ in} \)

Temperature correction factor for nut strength \( TS_{\text{nut}} := 0.96 \)

Ultimate allowable stress, tensile: \( F_{\text{tu,nut}} := 160000 \text{ psi} \)  
Shear: \( F_{\text{su,nut}} := 0.6 F_{\text{tu,nut}} \)

Ultimate axial strength of nut \( P_{\text{tu,nut}} := 4580 \text{ lbf} \)  
(Reference NAS1291)
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

<table>
<thead>
<tr>
<th>Thickness of flange 1:</th>
<th>tf1 := .245 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>flange 2:</td>
<td>tf2 := .250 in</td>
</tr>
<tr>
<td>Diameter of thru hole</td>
<td>D_hole := 0.288 in</td>
</tr>
</tbody>
</table>

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint

| E_flange1 := (10.3 x 10^6 psi) |
| E_flange2 := (10.4 x 10^6 psi) |

Temperature correction factor (modulus) for flange 1: Tf1E := 0.95

Flange 2: Tf2E := 0.95

Coefficient of thermal expansion for flanges

| \( \beta_{\text{flange1\_hot}} := 12.75 \times 10^{-6} \) in/deg |
| \( \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \) in/deg |
| \( \beta_{\text{flange2\_hot}} := 12.75 \times 10^{-6} \) in/deg |
| \( \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \) in/deg |

Torque/Preload data

| Maximum torque | Tmax := 78 in-lbf |
| Minimum torque | Tmin := 66in-lbf |

Joint is lubed/dry

Preload Uncertainty u := 0.25

Torque coefficient k := 0.15

Loading plane factor n := 0.5

Joint separation load Psep = 37.5 lbf

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escfii02\2111_mathcad\8307_bolts\Rev_D\bolt\stiffness\nut.mcd

Bolt Load data

<table>
<thead>
<tr>
<th>Bolt/joint stiffness factor</th>
<th>= 0.493</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. preload</td>
<td>PLDmax = 2793 lbf</td>
</tr>
<tr>
<td>Min. preload</td>
<td>PLDmin = 818 lbf</td>
</tr>
<tr>
<td>Nom. preload</td>
<td>PLDnom = 2080 lbf</td>
</tr>
<tr>
<td>Preload to yield ratio(nom.)</td>
<td>PLDratio = 0.646</td>
</tr>
<tr>
<td>Joint separation load</td>
<td>Psep = 37.5 lbf</td>
</tr>
</tbody>
</table>

Preload due to temperature

| Pthr_pos := 193 lbf |
| Pthr_neg := −371.5 lbf |

Uncertainty factor u := 0.25

Torque coefficient k := 0.15

Loading plane factor n := 0.5

5.11.11-6 ESCG-4005-05-AMS-0039
Bolt Analysis for Exterior Bolt through Base Panel & Stiffener to USS Beam

Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 31.25$ lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety</td>
<td>$P_b = 281.1$ lbf</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 752.275$ lbf</td>
</tr>
<tr>
<td>(yield)</td>
<td>$P_{by} = 2804$ lbf</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0$ in-lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload without factor of safety</td>
<td>$P_{bapp} = 2802$ lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$P_{At} = 4742$ lbf</td>
</tr>
<tr>
<td>Bolt shear strength</td>
<td>$V_{Au} = 3943$ lbf</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>$P_{As} = 4397$ lbf</td>
</tr>
<tr>
<td>Bolt bending strength</td>
<td>$M_{Au} = 132$ in-lbf</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>$P_{tu_nut} = 4397$ lbf</td>
</tr>
</tbody>
</table>

General Checks

- length_check = "Bolt length sufficient, but not enough threaded length (shank within nut threads)"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_1 = 24.19$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_6 = 60.17$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$MS_2 = 64.98$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_7 = 0.56$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$MS_3 = 70.63$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_8 = 1.28$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_4 = 0.69$</td>
</tr>
<tr>
<td>Smallest margin of safety for the bolt, and the failure mode:</td>
<td>$MS_{bolt} = 0.15$</td>
</tr>
</tbody>
</table>

Failure_Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

### Fail-safe Loads

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Applied Load</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Load</td>
<td>$P_{FS} = 62.5 \text{ lbf}$</td>
<td>Ultimate</td>
</tr>
<tr>
<td>Shear Load</td>
<td>$V_{FS} = 1504.55 \text{ lbf}$</td>
<td>Joint Separation</td>
</tr>
<tr>
<td>Bending Moment</td>
<td>$M_{FS} = 0 \text{ in-lbf}$</td>
<td></td>
</tr>
</tbody>
</table>

### Fail-safe Factors of Safety

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>$SF_{U_{FS}} = 1.0$</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>$SF_{Sep_{FS}} = 1.0$</td>
</tr>
</tbody>
</table>

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfli02\211_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

### Bolt Fail-safe Load data

- Joint separation load $P_{Sep_{FS}} = 62.5 \text{ lbf}$
- Max. load on the bolt (ultimate) $P_{B_{FS}} = 2810.7 \text{ lbf}$

### Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$MS_{FS_1} = 14.11$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$MS_{FS_2} = 64.98$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$MS_{FS_3} = 0.69$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$MS_{FS_4} = 60.17$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$MS_{FS_5} = 0.56$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$MS_{FS_6} = 1.28$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$MS_{FS_8} = 0.45$</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

- $MS_{Bolt_{FS}} = 0.45$
- $Failure\_Mode_{FS} = "Combined\ Shear\ Tension\ Bending\ Ultimate"$
Base Panel and Handrail (SDG39137685, SDG39135878) to USS Trunnion Beam (SDG39135735)


Shared Fasteners connecting the lower edge of IPA to Trunnion Beam (NAS1004-8A, Qty 2)
Base Panel and Handrail (SDG39137685, SDG39135878) to USS Trunnion Beam (SDG39135735)

Washers( NAS1149E0463R, Material-A-286)

Combined Flange 1: Base Panel & Handrail
Part numbers: SDG39137685, 5878
Material: AL ALY 7075-T73

Flange 2: USS Beam
Part number: SDG39135735
Material: AL ALY 7075-T73511

Minimum edge distance of flange one: \(\text{edge1} := 0.420\ \text{in}\)

\(\text{flange two: } \text{edge2} := 0.375\ \text{in}\)

Loads

- Applied tensile load \(\text{P} := 5.315\ \text{lbf}\)
- Applied shear load \(\text{V} := 535.794\ \text{lbf}\)
- Applied bending moment \(\text{M} := 0\ \text{in-lbf}\)

Factors of Safety

- Ultimate \(\text{SFu} := 2.0\)
- Yield \(\text{SFy} := 1.25\)
- Joint Separation \(\text{SFsep} := 1.2\)

Fitting factor \(\text{FF} := 1.15\)

Temperature data

- Assembly \(\text{Temp initial} := 70\ \text{deg}\)
- Maximum \(\text{Temp max} := 220\ \text{deg}\)
- Minimum \(\text{Temp min} := -180\ \text{deg}\)

Bolt Data

- Nominal diameter of bolt \(\text{D} := .25\ \text{in}\)
- Number of threads/inch \(\text{Nt} := 28\ \text{in}^{-1}\)
- Shank diameter of bolt \(\text{D}_{\text{shank}} := .249\ \text{in}\)
- Total length of bolt \(\text{L} := 1.044\ \text{in}\)
- Threaded length \(\text{Lt} := 0.544\ \text{in}\)
- Bolt head dia. across flats \(\text{dw} := 0.439\ \text{in}\)
- Bolt head height \(\text{bh} := .156\ \text{in}\)

Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

(If bolt is fully threaded, input Lt = L)

(dia of pressure boss if it exists, otherwise dia of head)

(head height is 0 if bolt is flat head)
Thread data lookup table is hidden

This file uses the data shown in `\escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd`

Temperature correction factor for bolt strength ultimate.  \( T_{Su} := 0.96 \)
Yield  \( T_{Sy} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate:  \( F_{tu} := 140000 \text{ psi} \)
Yield  \( F_{ty} := 95000 \text{ psi} \)

Bolt ultimate shear allowable stress  \( F_{su} := 0.6 \times F_{tu} \)

Temperature correction factor for bolt modulus  \( T_{E} := 0.96 \)

Modulus of elasticity of bolt  \( E := \left(29.1 \times 10^6 \text{ psi}\right) \)

Thermal coefficients for bolt  \( \beta_{hot} := 9.2 \times 10^{-6} \text{ in/in/deg} \)
\( \beta_{cold} := 8.0 \times 10^{-6} \text{ in/in/deg} \)

Washer Data

Thickness of washers: head  \( t_{wh} := 0.063 \text{ in} \)
these are total washer thickness, if there are more than one
Nut  \( t_{wn} := 0.063 \text{ in} \)

Diameter of washer under head, Outer:  \( D_{woh} := 0.500 \text{ in} \)
Inner:  \( D_{wih} := 0.265 \text{ in} \)
Diameter of washer under nut, Outer:  \( D_{won} := 0.500 \text{ in} \)
Inner:  \( D_{win} := 0.265 \text{ in} \)

Note: If there are no washer \( tw \)'s, \( Dw \)'s and \( Dw \)'s should be zero

Modulus of elasticity, head:  \( E_{washerh} := \left(29.1 \times 10^6 \text{ psi}\right) \)
Temperature correction factor for modulus, head:  \( T_{E_{washerh}} := 0.96 \)
Nut:  \( E_{washern} := \left(29.1 \times 10^6 \text{ psi}\right) \)
Nut:  \( T_{E_{washern}} := 0.96 \)

Nut Data

Height of nut  \( H := 0.219 \text{ in} \)
Nut dia. across flats  \( D_n := 0.316 \text{ in} \)

Temperature correction factor for nut strength  \( T_{S_n} := 0.96 \)

Ultimate allowable stress, tensile:  \( F_{tu_n} := 160000 \text{ psi} \)
Shear:  \( F_{su_n} := 0.6 \times F_{tu_n} \)
Ultimate axial strength of nut  \( P_{tu_n} := 4580 \text{ lbf} \) (Reference NAS1291)
**Flange data**

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

- Thickness of flange 1: \( t_{f1} := .245 \text{ in} \)
- Thickness of flange 2: \( t_{f2} := .250 \text{ in} \)
- Diameter of thru hole: \( D_{\text{hole}} := 0.288 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors

- Compressive Modulus of elasticity for the parts in the joint: 
  \[
  E_{\text{flange1}} := (10.3 \times 10^6 \text{ psi}) \\
  E_{\text{flange2}} := (10.3 \times 10^6 \text{ psi})
  \]

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \)

- Coefficient of thermal expansion for flanges:
  \[
  \beta_{\text{flange1\_hot}} := 12.75 \times 10^{-6} \text{ in} / \text{deg} \\
  \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \text{ in} / \text{deg} \\
  \beta_{\text{flange2\_hot}} := 12.75 \times 10^{-6} \text{ in} / \text{deg} \\
  \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ in} / \text{deg}
  \]

**Torque/Preload data**

- Maximum torque: \( T_{\text{max}} := 78 \text{ in-lbf} \)
- Minimum torque: \( T_{\text{min}} := 66 \text{ in-lbf} \)

- Joint is lubed/dry
- Preload Uncertainty: \( u := 0.25 \)
- Torque coefficient: \( k := 0.15 \)
- Loading plane factor: \( n := 0.5 \)

**Stiffness and Margin calculations are hidden**

This file uses the calculations shown in \escf02\2111_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

**Bolt Load data**

- Bolt/joint stiffness factor: \( = 0.467 \)
- Preload due to temperature: \( P_{\text{thr\_pos}} := 213.4 \text{ lbf} \)
- Max. preload: \( PLD_{\text{max}} := 2813 \text{ lbf} \)
- Min. preload: \( PLD_{\text{min}} := 779 \text{ lbf} \)
- Nom. preload: \( PLD_{\text{nom}} := 2080 \text{ lbf} \)
- Preload to yield ratio(nom.): \( PLD_{\text{ratio}} := 0.646 \)
- Preload due to temperature: \( P_{\text{thr\_pos}} := 213.4 \text{ lbf} \)
- Uncertainty factor: \( u := 0.25 \)
- Torque coefficient: \( k := 0.15 \)
- Loading plane factor: \( n := 0.5 \)
- Joint separation load: \( P_{\text{sep}} := 6.378 \text{ lbf} \)
Bolt Load data (cont.)

| Applied Tensile load on the bolt | P = 5.315 lbf |
| Applied shear on the bolt         | V = 535.794 lbf |
| Applied bending on the bolt       | M = 0 in-lbf   |

Max. load on the bolt with preload and Factor of safety

| (ultimate) | Pb = 2816 lbf |
| (yield)    | Pby = 2815 lbf |

Max. load on the bolt with preload without factor of safety

| Pbapp = 2815 lbf |

Bolt ultimate tensile strength

| PAt = 4742 lbf |

Bolt shear strength

| VAu = 3927 lbf |

Thread pullout strength

| PAs = 4397 lbf |

Bolt bending strength

| MAu = 132 in-lbf |

Nut ultimate tensile strength

| Ptu_nut = 4397 lbf |

Summary of Margins for bolt:

| MS1 = 137.57 | Direct Thread shear Ultimate | MS6 = 358.67 |
| MS2 = 386.91 | Total Thread shear Ultimate  | MS7 = 0.56  |
| MS3 = 420.16 | Shear Ultimate               | MS8 = 2.19  |
| MS4 = 0.68   | Bending Ultimate             | MS9 = 100   |
| MS5 = 0.14   | Combined shear, tension and bending ultimate | MS10 = 0.58 |

Smallest margin of safety for the bolt, and the failure mode:

| MSbolt = 0.14 | Failure_Mode = "Total Tension Yield" |

length_check = "Bolt length sufficient, but not enough threaded length (shank within nut threads)"

cone_check = "Joint pressure cone does not extend pass flange edge"

preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"

washer_check = "Washers under head and nut do not extend past flanges"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

Fail-safe Loads

- **Applied tensile load**
  \[ P_{FS} := 10.63 \text{ lbf} \]

- **Applied shear load**
  \[ V_{FS} := 1071.59 \text{ lbf} \]

- **Applied bending moment**
  \[ M_{FS} := 0 \text{ in-lbf} \]

Fail-safe Factors of Safety

- **Ultimate**
  - \[ SF_{u,FS} := 1.0 \]

- **Joint Separation**
  - \[ SF_{sep,FS} := 1.0 \]

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfil02\211_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Bolt Fail-safe Load data

- **Joint separation load**
  \[ P_{sep,FS} = 10.63 \text{ lbf} \]

- **Max. load on the bolt(ultimate)**
  \[ P_{b,FS} = 2816.3 \text{ lbf} \]

Summary of fail-safe Margins for bolt:

- **Joint separation**
  \[ MS_{FS}^1 = 82.14 \]

- **Direct Tension Ultimate**
  \[ MS_{FS}^2 = 386.91 \]

- **Total Tension Ultimate**
  \[ MS_{FS}^3 = 0.68 \]

- **Direct Thread shear Ultimate**
  \[ MS_{FS}^4 = 358.67 \]

- **Total Thread shear Ultimate**
  \[ MS_{FS}^5 = 0.56 \]

- **Shear Ultimate**
  \[ MS_{FS}^6 = 2.19 \]

- **Bending Ultimate**
  \[ MS_{FS}^7 = 10 \]

- **Combined shear, tension and bending ultimate**
  \[ MS_{FS}^8 = 0.58 \]

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{bolt,FS} = 0.56 \]

**Failure Mode_FS = "Total Thread Shear Ultimate (Bolt)"**
Base Panel (SDG39137685) to USS Trunnion Beam (SDG39135735)

Washers( NAS1149E0463R, Material-A-286)

Fasteners connecting the lower edge of IPA to Trunnion Beam
(NAS1004-6A, Qty 6)
Base Panel (SDG39137685) to USS Trunnion Beam (SDG39135735)

Washers( NAS1149E0463R, Material-A-286)

Flange 1: Base Panel
Part numbers: SDG39137685
Material: AL ALY 7075-T73

Flange 2: USS Beam
Part number: SDG39135735
Material: AL ALY 7075-T73511

Minimum edge distance of flange one: edge1 := 0.420 in
flange two: edge2 := 0.375 in

Loads
Applied tensile load
P := 5.724 lbf

Applied shear load
V := 612.266 lbf

Applied bending moment
M := 0 in·lbf

Factors of Safety
Ultimate
SFu := 2.0
Yield
SFy := 1.25
Joint Separation
SFsep := 1.2

Fitting factor
FF := 1.15

Temperature data
Maximum
Temp_max := 220 deg

Minimum
Temp_min := -180 deg

Bolt Data
Nominal diameter of bolt
D := .25 in

Number of threads/inch
Nt := 28 \frac{1}{in}

Shank diameter of bolt
D_{shank} := .249 in

Total length of bolt
L := .919 in

Threaded length
Lt := 0.544 in

Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

Bolt head dia. across flats
dw := 0.439 in

(Bia of pressure boss if it exists, otherwise dia of head)

Bolt head height
bh := .156 in

(head height is 0 if bolt is flat head)
Thread data lookup table is hidden

This file uses the data shown in \escfil02\i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength ultimate. \( T_{Su_{bolt}} := 0.96 \)  
Yield \( T_{Sy_{bolt}} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{tu_{bolt}} := 140000 \text{ psi} \)  
Yield \( F_{ty_{bolt}} := 95000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su_{bolt}} := 0.6 \times F_{tu_{bolt}} \)

Temperature correction factor for bolt modulus \( T_{E_{bolt}} := 0.96 \)

Modulus of elasticity of bolt \( E_{bolt} : (29.1 \times 10^6 \text{ psi}) \)

Thermal coefficients for bolt \( \beta_{bolt_{hot}} := 9.2 \times 10^{-6} \text{ in}/\text{deg} \) \( \beta_{bolt_{cold}} := 8.0 \times 10^{-6} \text{ in}/\text{deg} \)

**Washer Data**

Thickness of washers: head \( t_{wh} := 0.063 \text{ in} \) 
these are total washer thickness, if there are more than one  
nut \( t_{wn} := 0.063 \text{ in} \)

Diameter of washer under head, Outer: \( D_{woh} := 0.500 \text{ in} \)  
Inner: \( D_{wih} := 0.265 \text{ in} \)

Diameter of washer under nut, Outer: \( D_{won} := 0.500 \text{ in} \)  
Inner: \( D_{win} := 0.265 \text{ in} \)

Note: If there are no washer tw's, Dw's and Dwi's should be zero

Modulus of elasticity, head: \( E_{washer_h} : (29.1 \times 10^6 \text{ psi}) \)  
Temperature correction factor for modulus, head: \( T_{E_{washer_h}} := 0.96 \)

Nut Data

Height of nut \( H := 0.219 \text{ in} \)  
Nut dia. across flats \( D_{n} := 0.316 \text{ in} \)

Temperature correction factor for nut strength \( T_{S_{nut}} := 0.96 \)

Ultimate allowable stress, tensile: \( F_{tu_{nut}} := 160000 \text{ psi} \)  
Shear: \( F_{su_{nut}} := 0.6 \times F_{tu_{nut}} \)

Ultimate axial strength of nut \( P_{tu_{nut}} := 4580 \text{ lbf} \)  
(Reference NAS1291)
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

Thickness of flange 1: \( t_{f1} := 0.125 \text{ in} \) flange 2: \( t_{f2} := 0.250 \text{ in} \)
Diameter of thru hole \( D_{\text{hole}} := 0.288 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint
\[ E_{\text{flange1}} := (10.3 \times 10^6 \text{ psi}) \]
\[ E_{\text{flange2}} := (10.3 \times 10^6 \text{ psi}) \]

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \)
flange 2: \( T_{f2E} := 0.95 \)

Coefficient of thermal expansion for flanges
\[ \beta_{\text{flange1\_hot}} := 12.75 \times 10^{-6} \text{ in/in/deg} \]
\[ \beta_{\text{flange2\_hot}} := 12.75 \times 10^{-6} \text{ in/in/deg} \]
\[ \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \text{ in/in/deg} \]
\[ \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ in/in/deg} \]

Torque/Preload data

Maximum torque \( T_{\text{max}} := 78 \text{ in-lbf} \)
Minimum torque \( T_{\text{min}} := 66 \text{ in-lbf} \)

Joint is lubed/dry
Preload Uncertainty \( u := 0.25 \)
Torque coefficient \( k := 0.15 \)
Loading plane factor \( n := 0.5 \)

Stiffness and Margin calculations are hidden

Friday Apr 27 14:15:49 2007
This file uses the calculations shown in \escflil02\balt\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Bolt Load data

Bolt/joint stiffness factor \( = 0.479 \)
Preload due to temperature
\( P_{\text{thr\_pos}} := 181.9 \text{ lbf} \)
\( P_{\text{thr\_neg}} := -350.1 \text{ lbf} \)

Max. preload \( P_{\text{LDMax}} := 2782 \text{ lbf} \)
Min. preload \( P_{\text{LDMin}} := 840 \text{ lbf} \)
Nom. preload \( P_{\text{LDNom}} := 2080 \text{ lbf} \)
Preload to yield ratio(nom.) \( P_{\text{LDratio}} := 0.646 \)
Joint separation load \( P_{\text{sep}} := 6.869 \text{ lbf} \)
Uncertainty factor \( u := 0.25 \)
Torque coefficient \( k := 0.15 \)
Loading plane factor \( n := 0.5 \)
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>P = 5.724 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety (ultimate)</td>
<td>Pb = 2785 lbf</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>V = 612.266 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety (yield)</td>
<td>Pby = 2784 lbf</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>M = 0 in·lbf</td>
</tr>
<tr>
<td>Max. load on the bolt with preload without factor of safety</td>
<td>Pbapp = 2783 lbf</td>
</tr>
</tbody>
</table>

Bolt ultimate tensile strength: PAu = 4742 lbf

Thread pullout strength: PAs = 4397 lbf

Nut ultimate tensile strength: Ptunut = 4397 lbf

length_check = "Bolt length is sufficient and nut fully engaged"

cone_check = "Joint pressure cone does not extend pass flange edge"

preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"

washer_check = "Washers under head and nut do not extend past flanges"

---

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_1 = 138.83</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_2 = 359.19</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS_3 = 390.07</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_4 = 0.7</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS_5 = 0.16</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_6 = 332.97</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS_7 = 0.58</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS_8 = 1.79</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS_9 = 100</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_10 = 0.55</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode: MSbolt = 0.16  Failure_Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P(_F_S) := 11.45 lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V(_F_S) := 1224.53 lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M(_F_S) := 0 in-lbf</td>
</tr>
</tbody>
</table>

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escf\02\211\_mathcad\8307\_bolts\Rev_D\bolt\_stiffness\_nut\_FS.mcd

Bolt Fail-safe Load data

- Joint separation load  P\(_{sep\_FS}\) = 11.45 lbf
- Max. load on the bolt(ultimate)  Pb\(_FS\) = 2785 lbf

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th></th>
<th>MS(_F_S) [1] = 82.88</th>
<th>Total Thread shear Ultimate</th>
<th>MS(_F_S) [5] = 0.58</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS(_F_S) [2] = 359.13</td>
<td>Shear Ultimate</td>
<td>MS(_F_S) [6] = 1.79</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS(_F_S) [3] = 0.7</td>
<td>Bending Ultimate</td>
<td>MS(_F_S) [7] = 10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS(_F_S) [4] = 332.91</td>
<td>Combined shear, tension and bending ultimate</td>
<td>MS(_F_S) [8] = 0.55</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MS\(_{bolt\_FS}\) = 0.55  Failure Mode\(_{FS}\) = "Combined Shear Tension Bending Ultimate"
5.12 Handle Brackets
Section 5.12 Handle Bracket Analysis

The Handle Bracket Analysis is performed in the following report sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.12.1</td>
<td>Handle Brackets</td>
</tr>
<tr>
<td>5.12.2</td>
<td>Handle Bracket Bolt Analysis</td>
</tr>
<tr>
<td>5.12.2</td>
<td>Handle Bracket Bolt Analysis (Fail-Safe)</td>
</tr>
</tbody>
</table>
5.12.1 Handle Brackets
Margins of Safety

Table 5.12.1-1: Minimum Margin of Safety Summary for Handle Bracket -303

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135878</td>
<td>Handle Bracket -303, USS-02 Assembly</td>
<td>AL ALY 6061-T651</td>
<td>Load Case 1 Right End</td>
<td>Principal Stress</td>
<td>0.04 (u)</td>
<td>5.12.1-19</td>
</tr>
</tbody>
</table>

Table 5.12.1-2: Minimum Margin of Safety Summary for Handle Bracket -305

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG39135878</td>
<td>Handle Bracket -305, USS-02 Assembly</td>
<td>AL ALY 6061-T651</td>
<td>Load Case 8 Left End</td>
<td>Shear Stress</td>
<td>0.049 (u)</td>
<td>5.12.1-32</td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield
2. u = ultimate
3. Load Cases are presented in Reference 1, Table 9, page 29 and Table 10, page 30

References:
1. Memorandum MSAD-04-0101A of March 26, 2004, Results of Handrail Interface Force Testing
Description of Handle Brackets

This analysis covers three Handle Bracket Assemblies used on USS-02 Assembly and presented in drawing SDG39135878. The three Handle Brackets Assemblies are:

1. Handle Bracket Assembly, part SDG39135878-303
2. Handle Bracket Assembly, part SDG39135878-301/307
3. Handle Bracket Assembly, part SDG39135878-305

The Handle Bracket -301 and -307 are identical with the exception of the mounting holes location for the Rail Post. The location for the part -307 is displaced by 0.050 inch relative to the location for the part -301. Therefore, for the purpose of this analysis, the two parts are considered identical.

Factors of Safety

The Handle Brackets are designed with a yield factor of 1.25 and an ultimate factor of 2.0 against the maximum stresses as predicted by the FEM and shown on page 5.12.1-18 and 5.12.1-31.
Handle Bracket Assembly, part SDG39135878-303

Location of Handle Bracket -303

Figure 5.12.1-1 below shows a typical location of the Handle Bracket -303 on the USS-02 Assembly.

Figure 5.12.1-1: Typical Location of Handle Bracket -303 on USS-02 Assembly
Handle Bracket -303 Load Cases

The Handle Bracket -303 load cases are presented in Reference 1 – Results of Handrail Interface Force Testing. Table 9, on page 29, summarized these cases and is presented below.

Table 9: Interface Forces, Top Mounted Handrails Long Handrails (SEG33106347-843).

<table>
<thead>
<tr>
<th>Load Case</th>
<th>End</th>
<th>Measured (at handrail interface, pounds force and inch-pounds)</th>
<th>RSS</th>
<th>Force</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left</td>
<td>263 -2 150 10 416 29</td>
<td>303</td>
<td>417</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-257 -4 63 6 -536 -26</td>
<td>265</td>
<td>537</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Left</td>
<td>16 -148 -1 396 31 -76</td>
<td>149</td>
<td>405</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-12 -72 0 200 -29 21</td>
<td>73</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Left</td>
<td>60 0 32 159 72 -1</td>
<td>68</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-59 0 15 109 -99 -17</td>
<td>61</td>
<td>149</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Left</td>
<td>1 -35 -3 260 5 -60</td>
<td>35</td>
<td>266</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0 -14 -1 156 4</td>
<td>9</td>
<td>156</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Left</td>
<td>0 6 70 -9 -30 4</td>
<td>70</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0 4 6 -8 7</td>
<td>2</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>45 -1 208 7 71</td>
<td>213</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-40 -1 9 1 -92 -5</td>
<td>41</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>2 -207 1 542 -1 -29</td>
<td>207</td>
<td>543</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>1 -13 0 53 8</td>
<td>3</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>207 -2 -4 -1 476 -18</td>
<td>207</td>
<td>476</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>15 0 1 -1 38 2</td>
<td>15</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Left</td>
<td>-4 -68 -5 192 -11 -31</td>
<td>68</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>2 -15 -1 59 7</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Left</td>
<td>2 -25 -3 119 1 45</td>
<td>25</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>1 3 0 9 5</td>
<td>0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Left</td>
<td>0 -2 0 13 4</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0 0 0 0</td>
<td>-1 0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The worst cases are selected by engineering judgment and are presented in Table 5.12.1-3 below.
Table 5.12.1-3: Worst Load Cases Summary for Handle Bracket -303

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Rail End</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left</td>
<td>263</td>
<td>-2</td>
<td>150</td>
<td>10</td>
<td>416</td>
<td>29</td>
</tr>
<tr>
<td>1</td>
<td>Right</td>
<td>-257</td>
<td>-4</td>
<td>63</td>
<td>6</td>
<td>-536</td>
<td>-26</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>2</td>
<td>-207</td>
<td>-1</td>
<td>542</td>
<td>-1</td>
<td>-29</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>207</td>
<td>-2</td>
<td>-4</td>
<td>-1</td>
<td>476</td>
<td>-18</td>
</tr>
</tbody>
</table>

The coordinate system associated with these loads is as per Reference 1, and is shown in Figure 5.12.1-2.

Figure 5.12.1-2: Loads Coordinate System

Figure 5.12.1-3 below shows the configuration of the Handle Bracket -303 with the Rail Post mounted on it and the system coordinate system.

Please note that this coordinate system is as per ProE model and I-DEAS FE model and is different than the above coordinate system (X and Y directions are reversed).
Figure 5.12.1-3: Handle Bracket -303 and Rail Post Assembly Configuration

Description of Model

A FE model of the Handle Bracket -303 is built using I-DEAS software.

1. The Handle Bracket is modeled using solid parabolic tetrahedral elements. These elements are best suited for complex and uneven geometry. The number of elements are selected based on the maximum unaveraged and averaged results in the critical area, such that convergence of results is achieved.

2. At the bolt holes, rigid elements are used to represent the bolt connections.

3. The model is constrained with DOF’s 1-3 at four bolt locations.
4. Four load cases are applied selected by engineering judgment from Reference 1, Table 9, page 29 and presented in Table 5.12.1-3. Please note that the ProE and I-DEAS models have a coordinate system different than the coordinate system shown in Reference 1 (see Figures 5.12.1-2 and 5.12.1-3 and note that X and Y directions are reversed). The FE model accounts for the difference in the two coordinate systems and inputs the loads accordingly.

5. The loads are applied at the top of the Bracket, as specified in Reference 1, using rigid elements that represent the four bolts and inserts. These elements connect the central Post bottom surface to the top face of the Bracket.

6. I-DEAS solver is used for analyzing the complete math model of the Handle Bracket. See page 5.12.1-22 for the FE model of the Handle Bracket.

7. I-DEAS is used to sort out the maximum of Principal, Von-Mises, and Shear stresses (see Appendix A19).

8. The FE model is checked using MSC/NASTRAN.

Model Checks

The quality of the model mesh was checked in I-DEAS for distortions and streches of elements. The distortion and strech filter is set at a treshhold of 0.1. All elements passed the criteria.

Rigid body checks are performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 6.677089E-04

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.799884E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>3.398598E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.153208E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>2.332561E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>1.270334E-06</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>7.235915E-08</td>
<td>PASS</td>
</tr>
</tbody>
</table>
A further check is done for the rigid body modes. The first 8 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.
Table 5.12.1-4: Eigenvalue Summary of Handle Bracket -303

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>ORDER</th>
<th>EXTRATION</th>
<th>EIGENVALUE</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td>-1.84E-04</td>
<td>1.36E-02</td>
<td>2.16E-03</td>
<td>1.00E+00</td>
<td>-1.84E-04</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td></td>
<td>-1.26E-04</td>
<td>1.12E-02</td>
<td>1.79E-03</td>
<td>1.00E+00</td>
<td>-1.26E-04</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td></td>
<td>-1.04E-04</td>
<td>1.02E-02</td>
<td>1.62E-03</td>
<td>1.00E+00</td>
<td>-1.04E-04</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td></td>
<td>1.74E-04</td>
<td>1.32E-02</td>
<td>2.10E-03</td>
<td>1.00E+00</td>
<td>1.74E-04</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td></td>
<td>2.48E-04</td>
<td>1.57E-02</td>
<td>2.50E-03</td>
<td>1.00E+00</td>
<td>2.48E-04</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td></td>
<td>7.01E-04</td>
<td>2.65E-02</td>
<td>4.21E-03</td>
<td>1.00E+00</td>
<td>7.01E-04</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td></td>
<td>1.12E+08</td>
<td>1.06E+04</td>
<td>1.69E+03</td>
<td>1.00E+00</td>
<td>1.12E+08</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td></td>
<td>2.05E+08</td>
<td>1.43E+04</td>
<td>2.28E+03</td>
<td>1.00E+00</td>
<td>2.05E+08</td>
</tr>
</tbody>
</table>

Material and Temperature

The Handle Bracket -303 is made from 6061-T651 Aluminum Alloy. Material properties are taken from MMPDS-01 (see page 5.12.1-18). Temperature limits are -47°F to 139°F, as defined in Appendix C2 (on-orbit case).

Analysis Approach

The Handle Bracket -303 is designed to withstand loads as determined by testing done at Johnson Space Center Static Test Lab during January 2004.

Four different critical load cases are considered, which are selected by engineering judgment from Reference 1, Table 9, page 29 (see also Table 5.12.1-3). The loads are input in the FEM and the recovered stresses are compared to the ultimate and yield stresses of 6061-T651 Aluminum Alloy, corrected for the maximum temperature of 139°F. All Margins of Safety are positive.

Handle Bracket Assembly, part SDG39135878-301/-307

The load cases for these brackets are identical with the load cases for Handle Bracket -303. A FE model of the Handle Bracket -301/-307 is built using I-DEAS software. The predicted stresses for these brackets are much lower than the stresses presented above for the Handle Bracket -303. Therefore, by engineering judgment, it is concluded that the Margins of Safety are comparatively higher and no further analysis is done for these Handle Brackets.
Handle Bracket Assembly, part SDG39135878-305

Location of Handle Bracket -305

Figure 5.12.1-4 below shows a typical location of the Handle Bracket -305 on the USS-02 Assembly.

![HANDLE BRACKET-305](image)

Figure 5.12.1-4: Typical Location of Handle Bracket -305 on USS-02 Assembly
Handle Bracket -305 Load Cases

The Handle Bracket -305 load cases are presented in Reference 1 – Results of Handrail Interface Force Testing. Table 10, on page 30, summarized these cases and is presented below.

Table 10: Interface Forces, Top Mounted Short Handrails (SEG33106347-833 and –861²)

<table>
<thead>
<tr>
<th>Load Case</th>
<th>End</th>
<th>Measured (at handrail interface, pounds force and inch-pounds)</th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fx</td>
<td>Fy</td>
</tr>
<tr>
<td>1</td>
<td>Left</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-13</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>Left</td>
<td>-2</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-4</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>Left</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>2</td>
<td>-1</td>
</tr>
<tr>
<td>4</td>
<td>Left</td>
<td>-2</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Left</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>7</td>
<td>-2</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-8</td>
<td>-1</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>4</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-1</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>219</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>3</td>
<td>-5</td>
</tr>
<tr>
<td>9</td>
<td>Left</td>
<td>2</td>
<td>-98</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-1</td>
<td>-6</td>
</tr>
<tr>
<td>10</td>
<td>Left</td>
<td>-3</td>
<td>-148</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>4</td>
<td>56</td>
</tr>
<tr>
<td>11</td>
<td>Left</td>
<td>9</td>
<td>-23</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>219</td>
<td>160</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>-13</td>
<td>-148</td>
</tr>
<tr>
<td>Absolute Value Max</td>
<td></td>
<td>219</td>
<td>160</td>
</tr>
</tbody>
</table>
The worst cases are selected by engineering judgment and are presented in Table 5.12.1-5 below.

**Table 5.12.1-5: Worst Load Cases Summary for Handle Bracket -305**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Rail End</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Left</td>
<td>-2</td>
<td>160</td>
<td>-3</td>
<td>-394</td>
<td>-8</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>6</td>
<td>2</td>
<td>171</td>
<td>3</td>
<td>-11</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>219</td>
<td>9</td>
<td>1</td>
<td>-30</td>
<td>485</td>
<td>-61</td>
</tr>
<tr>
<td>10</td>
<td>Left</td>
<td>-3</td>
<td>-148</td>
<td>-7</td>
<td>523</td>
<td>-29</td>
<td>148</td>
</tr>
</tbody>
</table>

The coordinate system associated with these loads is as per Reference 1, and is shown in Figure 5.12.1-5.

Figure 5.12.1-5: Loads Coordinate System

Figure 5.12.1-6 below shows the configuration of the Handle Bracket -305 with the Rail Post mounted on it and the system coordinate system.

Please note that this coordinate system is as per ProE model and I-DEAS FE model and is different than the above coordinate system (X and Y directions are reversed).
Figure 5.12.1-6: Handle Bracket-305 and Rail Post Assembly Configuration

Description of Model

A FE model of the Handle Bracket -305 is built using I-DEAS software.
9. The Handle Bracket is modeled using solid parabolic tetrahedral elements. These elements are best suited for complex and uneven geometry. The number of elements are selected based on the maximum unaveraged and averaged results in the critical area, such that convergence of results is achieved.

10. At the bolt holes, rigid elements are used to represent the bolt connections.

11. The model is constrained with DOF’s 1-3 at four bolt locations.

12. Four load cases are applied selected by engineering judgment from Reference 1, Table 10, page 30 and presented in Table 5.12.1-5. Please note that the ProE and I-DEAS models have a coordinate system different than the coordinate system shown in Reference 1 (see Figures 5.12.1-5 and 5.12.1-6 and note that X and Y directions are reversed). The FE model accounts for the difference in the two coordinate systems and inputs the loads accordingly.

13. The loads are applied at the top of the Bracket, as specified in Reference 1, using rigid elements that represent the four bolts and inserts. These elements connect the central Post bottom surface to the top face of the Bracket.

14. I-DEAS solver is used for analyzing the complete math model of the Handle Bracket. See page 5.12.1-35 for the FE model of the Handle Bracket.

15. I-DEAS is used to sort out the maximum of Principal, Von-Mises, and Shear stresses (see Appendix A19).

16. The FE model is checked using MSC/NASTRAN.

Model Checks

The quality of the model mesh was checked in I-DEAS for distortions and stretches of elements. The distortion and stretch filter is set at a threshold of 0.1. All elements passed the criteria.

Rigid body checks are performed using MSC/NASTRAN. Results are shown below. The KGG, KNN and KFF matrices all pass with low strain energies.
**AMS-02 HANDLE BRACKETS**

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG  (G-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  8.320577E-04

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.197907E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.209781E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>3.591731E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.356846E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>5.983033E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>9.964705E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN  (N-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  2.166578E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.707969E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.560937E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>5.069541E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.246116E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.933008E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>4.100027E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KFF  (F-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  2.166578E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.707969E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.560937E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>5.069541E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.246116E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>3.933008E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>4.100027E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

*** USER INFORMATION MESSAGE 7570 (GPWG1D)  
RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1  (A-SET) FOLLOW:  
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF  2.166578E-02

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.707969E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>4.560937E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>5.069541E-08</td>
<td>PASS</td>
</tr>
</tbody>
</table>

5.12.1-16  ESCG-4005-05-AMS-0039
A further check is done for the rigid body modes. The first 8 unconstrained modes are shown below. There are six rigid body modes (~ 0.0), and then good separation with the first non-rigid body mode.

Table 5.12.1-6: Eigenvalue Summary of Handle Bracket -305

<table>
<thead>
<tr>
<th>Mode NO.</th>
<th>Extraction Order</th>
<th>Eigenvalue</th>
<th>Mass</th>
<th>Cycles</th>
<th>Generalized Mass</th>
<th>Generalized Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.95E-04</td>
<td>1.39E-02</td>
<td>2.22E-03</td>
<td>1.00E+00</td>
<td>-1.95E-04</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.69E-04</td>
<td>1.30E-02</td>
<td>2.07E-03</td>
<td>1.00E+00</td>
<td>-1.69E-04</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-1.31E-04</td>
<td>1.15E-02</td>
<td>1.82E-03</td>
<td>1.00E+00</td>
<td>-1.31E-04</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>5.31E-05</td>
<td>7.29E-03</td>
<td>1.16E-03</td>
<td>1.00E+00</td>
<td>5.31E-05</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.03E-04</td>
<td>1.01E-02</td>
<td>1.61E-03</td>
<td>1.00E+00</td>
<td>1.03E-04</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2.76E-04</td>
<td>1.66E-02</td>
<td>2.64E-03</td>
<td>1.00E+00</td>
<td>2.76E-04</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>1.01E+09</td>
<td>3.17E+04</td>
<td>5.05E+03</td>
<td>1.00E+00</td>
<td>1.01E+09</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1.20E+09</td>
<td>3.46E+04</td>
<td>5.51E+03</td>
<td>1.00E+00</td>
<td>1.20E+09</td>
</tr>
</tbody>
</table>

Material and Temperature

The Handle Bracket -305 is made from 6061-T651 Aluminum Alloy. Material properties are taken from MMPDS-01 (see page 5.12.1-31). Temperature limits are -47° F to 139° F, as defined in Appendix C2 (on-orbit case).

Analysis Approach

The Handle Bracket -305 is designed to withstand loads as determined by testing done at Johnson Space Center Static Test Lab during January 2004.

Four different critical load cases are considered, which are selected by engineering judgment from Reference 1, Table 10, page 30 (see also Table 5.12.1-5). The loads are input in the FEM and the recovered stresses are compared to the ultimate and yield stresses of 6061-T651 Aluminum Alloy, corrected for the maximum temperature of 139° F. All Margins of Safety are positive.
MARGINS OF SAFETY FOR HANDLE BRACKET -303

The load cases are presented in Reference 1, Table 9, page 29 and summarized in Table 5.12.1-3 (see page 5.12.1-6). The worst cases are determined by engineering judgement and they are:

Load Case 1 - Left
The Bracket restraint points are shown in the picture on page 5.12.1-20
Load Case 1 - Right
The loads application point is shown in the picture on page 5.12.1-21
Load Case 7 - Left
Load Case 8 - Left

The loads are input in the FEM and the stresses are recovered and presented in Appendix A19.


\[
\begin{align*}
\text{maxU} & := \begin{pmatrix} 16190 \\ 19380 \\ 11890 \\ 16570 \end{pmatrix} \text{ psi} \\
\text{maxY} & := \begin{pmatrix} 16210 \\ 18000 \\ 11650 \\ 14920 \end{pmatrix} \text{ psi} \\
\text{maxS} & := \begin{pmatrix} 8778 \\ 9782 \\ 5942 \\ 8514 \end{pmatrix} \text{ psi}
\end{align*}
\]

\(i := 1..4\)


From MMPDS-01, Table 3.6.2.0(b2) for thickness of 0.25 inch to 2.00 inch

\(F_{tu} := 42000\text{psi} \quad F_{ty} := 35000\text{psi} \quad F_{su} := 27000\text{psi}\)

\(f_{tu} := 0.96 \quad f_{ty} := 0.96\)

Temperature correction factors for 139 deg F, from MMPDS-01, Figure 3.6.2.2.1(a) and (b)

\(F_{tu} := f_{tu} \cdot F_{tu} \quad F_{ty} := f_{ty} \cdot F_{ty} \quad F_{su} := f_{tu} \cdot F_{su}\)

Factors of Safety:

\(FSu := 2.0 \quad FSy := 1.25\)
## Margins of Safety

Margins of Safety:

\[
MS_u_i := \frac{F_{tu}}{F_{Su-maxU_i}} - 1
\]

\[
MS_y_i := \frac{F_{ty}}{F_{Sy-maxY_i}} - 1
\]

\[
MS_s_i := \frac{F_{su}}{F_{Su-maxS_i}} - 1
\]

\[
MS_u = \begin{pmatrix}
0.245 \\
0.04 \\
0.696 \\
0.217
\end{pmatrix}
\]

\[
MS_y = \begin{pmatrix}
0.658 \\
0.493 \\
1.307 \\
0.802
\end{pmatrix}
\]

\[
MS_s = \begin{pmatrix}
0.476 \\
0.325 \\
1.181 \\
0.522
\end{pmatrix}
\]

### MARGINS OF SAFETY FOR HANDLE BRACKET -303

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MS_u)</td>
<td>0.04</td>
<td>Ultimate - using principal - Load Case 1 - Right</td>
</tr>
<tr>
<td>(MS_y)</td>
<td>0.493</td>
<td>Yield - using Von-Mises - Load Case 1 - Right</td>
</tr>
<tr>
<td>(MS_s)</td>
<td>0.325</td>
<td>Shear - using shear - Load Case 1 - Right</td>
</tr>
</tbody>
</table>

See the location of maximum stresses on the stress plots on pages 5.12.1-23 to 5.12.1-30.
HANDLE BRACKET-303 AND RAIL POST ASSEMBLY

RESTRAINT POINTS
LOADS APPLICATION POINT

HANDLE BRACKET SDG39135878-303
FE MODEL OF HANDLE BRACKET-303
RESULTS: 3. B.C. 1, STRESS 3, CASE 1 LEFT
STRESS - MAX PRIN MIN: -2.33E+03 MAX: 1.62E+04
FRAME OF REF: PART

LOCATION OF HIGH STRESSES FOR LOAD CASE 1 LEFT – TOP VIEW
LOCATION OF HIGH STRESSES FOR LOAD CASE 1 LEFT – BOTTOM VIEW
LOCATION OF HIGH STRESSES FOR LOAD CASE 1 RIGHT – TOP VIEW
RESULTS: 7- B.C. 2 STRESS 7 CASE 1 RIGHT
STRESS - MAX PR IN MIN: -4.29E+03 MAX: 1.98E+04
FRAME OF REF: PART

LOCATION OF HIGH STRESSES FOR LOAD CASE 1 RIGHT – BOTTOM VIEW
RESULTS: 11-BC, 3-STRESS_11, CASE 7 LEFT
STRESS - MAX PRIN MIN: -3.61E+03 MAX: 1.28E+04
FRAME OF REF: PART

LOCATION OF HIGH STRESSES FOR LOAD CASE 7 LEFT – TOP VIEW
LOCATION OF HIGH STRESSES FOR LOAD CASE 7 LEFT – BOTTOM VIEW
RESULTS: 15- B.C. 4, STRESS 15 CASE 8 LEFT
STRESS: MAX PRIN MIN: -4.12E+03 MAX: 1.70E+04
FRAME OF REF: PART

VALUE OPTION: ACTUAL

LOCATION OF HIGH STRESSES FOR LOAD CASE 8 LEFT – BOTTOM VIEW
MARGINS OF SAFETY FOR HANDLE BRACKET -305

The load cases are presented in Reference 1, Table 10, page 30 and summarized in Table 5.12.1-5 (see page 5.12.1-13).

The worst cases are determined by engineering judgement and they are:

Load Case 2 - Left
Load Case 6 - Left
Load Case 8 - Left
Load Case 10 - Left

The loads are input in the FEM and the stresses are recovered and presented in Appendix A19.

See pages A19-15, A19-17, A19-21, and A19-23 for maximum values.

\[
\begin{align*}
\text{maxU} & := \begin{pmatrix}
11680 \\
12660 \\
17420 \\
16880 \\
\end{pmatrix} \text{psi} \\
\text{maxY} & := \begin{pmatrix}
8660 \\
15880 \\
23140 \\
11610 \\
\end{pmatrix} \text{psi} \\
\text{maxS} & := \begin{pmatrix}
4417 \\
9150 \\
12350 \\
5936 \\
\end{pmatrix} \text{psi}
\end{align*}
\]

\(i := 1, 4\)


From MMPDS-01, Table 3.6.2.0(b2) for thickness of 0.25 inch to 2.00 inch

\[
\begin{align*}
F_{tu} & := 42000 \text{psi} \\
F_{ty} & := 35000 \text{psi} \\
F_{su} & := 27000 \text{psi}
\end{align*}
\]

\[f_{tu} := 0.96\]

Temperature correction factors for 139 deg F, from MMPDS-01, Figure 3.6.2.2.1(a) and (b)

\[f_{ty} := 0.96\]

Temperature are defined in Appendix C2.

\[
\begin{align*}
F_{tu} & := f_{tu} \cdot F_{tu} \\
F_{ty} & := f_{ty} \cdot F_{ty} \\
F_{su} & := f_{tu} \cdot F_{su}
\end{align*}
\]

Ftu = 40320 psi

Fty = 33600 psi

Fsu = 25920 psi

Factors of Safety:

\[
\begin{align*}
F_{Su} & := 2.0 \\
F_{Sy} & := 1.25
\end{align*}
\]
Margins of Safety:

\[
\text{MSu}_i := \frac{\text{Ftu}}{\text{FSu-maxU}_i} - 1 \quad \text{MSu} = \begin{pmatrix}
0.726 \\
0.592 \\
0.157 \\
0.194
\end{pmatrix}
\]

\[
\text{MSy}_i := \frac{\text{Fty}}{\text{FSy-maxY}_i} - 1 \quad \text{MSy} = \begin{pmatrix}
2.104 \\
0.693 \\
0.162 \\
1.315
\end{pmatrix}
\]

\[
\text{MSs}_i := \frac{\text{Fsu}}{\text{FSu-maxS}_i} - 1 \quad \text{MSs} = \begin{pmatrix}
1.934 \\
0.416 \\
0.049 \\
1.183
\end{pmatrix}
\]

MARGINS OF SAFETY FOR HANDLE BRACKET -305

\[
\text{MSu} := \min(\text{MSu}) \quad \text{MSu} = 0.157
\]

Ultimate - using principal - Load Case 8 - Left

\[
\text{MSy} := \min(\text{MSy}) \quad \text{MSy} = 0.162
\]

Yield - using Von-Mises - Load Case 8 - Left

\[
\text{MSs} := \min(\text{MSs}) \quad \text{MSs} = 0.049
\]

Shear - using shear - Load Case 8 - Left

See the location of maximum stresses on the stress plots on pages 5.12.1-36 to 5.12.1-39.
HANDLE BRACKET-305 AND RAIL POST ASSEMBLY

RESTRAINT POINTS (TWO ON EACH SIDE)
LOCATION OF HIGH STRESSES FOR LOAD CASE 2 LEFT
LOCATION OF HIGH STRESSES FOR LOAD CASE 6 LEFT
LOCATION OF HIGH STRESSES FOR LOAD CASE 8 LEFT
LOCATION OF HIGH STRESSES FOR LOAD CASE 10 LEFT
5.12.2 Handle Bracket Bolt Analysis
Margins of Safety

Table 5.12.2-1: Minimum Margins of Safety Summary for Handle Bracket Bolts

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1954C6</td>
<td>Handle Bracket -303, Bottom Bolts</td>
<td>A-286</td>
<td>Load Case 1 Right End</td>
<td>Comb Shear Tension Bend Ultim</td>
<td>0.154</td>
<td>5.12.2-7</td>
</tr>
<tr>
<td>NAS1351N3-8</td>
<td>Handle Bracket -303, Top Bolts</td>
<td>A-286</td>
<td>Load Case 1 Right End</td>
<td>Total Tension Yield</td>
<td>0.033</td>
<td>5.12.2-17</td>
</tr>
<tr>
<td>NAS1954C4</td>
<td>Handle Bracket -305, Bottom Bolts</td>
<td>A-286</td>
<td>Load Case 8 Left End</td>
<td>Total Tension Yield</td>
<td>0.181</td>
<td>5.12.2-28</td>
</tr>
<tr>
<td>NAS1351N3-8</td>
<td>Handle Bracket -305, Top Bolts</td>
<td>A-286</td>
<td>Load Case 8 Left End</td>
<td>Total Tension Yield</td>
<td>0.038</td>
<td>5.12.2-38</td>
</tr>
</tbody>
</table>

Table 5.12.2-2: Minimum Fail-Safe Margins of Safety Summary for Handle Bracket Bolts

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1954C6</td>
<td>Handle Bracket -303, Bottom Bolts</td>
<td>A-286</td>
<td>Load Case 1 Right End</td>
<td>Comb Shear Tension Bend Ultim</td>
<td>0.16</td>
<td>5.12.2-8</td>
</tr>
<tr>
<td>NAS1351N3-8</td>
<td>Handle Bracket -303, Top Bolts</td>
<td>A-286</td>
<td>Load Case 1 Right End</td>
<td>Joint Separation</td>
<td>0.243</td>
<td>5.12.2-23</td>
</tr>
<tr>
<td>NAS1954C4</td>
<td>Handle Bracket -305, Bottom Bolts</td>
<td>A-286</td>
<td>Load Case 8 Left End</td>
<td>Total Thread Shear Ultim</td>
<td>0.485</td>
<td>5.12.2-29</td>
</tr>
<tr>
<td>NAS1351N3-8</td>
<td>Handle Bracket -305, Top Bolts</td>
<td>A-286</td>
<td>Load Case 8 Left End</td>
<td>Comb Shear Tension Bend Ultim</td>
<td>0.351</td>
<td>5.12.2-44</td>
</tr>
</tbody>
</table>

This analysis covers the fasteners for the three Handle Bracket Assemblies used on USS-02 Assembly and presented in drawing SDG39135878. The three Handle Brackets Assemblies are: (1) Handle Bracket Assembly, part SDG39135878-303, (2) Handle Bracket Assembly, part SDG39135878-301/307 and (3) Handle Bracket Assembly, part SDG39135878-305.

Each Bracket Assembly has two sets of fasteners: (1) the bottom fasteners connecting the Bracket Assembly to the Lower / Upper USS-02 Assembly and (2) the top fasteners connecting the Rail Post to the Bracket Assembly.
Handle Bracket-303 Bottom Bolts Analysis

The Handle Bracket (drawing SDG39135878-303) is attached to the Bridge Beam Elbow (drawing SDG39135734) with 4 bolts, nuts and washers.

From Appendix A19, pages 10 and 11 find the bolt reactions for the four cases (use maximum absolute values):

Note that the X and Y components are the shear loads in the X and Y directions and the Z component is the normal load.

\[
\begin{align*}
V_x &= 517.1 \text{ lbf} & V_y &= 121.9 \text{ lbf} & P_1 &= 173.8 \text{ lbf} & \text{Load Case 1 Left Rail End} \\
V_x &= 593.8 \text{ lbf} & V_y &= 88.65 \text{ lbf} & P_2 &= 213.2 \text{ lbf} & \text{Load Case 1 Right Rail End} \\
V_x &= 54.41 \text{ lbf} & V_y &= 25.84 \text{ lbf} & P_3 &= 34.94 \text{ lbf} & \text{Load Case 7 Left Rail End} \\
V_x &= 493.1 \text{ lbf} & V_y &= 54.57 \text{ lbf} & P_4 &= 181.4 \text{ lbf} & \text{Load Case 8 Left Rail End}
\end{align*}
\]

\[
\begin{align*}
V_1 &= \sqrt{(V_x)^2 + (V_y)^2} & V_2 &= \sqrt{(V_x)^2 + (V_y)^2} & V_3 &= \sqrt{(V_x)^2 + (V_y)^2} & V_4 &= \sqrt{(V_x)^2 + (V_y)^2} \\
V_1 &= 531.3 \text{ lbf} & V_2 &= 600.4 \text{ lbf} & V_3 &= 60.2 \text{ lbf} & V_4 &= 496.1 \text{ lbf}
\end{align*}
\]
AMS-02 HANDLE BRACKET BOLTS

CHECK

Bolt (NAS1954C6, 0.2500-28, 0.2481 Dia, 0.800 L, .425 Lt, CRES A286 180 KSI, Passivate)
Bolt Head Washer (NAS1587-4C, .531 OD, .260 ID, .078 Thk, CRES 75 KSI, Passivate)
Nut Washer (NAS1149E0463R, .500 OD, .265 ID, .063 Thk, CRES A286 160 KSI, Passivate)
Nut (NAS1291C4M, CRES A286 125 KSI)

Flange 1: Handle Bracket
Part number: Drawing SDG39135878-303
Material: 6061-T651

Flange 2: Bridge Beam Elbow
Part number: Drawing SDG39135734
Material: 7050-T7451

Use the bolt loads for Load Case 1 Right Rail End, since they are the highest loads.

Loads

Applied tensile load \( P := P_2 \)
Applied shear load \( V := V_2 \)
Applied bending moment \( M := 0 \text{in-lbf} \)

Factors of Safety

Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)
Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)

Temperature data

Assembly
Temp_initial := 70 deg

Maximum
Temp_max := 139 deg

Minimum
Temp_min := -47 deg

Bolt and Nut Data

Nominal diameter of bolt \( D := .25 \text{-in} \)
Number of threads/inch \( N_t := 28 \frac{1}{\text{in}} \)
Total length of bolt \( L := 0.800 \text{-in} \)
Height of nut \( H := 0.204 \text{-in} \)
Threaded length \( L_t := 0.425 \text{-in} \)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\thread_data.mcd

Tue Feb 15 10:54:02 AM 2005
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**Washer Data**

- Thickness of washers (2X): \( tw := 0.141\text{ in} \)
- Outer Diameter of washer: \( Dw := 0.500\text{ in} \)
- Inner Diameter of washer: \( Dwi := 0.265\text{ in} \)
- Bolt head dia. across flats: \( dw := 0.430\text{ in} \) (used only if there is no washer)

**Flange data**

- Thickness of flange 1: \( tf1 := 0.125\text{ in} \)
- Thickness of flange 2: \( tf2 := 0.25\text{ in} \)
- Diameter of hole: \( D_{\text{hole}} := 0.288\text{ in} \)

Note: If there is no washer \( tw \), \( Dw \) and \( Dwi \) should be zero

**Material Property Data**

**Bolt**

- Temperature correction factor for bolt strength, ultimate and yield: \( TS_{\text{bolt}} := 0.97 \) \( TS_{\text{y bolt}} := 0.97 \) (Ref. MMPDS-01, fig.6.2.1.1.1)
- Bolt ultimate tensile allowable stress: \( F_{tu\_bolt} := 180000\text{ psi} \) (Ref. NAS1954C6)
- Bolt ultimate shear allowable stress: \( F_{su\_bolt} := 0.6 \times F_{tu\_bolt} \)
- Bolt yield Tensile allowable stress: \( F_{ty\_bolt} := 132353\text{ psi} \) (Ref. Appendix C10)
- Temperature correction factor for bolt modulus: \( TE_{\text{bolt}} := 0.98 \) (Ref. MMPDS-01, fig. 6.2.1.1.4(a))
- Modulus of elasticity of bolt: \( E_{\text{bolt}} := \left(29.1 \times 10^6\right)\text{ psi} \) (Ref. MMPDS-01, table 6.2.1.0(b))
- Thermal coefficient for bolt:
  \[ \beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
  \[ \beta_{\text{bolt\_cold}} := 8.7 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

**Nut**

- Temperature correction factor for nut strength: \( TS_{\text{nut}} := 0.97 \) (Ref. MMPDS-01, fig. 6.2.1.1.1)
- Ultimate tensile allowable stress: \( F_{tu\_nut} := 125000\text{ psi} \)
- Ultimate Shear allowable stress: \( F_{su\_nut} := 0.6 \times F_{tu\_nut} \)
- Ultimate axial strength of nut: \( P_{tu\_nut} := 4580\text{ lbf} \) (Ref. NAS1291C4M page 2)

**Washer**

- Temperature correction factor for washer modulus: \( TE_{\text{washer}} := 0.97 \) (Ref MMPDS-01, fig. 6.2.1.1.4(a))
- Modulus of elasticity of washer: \( E_{\text{washer}} := \left(29.1 \times 10^6\right)\text{ psi} \) (Ref MMPDS-01, table. 6.2.1.0(b))
AMS-02 HANDLE BRACKET BOLTS

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 (6061 Al Alloy)  \( T_{1E} := 0.98 \) (modulus)  
(Ref. MMPDS-01, fig. 3.6.2.2.4)

Temperature correction factor for flange 2 (7075 Al Alloy)  \( T_{2E} := 0.98 \) (modulus)  
(Ref. MMPDS-01, fig. 3.7.6.1.4)

(Aluminum 7050 and 7075 have similar material properties)

Modulus of elasticity for the parts in the joint  
\[ E_{\text{flange}1} := 9.9 \times 10^6 \text{ psi} \]  
\[ E_{\text{flange}2} := 10.3 \times 10^6 \text{ psi} \]  
(Ref. MMPDS-01, tables 3.6.2.0(b2) and 3.7.4.0(b1))

Coefficient of thermal expansion for flanges  
\[ \beta_{\text{flange}1_{\text{hot}}} := 12.8 \times 10^{-6} \text{ in}^{-1} \text{ deg}^{-1} \]  
\[ \beta_{\text{flange}2_{\text{hot}}} := 12.3 \times 10^{-6} \text{ in}^{-1} \text{ deg}^{-1} \]  
(Ref. MMPDS-01, fig. 3.6.2.0 and 3.7.6.0)

Torque/Preload data

Maximum torque (65% of yield)  
\( T_{\text{max}} := 107 \text{ in-lbf} \)  
Loading plane factor  \( n := 0.5 \)

Minimum torque (95% of max. torque)  
\( T_{\text{min}} := 101 \text{ in-lbf} \)  
Preload Uncertainty  \( u := 0.25 \)

Torque coefficient (Lubricated)  
\( k := 0.15 \)

This file uses the calculations shown in \esccf/02/11_mathcad/8307_bolts/bolt_stiffness_nut_RevC

Bolt Load data

Bolt/joint stiffness factor  \( = 0.343 \)  
Preload due to temperature  \( P_{\text{thr\_pos}} = 140.3 \text{ lbf} \)

Max. preload  \( PLD_{\text{max}} = 3707 \text{ lbf} \)  
Uncertainty factor  \( u = 0.25 \)

Min. preload  \( PLD_{\text{min}} = 1594.4 \text{ lbf} \)  
Torque coefficient  \( k = 0.15 \)

Joint separation load  \( P_{\text{sep}} = 255.84 \text{ lbf} \)  
Loading plane factor  \( n = 0.5 \)

Max. load on the bolt(ultimate)  \( P_b = 3791 \text{ lbf} \)  
Thread pullout strength required to develop full strength of bolt  \( P_{\text{As}} = 7392.4 \text{ lbf} \)

Max. load on the bolt(yield)  \( P_{\text{by}} = 3759.5 \text{ lbf} \)  
Nut ultimate tensile strength  \( P_{\text{tu\_nut}} = 4442.6 \text{ lbf} \)

Bolt ultimate tensile strength  \( P_{\text{At}} = 4442.6 \text{ lbf} \)

Length_check = "Bolt length is sufficient"
Summary of Margins for bolt:

- Joint separation: $MS_1 = 5.54$ Direct Thread shear Ultimate $MS_6 = 14.08$
- Direct Tension Ultimate: $MS_2 = 8.06$ Total Thread shear Ultimate $MS_7 = 0.95$
- Direct Tension Yield: $MS_3 = 13.78$ Shear Ultimate $MS_8 = 2.72$
- Total Tension Ultimate: $MS_4 = 0.17$ Bending Ultimate $MS_9 = 10$
- Total Tension Yield: $MS_5 = 0.205$ Combined shear, tension and bending ultimate $MS_{10} = 0.154$

Determination of the smallest margin of safety for the bolt, and the failure mode:

$$MS_{bolt} := \min(MS)$$

$$MS_{bolt} = 0.154 \quad \text{Failure Mode = "Combined Shear Tension Bending Ultimate"}$$

Bolt Fail-Safe Analysis

For bolt fail-safe analysis, the bolt with the highest load is removed and the FEM run with only three constraints.

From Appendix A19, pages 25, 26 and 27 find the bolt reactions for the four cases (use maximum absolute values):

Note that the X and Y components are the shear loads in the X and Y directions and the Z component is the normal load.

$$V_x := 939.2 \text{-lbf} \quad V_y := 271.4 \text{-lbf} \quad P_1 := 343.1 \text{-lbf}$$
Load Case 1 Left Rail End

$$V_x := 1055.0 \text{-lbf} \quad V_y := 269.3 \text{-lbf} \quad P_2 := 390.9 \text{-lbf}$$
Load Case 1 Right Rail End

$$V_x := 163.1 \text{-lbf} \quad V_y := 33.3 \text{-lbf} \quad P_3 := 64.97 \text{-lbf}$$
Load Case 7 Left Rail End

$$V_x := 942.4 \text{-lbf} \quad V_y := 249.2 \text{-lbf} \quad P_4 := 359.2 \text{-lbf}$$
Load Case 8 Left Rail End

$$V_1 := \sqrt{(V_x_1)^2 + (V_y_1)^2} \quad V_2 := \sqrt{(V_x_2)^2 + (V_y_2)^2} \quad V_3 := \sqrt{(V_x_3)^2 + (V_y_3)^2} \quad V_4 := \sqrt{(V_x_4)^2 + (V_y_4)^2}$$

$$V_1 = 977.6 \text{-lbf} \quad V_2 = 1088.8 \text{-lbf} \quad V_3 = 166.5 \text{-lbf} \quad V_4 = 974.8 \text{-lbf}$$

Use the bolt loads for Load Case 1 Right Rail End, since they are the highest loads.
AMS-02 HANDLE BRACKET BOLTS

**Fail-safe Loads**

- **Applied tensile load**
  
  \[ P_{FS} := 390.9 \text{ lbf} \]

- **Applied shear load**
  
  \[ V_{FS} := 1088.8 \text{ lbf} \]

- **Applied bending moment**
  
  \[ M_{FS} := 0 \text{ in-lbf} \]

**Fail-safe Factors of Safety**

- **Ultimate**
  
  \[ SF_{u,FS} := 1.0 \]

- **Joint Separation**
  
  \[ SF_{sep,FS} := 1.0 \]

---

**Bolt Fail-safe Load data**

- **Joint separation load**
  
  \[ P_{sep,FS} = 390.9 \text{ lbf} \]

- **Max. load on the bolt (ultimate)**
  
  \[ P_{b,FS} = 3784 \text{ lbf} \]

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Margin of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>[ MS_{FS,1} = 3.28 ]</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>[ MS_{FS,2} = 8.88 ]</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>[ MS_{FS,3} = 0.17 ]</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>[ MS_{FS,4} = 15.44 ]</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>[ MS_{FS,5} = 0.95 ]</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>[ MS_{FS,6} = 3.11 ]</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>[ MS_{FS,7} = 10 ]</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>[ MS_{FS,8} = 0.16 ]</td>
</tr>
</tbody>
</table>

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ MS_{bolt,FS} := \min(\text{MS}_{FS}) \]

\[ MS_{bolt,FS} = 0.16 \]

**Failure Mode**: Combined Shear Tension Bending Ultimate
Handle Bracket-303 Top Bolts Analysis

The Rail Post (Bracket, ISS Handrail Assembly), drawing SDG33106341, is attached to the Handle Bracket Assembly, drawing SDG39135878-303, with 4 bolts NAS 1351N3 (0.190-32UNJF-3A). The bolts are screwed into inserts MS51831CA-201L, which are part of the Handle Bracket Assembly. The analysis of the Handle Bracket Assembly is covered in Section 5.12.1.

Bolt Geometry

$$\begin{align*}
\text{size} & \quad \text{thread/in} \\
0.19 & \quad 32 \\
0.19 & \quad 32 \\
0.19 & \quad 32 \\
0.19 & \quad 32 \\
\end{align*}$$

$$\text{bolt} := \begin{bmatrix}
0.19 \\
0.19 \\
0.19 \\
0.19 \\
\end{bmatrix}$$

$$\text{i} := 1..\text{rows(bolt)}$$

$$\text{Ni} \ := \ \text{bolt}_{1,2} \ \frac{1}{\text{in}} \ \text{pitch of bolt}$$

$$\text{Di} \ := \ \text{bolt}_{1,1} \ \text{in} \ \text{bolt diameter}$$
Handle Bracket Bolt Pattern

Bolt no.  x co-ord  y co-ord  z co-ord
1         0.375  0.375  -0.375
2         0.375  0.375  -0.375
3         -0.375 -0.375  -0.375
4         -0.375 -0.375  -0.375

Location of Applied Forces and Moments

xforce := 0.0in  yforce := 0.0in  zforce := 0.0in

cgload := [xforce  yforce  zforce]  
cgload = [0  0  0]in

\[ \text{At}_{i} := \beta \left( \frac{D_{i} - 0.9743 \frac{1}{N_{i}}}{2} \right)^{2} \]

\[ \text{As}_{i} := \beta \left( \frac{D_{i} - 1.299038 \frac{1}{N_{i}}}{2} \right)^{2} \]

Tensile Area of bolt  
Shear Area of bolt
AMS-02 HANDLE BRACKET BOLTS

Center of Gravity of Bolt Group

\[
\begin{align*}
\text{xcg} &= \frac{\sum x_i}{\text{rows}(x)} \quad \text{xcg} = 0\text{-in} \\
\text{ycg} &= \frac{\sum y_i}{\text{rows}(y)} \quad \text{ycg} = 0\text{-in} \\
\text{zcg} &= \frac{\sum z_i}{\text{rows}(z)} \quad \text{zcg} = 0\text{-in}
\end{align*}
\]

\[
\text{cg}_{\text{bolt}} := \left( \begin{array}{c} \text{xcg} \\ \text{ycg} \\ \text{zcg} \end{array} \right) = \left( \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right) \text{ in}
\]

Note: The bolt pattern is symmetric about all three axes.

Load Vector

\[
\text{r}_{\text{load}} := \text{cg}_{\text{load}} - \text{cg}_{\text{bolt}} = \left( \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right) \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_i := \sqrt{(x_i - \text{xcg})^2 + (y_i - \text{ycg})^2}
\]

\[
r = \left( \begin{array}{c} 0.783 \\ 0.783 \\ 0.783 \end{array} \right) \text{ in}
\]

Bolt loads are retrieved from the FEM for the four worst cases (see Report 5.12.1, page 6). These loads are presented in the Table below.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Rail End</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left</td>
<td>263</td>
<td>-2</td>
<td>150</td>
<td>10</td>
<td>416</td>
<td>29</td>
</tr>
<tr>
<td>1</td>
<td>Right</td>
<td>-257</td>
<td>-4</td>
<td>63</td>
<td>6</td>
<td>-536</td>
<td>-26</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>2</td>
<td>-207</td>
<td>-1</td>
<td>542</td>
<td>-1</td>
<td>-29</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>207</td>
<td>-2</td>
<td>-4</td>
<td>-1</td>
<td>476</td>
<td>-18</td>
</tr>
</tbody>
</table>

Database for Bolted Joint

\[
data := \begin{pmatrix} 1 & 1 & 263 & -2 & 150 & 10 & 416 & 29 \\ 1 & 2 & -257 & -4 & 63 & 6 & -536 & -26 \\ 7 & 1 & 2 & -207 & -1 & 542 & -1 & -29 \\ 8 & 1 & 207 & -2 & -4 & -1 & 476 & -18 \end{pmatrix}
\]

Note: In the second column of the data matrix, number 1 represents "Rail End Left" and number 2 represents "Rail End Right".
num_bolts := rows(bolt)  j := 1..rows(data)

num_bolts = 4

Axial Load  Fz_j := data.j,5 · lbf  Torsion  Mz_j := data.j,8 · in·lbf
Shear in Y axis  Fy_j := data.j,4 · lbf  Moment about Y axis  My_j := data.j,7 · in·lbf
Shear in X axis  Fx_j := data.j,3 · lbf  Moment about X axis  Mx_j := data.j,6 · in·lbf

Applied Bending Moment at Bolts  M_j := 0·in·lbf

Moment Distribution

\[
M_{\text{tot}}^{(j)} := \begin{pmatrix}
Mx_j \\
My_j \\
Mz_j
\end{pmatrix} + r_{\text{load}} \times \begin{pmatrix}
Fx_j \\
Fy_j \\
Fz_j
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

Mx_boltcg_j := M_{\text{tot1},j}  My_boltcg_j := M_{\text{tot2},j}  Mz_boltcg_j := M_{\text{tot3},j}

Tension on Bolts

Fdirect_{i,j} := \begin{cases} 
0·lbf & \text{if } Fz_j \leq 0\text{lbf} \\
\frac{Fz_j}{\text{num_bolts}} & \text{otherwise}
\end{cases}

Direct tensile load calculation - (The "if" statement checks for compression)

\[
F_{\text{mx}}_{i,j} := \begin{cases} 
0·lbf & \text{if } (y_i - y_{\text{ycg}}) = 0\text{ in} \\
\frac{\text{My}_j \cdot (y_i - y_{\text{ycg}})}{\sum_i (y_i - y_{\text{ycg}})^2 \cdot A_i} & \text{otherwise}
\end{cases}
\]

\[
F_{\text{my}}_{i,j} := \begin{cases} 
0·lbf & \text{if } (x_i - x_{\text{xcg}}) = 0\text{ in} \\
\frac{\text{My}_j \cdot (x_i - x_{\text{xcg}})}{\sum_i (x_i - x_{\text{xcg}})^2 \cdot A_i} & \text{otherwise}
\end{cases}
\]

\[
F_{t,i,j} := F_{\text{direct}}_{i,j} + F_{\text{mx}}_{i,j} + F_{\text{my}}_{i,j}
\]

Total Tensile load

Shear on Bolts

Secondary shear on bolts  \[
F_{s,i,j} := \frac{Mz_{\text{boltcg}} \cdot r_i \cdot A_i}{\sum_i (r_i)^2 \cdot (A_i)}
\]

\[5.12.2 - 12\]
Direct shear loads
\[ F_{sd\ i,j} := \sqrt{\left(F_{yj}\right)^2 + \left(F_{xj}\right)^2} \over \text{num_bolts} \]

Total shear load
\[ F_{stot\ i,j} := F_s\ i,j + F_{sd\ i,j} \]

The stack commands below are used to stack the Load Case (LC) and Rail End identification (ID) in ascending order per bolt. The Load Case (LC) number is located in the first column and the Rail End (ID) numbers in the second column. For each Load Case, the bolt number within the bolt pattern is added to the end of each LC number. For example, the Load Case identification number 1 will have bolt numbers 1 thru 4 attached to the end for all 4 load cases. This brings the total number of load cases to 16 (4 bolts x 4 load cases).

Load Case
\[ LC_\ j := \text{data}_{\ j,1} \]
\[ LC_\ j := LC_\ j \cdot 10 + 1 \] Counter for number of bolts in pattern

Rail End ID
\[ ID_\ j := \text{data}_{\ j,2} \]

LC := stack(LC, LC + 1, LC + 2, LC + 3)

ID := stack(ID, ID, ID, ID)

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the Load Case (LC) number and Rail End (ID) number from above. See the "Output" file below.

\[ P := \text{stack}\left[\left(F_t\right)^{(1)}, \left(F_t\right)^{(2)}, \left(F_t\right)^{(3)}, \left(F_t\right)^{(4)}\right] \]

\[ V := \text{stack}\left[\left(F_{stot}T\right)^{(1)}, \left(F_{stot}T\right)^{(2)}, \left(F_{stot}T\right)^{(3)}, \left(F_{stot}T\right)^{(4)}\right] \]

\[ M := \text{stack}(M, M, M, M) \]

The "Output" file below outputs an array from left to right starting with the Load Case (LC), Rail End Identification (ID), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M).

\[ \text{Output} := \text{augment}\left( LC, ID, \frac{P}{\text{lbf}}, \frac{V}{\text{lbf}}, \frac{M}{\text{in lbf}} \right) \]

(Note: Since the LC and ID numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)
The array from the Output above is read.

data := Output
s := 1..rows(data)

Flange 1: Bracket, ISS Handrail Assembly
Part number: SDG33106341
Material: 7075-T7351

Flange 2: Handle Bracket Assembly
Part number: SDG39135878
Material: 6061-T651
# AMS-02 HANDLE BRACKET BOLTS

## Factors of Safety

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu := 2.0</td>
</tr>
<tr>
<td>Yield</td>
<td>SFy := 1.25</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep := 1.2</td>
</tr>
<tr>
<td>Fitting factor</td>
<td>FF := 1.15</td>
</tr>
</tbody>
</table>

## Temperature Data (Ref Appendix C2), On-Orbit Case

- **Assembly**: Temp_initial := 70-deg
- **Maximum**: Temp_max := 139-deg
- **Minimum**: Temp_min := -47-deg

## Bolt and Insert Data

- **Nominal diameter of bolt**: D := 0.190-in
- **Total length of bolt**: L := 0.500-in
- **Threaded length**: Lt := L
- **Number of threads/inch**: Nt := \( \frac{32}{1} \) in
- **Length of insert**: Lins := 0.312-in
- **Min. external diameter of insert**: Fmin := 0.312-in
- **Depth of recess for insert**: lr := 0.02-in

## Washer Data

- **Thickness of washer**: tw := 0.0-in
- **Outer Diameter of washer**: Dw := 0.0-in
- **Inner Diameter of washer**: Dwi := 0.0-in
- **Bolt head dia. across flats**: dw := 0.303-in

## Flange data

- **Thickness of flange 1** (Ref. SDG33106341): tf1 := .188-in
- **Thickness of flange 2** (insert length): tf2 := .312-in
- **Diameter of hole** (Ref. SDG33106341): D_hole := 0.23-in

## Material Property Data

### Bolt

- **Temperature correction factor for bolt strength ultimate** (Ref. MMPDS-01, fig. 6.2.1.1.1): TSu_bolt := 0.97
- **Bolt ultimate tensile allowable stress**: Ftu_bolt := 160000-psi (Ref. NAS1351N3)
- **Bolt ultimate shear allowable stress**: Fsu_bolt := 0.6\(\times\)Ftu_bolt
- **Bolt yield tensile allowable**: Fty_bolt := 120000-psi
- **Temperature correction factor for bolt modulus** (Ref. MMPDS-01, fig. 6.2.1.1.4(a)): TE_bolt := .98
- **Modulus of elasticity of bolt**: E_bolt := \( \left( \frac{29.1 \times 10^6}{\text{psi}} \right) \) (Ref. MMPDS-01, table 6.2.1.0(b))
Thermal coefficient for bolt: \( u_{\text{bolt\_hot}} := 9.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \) \( u_{\text{bolt\_cold}} := 8.7 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)  
(Ref. MMPDS-01, fig. 6.2.1.0)

**Insert**

Temperature correction factor for insert strength \( TS_{\text{ins}} := .97 \)  
(Ref. MMPDS-01, fig. 6.2.1.1.1)
Ultimate tensile allowable stress \( F_{tu_{\text{ins}}} := 140000\text{-psi} \)  
(Ref. MS51831)
Ultimate shear allowable stress \( F_{su_{\text{ins}}} := 0.6F_{tu_{\text{ins}}} \)

**Washer**

Temperature correction factor for washer modulus \( TE_{\text{washer}} := .97 \)  
(Ref. MMPDS-01, fig. 6.2.1.1.4(a))
Modulus of elasticity of washer \( E_{\text{washer}} := \left(29.1 \cdot 10^6\text{-psi}\right) \)  
(Ref. MMPDS-01, table 6.2.1.0(b))

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, 
Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{f1E} := .98 \) (modulus)  
(Ref. MMPDS-01, fig. 3.7.6.1.4)
Temperature correction factor for flange 2 \( T_{f2E} := .98 \) (modulus)  
(Ref. MMPDS-01, fig. 3.6.2.2.4)
\( T_{f2s} := .96 \) (strength)  
(Ref. MMPDS-01, fig. 3.6.2.2.1(a) and (b))

Shear Strength Allowable for flanges \( F_{su_{f2}} := 27000\text{-psi} \)  
(Ref. MMPDS-01, table 3.6.2.0(b2))

Modulus of elasticity for the parts in the joint \( E_{\text{flange1}} := \left(10.3 \cdot 10^6\text{-psi}\right) \) \( E_{\text{flange2}} := \left(9.9 \cdot 10^6\text{-psi}\right) \)  
(Ref. MMPDS-01, table 3.7.6.0(b1) and 3.6.2.0(b2))

Coefficient of thermal expansion for flanges \( u_{\text{flange1\_hot}} := 12.3 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \) \( u_{\text{flange2\_hot}} := 12.8 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)  
(Ref. MMPDS-01, fig. 3.7.6.0 and 3.6.2.0)
\( u_{\text{flange1\_cold}} := 12.1 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \) \( u_{\text{flange2\_cold}} := 12.4 \cdot 10^{-6} \frac{\text{in}}{\text{deg}} \)

**Torque/Preload Data**

Maximum torque (65% of yield) \( T_{\text{max}} := 44.4\text{-in-lbf} \) \( \text{Loading plane factor: } n := .5 \)
Minimum torque (95% of max. torque) \( T_{\text{min}} := 42.2\text{-in-lbf} \)  
Preload Uncertainty: \( := 0.25 \)
Torque coefficient (Lubricated): \( k := 0.15 \)

This file uses the calculations shown in \escfli02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Bolt/joint stiffness factor: $v = 0.424$

Max. preload: PLD$_{\text{max}} = 2055.5$-lbf

Min. preload: PLD$_{\text{min}} = 825.9$-lbf

Joint separation load: $\text{max}(P_{\text{sep}}) = 450.318$-lbf

Max. load on the bolt (ultimate): $\text{max}(P_{\text{b}}) = 2238.7$-lbf

Max. load on the bolt (yield): $\text{max}(P_{\text{by}}) = 2170$-lbf

Bolt ultimate tensile strength: $P_{\text{At}} = 2987.4$-lbf

Preload due to temperature: Pthr$_{\text{pos}} = 108.1$-lbf

Uncertainty factor: = 0.25

Torque coefficient: $k = 0.15$

Loading plane factor: $n = 0.5$

Thread shear pullout load of bolt or insert: Pths = 6342.1-lbf

Thread shear pullout load in parent metal: P$pths = 3963.4$-lbf

Length check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>MS$_{\text{min}}$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS$<em>{\text{min}}</em>{1,1} = 1.024$</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS$<em>{\text{min}}</em>{2,1} = 2.461$</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS$<em>{\text{min}}</em>{3,1} = 3.153$</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS$<em>{\text{min}}</em>{4,1} = 0.334$</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS$<em>{\text{min}}</em>{5,1} = 0.033$</td>
<td>Combined shear, tension and bending</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

$\text{MS}_{\text{bolt}} := \text{min}(\text{MS})$

$\text{MS}_{\text{bolt}} = 0.033$  

Failure Mode = "Total Tension Yield"

<table>
<thead>
<tr>
<th>MS$<em>{\text{min}}</em>{\text{LC}}$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Load Case ID (1) and Bolt Number (3) for Minimum Margin</td>
</tr>
<tr>
<td>2</td>
<td>Rail End ID for Minimum Margin</td>
</tr>
<tr>
<td>375.3</td>
<td>Applied Tensile Load for Minimum Margin</td>
</tr>
<tr>
<td>56</td>
<td>Applied Shear Load for Minimum Margin</td>
</tr>
<tr>
<td>0</td>
<td>Applied Bending Moment for Minimum Margin</td>
</tr>
</tbody>
</table>
Bolt Fail-Safe Analysis

Since bolt number 3 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 3, NAS 1351N3 0.19-32 fasteners, holding the Post to the Bracket.

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
\text{bolt2} & := \begin{pmatrix} 0.19 & 32 \\ 0.19 & 32 \\ 0.19 & 32 \end{pmatrix} \\
s & := 1 .. \text{rows(bolt2)} \\
N_2^s & := \text{bolt2}_s, \frac{1}{\text{in}} \\
D_2^s & := \text{bolt2}_s, \text{in} \\
\beta \text{ tensile area of bolt} & := \beta \left( \frac{D_2^s - 1.299038 \frac{1}{N_2^s}}{2} \right)^2 \\
\beta \text{ shear area of bolt} & := \beta \left( D_2^s - 1.9743 \frac{1}{N_2^s} \right)^2 \\
\end{align*}
\]

Bolt no. \quad x co-ord \quad y co-ord \quad z co-ord
\[
\begin{pmatrix}
1 & 0.375 \\
2 & 0.375 & -0.375 \\
4 & 0.375 & -0.375 \\
\end{pmatrix}
\]

Location of applied forces and moments

\[
\begin{align*}
x_{\text{force2}} & := 0.0 \text{in} \\
y_{\text{force2}} & := 0.0 \text{in} \\
z_{\text{force2}} & := 0.0 \text{in}
\end{align*}
\]
Center of gravity of bolt group

\[
\begin{align*}
\sum_{s} x_{s}^2 & \quad \text{xcg}_2 := \frac{\sum_{s} x_{s}^2}{\text{rows}(x_2)} \quad \text{xcg}_2 = 0.125 \text{ in} \\
\sum_{s} y_{s}^2 & \quad \text{ycg}_2 := \frac{\sum_{s} y_{s}^2}{\text{rows}(y_2)} \quad \text{ycg}_2 = -0.229 \text{ in} \\
\sum_{s} z_{s}^2 & \quad \text{zcg}_2 := \frac{\sum_{s} z_{s}^2}{\text{rows}(z_2)} \quad \text{zcg}_2 = 0 \text{ in}
\end{align*}
\]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 3, the x and y directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[
r_{\text{load}_2} := \text{cgload}_2 - \text{cgbolt}_2 \quad r_{\text{load}_2} = \begin{pmatrix} -0.125 \\ -0.229 \\ 0 \end{pmatrix} \text{ in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
r_{s}^2 := \left( x_{s}^2 - \text{xcg}_2 \right)^2 + \left( y_{s}^2 - \text{ycg}_2 \right)^2 \quad r_{s} = \begin{pmatrix} 0.950 \\ 0.522 \\ 0.678 \end{pmatrix} \text{ in}
\]

Reading database file for bolted joint

\[
data := \begin{pmatrix} 1 & 1 & 263 & -2 & 150 & 10 & 416 & 29 \\ 1 & 2 & -257 & -4 & 63 & 6 & -536 & -26 \\ 7 & 1 & 2 & -207 & -1 & 542 & -1 & -29 \\ 8 & 1 & 207 & -2 & -4 & -1 & 476 & -18 \end{pmatrix}
\]

Note: The second column of the data matrix, number 1 represents "Left" and number 2 represents "Right".

\[
q := 1 .. \text{rows(data)} \quad \text{num_bolts}_2 := \text{rows(bolt2)}
\]
AMS-02 HANDLE BRACKET BOLTS

Axial Load \( F_{z2q} := \text{data}_q,5\cdot\text{lbf} \)  
Shear in Y axis \( F_{y2q} := \text{data}_q,4\cdot\text{lbf} \)  
Shear in Z axis \( F_{x2q} := \text{data}_q,3\cdot\text{lbf} \)  

Applied Bending Moment at Bolts \( M_{2q} := 0\cdot\text{in-lbf} \)

**Moment Distribution**

\[
M_{\text{tot2}}(q) := \begin{cases} 
M_{x2q} & \text{if } F_{z2q} \leq 0\text{lbf} \\
M_{y2q} & \text{otherwise}
\end{cases}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

\[
M_{x2q} := M_{\text{boltcg2}} := M_{\text{tot1,q}} \quad M_{y2q} := M_{\text{boltcg2}} := M_{\text{tot2,q}} \quad M_{z2q} := M_{\text{boltcg2}} := M_{\text{tot3,q}}
\]

**Tension on bolts**

\[
F_{\text{direct2}}(s,q) := \begin{cases} 
0\cdot\text{lbf} & \text{if } F_{z2q} \leq 0\text{lbf} \\
\frac{F_{z2q}}{\text{num_bolts2}} & \text{otherwise}
\end{cases}
\]

Direct tensile load calculation

\[
F_{mx2}(s,q) := 0\cdot\text{lbf} \quad F_{my2}(s,q) := 0\cdot\text{lbf}
\]

\[
F_{t2}(s,q) := F_{\text{direct2}}(s,q) + F_{mx2}(s,q) + F_{my2}(s,q)
\]

Total Tensile load

**Shear on bolts**

\[
F_{s2}(s,q) := \frac{M_{z2q} \cdot r_s \cdot A_{s2}}{\sum_s \left( \frac{r_s^2}{A_{s2}} \right)}
\]

Secondary shear on bolts
AMS-02 HANDLE BRACKET BOLTS

Direct shear Loads

\[ F_{s2d}^{s,q} = \frac{\left\{ F_{y2}^{q}\right\}^2 + \left\{ F_{x2}^{q}\right\}^2}{\text{num_bolts}} \]

Total shear load

\[ F_{stot}^{s,q} = F_{s}^{s,q} + F_{s2d}^{s,q} \]

(Note: The Fs variable is the secondary shear and calculated above.)

Load Case

\[ LC_{2,q} = \text{data}_{q,1} \]
\[ LC_{2,q} = LC_{2,q} \cdot 10 + 1 \text{ Counter for number of bolts in pattern} \]

Rail End ID

\[ ID_{2,q} = \text{data}_{q,2} \]

The stack command below is used to stack the Load Case Number (LC2) and Rail End (ID2) in ascending order per bolt. Note: bolt number 3 is not included.

\[ LC := \text{stack}(LC2,LC2 + 1,LC2 + 3) \]
\[ ID := \text{stack}(ID2,ID2,ID2) \]

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the Load Case (LC2) and Rail End (ID2) from above. See the "Output" file below. Notice that there are only 3 bolts, since bolt number 3 is not included.

\[ P_2 := \text{stack}\left(\left[F_{2T}^{(1)}\right],\left[F_{2T}^{(2)}\right],\left[F_{2T}^{(3)}\right]\right) \]
\[ V_2 := \text{stack}\left(\left[F_{stot2T}^{(1)}\right],\left[F_{stot2T}^{(2)}\right],\left[F_{stot2T}^{(3)}\right]\right) \]
\[ M_2 := \text{stack}(M2,M2,M2) \]

The "Output2" file below outputs an array from left to right starting with the Load Case number (LC2), Rail End Identification (ID2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2).

\[ \text{Output2} := \text{augment}\left(\text{LC2,ID2,P2\ lbf,V2\ lbf,M2\ in\ lbf}\right) \]

(Note: Since the LC2 and ID2 numbers are dimensionless, the P2, V2, and M2 values are divided by their units in order to make the array dimensionless.)
Bolt Fail-safe Results

The array from the Output2 is read:

data_fs := Output2
s := 1..rows(data_fs)

Fail-safe Loads

Applied tensile load
\[ P_{FS} := data_{fs,3}, lbf \]
\[ ID_{FS} := data_{fs,1}, lbf \]

Applied shear load
\[ V_{FS} := data_{fs,4}, lbf \]
\[ LC_{FS} := data_{fs,2}, lbf \]

Applied bending moment
\[ M_{FS} := data_{fs,5}, \text{in}\cdot\text{lbf} \]

Fail-safe Factors of Safety

Ultimate \( SFu_{FS} := 1.0 \)
Joint Separation \( SFsep_{FS} := 1.0 \)

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC

Bolt Fail-safe Load data

Joint separation load \( \max(Psep_{FS}) = 733.485 \text{lbf} \)
Max. load on the bolt(ultimate) \( \max(Pb_{FS}) = 2234.5 \text{lbf} \)

Size of the "Output" Array:

\( (3 \text{ bolts} \times 4 \text{ load cases}) = 12 \text{ load cases} \)
Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Component</th>
<th>MS_minFS</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_minFS₁,₁ = 0.243</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_minFS₂,₁ = 2.542</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_minFS₃,₁ = 0.337</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_minFS₄,₁ = 3.7</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[
\text{MSbolt}_{\text{FS}} := \min(\text{MS}_{\text{FS}}) = 0.243
\]

Failure Mode FS = "Joint Separation"

Load Case ID (1) and Bolt Number (4) for Minimum Margin

Rail End ID for Minimum Margin

Applied Tensile Load for Minimum Margin

Applied Shear Load for Minimum Margin

Applied Bending Moment for Minimum Margin
Handle Bracket-305 Bottom Bolts Analysis

The Handle Bracket (drawing SDG39135878-305) is attached to the Lower Angle Beam (drawing SDG39135764) with 4 bolts, washers and inserts. The inserts are part of the Handle Bracket.

From Appendix A19, pages 23, 24 and 25 find the bolt reactions for the four cases (use maximum absolute values):

Note that the X and Y components are the shear loads in the X and Y directions and the Z component is the normal load.

\[
\begin{align*}
V_x_1 &= 51.08 \text{ lbf} & \quad V_y_1 &= 48.85 \text{ lbf} & \quad P_1 &= 77.56 \text{ lbf} & \quad \text{Load Case 2 Left Rail End} \\
V_x_2 &= 100.0 \text{ lbf} & \quad V_y_2 &= 9.265 \text{ lbf} & \quad P_2 &= 88.35 \text{ lbf} & \quad \text{Load Case 6 Left Rail End} \\
V_x_3 &= 145.8 \text{ lbf} & \quad V_y_3 &= 92.2 \text{ lbf} & \quad P_3 &= 170.4 \text{ lbf} & \quad \text{Load Case 8 Left Rail End} \\
V_x_4 &= 66.84 \text{ lbf} & \quad V_y_4 &= 45.22 \text{ lbf} & \quad P_4 &= 106.7 \text{ lbf} & \quad \text{Load Case 10 Left Rail End} \\
V_1 &= \sqrt{(V_x_1)^2 + (V_y_1)^2} & \quad V_2 &= \sqrt{(V_x_2)^2 + (V_y_2)^2} & \quad V_3 &= \sqrt{(V_x_3)^2 + (V_y_3)^2} & \quad V_4 &= \sqrt{(V_x_4)^2 + (V_y_4)^2} \\
V_1 &= 70.7 \text{ lbf} & \quad V_2 &= 100.4 \text{ lbf} & \quad V_3 &= 172.5 \text{ lbf} & \quad V_4 &= 80.7 \text{ lbf}
\end{align*}
\]
AMS-02 HANDLE BRACKET BOLTS

CHECK
Bolt (NAS1954C4, .2500x28, 0.2481 Dia, .675 L, .425 Lt, CRES A286, 180 KSI, Passivate)
Washer (NAS1587-4C, .531 OD, .260 ID, .078 Thk, CRES 75 KSI, Passivate)
Insert (MS51831CA202L, .2500-28, .375 L, .375 W, CRES A286 140 KSI, Passivate)

Flange 1: Lower Angle Beam
Part number: SDG39135764
Material: 7050-T7451

Flange 2: Handle Bracket
Part number: SDG39135878-305
Material: 6061-T651

Loads
Use the bolt loads for Load Case 8 Left Rail End, since they are the highest loads.

Applied tensile load P := 170.4 lbf
Applied shear load V := 172.5 lbf
Applied bending moment M := 0 in-lbf

Factors of Safety

<table>
<thead>
<tr>
<th></th>
<th>Ultimate</th>
<th>Yield</th>
<th>Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFu := 2.0</td>
<td>SFy := 1.25</td>
<td></td>
<td>Temp_initial := 70 deg</td>
</tr>
<tr>
<td>SFsep := 1.2</td>
<td>FF := 1.15</td>
<td></td>
<td>Temp_max := 139 deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temp_min := -47 deg</td>
</tr>
</tbody>
</table>

Bolt and Insert Data
Nominal diameter of bolt D := 0.250 in
Total length of bolt L := 0.675 in
Threaded length Lt := 0.425 in
(If bolt is fully threaded, input Lt = L)

Number of threads/inch Nt := 28 \( \frac{1}{\text{in}} \)
Length of insert Lins := 0.375 in
Min. external diameter of insert Fmin := 0.375 in
Depth of recess for insert lr := 0.02 in

Temperature data (Ref Appendix C2), On-Orbit Case

<table>
<thead>
<tr>
<th></th>
<th>Ultimate</th>
<th>Yield</th>
<th>Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFu := 2.0</td>
<td>SFy := 1.25</td>
<td></td>
<td>Temp_initial := 70 deg</td>
</tr>
<tr>
<td>SFsep := 1.2</td>
<td>FF := 1.15</td>
<td></td>
<td>Temp_max := 139 deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temp_min := -47 deg</td>
</tr>
</tbody>
</table>

Washer Data
Thickness of washer tw := 0.078 in

Flange data
Thickness of flange 1 tf1 := 0.25 in

This file uses the calculations shown in \escf02\2i11_mathcad\8307_bolts\thread_data.mcd

Tue Feb 15 10:38:17 AM 2005

5.12.2-25

ESCG-4005-05-AMS-0039
### Title
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<table>
<thead>
<tr>
<th>Outer Diameter of washer</th>
<th>Thickness of flange 2</th>
<th>Inner Diameter of washer</th>
<th>Diameter of hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dw := 0.531 in</td>
<td>tf2 := 0.375 in</td>
<td>Dwi := 0.260 in</td>
<td>D霍le := 0.288 in</td>
</tr>
</tbody>
</table>

Bolt head dia. across flats \( \text{dw} := 0.430 \text{ in} \) (used only if there is no washer)

Note: If there is no washer, \( \text{tw}, \text{Dw}, \text{and Dwi} \) should be zero.

### Material Property Data

#### Bolt

- **Temperature correction factor for bolt strength ultimate**
  \( \text{TSu}_\text{bolt} := 0.97 \)
  (Ref. MMPDS-01, fig. 6.2.1.1.1)

- **Bolt ultimate tensile allowable stress**
  \( \text{Ft}\text{u}_\text{bolt} := 180000 \text{ psi} \) (Ref. NAS1954C4)

- **Bolt ultimate shear allowable stress**
  \( \text{Fsu}_\text{bolt} := 0.6 \times \text{Ft}\text{u}_\text{bolt} \) \( \text{Fsu}_\text{bolt} = 108000 \text{ psi} \)

- **Bolt yield tensile allowable**
  \( \text{Fy}_\text{bolt} := 132353 \text{ psi} \) (Ref. Appendix C10)

- **Temperature correction factor for bolt modulus**
  \( \text{TE}_\text{bolt} := 0.98 \) (Ref. MMPDS-01, fig.6.2.1.1.4 (a))

- **Modulus of elasticity of bolt**
  \( \text{E}_\text{bolt} := \left( 29.1 \times 10^6 \right) \text{ psi} \) (Ref. MMPDS-01, table 6.2.1.0(b))

- **Thermal coefficient for bolt:**
  \( \beta_{\text{bolt\_hot}} := 9.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \)
  \( \beta_{\text{bolt\_cold}} := 8.7 \times 10^{-6} \frac{\text{in}}{\text{deg}} \)
  (Ref. MMPDS-01, fig.6.2.1.0)

#### Insert

- **Temperature correction factor for insert strength**
  \( \text{TS}_\text{ins} := 0.97 \) (Ref. MMPDS-01, fig.6.2.1.1.1)

- **Ultimate tensile allowable stress**
  \( \text{Ft}\text{u}_\text{ins} := 140000 \text{ psi} \) (Ref. MS51831)

- **Ultimate shear allowable stress**
  \( \text{Fsu}_\text{ins} := 0.6 \times \text{Ft}\text{u}_\text{ins} \)

#### Washer

- **Temperature correction factor for washer modulus**
  \( \text{TE}_\text{washer} := 0.97 \) (Ref. MMPDS-01, fig.6.2.1.1.4 (a))

- **Modulus of elasticity of washer**
  \( \text{E}_\text{washer} := \left( 29.1 \times 10^6 \right) \text{ psi} \) (Ref. MMPDS-01, table 6.2.1.0(b))

#### Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, modulus of elasticity of these members, and diameters of the bolt and the washer.
Temperature correction factor for flange 1

\[ T_{f1E} := 0.98 \text{(modulus)} \]  
(Ref. MMPDS-01, fig.3.7.6.1.4)

Temperature correction factor for flange 2

\[ T_{f2E} := 0.98 \text{(modulus)} \]  
(Ref. MMPDS-01, fig.3.6.2.2.4)

Aluminum 7050 and 7075 have similar properties.

\[ T_{f2s} := 0.96 \text{(strength)} \]  
(Ref. MMPDS-01, fig.3.6.2.2.1(a) and (b))

Shear strength allowable for flange

\[ F_{su,f2} := 27000 \text{ psi} \]  
(Ref. MMPDS-01, table 3.6.2.0(b2))

Modulus of elasticity for the parts in the joint

\[ E_{flange1} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{flange2} := \left(9.9 \times 10^6 \text{ psi}\right) \]
(Ref. MMPDS-01, table 3.7.6.0(b3) and 3.6.2.0(b2))

Coefficient of thermal expansion for flanges

\[ \beta_{flange1}_{\text{hot}} := 12.3 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{flange1}_{\text{cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]
(Ref. MMPDS-01, fig.3.7.6.0 and 3.6.2.0)

\[ \beta_{flange2}_{\text{hot}} := 12.8 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{flange2}_{\text{cold}} := 12.4 \times 10^{-6} \frac{\text{in}}{\text{deg}} \]

**Torque/Preload data**

Maximum torque (65% of yield)

\[ T_{\text{max}} := 107 \text{ in-lbf} \]
Loading plane factor: \( n := 0.5 \)

Minimum torque (95% of max. torque)

\[ T_{\text{min}} := 101 \text{ in-lbf} \]
Preload Uncertainty: \( u := 0.25 \)

Torque coefficient:

\( k := 0.15 \)

This file uses the calculations shown in `\escfii02\211_mathcad\8307_bolts\bolt_stiffness_insert_RevC`

**Bolt Load data**

Bolt/joint stiffness factor \( = 0.293 \)

Preload due to temperature

\[ P_{\text{thr, pos}} = 231.9 \text{ lbf} \]

\[ P_{\text{thr, neg}} = -402.6 \text{ lbf} \]

Max. preload

\[ P_{\text{LDMax}} = 3798.5 \text{ lbf} \]

Min. preload

\[ P_{\text{LDMin}} = 1439.1 \text{ lbf} \]

Uncertainty factor \( u := 0.250 \)

Joint separation load

\[ P_{\text{sep}} = 204.480 \text{ lbf} \]

Torque coefficient \( k := 0.150 \)

Max. load on the bolt (ultimate)

\[ P_{b} = 3855.9 \text{ lbf} \]

Loading plane factor \( n := 0.500 \)

Max. load on the bolt (yield)

\[ P_{by} = 3834.4 \text{ lbf} \]

Thread shear pullout load of bolt or insert

\[ P_{\text{ths}} = 9492.1 \text{ lbf} \]

Bolt ultimate tensile strength

\[ P_{A_t} = 6160.4 \text{ lbf} \]

Thread shear pullout load in parent metal

\[ P_{p\text{ths}} = 5725.6 \text{ lbf} \]

Length_check = "Bolt length is sufficient"
Summary of Margins for bolt:

Joint separation \[ MS_1 = 6.17 \]  
Direct Thread shear Ultimate \[ MS_6 = 13.61 \]  
Direct Tension Ultimate \[ MS_2 = 14.72 \]  
Total Thread shear Ultimate \[ MS_7 = 0.48 \]  
Direct Tension Yield \[ MS_3 = 17.49 \]  
Shear Ultimate \[ MS_8 = 7.6 \]  
Total Tension Ultimate \[ MS_4 = 0.6 \]  
Bending Ultimate \[ MS_9 = 10 \]  
Total Tension Yield \[ MS_5 = 0.181 \]  
Combined shear, tension and bending ultimate \[ MS_{10} = 0.593 \]  

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ MS_{\text{Bolt}} := \min(\text{MS}) \]

\[ MS_{\text{Bolt}} = 0.181 \]

Failure Mode = "Total Tension Yield"

Bolt Fail-Safe Analysis

For bolt fail-safe analysis, the bolt with the highest load is removed and the FEM run with only three constraints.

From Appendix A19, pages 27 and 28 find the bolt reactions for the four cases (use maximum absolute values):

Note that the X and Y components are the shear loads in the X and Y directions and the Z component is the normal load.

\[
\begin{align*}
V_x_1 & := 70.16 \text{ lbf} & V_y_1 & := 42.56 \text{ lbf} & P_1 & := 75.79 \text{ lbf} & \text{Load Case 2 Left Rail End} \\
V_x_2 & := 123.0 \text{ lbf} & V_y_2 & := 7.341 \text{ lbf} & P_2 & := 88.85 \text{ lbf} & \text{Load Case 6 Left Rail End} \\
V_x_3 & := 316.0 \text{ lbf} & V_y_3 & := 203.1 \text{ lbf} & P_3 & := 334.8 \text{ lbf} & \text{Load Case 8 Left Rail End} \\
V_x_4 & := 69.77 \text{ lbf} & V_y_4 & := 53.62 \text{ lbf} & P_4 & := 101.0 \text{ lbf} & \text{Load Case 10 Left Rail End} \\
V_1 & := \sqrt{(V_x_1)^2 + (V_y_1)^2} & V_2 & := \sqrt{(V_x_2)^2 + (V_y_2)^2} & V_3 & := \sqrt{(V_x_3)^2 + (V_y_3)^2} & V_4 & := \sqrt{(V_x_4)^2 + (V_y_4)^2} \\
V_1 & = 82.1 \text{ lbf} & V_2 & = 123.2 \text{ lbf} & V_3 & = 375.6 \text{ lbf} & V_4 & = 88 \text{ lbf}
\end{align*}
\]

Use the bolt loads for Load Case 8 Left Rail End, since they are the largest loads.
**Fail-safe Loads**

- **Applied tensile load**
  \[ P_{FS} := 334.8 \text{ lbf} \]

- **Applied shear load**
  \[ V_{FS} := 375.6 \text{ lbf} \]

- **Applied bending moment**
  \[ M_{FS} := 0 \text{ in-lbf} \]

**Fail-safe Factors of Safety**

- **Ultimate**
  \[ S_{FU,FS} := 1.0 \]

- **Joint Separation**
  \[ S_{FSEP,FS} := 1.0 \]

**Summary of fail-safe Margins for bolt:**

- **Joint separation**
  \[ M_{FS,1} = 3.38 \]
  **Total Thread shear Ultimate**
  \[ M_{FS,5} = 0.49 \]

- **Direct Tension Ultimate**
  \[ M_{FS,2} = 15 \]
  **Shear Ultimate**
  \[ M_{FS,6} = 6.9 \]

- **Total Tension Ultimate**
  \[ M_{FS,3} = 0.6 \]
  **Bending Ultimate**
  \[ M_{FS,7} = 10 \]

- **Direct Thread shear Ultimate**
  \[ M_{FS,4} = 13.87 \]
  **Combined shear, tension and bending ultimate**
  \[ M_{FS,8} = 0.59 \]

**Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:**

\[ M_{SBOLT,FS} := \min(M_{FS}) \]

\[ M_{SBOLT,FS} = 0.485 \quad \text{Failure Mode FS = "Total Thread Shear Ultimate"} \]
Handle Bracket-305 Top Bolts Analysis

The Rail Post (Bracket, ISS Handrail Assembly), drawing SDG33106341, is attached to the Handle Bracket Assembly, drawing SDG39135878-305, with 4 bolts NAS 1351N3 (0.190-32UNJF-3A). The bolts are screwed into inserts MS51831CA-201L, which are part of the Handle Bracket Assembly. The analysis of the Handle Bracket Assembly is covered in Section 5.12.1.

Bolt Geometry

\[
\begin{align*}
\text{size} & \quad \text{thread/in} \\
\text{b bolt} & := \\
& \begin{pmatrix}
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
0.19 & 32 \\
\end{pmatrix} \\
i & := 1.. \text{rows(bolt)} \\
\text{N}_i & := \text{b bolt}_{1,2 \frac{1}{\text{in}}} \
\text{pitch of bolt} & := i \\
\text{D}_i & := \text{b bolt}_{1,1 \text{in}} \
\text{bolt diameter} & := i 
\end{align*}
\]
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\[ A_{ti} := \beta \left( D_i - 0.9743 \frac{1}{N_i} \right)^2 \]  
Tensile Area of bolt

\[ A_{si} := \beta \left( D_i - 1.299038 \frac{1}{N_i} \right)^2 \]  
Shear Area of bolt

Handle Bracket Bolt Pattern

<table>
<thead>
<tr>
<th>Bolt no.</th>
<th>x co-ord</th>
<th>y co-ord</th>
<th>z co-ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.375</td>
<td>0.6875</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.375</td>
<td>-0.6875</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-0.375</td>
<td>0.6875</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-0.375</td>
<td>-0.6875</td>
<td>0</td>
</tr>
</tbody>
</table>

Location of Applied Forces and Moments

\[ x_{force} := 0.0 \text{in} \quad y_{force} := 0.0 \text{in} \quad z_{force} := 0.0 \text{in} \]

\[ \text{cgload} := \begin{pmatrix} x_{force} \\ y_{force} \\ z_{force} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{in} \]
Center of Gravity of Bolt Group

\[
\begin{align*}
\sum_{i} x_i & \quad \text{x}_{cg} := \frac{i}{\text{rows}(x)} \quad \text{x}_{cg} = 0 \text{-in} \\
\sum_{i} y_i & \quad \text{y}_{cg} := \frac{i}{\text{rows}(y)} \quad \text{y}_{cg} = 0 \text{-in} \\
\sum_{i} z_i & \quad \text{z}_{cg} := \frac{i}{\text{rows}(z)} \quad \text{z}_{cg} = 0 \text{-in}
\end{align*}
\]

\[
\text{c}_{gbolt} := \begin{pmatrix} \text{x}_{cg} \\ \text{y}_{cg} \\ \text{z}_{cg} \end{pmatrix} \\
\text{c}_{gbolt} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{-in}
\]

Note: The bolt pattern is symmetric about all three axes.

Load Vector

\[
\text{r}_{load} := \text{cgload} - \text{c}_{gbolt} \\
\text{r}_{load} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{-in}
\]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[
\text{r}_i := \sqrt{(x_i - \text{x}_{cg})^2 + (y_i - \text{y}_{cg})^2} \\
\text{r} = \begin{pmatrix} 0.783 \\ 0.783 \\ 0.783 \end{pmatrix} \text{-in}
\]

Bolt loads are retrieved from the FEM for the four worst cases (see Report 5.12.1, page 13). These loads are presented in the Table below.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Rail End</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Left</td>
<td>-2</td>
<td>160</td>
<td>-3</td>
<td>-394</td>
<td>-8</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>6</td>
<td>2</td>
<td>171</td>
<td>3</td>
<td>-11</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>219</td>
<td>9</td>
<td>1</td>
<td>-30</td>
<td>485</td>
<td>-61</td>
</tr>
<tr>
<td>10</td>
<td>Left</td>
<td>-3</td>
<td>-148</td>
<td>-7</td>
<td>523</td>
<td>-29</td>
<td>148</td>
</tr>
</tbody>
</table>

Database for Bolted Joint

\[
\]

Note: In the second column of the data matrix, number 1 represents "Rail End Left".
num_bolts := rows(bolt)  \( j := 1 \ldots \text{rows(data)} \)

num_bolts = 4

**Axial Load**
\[ Fz_j := \text{data}_{j,5} \cdot \text{lbf} \]

**Torsion**
\[ Mz_j := \text{data}_{j,8} \cdot \text{in-lbf} \]

**Shear in Y axis**
\[ Fy_j := \text{data}_{j,4} \cdot \text{lbf} \]

**Moment about Y axis**
\[ My_j := \text{data}_{j,7} \cdot \text{in-lbf} \]

**Shear in X axis**
\[Fx_j := \text{data}_{j,3} \cdot \text{lbf} \]

**Moment about X axis**
\[ Mx_j := \text{data}_{j,6} \cdot \text{in-lbf} \]

**Applied Bending Moment at Bolts**
\[ M_j := 0 \cdot \text{in-lbf} \]

**Moment Distribution**
\[
M_{\text{tot}}^{(j)} := \begin{pmatrix}
Mx_j \\
My_j \\
Mz_j
\end{pmatrix} + r_{\text{load}} \times \begin{pmatrix}
Fx_j \\
Fy_j \\
Fz_j
\end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

**Mx_boltcg\_j := M_{\text{tot1},j}**

**My_boltcg\_j := M_{\text{tot2},j}**

**Mz_boltcg\_j := M_{\text{tot3},j}**

**Tension on Bolts**

Direct tensile load calculation - (The "if" statement checks for compression)

\[
F_{\text{direct}}^{ij} := \begin{cases}
0 \cdot \text{lbf} & \text{if } Fz_j \leq 0\text{lbf} \\
\frac{Fz_j}{\text{num_bolts}} & \text{otherwise}
\end{cases}
\]

\[
F_{\text{mx}}^{ij} := \begin{cases}
0 \cdot \text{lbf} & \text{if } \left( y_i - y_{\text{ycg}} \right) = 0 \text{ in} \\
\frac{\left[ \text{Mx}_\text{boltcg}\_j \left( y_i - y_{\text{ycg}} \right) \right] \cdot A_{t_i}}{\sum_i \left( y_i - y_{\text{ycg}} \right)^2 \cdot A_{t_i}} & \text{otherwise}
\end{cases}
\]

\[
F_{\text{my}}^{ij} := \begin{cases}
0 \cdot \text{lbf} & \text{if } \left( x_i - x_{\text{xcg}} \right) = 0 \text{ in} \\
\frac{\left[ \text{My}_\text{boltcg}\_j \left( x_i - x_{\text{xcg}} \right) \right] \cdot A_{t_i}}{\sum_i \left( x_i - x_{\text{xcg}} \right)^2 \cdot A_{t_i}} & \text{otherwise}
\end{cases}
\]

\[
F_{\text{t}}^{ij} := F_{\text{direct}}^{ij} + F_{\text{mx}}^{ij} + F_{\text{my}}^{ij}
\]

**Total Tensile load**

**Shear on Bolts**

Secondary shear on bolts
\[
F_{\text{s}}^{ij} := \frac{\text{Mz}_\text{boltcg}\_j \cdot r_i \cdot A_{s_i}}{\sum_i \left( r_i \right)^2 \left( A_{s_i} \right)}
\]
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Direct shear loads
\[ F_{sd_{i,j}} = \sqrt{\left(\frac{F_{y_{j}}}{\text{num\_bolts}}\right)^2 + \left(\frac{F_{x_{j}}}{\text{num\_bolts}}\right)^2} \]

Total shear load
\[ F_{stot_{i,j}} = F_{s_{i,j}} + F_{sd_{i,j}} \]

The stack commands below are used to stack the Load Case (LC) and Rail End identification (ID) in ascending order per bolt. The Load Case (LC) number is located in the first column and the Rail End (ID) numbers in the second column. For each Load Case, the bolt number within the bolt pattern is added to the end of each LC number. For example, the Load Case identification number 1 will have bolt numbers 1 thru 4 attached to the end for all 4 load cases. This brings the total number of load cases to 16 (4 bolts x 4 load cases).

Load Case
\[ \text{LC}_{j} := \text{data}_{j,1} \quad \text{LC}_{j} := \text{LC}_{j,10} + 1 \quad \text{Counter for number of bolts in pattern} \]

Rail End ID
\[ \text{ID}_{j} := \text{data}_{j,2} \]

\[ \text{LC} := \text{stack(}\text{LC,LC + 1,LC + 2,LC + 3)} \]

\[ \text{ID} := \text{stack(}\text{ID,ID,ID,ID)} \]

The stack commands below are used to stack applied axial load (P), applied shear load (V), and applied moment (M) in ascending order per bolt. These loads are put into an array with the Load Case (LC) number and Rail End (ID) number from above. See the "Output" file below.

Axial load
\[ P := \text{stack}\left[\left(\text{Ft}_{T}^{(1)}\right),\left(\text{Ft}_{T}^{(2)}\right),\left(\text{Ft}_{T}^{(3)}\right),\left(\text{Ft}_{T}^{(4)}\right)\right] \]

Shear load
\[ V := \text{stack}\left[\left(\text{Fstot}_{T}^{(1)}\right),\left(\text{Fstot}_{T}^{(2)}\right),\left(\text{Fstot}_{T}^{(3)}\right),\left(\text{Fstot}_{T}^{(4)}\right)\right] \]

Moment
\[ M := \text{stack}(\text{M,M,M,M}) \]

The "Output" file below outputs an array from left to right starting with the Load Case (LC), Rail End Identification (ID), applied load on the bolt (P), applied shear on the bolt (V), and applied moment on the bolt (M).

\[ \text{Output} := \text{augment}\left(\text{LC,ID}, \frac{P}{\text{lbf}}, \frac{V}{\text{lb}_{f}}, \frac{M}{\text{in}\cdot\text{lbf}}\right) \]

(Note: Since the LC and ID numbers are dimensionless, the P, V, and M values are divided by their units in order to make the array dimensionless.)
AMS-02 HANDLE BRACKET BOLTS

<table>
<thead>
<tr>
<th>LC</th>
<th>ID</th>
<th>P</th>
<th>V</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>-148.606</td>
<td>43.834</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>61</td>
<td>36.508</td>
<td>3.497</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>312.674</td>
<td>35.323</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>101</td>
<td>170.848</td>
<td>84.254</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>137.939</td>
<td>43.834</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>62</td>
<td>34.326</td>
<td>3.497</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>82</td>
<td>334.492</td>
<td>35.323</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>102</td>
<td>-209.515</td>
<td>84.254</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>23</td>
<td>-137.939</td>
<td>43.834</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>63</td>
<td>51.174</td>
<td>3.497</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>83</td>
<td>-333.992</td>
<td>35.323</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>103</td>
<td>209.515</td>
<td>84.254</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>24</td>
<td>148.606</td>
<td>43.834</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>64</td>
<td>48.992</td>
<td>3.497</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>84</td>
<td>-312.174</td>
<td>35.323</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>104</td>
<td>-170.848</td>
<td>84.254</td>
<td>0</td>
</tr>
</tbody>
</table>

Size of the "Output" Array:
(4 bolts x 4 load cases) = 16 Load Cases

**CHECK**

**Bolt** (NAS1351N3-8, 0.1900-32, 0.50 L, HRES A286 160 KSI, Passivate)

**No Washer**

**Insert** (MS51831CA-201L, .1900-32, .312 L, .312 W, CRES A286 140 KSI, Passivate)

The array from the Output above is read.

\[
data := \text{Output}
\]
\[
s := 1..\text{rows}(data)
\]

**Flange 1:** Bracket, ISS Handrail Assembly

Part number: SDG33106341
Material: 7075-T7351

**Flange 2:** Handle Bracket Assembly

Part number: SDG39135878
Material: 6061-T651

Applied tensile load \[ P_s := \text{data}_{s,3}, \text{lbf} \]

Applied shear load \[ V_s := \text{data}_{s,4}, \text{lbf} \]

Applied bending moment \[ M_s := \text{data}_{s,5}, \text{in-lbf} \]

Load Case LC \[ \text{LC}_s := \text{data}_{s,1} \]

Rail End ID \[ \text{ID}_s := \text{data}_{s,2} \]
Factors of Safety

Ultimate SFu := 2.0
Yield SFy := 1.25
Joint Separation SFsep := 1.2
Fitting factor FF := 1.15

Temperature Data (Ref Appendix C2), On-Orbit Case

Assembly Temp_initial := 70-deg
Maximum Temp_max := 139-deg
Minimum Temp_min := -47-deg

Bolt and Insert Data

Nominal diameter of bolt D := 0.190-in
Total length of bolt L := 0.500-in
Threaded length Lt := L
(If bolt is fully threaded, input Lt = L)

Number of threads/inch Nt := 32 \frac{1}{in}
Length of insert Lins := 0.312-in
Min. external diameter of insert Fmin := 0.312-in
Depth of recess for insert l_r := 0.02-in

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate TSu_bolt := 0.97
Bolt ultimate tensile allowable stress Ftu_bolt := 160000 psi
Bolt ultimate shear allowable stress Fsu_bolt := 0.6 Ftu_bolt
Bolt yield tensile allowable Fty_bolt := 120000 psi
Temperature correction factor for bolt modulus TE_bolt := 0.98
Modulus of elasticity of bolt E_bolt := \left(29.1 \times 10^6\right) psi

Thread Data File

Washer Data

Thickness of washer tw := 0.0-in
Outer Diameter of washer Dw := 0.0-in
Inner Diameter of washer Dwi := 0.0-in
Bolt head dia. across flats dw := 0.303-in

Flange data

Thickness of flange 1 tf1 := .188-in
(Ref. SDG33106341)
Thickness of flange 2 tf2 := .312-in (insert length)
Diameter of hole D_hole := 0.23-in
(Ref. SDG33106341)

This file uses the calculations shown in \escfi02\2i11_mathcad8307_bolts\thread_data.mcd
AMS-02 HANDLE BRACKET BOLTS

Thermal coefficient for bolt: \[ u_{\text{bolt\_hot}} = 9.1 \times 10^{-6} \text{ in} / \text{deg} \quad u_{\text{bolt\_cold}} = 8.7 \times 10^{-6} \text{ in} / \text{deg} \]

(Ref. MMPDS-01, fig. 6.2.1.0)

**Insert**

Temperature correction factor for insert strength \[ TS_{\text{ins}} = .97 \]

(Ref. MMPDS-01, fig. 6.2.1.1.1)

Ultimate tensile allowable stress \[ F_{\text{tu\_ins}} = 140000 \text{ psi} \]

(Ref. MS51831)

Ultimate shear allowable stress \[ F_{\text{su\_ins}} = 0.6 F_{\text{tu\_ins}} \]

**Washer**

Temperature correction factor for washer modulus \[ TE_{\text{washer}} = .97 \]

(Ref. MMPDS-01, fig. 6.2.1.1.4(a))

Modulus of elasticity of washer \[ E_{\text{washer}} = (29.1 \times 10^6 \text{ psi}) \]

(Ref. MMPDS-01, table 6.2.1.0(b))

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \[ T_{\text{f1E}} = .98 \]

(modulus) \quad (Ref. MMPDS-01, fig. 3.7.6.1.4)

Temperature correction factor for flange 2 \[ T_{\text{f2E}} = .98 \]

(modulus) \quad (Ref. MMPDS-01, fig. 3.6.2.2.4)

Texture \[ T_{\text{f2s}} = .96 \]

(strength) \quad (Ref. MMPDS-01, fig. 3.6.2.2.1(a) and (b))

Shear Strength Allowable for flanges \[ F_{\text{su\_f2}} = 27000 \text{ psi} \]

(Ref. MMPDS-01, table 3.6.2.0(b2))

Modulus of elasticity for the parts in the joint \[ E_{\text{flange1}} = (10.3 \times 10^6 \text{ psi}) \quad E_{\text{flange2}} = (9.9 \times 10^6 \text{ psi}) \]

(Ref. MMPDS-01, table 3.7.6.0(b1) and 3.6.2.0(b2))

Coefficient of thermal expansion for flanges \[ u_{\text{flange1\_hot}} = 12.3 \times 10^{-6} \text{ in} / \text{deg} \quad u_{\text{flange2\_hot}} = 12.8 \times 10^{-6} \text{ in} / \text{deg} \]

(Ref. MMPDS-01, fig. 3.7.6.0 and 3.6.2.0)

\[ u_{\text{flange1\_cold}} = 12.1 \times 10^{-6} \text{ in} / \text{deg} \quad u_{\text{flange2\_cold}} = 12.4 \times 10^{-6} \text{ in} / \text{deg} \]

**Torque/Preload Data**

Maximum torque (65% of yield) \[ T_{\text{max}} = 44.4 \text{ in-lbf} \]

Loading plane factor: \[ n = .5 \]

Minimum torque (95% of max. torque) \[ T_{\text{min}} = 42.2 \text{ in-lbf} \]

Preload Uncertainty: \[ = 0.25 \]

Torque coefficient (Lubricated): \[ k = 0.15 \]

This file uses the calculations shown in \escf02\2i11\mathcad\8307_bolts\multi_bolt_stiffness_insert_RevC
Bolt Load data

Bolt/joint stiffness factor \( \phi = 0.424 \)

Max. preload \( \text{PLD}_{\text{max}} = 2055.5 \text{ lbf} \)

Min. preload \( \text{PLD}_{\text{min}} = 825.9 \text{ lbf} \)

Joint separation load \( \max(P_{\text{sep}}) = 401.391 \text{ lbf} \)

Max. load on the bolt(ultimate) \( \max(P_{b}) = 2218.8 \text{ lbf} \)

Max. load on the bolt(yield) \( \max(P_{by}) = 2157.6 \text{ lbf} \)

Bolt ultimate tensile strength \( P_{\text{At}} = 2987.4 \text{ lbf} \)

Preload due to temperature

\( \text{P}_{\text{thr\_pos}} = 108.1 \text{ lbf} \)

\( \text{P}_{\text{thr\_neg}} = -187.3 \text{ lbf} \)

Uncertainty factor \( = 0.25 \)

Torque coefficient \( k = 0.15 \)

Loading plane factor \( n = 0.5 \)

Thread shear pullout load of bolt or insert \( \text{P}_{\text{ths}} = 6342.1 \text{ lbf} \)

Thread shear pullout load in parent metal \( \text{P}_{\text{pths}} = 3963.4 \text{ lbf} \)

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Minimum Margin</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>1.271</td>
<td>Direct Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>2.883</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>3.660</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.346</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.038</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ \text{MS}_{\text{bolt}} = \min(\text{MS}) \]

\[ \text{MS}_{\text{bolt}} = 0.038 \quad \text{Failure Mode} = "\text{Total Tension Yield}" \]

\[ \begin{align*}
\text{MS}_{\text{min\_LC}} &= 82 & \text{Load Case ID (8) and Bolt Number (2) for Minimum Margin} \\
\text{MS}_{\text{min\_ID}} &= 1 & \text{Rail End ID for Minimum Margin} \\
\text{MS}_{\text{min\_P}} &= 334.5 & \text{Applied Tensile Load for Minimum Margin} \\
\text{MS}_{\text{min\_V}} &= 35.3 & \text{Applied Shear Load for Minimum Margin} \\
\text{MS}_{\text{min\_M}} &= 0 & \text{Applied Bending Moment for Minimum Margin}
\end{align*} \]
Bolt Fail-Safe Analysis

Since bolt number 2 has the lowest margin of safety it is assumed that this bolt will be the first bolt to fail. There are now 3, NAS 1351N3 0.19-32 fasteners, holding the Post to the Bracket.

\[
\text{size thread/in } \begin{pmatrix} 0.19 & 32 \\ 0.19 & 32 \\ 0.19 & 32 \end{pmatrix}
\]

\[
bolt2 := \begin{pmatrix} 0.19 \\ 0.19 \\ 0.19 \end{pmatrix}
\]

\[
s := 1 \text{ rows(bolt2)}
\]

\[
N^2_s := bolt2_s \cdot \frac{1}{\text{in}} \quad \text{pitch of bolt} \\
D^2_s := bolt2_s \cdot \frac{1}{\text{in}} \quad \text{bolt diameter}
\]

\[
\text{Tensile Area of bolt } \quad \begin{align*}
\text{At}^2_s & := \beta \left( \frac{D^2_s - 0.9743}{2} \frac{1}{N^2_s} \right)^2 \\
\text{Shear Area of bolt } \quad \text{As}^2_s & := \beta \cdot \frac{D^2_s - 1.299038}{2} \frac{1}{N^2_s} \end{align*}
\]

Bolt no. \hspace{1cm} x co-ord \hspace{1cm} y co-ord \hspace{1cm} z co-ord
\[
\begin{align*}
1 & : x_2 := 0.375 \text{ in} \quad y_2 := 0.6875 \text{ in} \\
3 & : x_2 := -0.375 \text{ in} \quad y_2 := 0.6875 \text{ in} \\
4 & : x_2 := 0 \text{ in} \quad y_2 := 0 \text{ in}
\end{align*}
\]

Location of applied forces and moments

\[
xforce2 := 0.0 \text{ in} \quad yforce2 := 0.0 \text{ in} \quad zforce2 := 0.0 \text{ in}
\]
AMS-02 HANDLE BRACKET BOLTS

Center of gravity of bolt group

\[ x_{cg2} := \frac{\sum x^2_s}{\text{rows}(x2)} \quad x_{cg2} = -0.125\text{ in} \]
\[ y_{cg2} := \frac{\sum y^2_s}{\text{rows}(y2)} \quad y_{cg2} = 0.229\text{ in} \]
\[ z_{cg2} := \frac{\sum z^2_s}{\text{rows}(z2)} \quad z_{cg2} = 0\text{ in} \]

\[ c_{gbolt2} := \begin{pmatrix} x_{cg2} \\ y_{cg2} \\ z_{cg2} \end{pmatrix} \quad c_{gbolt2} = \begin{pmatrix} -0.125 \\ 0.229 \\ 0 \end{pmatrix}\text{ in} \]

Note: Since the z direction is into the plate the loads are shared equally between the bolts. However, due to a failure in bolt 3, the x and y directions in the bolt pattern are unsymmetric and have offsets from the center of gravity.

Load Vector

\[ r_{load2} := \text{cgload2} - c_{gbolt2} \quad r_{load2} = \begin{pmatrix} 0.125 \\ -0.229 \\ 0 \end{pmatrix}\text{ in} \]

Distance from CG of Bolts to Individual Bolts for shear calculations

\[ r^2_s := \sqrt{(x^2_s - x_{cg2})^2 + (y^2_s - y_{cg2})^2} \]
\[ r^2 = \begin{pmatrix} 0.678 \\ 0.522 \\ 0.950 \end{pmatrix}\text{ in} \]

Reading database file for bolted joint

Note: The second column of the data matrix, number 1 represents "Left".

\[ \text{data} := \begin{pmatrix} 2 & 1 & -2 & 160 & -3 & -394 & -8 & 12 \\ 6 & 1 & 6 & 2 & 171 & 3 & -11 & 6 \\ 8 & 1 & 219 & 9 & 1 & -30 & 485 & -61 \\ 10 & 1 & -3 & -148 & -7 & 523 & -29 & 148 \end{pmatrix} \]

\[ q := 1..\text{rows(data)} \quad \text{num_bolts2} := \text{rows(bolt2)} \]
### AMS-02 HANDLE BRACKET BOLTS

<table>
<thead>
<tr>
<th>Axial Load</th>
<th>( F_{z_2} ) := data_{q, 5 \text{ lbf}}</th>
<th>Torsion</th>
<th>( M_{z_2} ) := data_{q, 8 \text{ in-lbf}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear in Y axis</td>
<td>( F_{y_2} ) := data_{q, 4 \text{ lbf}}</td>
<td>Moment about Y axis</td>
<td>( M_{y_2} ) := data_{q, 7 \text{ in-lbf}}</td>
</tr>
<tr>
<td>Shear in Z axis</td>
<td>( F_{x_2} ) := data_{q, 3 \text{ lbf}}</td>
<td>Moment about Z axis</td>
<td>( M_{x_2} ) := data_{q, 6 \text{ in-lbf}}</td>
</tr>
</tbody>
</table>

**Applied Bending Moment at Bolts** \( M_2 \) := 0 \text{ in-lbf}

**Moment Distribution**

\[
M_{\text{tot2}}(q) := \begin{pmatrix} M_{x_2} \\ M_{y_2} \\ M_{z_2} \end{pmatrix} = f_{\text{load}} \times \begin{pmatrix} F_{x_2} \\ F_{y_2} \\ F_{z_2} \end{pmatrix}
\]

Use the cross-product to determine the additional moments acting on the fasteners.

**Mx_boltcg2** := \( M_{\text{tot2}}(1, q) \)

**My_boltcg2** := \( M_{\text{tot2}}(2, q) \)

**Mz_boltcg2** := \( M_{\text{tot2}}(3, q) \)

**Tension on bolts**

\[
F_{\text{direct2}}(s, q) := \begin{cases} 0\text{ lbf} & \text{if } F_{z_2}(s, q) \leq 0\text{ lbf} \\ \frac{F_{z_2}(s, q)}{\text{num_bolts2}} & \text{otherwise} \end{cases}
\]

Direct tensile load calculation

**Total Tensile load**

\[
F_{t_2}(s, q) := F_{\text{direct2}}(s, q) + F_{mx_2}(s, q) + F_{my_2}(s, q)
\]

**Shear on bolts**

**Secondary shear on bolts**

\[
F_{s_2}(s, q) := \frac{M_{z_boltcg2}(r_2^2 - r_2^2 \cdot s)}{\sum s} \cdot \frac{A_s}{s}
\]
\[
F_{s2d_{s,q}} = \sqrt{\left(\frac{F_{y2}}{q}\right)^2 + \left(\frac{F_{x2}}{q}\right)^2}
\]

\[
F_{s2_{s,q}} = F_{s2_{s,q}} + F_{s2d_{s,q}}
\]  
(Note: The \( F_{s} \) variable is the secondary shear and calculated above.)

Load Case
\[
LC2_{q} := data_{q,1}
\]
\[
LC2_{q} := LC2_{q} \cdot 10 + 1 \quad \text{Counter for number of bolts in pattern}
\]

Rail End ID
\[
ID2_{q} := data_{q,2}
\]

The stack command below is used to stack the Load Case Number (LC2) and Rail End (ID2) in ascending order per bolt. Note: bolt number 2 is not included.

\[
LC2 := \text{stack}(LC2, LC2 + 2, LC2 + 3)
\]

\[
ID2 := \text{stack}(ID2, ID2, ID2)
\]

The stack commands below are used to stack applied axial load (P2), applied shear load (V2), and applied moment (M2) in ascending order per bolt. These loads are put into an array with the Load Case (LC2) and Rail End (ID2) from above. See the "Output" file below. Notice that there are only 3 bolts, since bolt number 3 is not included.

\[
P2 := \text{stack}\left(\left\{F_{t2}^T\right\}^{(1)}, \left\{F_{t2}^T\right\}^{(2)}, \left\{F_{t2}^T\right\}^{(3)}\right)
\]

\[
V2 := \text{stack}\left(\left\{F_{stot2}^T\right\}^{(1)}, \left\{F_{stot2}^T\right\}^{(2)}, \left\{F_{stot2}^T\right\}^{(3)}\right)
\]

\[
M2 := \text{stack}(M2, M2, M2)
\]

The "Output2" file below outputs an array from left to right starting with the Load Case number (LC2), Rail End Identification (ID2), applied load on the bolt (P2), applied shear on the bolt (V2), and applied moment on the bolt (M2).

\[
\text{Output2} := \text{augment}\left(\text{LC2, ID2, } \frac{P2}{\text{lbf}}, \frac{V2}{\text{lbf}}, \frac{M2}{\text{in-lbf}}\right)
\]  
(Note: Since the LC2 and ID2 numbers are dimensionless, the \( P2, V2, \) and \( M2 \) values are divided by their units in order to make the array dimensionless.)
AMS-02 HANDLE BRACKET BOLTS

<table>
<thead>
<tr>
<th>LC2</th>
<th>ID2</th>
<th>P2</th>
<th>V2</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>1</td>
<td>-153.939</td>
<td>44.98</td>
</tr>
<tr>
<td>2</td>
<td>61</td>
<td>1</td>
<td>43.424</td>
<td>4.07</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>1</td>
<td>636.091</td>
<td>29.497</td>
</tr>
<tr>
<td>4</td>
<td>101</td>
<td>1</td>
<td>151.515</td>
<td>98.39</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
<td>1</td>
<td>-137.939</td>
<td>43.834</td>
</tr>
<tr>
<td>6</td>
<td>63</td>
<td>1</td>
<td>65.424</td>
<td>3.497</td>
</tr>
<tr>
<td>7</td>
<td>83</td>
<td>1</td>
<td>333.909</td>
<td>35.323</td>
</tr>
<tr>
<td>8</td>
<td>103</td>
<td>1</td>
<td>209.515</td>
<td>84.254</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>1</td>
<td>291.879</td>
<td>46.975</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
<td>1</td>
<td>62.152</td>
<td>5.067</td>
</tr>
<tr>
<td>11</td>
<td>84</td>
<td>1</td>
<td>-301.182</td>
<td>19.356</td>
</tr>
<tr>
<td>12</td>
<td>104</td>
<td>1</td>
<td>-361.03</td>
<td>122.993</td>
</tr>
</tbody>
</table>

(rows(Output2) = 12)

Size of the "Output" Array:

(3 bolts x 4 load cases) = 12 load cases

**Bolt Fail-safe Results**

The array from the Output2 is read:

```math
\text{data}\_fs := \text{Output2}
\text{s} := 1..\text{rows(data}\_fs)
```

**Fail-safe Loads**

- **Applied tensile load**
  \[
  P\_FS\_s := \text{data}\_fs\_s,3, \text{lbf}
  \]
  \[
  \text{ID}\_FS\_s := \text{data}\_fs\_s,1
  \]

- **Applied shear load**
  \[
  V\_FS\_s := \text{data}\_fs\_s,4, \text{lbf}
  \]
  \[
  \text{LC}\_FS\_s := \text{data}\_fs\_s,2
  \]

- **Applied bending moment**
  \[
  M\_FS\_s := \text{data}\_fs\_s,5, \text{in}\cdot\text{lbf}
  \]

**Fail-safe Factors of Safety**

- **Ultimate**
  \[
  \text{SFu}\_FS := 1.0
  \]

- **Joint Separation**
  \[
  \text{SFsep}\_FS := 1.0
  \]

**This file uses the calculations shown in \escfil02\2111_mathcad\8307_bolts\multi_bolt_stiffness_insert_FS_RevC**

**Bolt Fail-safe Load data**

- **Joint separation load**
  \[
  \max(P\_sep\_FS) = 636.091 \text{\ lbf}
  \]

- **Max. load on the bolt (ultimate)**
  \[
  \max(P\_b\_FS) = 2210.8 \text{\ lbf}
  \]
  \[
  \max(V\_FS) = 122.993 \text{\ lbf}
  \]
### Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margin Type</th>
<th>Failure Mode</th>
<th>MS &lt;sub&gt;min&lt;/sub&gt;FS &lt;sub&gt;1,1&lt;/sub&gt;</th>
<th>MS &lt;sub&gt;min&lt;/sub&gt;FS &lt;sub&gt;5,1&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>Total Thread shear Ultimate</td>
<td>0.433</td>
<td>0.793</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>Shear Ultimate</td>
<td>3.084</td>
<td>10.54</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>Bending Ultimate</td>
<td>0.3513</td>
<td>10</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>Combined shear, tension and bending</td>
<td>4.42</td>
<td>0.3513</td>
</tr>
<tr>
<td></td>
<td>ultimate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MS<sub>bolt_FS</sub> := min(MS<sub>FS</sub>)

MS<sub>bolt_FS</sub> = 0.351  

Failure Mode<sub>FS</sub> = "Combined Shear Tension Bending Ultimate"

- MS<sub>_min_IDFS</sub> = 81  
  Load Case ID (8) and Bolt Number (1) for Minimum Margin
- MS<sub>_min_LCFS</sub> = 1  
  Rail End ID for Minimum Margin
- MS<sub>_min_PFS</sub> = 636.1  
  Applied Tensile Load for Minimum Margin
- MS<sub>_min_VFS</sub> = 29.5  
  Applied Shear Load for Minimum Margin
- MS<sub>_min_MFS</sub> = 0  
  Applied Bending Moment for Minimum Margin
5.13  Interface Panel A
Section 5.13: Interface Panel A Stress Analysis

Margins of Safety

Table 5.13-1: Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Critical Load Condition</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEG39137684</td>
<td>Interface Panel A</td>
<td>AL ALY 7075-T73</td>
<td>Kickload</td>
<td>Ultimate</td>
<td>0.136 (u)</td>
<td>5.13-19</td>
</tr>
</tbody>
</table>

Table 5.13-2: Fasteners Minimum Margin of Safety Summary

<table>
<thead>
<tr>
<th>Part / Dwg Number</th>
<th>Part Name / Description</th>
<th>Material &amp; Heat Treatment</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Reference Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1153E36</td>
<td>Fasteners connecting Front Sub-Panel to Standoff to Rear</td>
<td>A286</td>
<td>Combined Shear, Tension,</td>
<td>0.07 (u)</td>
<td>5.13-42</td>
</tr>
<tr>
<td></td>
<td>Sub-Panel</td>
<td></td>
<td>Bending Ultimate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Factors of Safety are 2.0 for Ultimate and 1.25 for Yield.
2. Boundary conditions are at eleven AMS-2 bolts distributed as three along the upper edge and eight along the lower edge.
3. 64 launch load cases, 64 landing load cases and 3 kickload cases were applied to the IPA.
4. u = ultimate
Factors of Safety

The hardware is designed with a yield factor of 1.25 and an ultimate factor of 2.0 against limit loads.

Description of IPA Structure

Interface Panel A (IPA) provides structural support for nine cable connectors. The cables are routed from the ROEU to front panel of the IPA. Cables attached to the back panel of the IPA distribute the power and data signals to the appropriate hardware. The IPA consists of several thin aluminum panels that are separated and stiffened by open-section beams. Bolts are used to connect the various panels and beams.

The IPA attaches to the USS-02 (Unique Support Structure -02) with three fasteners at the upper trunnion bridge beam and eight fasteners at the lower trunnion bridge beam as shown in Figure 5.13-1. Note that two of the eight fasteners at the lower interface location are shared with an EVA hand rail.

![Figure 5.13-1](image)

Figure 5.13-1  Interface Panel A attached to USS-02 upper and lower trunnion bridge beams
Description of the IPA Math Model

The FEMAP modeling software was used to generate a finite element model of the IPA for structural analysis using NASTRAN.

1. The geometry of each part was identified by a CAD model (Parasolid format) that was provided by the design group. This geometry was used as the basis for generating the finite element mesh. Views of the IPA assembly from the CAD model are shown in Figures 5.13-2 and 5.13-3.

Figure 5.13-2  Front view of IPA with cover plate and cable connectors (CAD Model)
2. The front, back, and sub-panels are modeled using plate elements (CQUAD4 and CTRIA3).
3. The web and flanges of the beams are modeled using plate elements (CQUAD4 and CTRIA3). Rigid elements (RBE2) are used to connect the flanges to the web for each beam.
4. The bolts are represented by CBUSH elements with stiffness values for the three translation directions that represent axial and shear stiffness.
5. The standoffs that provide separation between the front and rear sub-panel assemblies are modeled with beam (CBAR) elements.

6. For stand-alone assessments, constraints are applied to the model at the locations where the IPA is bolted to the USS beams. There are eight constrained nodes along the lower edge of the IPA and three constrained nodes along the upper edge. When the IPA model is integrated with the USS model, the constraints are replaced by CBUSH elements that represent the bolts connecting the IPA to the USS.

7. The cable connectors that attach to the front sub-panel assembly are model with mass elements and rigid elements that connect to the nodes around the circumference of each cutout.

A summary from NASTRAN of the finite elements comprising the model is provided below.

<table>
<thead>
<tr>
<th>MODEL SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF GRID POINTS = 55284</td>
</tr>
<tr>
<td>NUMBER OF CBAR ELEMENTS = 4</td>
</tr>
<tr>
<td>NUMBER OF CBUSH ELEMENTS = 71</td>
</tr>
<tr>
<td>NUMBER OF CONM2 ELEMENTS = 9</td>
</tr>
<tr>
<td>NUMBER OF CQUAD4 ELEMENTS = 51186</td>
</tr>
<tr>
<td>NUMBER OF CTRIA3 ELEMENTS = 51</td>
</tr>
<tr>
<td>NUMBER OF RBE2 ELEMENTS = 1904</td>
</tr>
</tbody>
</table>

The weight of the IPA is 13.2 pounds excluding the cable connectors. This is an estimate based on the CAD model. The weight for the finite element model (as computed by FEMAP) is 13.5 pounds. The complete mass property output from FEMAP is shown below.

**Check Mass Properties**

53225 Element(s) Selected...

<table>
<thead>
<tr>
<th>Mass</th>
<th>Center of Gravity in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural = 0.0350358</td>
<td>X = 6.850224 Y = -14.92744 Z = -11.75095</td>
</tr>
<tr>
<td>NonStructural = 0</td>
<td>X = 0 Y = 0 Z = 0</td>
</tr>
<tr>
<td>Total Mass = 0.0350358</td>
<td>X = 6.850224 Y = -14.92744 Z = -11.75095</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inertias about CSys 0</th>
<th>Inertias about C.G. in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ixx = 14.2106</td>
<td>Ixx = 1.565735</td>
</tr>
<tr>
<td>Ixy = -3.580659</td>
<td>Ixy = 0.00196897</td>
</tr>
<tr>
<td>Iyy = 7.760062</td>
<td>Iyy = 1.278085</td>
</tr>
<tr>
<td>Iyz = 6.084971</td>
<td>Iyz = -0.0607058</td>
</tr>
<tr>
<td>Izz = 9.797274</td>
<td>Izz = 0.346236</td>
</tr>
<tr>
<td>Izx = -2.80684</td>
<td>Izx = 0.0134194</td>
</tr>
</tbody>
</table>

A measured value of the weight is not currently available for comparison with the math models because manufacturing and assembly of the components is not complete.
For reference purposes, a front-view of the finite element math model is shown in Figure 5.13-4.

![Front view of the IPA finite element math model](image)

**Figure 5.13-4** Front view of the IPA finite element math model

**Checks for the IPA Math Model**

FEMAP and NASTRAN were used to check for element distortion. All of the checks were satisfactory except for a small percentage of CQUAD elements that had an aspect ratio and/or taper ratio that exceeded the default threshold values suggested by NASTRAN. It is the judgment of the modeler that the distortion is not severe enough to cause erroneous results and does not warrant the effort required to improve the mesh.
Constraint and grounding checks were performed using MSC Nastran. The results of these checks are shown below for an unconstrained model. The model passes the checks at all degree-of-freedom set levels with sufficiently low strain energy to indicate that there are no unintended constraints or grounding issues.

### RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET)

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.68779E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.51687E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.02508E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.97004E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>7.29303E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.54893E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Some possible reasons may lead to the failure:
1. CELASI elements connecting to only one grid point;
2. CELASI elements connecting to non-coincident points;
3. CELASI elements connecting to non-collinear DOF;
4. Improperly defined DMIG matrices;

### RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET)

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.62158E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.48538E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.08096E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.81064E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>8.91151E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.55629E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Some possible reasons may lead to the failure:
1. Multipoint constraint equations which do not satisfy rigid-body motion;
2. RBE3 elements for which the independent degree-of-freedom cannot describe all possible rigid-body motions.

### RESULTS OF RIGID BODY CHECKS OF MATRIX KFF (F-SET)

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.62158E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.48538E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>1.08096E-07</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>1.81064E-05</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>8.91151E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>2.55629E-06</td>
<td>PASS</td>
</tr>
</tbody>
</table>

Some possible reasons may lead to the failure:
1. Constraints which prevent rigid-body motion.

### RESULTS OF RIGID BODY CHECKS OF MATRIX KAA1 (A-SET)

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>STRAIN ENERGY</th>
<th>PASS/FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.62158E-08</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>2.48538E-07</td>
<td>PASS</td>
</tr>
</tbody>
</table>

### File Name
Panel A.mcd
A modal analysis was performed using NASTRAN to determine the modal frequencies and confirm that the model has appropriate rigid-body modes. A list of the rigid-body modes and elastic modes are provided below.

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACTION ORDER</th>
<th>EIGENVALUE</th>
<th>R A D I A N S</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.626237E-05</td>
<td>4.032663E-03</td>
<td>6.418182E-04</td>
<td>1.000000E+00</td>
<td>-1.626237E-05</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-7.522649E-06</td>
<td>2.742745E-03</td>
<td>2.429145E-04</td>
<td>1.000000E+00</td>
<td>-7.522649E-06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2.329522E-06</td>
<td>1.526277E-03</td>
<td>2.429145E-04</td>
<td>1.000000E+00</td>
<td>2.329522E-06</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1.249298E-05</td>
<td>5.354541E-03</td>
<td>6.418182E-04</td>
<td>1.000000E+00</td>
<td>1.249298E-05</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.490180E-05</td>
<td>3.860285E-03</td>
<td>6.418182E-04</td>
<td>1.000000E+00</td>
<td>1.490180E-05</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1.721638E-05</td>
<td>4.149292E-03</td>
<td>6.418182E-04</td>
<td>1.000000E+00</td>
<td>1.721638E-05</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3.534344E-05</td>
<td>9.461817E-03</td>
<td>9.461817E-04</td>
<td>1.000000E+00</td>
<td>3.534344E-05</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>3.677752E+05</td>
<td>6.064447E+02</td>
<td>9.651867E+01</td>
<td>1.000000E+00</td>
<td>3.677752E+05</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>9.190506E+05</td>
<td>9.856173E+02</td>
<td>1.525777E+02</td>
<td>1.000000E+00</td>
<td>9.190506E+05</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.343090E+06</td>
<td>1.158917E+03</td>
<td>1.844474E+02</td>
<td>1.000000E+00</td>
<td>1.343090E+06</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>1.491253E+06</td>
<td>1.221169E+03</td>
<td>1.943550E+02</td>
<td>1.000000E+00</td>
<td>1.491253E+06</td>
</tr>
</tbody>
</table>

The highlighted rows show that there are seven modes with “zero” frequency. An examination of the mode shapes for each of these “zero frequency” modes shows that six of the modes correspond to the standard rigid-body modes of an unconstrained structure. The seventh “zero frequency” mode corresponds to rigid-body rotation of the upper stiffener panel about an axis through the two bolts that connect it to the rear panel. When the model is constrained for structural analysis the upper stiffener panel is constrained at three additional locations that eliminate this seventh rigid-body mode. The first elastic mode of the structure has a frequency of 96.5 hertz for the unconstrained condition. The results of the modal analysis indicate that the math model is responding dynamically as expected.
Overview of the IPA Loads Analyses

The stand-alone math model of the IPA described in the previous sections was used to assess the structural for the EVA kick-loads as specified in SSP-57003. The EVA kick-load is defined as an inadvertent bump by a crew member that induces a force of 125 pounds concentrated in a 0.5-inch diameter circular area.

An initial assessment of the Shuttle flight loads was made using the secondary structure load factors provided in Table 4-4 of the AMS-02 Structural Verification Plan (JSC-28792, Rev. E). However, these loads are very conservative and the results of the analysis showed that the structural margins were unacceptable. The load factors are provided in Table 5.13-3 for reference.

<table>
<thead>
<tr>
<th>Weight (pounds)</th>
<th>Load Factor (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>40</td>
</tr>
<tr>
<td>20-50</td>
<td>31</td>
</tr>
<tr>
<td>50-100</td>
<td>22</td>
</tr>
<tr>
<td>100-200</td>
<td>17</td>
</tr>
<tr>
<td>200-500</td>
<td>13</td>
</tr>
</tbody>
</table>

To reduce the conservatism for the flight loads assessment, the IPA math model was integrated with the math model of the full AMS-02 payload. The liftoff and landing load factors from the AMS-02 design coupled loads analysis (as specified in Table 5-2 of the AMS-02 SVP) were applied to the integrated math model. These loads are provided in Table 5.13-4 for reference.

<table>
<thead>
<tr>
<th>Event</th>
<th>Nx</th>
<th>Ny</th>
<th>Nz</th>
<th>Rx</th>
<th>Ry</th>
<th>Rz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liftoff</td>
<td>-3.7 / 0.4</td>
<td>-1.4 / 1.6</td>
<td>-1.4 / 1.5</td>
<td>-4.5 / 4.1</td>
<td>-8.4 / 4.1</td>
<td>-3.9 / 4.1</td>
</tr>
<tr>
<td>Abort Landing</td>
<td>-1.2 / 1.3</td>
<td>-0.7 / 0.6</td>
<td>-2.1 / 5.6</td>
<td>-5.2 / 4.7</td>
<td>-10.7 / 13.9</td>
<td>-6.0 / 4.8</td>
</tr>
</tbody>
</table>

A static loads analysis was performed using NASTRAN with 64 subcases representing all combinations of the liftoff load factors and 64 subcases representing all combinations of the landing load factors. Loads and stresses were then recovered from this integrated...
analysis for the IPA interface and internal components and used to compute the structural strength margins.

The next sections provide a description of the integrated finite element model and the checks that were performed.

**Description of the Integrated IPA and Full Payload Math Model**

The 2-06 version of the AMS-02 loads model was used to represent the payload in the integrated model. The IPA math model described in the preceding sections was connected to the payload model using two rigid elements (RBE2). The independent nodes for the two rigid elements are the nodes on the beam elements representing the IPA interface with the upper trunnion bridge beam and the lower trunnion bridge beam. The dependent nodes of the rigid elements are the IPA nodes that represent the interface bolt locations. Views of the full payload math model are shown in Figures 5.13-5 and 5.13-6.
Checks for the Integrated IPA and Full Payload Math Model

Constraint and grounding checks were performed using MSC Nastran. The results of these checks are shown below for an unconstrained model. The model passes the checks at all degree-of-freedom set levels with sufficiently low strain energy to indicate that there are no unintended constraints or grounding issues.

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KGG (G-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 4.703487E-01
DIRECTION STRAIN ENERGY PASS/FAIL
--------- -------------  ---------
1 2.241968E-06 PASS
2 1.058008E-06 PASS
3 4.164460E-06 PASS
4 6.646296E-03 PASS
5 2.698223E-03 PASS
6 2.730940E-03 PASS

SOME POSSIBLE REASONS MAY LEAD TO THE FAILURE:
1. CELASI ELEMENTS CONNECTING TO ONLY ONE GRID POINT;
2. CELASI ELEMENTS CONNECTING TO NON-COINCIDENT POINTS;
3. CELASI ELEMENTS CONNECTING TO NON-COLINEAR DOF;
4. IMPROPERLY DEFINED DMIG MATRICES;

*** USER INFORMATION MESSAGE 7570 (GPWG1D)
RESULTS OF RIGID BODY CHECKS OF MATRIX KNN (N-SET) FOLLOW:
PRINT RESULTS IN ALL SIX DIRECTIONS AGAINST THE LIMIT OF 9.176609E-01
DIRECTION STRAIN ENERGY PASS/FAIL
--------- -------------  ---------
1 1.497954E-06 PASS
A modal analysis was performed using NASTRAN to determine the modal frequencies and confirm that the model has appropriate rigid-body modes. A list of the rigid-body modes and elastic modes are provided below.

### Mode Checks of Full Payload with IPA

<table>
<thead>
<tr>
<th>MODE NO.</th>
<th>EXTRACION ORDER</th>
<th>EIGENVALUE</th>
<th>REAL EIGENVALUES</th>
<th>RADIANS</th>
<th>CYCLES</th>
<th>GENERALIZED MASS</th>
<th>GENERALIZED STIFFNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1.303845E-08</td>
<td>1.141860E-04</td>
<td>1.817327E-05</td>
<td>1.000000E+00</td>
<td>-1.303845E-08</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.565184E-07</td>
<td>3.956241E-04</td>
<td>6.296552E-05</td>
<td>1.000000E+00</td>
<td>1.565184E-07</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2.830780E-07</td>
<td>5.320507E-04</td>
<td>8.467850E-05</td>
<td>1.000000E+00</td>
<td>2.830780E-07</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2.986428E-07</td>
<td>5.466822E-04</td>
<td>8.697534E-05</td>
<td>1.000000E+00</td>
<td>2.986428E-07</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.328547E-06</td>
<td>1.152626E-03</td>
<td>1.834462E-04</td>
<td>1.000000E+00</td>
<td>1.328547E-06</td>
<td></td>
</tr>
</tbody>
</table>
The weight of the integrated system math model is 15119 pounds. This is a conservative (slightly greater than the budget) weight for analysis purposes and can not be verified at the present time because assembly of the payload flight article is not complete. The mass properties for the integrated math model are shown below as computed by FEMAP.

**Check Mass Properties**

199297 Element(s) Selected...

<table>
<thead>
<tr>
<th>Mass</th>
<th>Center of Gravity in CSys 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural =</td>
<td>X= -0.419056 Y= 3.247873 Z= 385.9702</td>
</tr>
<tr>
<td>NonStructural=</td>
<td>X= -0.0154423 Y= 0.999418 Z= 388.9703</td>
</tr>
<tr>
<td>Total Mass =</td>
<td>X= -0.372826 Y= 2.99033 Z= 386.3138</td>
</tr>
</tbody>
</table>

**Material and Temperature**

The cover panel and the base panels are made from 7075-T73 sheet and all the C-channel and stiffeners are made from 7075-T7351 plate. The temperature extremes for the Interface Panel A are -180°F to 220°F.

**Analysis**

The critical stresses for the Interface Panel A are compared to the ultimate and yield strength of 7075-T73 Aluminum Alloy. Analysis to the fasteners used to assemble the IPA was also performed. All margins of safety are positive.
CHECK OF INTERFACE PANEL A

Material Properties : 7075-T73 AL ALY (Ref. MMPDS-01, Table 3.7.6.0(b2j))

\[
F_{u} := 67000 \text{ psi} \\
F_{y} := 56000 \text{ psi} \\
F_{su} := 38000 \text{ psi}
\]

Factors of Safety, \( FS_u := 2.0 \quad FS_y := 1.25 \)

Temperature reduction factors,

+ At 220°F: (For Interface Panel A, the temperature extremes are -180°F to 220°F; These temperature reduction factors are conservative for liftoff/landing conditions)

\[
\beta_{u1} := 0.88 \quad (\text{Ref. MMPDS-01, Figure 3.7.6.1.1(c)})
\]

\[
\beta_{y1} := 0.90 \quad (\text{Ref. MMPDS-01, Figure 3.7.6.1.1(d)})
\]

Allowable stresses:

\[
F_{u1,a} := \beta_{u1} \cdot F_{u} \\
F_{u1,a} = 58960 \text{ psi}
\]

\[
F_{y1,a} := \beta_{y1} \cdot F_{y} \\
F_{y1,a} = 50400 \text{ psi}
\]

\[
F_{su1,a} := \beta_{u1} \cdot F_{su} \\
F_{su1,a} = 33440 \text{ psi}
\]
NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Launch and Landing Cases, the elements at the bolt holes were removed from the NASPOST sort (see table below). These elements resulted with localized stresses and therefore the stresses were not real.
Liftoff Loads

The Interface Panel A model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 liftoff load cases (Load Case 1001 - 1064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

\[ u_{uu,\text{max}} := 19316.1 \text{ psi} \quad \text{LC# 1032, ELEM# 1005557} \]

* (Maximum Principal Stress)

* (See Appendix A25, p.A25-8)

\[ u_{uy,\text{max}} := 18677.6 \text{ psi} \quad \text{LC# 1032, ELEM# 1005553} \]

* (Maximum Von-Mises Stress)

* (See Appendix A25, p.A25-9)

\[ u_{us,\text{max}} := 9658.1 \text{ psi} \quad \text{LC# 1032; ELEM# 1005557} \]

* (Maximum Shear Stress)

* (see Appendix A25, p.A25-10)

Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{FS_u \cdot u_{uu,\text{max}}} - 1 \quad MS_{u1} = 0.526 \]

\[ MS_{y1} := \frac{F_{y1,a}}{FS_y \cdot u_{uy,\text{max}}} - 1 \quad MS_{y1} = 1.16 \]

\[ MS_{s1} := \frac{F_{su1,a}}{FS_u \cdot u_{us,\text{max}}} - 1 \quad MS_{s1} = 0.73 \]
Landing Loads

The Interface Panel A model was integrated with the AMS-02 payload loads model. For the following analysis, the maximum Von-Mises, principal, and shear stresses of plate elements are selected from 64 landing load cases (Load Case 2001 - 2064). NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. Note that the elements at the bolt holes were removed from the NASPOST sort.

\[ u_{uu1,max} = 24795.1 \text{ psi} \quad \text{LC# 2032, ELEM# 1005557} \quad \text{(Maximum Principal Stress)} \]

\[ u_{uy1,max} = 23655.5 \text{ psi} \quad \text{LC# 2032, ELEM# 1005553} \quad \text{(Maximum Von-Mises Stress)} \]

\[ u_{us1,max} = 12397.6 \text{ psi} \quad \text{LC# 2032; ELEM# 1005557} \quad \text{(Maximum Shear Stress)} \]

Margins of Safety,

\[ MS_{u1} := \frac{F_{u1,a}}{FS_u u_{uu1,max}} - 1 \quad MS_{u1} = 0.189 \]

\[ MS_{y1} := \frac{F_{y1,a}}{FS_y u_{uy1,max}} - 1 \quad MS_{y1} = 0.7 \]

\[ MS_{s1} := \frac{F_{s1,a}}{FS_s u_{us1,max}} - 1 \quad MS_{s1} = 0.35 \]
Applying 125 lb Kickload

Maximum Von-Mises, principal, and shear stresses of plate elements are selected from the 125 lb kickload cases. The kickload was applied at 3 different locations on the Interface Panel A. NASPOST V.2.2 is used to sort out the maximum stresses within the load cases. For the Kickload Case, elements 60633, 63739, 61028, 64906, 61027, 73547, and 50298 were removed from the NASPOST sort. These elements resulted with localized stresses and therefore the stresses were not real.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Node Where Load is Applied</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1065</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1067</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1168</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1170</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1167</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>26</td>
<td>3015</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3287</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3294</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3017</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3285</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>64966</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>65519</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>64111</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>64955</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>65517</td>
<td>-25</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\( u_{uu1}\) max := 25945.9 psi \( LC\# 25, ELEM\# 50163 \) (Maximum Principal Stress)

(See Appendix A25, p.A25-38)

\( u_{uy1}\) max := 24375.0 psi \( LC\# 25, ELEM\# 50163 \) (Maximum Von-Mises Stress)

(See Appendix A25, p.A25-39)

\( u_{us1}\) max := 12973.0 psi \( LC\# 25; ELEM\# 50163 \) (Maximum Shear Stress)

(see Appendix A25, p.A25-40)

Margins of Safety,

\[
MS_{u1} := \frac{F_{u1,a}}{FS_{u}u_{uu1,\text{max}}} - 1 \quad MS_{u1} = 0.136
\]

\[
MS_{y1} := \frac{F_{y1,a}}{FS_{y}u_{uy1,\text{max}}} - 1 \quad MS_{y1} = 0.65
\]

\[
MS_{s1} := \frac{F_{s1,a}}{FS_{u}u_{us1,\text{max}}} - 1 \quad MS_{s1} = 0.29
\]
Bolt Analysis

Base Panel (SDG39137685-001) to C-Channel Assemblies (SEG39137686-701, -702, -703, -704) Bolts

Bolts NAS1133E4, 0.190-32UNJF, 0.526L, Washer NAS1149E0332R, Nut Plate MS21076L3E

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

```
loads := READPRN("1-52.txt")
```

```
i := 1..rows(loads) rows(loads) = 6812
j := 2..cols(loads) cols(loads) = 8
ID := loads[i,1] Fx := loads[i,3] lbf
Fz := loads[i,5] lbf
My := loads[i,7] in-lbf
LC := loads[i,2] Fy := loads[i,4] lbf
Mx := loads[i,6] in-lbf
Mz := loads[i,8] in-lbf
```

* Note that "1-52.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

```
Ft_i := |Fx_i |
max(Ft) = 65.12 lbf Tensile Load
```

```
Fv_i := \sqrt{(Fx_i)^2 + (Fz_i)^2}
max(Fv) = 318.21 lbf Shear Load
```
Bolt Analysis for Front or Base Panel to C-channel

Base Panel (SDG39137685-001) to C-Channel Assemblies (SEG39137686-701, -702, -703, -704) Bolts

Bolts NAS1133E4, 0.190-32UNJF, 0.526L, Washer NAS1149E0332R, Nut Plate MS21076L3E

Flange 1  Front Panel/Base Panel,
Part numbers: SDG39137685
Material: AL ALY 7075-T73

Flange 2  C-channel, Panel A Assembly
Part number: SDG39137686
Material: AL ALY 7075-T7351

Minimum edge distance of flange one:  
\[\text{edge}_1 := 0.438 \text{ in} \]

Minimum edge distance of flange two:  
\[\text{edge}_2 := 0.312 \text{ in} \]

Loads

Applied tensile load  \( P := 65.12 \text{lbf} \)

Applied shear load  \( V := 318.21 \text{lbf} \)

Applied bending moment  \( M := 0 \text{in-lbf} \)

Factors of Safety

Ultimate  \( SF_u := 2.0 \)

Yield  \( SF_y := 1.25 \)

Joint Separation  \( SF_{sep} := 1.2 \)

Fitting factor  \( FF := 1.15 \)

Temperature data

Assembly  \( \text{Temp}_{initial} := 70 \text{ deg} \)

Maximum  \( \text{Temp}_{\text{max}} := 220 \text{ deg} \)

Minimum  \( \text{Temp}_{\text{min}} := -180 \text{ deg} \)

Bolt Data

Nominal diameter of bolt  \( D := 0.19 \text{ in} \)

Number of threads/inch  \( N_t := 32 \frac{\text{in}}{} \)

Shank diameter of bolt  \( D_{\text{shank}} := 0.1895 \text{ in} \)

Total length of bolt  \( L := 0.526 \text{ in} \)

Threaded length  \( L_t := 0.276 \text{ in} \)

Note: Figure is for reference only. Not to scale, and actual joint may differ. Washer may be on nut side, head side, or both.

Note, these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative.

5.13-21
**Thread data lookup table is hidden**

This file uses the data shown in `\escll02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd`

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature correction factor for bolt strength ultimate.</td>
<td>$T_{Su_{-}bolt} := 0.96$</td>
</tr>
<tr>
<td>Bolt strength ultimate tensile allowance</td>
<td>$F_{tu_{-}bolt} := 160000 \text{ psi}$</td>
</tr>
<tr>
<td>Bolt ultimate shear allowance</td>
<td>$F_{su_{-}bolt} := 0.6 \cdot F_{tu_{-}bolt}$</td>
</tr>
<tr>
<td>Temperature correction factor for modulus</td>
<td>$T_{E_{-}bolt} := 0.96$</td>
</tr>
<tr>
<td>Bolt modulus</td>
<td>$E_{-}bolt := (29.1 \cdot 10^6 \text{ psi})$</td>
</tr>
<tr>
<td>Thermal coefficients for bolt</td>
<td>$\beta_{bolt_{-}hot} := 9.2 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$</td>
</tr>
<tr>
<td></td>
<td>$\beta_{bolt_{-}cold} := 8.0 \cdot 10^{-6} \frac{\text{in}}{\text{deg}}$</td>
</tr>
<tr>
<td>Washer Data</td>
<td></td>
</tr>
<tr>
<td>Thickness of washers, head</td>
<td>$t_{wh} := 0.032\text{ in}$</td>
</tr>
<tr>
<td></td>
<td>$t_{wn} := 0.0 \text{ in}$</td>
</tr>
<tr>
<td>Diameter of washer under head, Outer:</td>
<td>$D_{woh} := 0.438\text{ in}$</td>
</tr>
<tr>
<td></td>
<td>$D_{wih} := 0.203\text{ in}$</td>
</tr>
<tr>
<td>Diameter of washer under nut, Outer:</td>
<td>$D_{won} := 0.0\text{ in}$</td>
</tr>
<tr>
<td></td>
<td>$D_{win} := 0.0 \text{ in}$</td>
</tr>
<tr>
<td>Nut Data</td>
<td></td>
</tr>
<tr>
<td>Height of nut</td>
<td>$H := 0.250 \text{ in}$</td>
</tr>
<tr>
<td>Nut diameter across flats</td>
<td>$D_{n} := 0.290 \text{ in}$</td>
</tr>
<tr>
<td>Temperature correction factor for nut strength</td>
<td>$T_{S_{-}nut} := 0.96$</td>
</tr>
</tbody>
</table>

**Note:** If there are no washer tw's, Dw's, and Dwi's should be zero.
Bolt Analysis for Front or Base Panel to C-channel

Ultimate allowable stress, tensile: \( F_{\text{nut}} := 125000 \text{ psi} \)  
Shear: \( F_{\text{su nut}} := 0.6 \times F_{\text{nut}} \)

Ultimate axial strength of nut: \( F_{\text{nut}} := 2460 \text{ lbf} \)  
\((\text{Reference MS21076})\)

**Flange data**

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

- Thickness of flange 1: \( t_{f1} := 0.125 \text{ in} \)  
- Thickness of flange 2: \( t_{f2} := 0.120 \text{ in} \)  
- Diameter of thru hole: \( D_{\text{hole}} := 0.213 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors:

- Compressive Modulus of elasticity for the parts in the joint: \( E_{\text{flange1}} := (10.3 \times 10^6 \text{ psi}) \)  
- \( E_{\text{flange2}} := (10.3 \times 10^6 \text{ psi}) \)

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \)  
flange 2: \( T_{f2E} := 0.95 \)

Coefficient of thermal expansion for flanges:

- \( \beta_{\text{flange1 hot}} := 12.75 \times 10^{-6} \text{ in/in deg} \)  
- \( \beta_{\text{flange2 hot}} := 12.75 \times 10^{-6} \text{ in/in deg} \)
- \( \beta_{\text{flange1 cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \)  
- \( \beta_{\text{flange2 cold}} := 12.1 \times 10^{-6} \text{ in/in deg} \)

**Torque/Preload data**

- Maximum torque: \( T_{\text{max}} := 35 \text{ in-lbf} \)  
- \((\text{Dwg. SEG39137684})\)
- Minimum torque: \( T_{\text{min}} := 30 \text{ in-lbf} \)

Joint is lubed/dry: \( u := 0.25 \)  
Preload Uncertainty: \( k := 0.15 \)  
Loading plane factor: \( n := 0.5 \)

**Stiffness and Margin calculations are hidden**

\[ \text{This file uses the calculations shown in } \text{\textbackslash escfl02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd} \]

**Bolt Load data**

- Bolt/joint stiffness factor: \( = 0.35 \)  
- Preload due to temperature: \( P_{\text{thr pos}} = 123.9 \text{ lbf} \)  
- \( P_{\text{thr neg}} = -238.4 \text{ lbf} \)
- Max. preload: \( PLD_{\text{max}} = 1659 \text{ lbf} \)  
- Min. preload: \( PLD_{\text{min}} = 474 \text{ lbf} \)  
- Nom. preload: \( PLD_{\text{nom}} = 1228 \text{ lbf} \)  
- Uncertainty factor: \( u = 0.25 \)
Title: Bolt Analysis for Front or Base Panel to C-channel

Torque coefficient \( k = 0.15 \)  
Loading plane factor \( n = 0.5 \)  
Preload to yield ratio (nom.) \( \text{PLDratio} = 0.554 \)

Joint separation load \( \text{P}_{\text{sep}} = 78.144 \text{lbf} \)

**Bolt Load data (cont.)**

<table>
<thead>
<tr>
<th>Applied Tensile load on the bolt</th>
<th>Max. load on the bolt with preload and Factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P = 65.12 \text{lbf} )</td>
<td>( \text{(ultimate)} ) ( \text{P}_{\text{b}} = 1685 \text{lbf} )</td>
</tr>
<tr>
<td>( \text{V} = 318.21 \text{lbf} )</td>
<td>( \text{(yield)} ) ( \text{P}_{\text{by}} = 1675 \text{lbf} )</td>
</tr>
<tr>
<td>( \text{M} = 0 \text{in} \cdot \text{lbf} )</td>
<td>( \text{Max. load on the bolt with preload without factor of safety} ) ( \text{P}_{\text{bapp}} = 1672 \text{lbf} )</td>
</tr>
</tbody>
</table>

Bolt ultimate tensile strength \( \text{P}_{\text{At}} = 2957 \text{lbf} \)

Thread pullout strength \( \text{P}_{\text{As}} = 2362 \text{lbf} \)

Nut ultimate tensile strength \( \text{P}_{\text{t nut}} = 2362 \text{lbf} \)

Bolt shear strength \( \text{V}_{\text{Au}} = 2599 \text{lbf} \)

Bolt bending strength \( \text{M}_{\text{Au}} = 61 \text{in} \cdot \text{lbf} \)

**General Checks**

length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"

cone_check = "Joint pressure cone does not extend pass flange edge"

preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"

washer_check = "Washers under head and nut do not extend past flanges"

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Joint separation ( \text{MS}_1 = 5.4 )</th>
<th>Direct Thread shear Ultimate ( \text{MS}_6 = 14.77 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate ( \text{MS}_2 = 18.74 )</td>
<td>Total Thread shear Ultimate ( \text{MS}_7 = 0.4 )</td>
</tr>
<tr>
<td>Direct Tension Yield ( \text{MS}_3 = 22.69 )</td>
<td>Shear Ultimate ( \text{MS}_8 = 2.55 )</td>
</tr>
<tr>
<td>Total Tension Ultimate ( \text{MS}_4 = 0.75 )</td>
<td>Bending Ultimate ( \text{MS}_9 = 100 )</td>
</tr>
<tr>
<td>Total Tension Yield ( \text{MS}_5 = 0.32 )</td>
<td>Combined shear, tension and bending ultimate ( \text{MS}_{10} = 0.66 )</td>
</tr>
</tbody>
</table>

**Smallest margin of safety for the bolt, and the failure mode:**

\( \text{MS}_{\text{bolt}} = 0.32 \)  
Failure Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

**Fail-safe Loads**

<table>
<thead>
<tr>
<th>Applied load type</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load</td>
<td>P_Fs := 130.24 lbf</td>
</tr>
<tr>
<td>Shear load</td>
<td>V_Fs := 636.42 lbf</td>
</tr>
<tr>
<td>Bending moment</td>
<td>M_Fs := 0 in-lbf</td>
</tr>
</tbody>
</table>

**Fail-safe Factors of Safety**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>SFu_Fs := 1.0</td>
</tr>
<tr>
<td>Joint Separation</td>
<td>SFsep_Fs := 1.0</td>
</tr>
</tbody>
</table>

---

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

Fri Apr 27 14:16:05 2007

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

**Bolt Fail-safe Load data**

<table>
<thead>
<tr>
<th>Load type</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation load</td>
<td>Psep_Fs = 130.24 lbf</td>
</tr>
<tr>
<td>Max. load on the bolt(ultimate)</td>
<td>Pb_Fs = 1685.2 lbf</td>
</tr>
</tbody>
</table>

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>MS_Fs_1 = 2.84</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS_Fs_2 = 18.74</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS_Fs_3 = 0.75</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>MS_Fs_4 = 14.77</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>MS_Fs_5 = 0.4</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>MS_Fs_6 = 2.55</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>MS_Fs_7 = 10</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>MS_Fs_8 = 0.66</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MSbolt_FS = 0.4  Failure_Mode_FS = "Total Thread Shear Ultimate (Nut)"
Base Panel (SDG39137685-001) to Rear Sub Panel Assembly(SDG39137809-702) Bolts

Bolts FIT7654-3-10-6, 0.190-32UNJF, A-286, 0.625L, Washer NAS1149E0332R, Nut Plate MS21076L3E

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[ \text{loads} := \text{READPRN("68-71.txt")} \]

\[ i := 1 .. \text{rows(load)} \quad \text{rows(load)} = 524 \quad j := 2 .. \text{cols(load)} \quad \text{cols(load)} = 8 \]

\[ \text{ID} := \text{load} \quad \text{Fx} := \text{load} \cdot \text{lbf} \quad \text{Fz} := \text{load} \cdot \text{lbf} \quad \text{My} := \text{load} \cdot \text{in-lbf} \quad \text{Mz} := \text{load} \cdot \text{in-lbf} \]

\[ \text{LC} := \text{load} \quad \text{Fy} := \text{load} \cdot \text{lbf} \quad \text{Mx} := \text{load} \cdot \text{in-lbf} \quad \text{Mz} := \text{load} \cdot \text{in-lbf} \]

* Note that "68-71.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[ \text{Ft}_i := \text{max(Ft)} = 9.47 \text{ lbf} \quad \text{Tensile Load} \]

\[ \text{Fv}_i := \sqrt{\left(\text{Fx}_i\right)^2 + \left(\text{Fz}_i\right)^2} \quad \text{max(Fv)} = 320.26 \text{ lbf} \quad \text{Shear Load} \]
Bolt Analysis for Base Panel to Rear Sub-Panel

Base Panel (SDG39137685-001) to Rear Sub Panel Assembly (SDG39137809-702) Bolts

Bolts FIT7654-3-10-6, 0.190-32UNJF, A-286, 0.625L, Washer NAS1149E0332R, Nut Plate MS21076L3E

Flange: Base Panel,
Part numbers: SDG39137685-001
Material: AL ALY 7075-T73

Flange_2: Rear SubPanel
Part number: SDG39137809-702
Material: AL ALY 7075-T7351

Minimum edge distance of flange one: edge1 := 0.438 in
flange two: edge2 := 0.312 in

Loads

Applied tensile load
P := 9.47lbf

Applied shear load
V := 320.26lbf

Applied bending moment
M := 0in-lbf

Factors of Safety

Ultimate SFu := 2.0
Yield SFy := 1.25
Joint Separation SFsep := 1.2
Fitting factor FF := 1.15

Temperature data

Assembly Temp_initial := 70 deg

Maximum Temp_max := 220 deg
Minimum Temp_min := -180 deg

Bolt Data

Nominal diameter of bolt
D := .19 in

Number of threads/inch
Nt := 32 \frac{1}{in}

Shank diameter of bolt
D_shank := .139 in

Total length of bolt
L := .625 in

Threaded length
Lt := 0.438 in

Bolt head dia. across flats
dw := 0.305 in

Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area

(If bolt is fully threaded, input Lt = L)

(dia of pressure boss if it exists, otherwise dia of head)
Bolt head height \( bh := .185 \text{-in} \)

**Thread data lookup table is hidden**

This file uses the data shown in `\escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd`

Temperature correction factor for bolt strength ultimate. \( TS_u_{\text{bolt}} := 0.96 \)

Yield \( TS_y_{\text{bolt}} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{tu_{\text{bolt}}} := 160000 \text{-psi}\)

Yield \( F_{ty_{\text{bolt}}} := 120000 \text{-psi}\)

Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 \times F_{tu_{\text{bolt}}} \)

Temperature correction factor for bolt modulus \( TE_{\text{bolt}} := 0.96 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} := \left(29.1 \times 10^6 \text{-psi}\right) \)

Thermal coefficients for bolt

\[
\beta_{\text{bolt\_hot}} := 9.2 \times 10^{-6} \text{-in/in \ deg} \\
\beta_{\text{bolt\_cold}} := 8.0 \times 10^{-6} \text{-in/in \ deg}
\]

**Washer Data**

Thickness of washers: head \( tw_h := 0.032 \text{-in} \)

Diameter of washer under head, Outer: \( D_{wo_{\text{h}}} := 0.438 \text{-in} \)

Inner: \( D_{wi_{\text{h}}} := 0.203 \text{-in} \)

Nut \( tw_n := 0.0 \text{-in} \)

Diameter of washer under nut, Outer: \( D_{wo_{\text{n}}} := 0.290 \text{-in} \)

Inner: \( D_{wi_{\text{n}}} := 0.0 \text{-in} \)

Note: If there are no washer tw's, Dw's and Dwi's should be zero

Modulus of elasticity, head: \( E_{\text{washerh}} := \left(29.1 \times 10^6 \text{-psi}\right) \)

Temperature correction factor for modulus, head: \( TE_{\text{washerh}} := 0.96 \)

Nut: \( E_{\text{washern}} := (0 \text{-psi}) \)

Temperature correction factor for modulus, nut: \( TE_{\text{washern}} := 0.96 \)

**Nut Data**

Height of nut \( H := 0.250 \text{-in} \)

Diameter of nut, across flats \( D_n := 0.290 \text{-in} \)

Temperature correction factor for nut strength \( TS_{\text{nut}} := 0.96 \)

Ultimate allowable stress, tensile: \( F_{tu_{\text{nut}}} := 125000 \text{-psi} \)

Shear: \( F_{su_{\text{nut}}} := 0.6 \times F_{tu_{\text{nut}}} \)
Bolt Analysis for Base Panel to Rear Sub-Panel

**Flange data**

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

- Thickness of flange 1: \( t_{f1} := 0.125 \text{ in} \)
- Thickness of flange 2: \( t_{f2} := 0.125 \text{ in} \)
- Diameter of thru hole \( D_{\text{hole}} := 0.213 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors

- Compressive Modulus of elasticity for the parts in the joint: \( E_{\text{flange1}} := (10.3 \times 10^6 \text{ psi}) \)
  \( E_{\text{flange2}} := (10.3 \times 10^6 \text{ psi}) \)

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \)
  
  Temperature correction factor (modulus) for flange 2: \( T_{f2E} := 0.95 \)

- Coefficient of thermal expansion for flanges:
  \( \beta_{\text{flange1\_hot}} := 12.75 \times 10^{-6} \text{ in/deg} \)
  \( \beta_{\text{flange1\_cold}} := 12.1 \times 10^{-6} \text{ in/deg} \)
  
  \( \beta_{\text{flange2\_hot}} := 12.75 \times 10^{-6} \text{ in/deg} \)
  \( \beta_{\text{flange2\_cold}} := 12.1 \times 10^{-6} \text{ in/deg} \)

**Torque/Preload data**

- Maximum torque \( T_{\text{max}} := 35\text{-in-lbf} \)
- Minimum torque \( T_{\text{min}} := 30\text{-in-lbf} \)

Joint is lubed/dry

- Preload Uncertainty \( u := 0.25 \)
- Loading plane factor \( n := 0.5 \)
  
  Torque coefficient \( k := 0.15 \)

**Stiffness and Margin calculations are hidden**

- Joint separation load \( P_{\text{sep}} := 11.364 \text{ lbf} \)

- Bolt/joint stiffness factor \( := 0.276 \)

**Bolt Load data**

- Preload due to temperature
  - Maximum preload \( PL_{\text{max}} := 1625 \text{ lbf} \)
  - Minimum preload \( PL_{\text{min}} := 539 \text{ lbf} \)
  - Nominal preload \( PL_{\text{nom}} := 1228 \text{ lbf} \)
  - Preload to yield ratio \( PL_{\text{ratio}} := 0.703 \)
  - Joint separation load \( P_{\text{sep}} := 11.364 \text{ lbf} \)

Preload due to temperature

- Pthr\_pos := 90.2 \text{ lbf} \)
  
  Pthr\_neg := 173.7 \text{ lbf} \)

- Uncertainty factor \( u := 0.25 \)
- Torque coefficient \( k := 0.15 \)
  
  Loading plane factor \( n := 0.5 \)
**Bolt Load data (cont.)**

<table>
<thead>
<tr>
<th>Applied Tensile load on the bolt</th>
<th>P = 9.47 lbf</th>
<th>Max. load on the bolt with preload and Factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied shear on the bolt</td>
<td>V = 320.26 lbf</td>
<td>(ultimate) Pb = 1628 lbf</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>M = 0 in-lbf</td>
<td>(yield) Pby = 1627 lbf</td>
</tr>
</tbody>
</table>

Max. load on the bolt with preload without factor of safety: Pbapp = 1627 lbf

**Bolt ultimate tensile strength**

PAt = 2331 lbf

Bolt shear strength

Vanguard = 1398 lbf

**Thread pullout strength**

PAs = 2362 lbf

Bolt bending strength

MAu = 61 in-lbf

**Nut ultimate tensile strength**

Ptu_nut = 2362 lbf

**General Checks**

- length_check = "Bolt length is sufficient and nut fully engaged"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "Nominal preload >= 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Joint separation</th>
<th>MS1 = 46.85</th>
<th>Direct Thread shear Ultimate</th>
<th>MS6 = 107.42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Tension Ultimate</td>
<td>MS2 = 106.01</td>
<td>Total Thread shear Ultimate</td>
<td>MS7 = 0.45</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>MS3 = 127.41</td>
<td>Shear Ultimate</td>
<td>MS8 = 0.9</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>MS4 = 0.43</td>
<td>Bending Ultimate</td>
<td>MS9 = 100</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>MS5 = 0.07</td>
<td>Combined shear, tension and</td>
<td>MS10 = 0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bending ultimate</td>
<td></td>
</tr>
</tbody>
</table>

**Smallest margin of safety for the bolt, and the failure mode:**

MSbolt = 0.07  
Failure Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

Fail-safe Loads
- Applied tensile load: \( P_{FS} := 18.94\text{ lbf} \)
- Applied shear load: \( V_{FS} := 640.52\text{ lbf} \)
- Applied bending moment: \( M_{FS} := 0\text{-in.\-lbf} \)

Fail-safe Factors of Safety
- Ultimate: \( SF_{u,FS} := 1.0 \)
- Joint Separation: \( SF_{sep,FS} := 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

Fri Apr 27 14:16:05 2007

This file uses the calculations shown in \esclf02\2111_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Bolt Fail-safe Load data

- Joint separation load: \( P_{sep,FS} = 18.94\text{ lbf} \)
- Max. load on the bolt (ultimate): \( P_{b,FS} = 1628.3\text{ lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Margin (MS)</th>
<th>Margin (MS)_FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>27.71</td>
<td>0.22</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>106.01</td>
<td>0.45</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.43</td>
<td>0.9</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>107.42</td>
<td>10</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>0.22</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt,FS} = 0.22 \)

Failure Mode FS = "Combined Shear Tension Bending Ultimate"
Front Panel (SDG39137687-001) to Front sub panel assembly (SDG39137809-701) Bolts

Bolts NAS1133E4, washer NAS1149E0332R, Nut plate MS21076L3E

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

loads := READPRN("64-67.txt")

\[ \text{max}(F_t) = 26.53 \text{lbf} \]
\[ \text{max}(F_v) = 108.82 \text{lbf} \]

* Note that "64-67.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.
Front Panel (SDG39137687-001) to Front sub panel assembly (SDG39137809-701) Bolts

Bolts NAS1133E4, washer NAS1149E0332R, Nut plate MS21076L3E

Flange 1: Front Panel,
Part numbers: SDG39137687
Material: AL ALY 7075-T73

Flange 2: Front SubPanel
Part number: SDG39137809
Material: AL ALY 7075-T7351

Minimum edge distance of flange one: edge1 := 0.438-in
flange two: edge2 := 0.25-in

Loads

- Applied tensile load $P := 26.53\text{lbf}$
- Applied shear load $V := 108.82\text{lbf}$
- Applied bending moment $M := 0\text{in-lbf}$

Factors of Safety

- Ultimate $SF_u := 2.0$
- Yield $SF_y := 1.25$
- Joint Separation $SF_{sep} := 1.2$
- Fitting factor $FF := 1.15$

Temperature data

- Assembly $Temp_{initial} := 70\text{-deg}$
- Maximum $Temp_{max} := 220\text{-deg}$
- Minimum $Temp_{min} := -180\text{-deg}$

Bolt Data

- Nominal diameter of bolt $D := 0.19\text{-in}$
- Shank diameter of bolt $D_{shank} := 0.1895\text{-in}$
- Total length of bolt $L := 0.526\text{-in}$
- Threaded length $L_t := 0.276\text{-in}$
- Number of threads/inch $N_t := \frac{32}{1}\text{in}$

Note: Figure is for reference only. Not to scale, and actual joint may differ. Washer is on head side only.

Note, these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative.

Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area.

If bolt is fully threaded, input $L_t = L$.
Bolt head dia. across flats \( dw := 0.331\text{ in} \) (dia of pressure boss if it exists, otherwise dia of head)

Bolt head height \( bh := 0.133\text{ in} \) (head height is 0 if bolt is flat head)

Thread data lookup table is hidden

This file uses the data shown in `\escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd`

Temperature correction factor for bolt strength ultimate. \( TS_u_{\text{bolt}} := 0.96 \)

Yield \( TS_y_{\text{bolt}} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{tu_{\text{bolt}}} := 160000 \text{ psi} \)

Yield \( F_{ty_{\text{bolt}}} := 120000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su_{\text{bolt}}} := 0.6 F_{tu_{\text{bolt}}} \)

Temperature correction factor for bolt modulus \( TE_{\text{bolt}} := 0.96 \)

Modulus of elasticity of bolt \( E_{\text{bolt}} := (29.1 \cdot 10^6 \text{ psi}) \)

\[
\beta_{\text{bolt\_hot}} := 9.2 \cdot 10^{-6} \text{ in}^2/\text{deg} \quad \beta_{\text{bolt\_cold}} := 8.0 \cdot 10^{-6} \text{ in}^2/\text{deg}
\]

Washer Data

Thickness of washers: head \( t_{wh} := 0.032\text{ in} \)

these are total washer thickness, if there are more than one

nut \( t_{wn} := 0.0\text{ in} \)

Diameter of washer under head, Outer: \( D_{woh} := 0.438\text{ in} \)

Inner: \( D_{wih} := 0.203\text{ in} \)

Diameter of washer under nut, Outer: \( D_{won} := 0.0\text{ in} \)

Inner: \( D_{win} := 0.0\text{ in} \)

Note: If there are no washer tw's, Dw's and Dwi's should be zero

Modulus of elasticity, head: \( E_{\text{washerh}} := (29.1 \cdot 10^6 \text{ psi}) \)

Temperature correction factor for modulus, head: \( TE_{\text{washerh}} := 0.96 \)

Nut Data

Height of nut \( H := 0.250\text{ in} \)

Nut dia. across flats \( D_{n} := 0.290\text{ in} \)

Temperature correction factor for nut strength \( TS_{\text{nut}} := 0.96 \)

Ultimate allowable stress, tensile: \( F_{tu_{\text{nut}}} := 125000 \text{ psi} \)

Shear: \( F_{su_{\text{nut}}} := 0.6 F_{tu_{\text{nut}}} \)
Ultimate axial strength of nut \( P_{tu,nut} := 2460\text{ lbf} \) \((Reference\ MS21076)\)

**Flange data**

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

Thickness of flange 1: \( t_f1 := .125\text{-in} \)  
flange 2: \( t_f2 := .125\text{in} \)  
Diameter of thru hole \( D\text{_hole} := 0.213\text{-in} \)

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint \( E_{flange1} := (10.3 \times 10^6\text{-psi}) \) \( E_{flange2} := (10.3 \times 10^6\text{-psi}) \)

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \)  
flange 2: \( T_{f2E} := 0.95 \)

Coefficient of thermal expansion for flanges

\( \beta_{flange1\_hot} := 12.75 \times 10^{-6}\text{-in/deg} \)  
\( \beta_{flange2\_hot} := 12.75 \times 10^{-6}\text{-in/deg} \)  
\( \beta_{flange1\_cold} := 12.1 \times 10^{-6}\text{-in/deg} \)  
\( \beta_{flange2\_cold} := 12.1 \times 10^{-6}\text{-in/deg} \)

**Torque/Preload data**

Maximum torque \( T_{max} := 35\text{-in-lbf} \) \((Dwg.\ SEG39137684)\)  
Minimum torque \( T_{min} := 30\text{in-lbf} \)

Joint is lubed/dry

Preload Uncertainty \( u := 0.25 \)  
Torque coefficient \( k := 0.15 \)

Loading plane factor \( n := 0.5 \)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \Escfli02\2111_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

**Bolt Load data**

Bolt/joint stiffness factor \( = 0.35 \)  
Max. preload \( PLD_{max} = 1660\text{lbf} \)  
Min. preload \( PLD_{min} = 472\text{ lbf} \)  
Nom. preload \( PLD_{nom} = 1228\text{ lbf} \)  
Preload to yield ratio(nom.) \( PLD_{ratio} = 0.554 \)  
Joint separation load \( P_{sep} = 31.836\text{lbf} \)

Preload due to temperature \( P_{thr\_pos} = 124.8\text{lbf} \)  
Uncertainty factor \( u := 0.25 \)  
Torque coefficient \( k := 0.15 \)  
Loading plane factor \( n := 0.5 \)
Bolt Load data (cont.)

**Applied Tensile load on the bolt**  
\[ P = 26.53\text{lb} \]  
**Max. load on the bolt with preload and Factor of safety**  
\[ (\text{ultimate}) \quad P_b = 1671\text{lb} \]  
\[ (\text{yield}) \quad P_y = 1667\text{lb} \]

**Applied shear on the bolt**  
\[ V = 108.82\text{lb} \]

**Applied bending on the bolt**  
\[ M = 0\text{in-lbf} \]  
**Max. load on the bolt with preload without factor of safety**  
\[ P_{b,\text{app}} = 1665\text{lb} \]

**Bolt ultimate tensile strength**  
\[ P_{\text{At}} = 2957\text{lb} \]

**Thread pullout strength**  
\[ P_{\text{As}} = 2362\text{lb} \]

**Nut ultimate tensile strength**  
\[ P_{\text{t, nut}} = 2362\text{lb} \]

---

**General Checks**

- length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

---

**Summary of Margins for bolt:**

- **Joint separation**  
  \[ MS_1 = 14.64 \]  
  \[ Direct\; Thread\; shear\; Ultimate \]  
  \[ MS_6 = 37.7 \]

- **Direct Tension Ultimate**  
  \[ MS_2 = 47.45 \]  
  \[ Total\; Thread\; shear\; Ultimate \]  
  \[ MS_7 = 0.41 \]

- **Direct Tension Yield**  
  \[ MS_3 = 57.14 \]  
  \[ Shear\; Ultimate \]  
  \[ MS_8 = 9.39 \]

- **Total Tension Ultimate**  
  \[ MS_4 = 0.77 \]  
  \[ Bending\; Ultimate \]  
  \[ MS_9 = 100 \]

- **Total Tension Yield**  
  \[ MS_5 = 0.33 \]  
  \[ Combined\; shear,\; tension\; and\; bending\; ultimate \]  
  \[ MS_{10} = 0.77 \]

**Smallest margin of safety for the bolt, and the failure mode:**

\[ MS_{\text{bolt}} = 0.33 \]  
**Failure Mode** = "Total Tension Yield"

---

5.13-36  
ESCG-4005-05-AMS-0039
Fail-safe Analysis (Conservatively, the loads were doubled to perform fail-safe analysis)

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td></td>
</tr>
<tr>
<td>Applied shear load</td>
<td></td>
</tr>
<tr>
<td>Applied bending moment</td>
<td></td>
</tr>
</tbody>
</table>

Applied tensile load: \( P_{FS} := 53.06 \text{ lbf} \)

Applied shear load: \( V_{FS} := 217.64 \text{ lbf} \)

Applied bending moment: \( M_{FS} := 0 \text{ in-lbf} \)

Fail-safe Factors of Safety:
- Ultimate: \( SF_{u,FS} := 1.0 \)
- Joint Separation: \( SF_{sep,FS} := 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut_FS.mcd

Bolt Fail-safe Load data

Joint separation load: \( P_{sep,FS} = 53.06 \text{ lbf} \)

Max. load on the bolt (ultimate): \( P_b,FS = 1670.6 \text{ lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Margins</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS_{FS}$_1$, Joint separation</td>
<td>8.38</td>
</tr>
<tr>
<td>MS_{FS}$_2$, Direct Tension Ultimate</td>
<td>47.45</td>
</tr>
<tr>
<td>MS_{FS}$_3$, Total Tension Ultimate</td>
<td>0.77</td>
</tr>
<tr>
<td>MS_{FS}$_4$, Direct Thread shear Ultimate</td>
<td>37.7</td>
</tr>
<tr>
<td>MS_{FS}$_5$, Total Thread shear Ultimate</td>
<td>0.41</td>
</tr>
<tr>
<td>MS_{FS}$_6$, Shear Ultimate</td>
<td>9.39</td>
</tr>
<tr>
<td>MS_{FS}$_7$, Bending Ultimate</td>
<td>10</td>
</tr>
<tr>
<td>MS_{FS}$_8$, Combined shear, tension and bending ultimate</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt,FS} = 0.41 \)

Failure Mode FS = "Total Thread Shear Ultimate (Nut)"

5.13-37 ESCG-4005-05-AMS-0039
Bolt Analysis for Front Sub-Panel/Standoff/Rear Sub-Panel Interface

Front Sub-Panel Assembly (SDG39137809-701) to Standoff (SDG39137844-001) to Rear Sub-Panel Assembly (SDG39137809-702) Bolts

Bolts NAS1153E36, 0.190-32UNJF-3A, A-286, 2.526L, Nut Plate MS21076L3E

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[
\text{loads} := \text{READPRN}("60-63.txt")
\]

\[
i := 1.. \text{rows}(\text{loads}) \quad \text{rows}(\text{loads}) = 524
\]

\[
j := 2.. \text{cols}(\text{loads}) \quad \text{cols}(\text{loads}) = 8
\]

\[
\begin{align*}
\text{ID} & := \text{loads}(1) \\
\text{Fx} & := \text{loads}(3) \cdot \text{lbf} \\
\text{Fz} & := \text{loads}(5) \cdot \text{lbf} \\
\text{My} & := \text{loads}(7) \cdot \text{in-lbf} \\
\text{LC} & := \text{loads}(2) \\
\text{Fy} & := \text{loads}(4) \cdot \text{lbf} \\
\text{Mx} & := \text{loads}(6) \cdot \text{in-lbf} \\
\text{Mz} & := \text{loads}(8) \cdot \text{in-lbf}
\end{align*}
\]

* Note that "60-63.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\begin{align*}
\text{Ft}_i := \left| \text{Fx}_i \right| & \quad \text{max}(\text{Ft}) = 11.84 \text{lbf} \\
\text{Fv}_i := \sqrt{\text{Fy}_i^2 + \text{Fz}_i^2} & \quad \text{max}(\text{Fv}) = 4.11 \text{lbf}
\end{align*}
\]

Tensile Load

Shear Load

5.13-38 ESCG-4005-05-AMS-0039
Bolt Analysis for Front Sub-Panel/Standoff/Rear Sub-Panel Interface

Front Sub-Panel Assembly (SDG39137809-701) to Standoff (SDG39137844-001) to Rear Sub-Panel Assembly (SDG39137809-702) Bolts

Bolts NAS1153E36, 0.190-32UNJF-3A, A-286, 2.526L, Nut Plate MS21076L3E

Flange 1: Front Sub-Panel Assembly
Part number: SDG39137809-701
Material: Al Alloy 7075-T73

Flange 2: Rear Sub-Panel Assembly
Part number: SDG39137809-702
Material: Al Alloy 7075-T73

Loads
- Applied tensile load \( P := 11.8 \text{lbf} \)
- Applied shear load \( V := 4.1 \text{lbf} \)
- Applied bending moment \( M := 8.2 \text{in-lbf} \)

Factors of Safety
- Ultimate \( SF_u := 2.0 \)
- Yield \( SF_y := 1.25 \)
- Joint Separation \( SF_{sep} := 1.2 \)
- Fitting factor \( FF := 1.15 \)

Temperature data
- Assembly \( Temp_{initial} := 70 \text{deg} \)
- Maximum \( Temp_{max} := 220 \text{deg} \)
- Minimum \( Temp_{min} := -180 \text{deg} \)

Bolt and Nut Data
- Nominal diameter of bolt \( D := 0.19 \text{in} \)
- Total length of bolt \( L := 2.526 \text{in} \)
- Threaded length \( Lt := 0.276 \text{in} \)
- Number of threads/inch \( N_t := 32 \frac{1}{\text{in}} \)
- Height of nut \( H := 0.25 \text{in} \)

5.13-39 ESCG-4005-05-AMS-0039
Bolt Analysis for Front Sub-Panel/Standoff/Rear Sub-Panel Interface

Washer Data

| Thickness of washers | tw := 0.0-in |
| Outer Diameter of washer | Dw := 0.0in |
| Inner Diameter of washer | Dwi := 0.0-in |
| Bolt head dia. across flats | dw := 0.375-in |

Note: If there is no washer tw, Dw and Dwi should be zero

Standoff Data

| Thickness of standoff | tw_ad2 := 2.0-in |
| Outer Diameter of standoff | Dw_ad2 := 0.38in |
| Inner Diameter of standoff | Dwi_ad2 := 0.2-in |

Material Property Data

Bolt

| Temperature correction factor for bolt strength ultimate | TSu_bolt := 0.96 |
| Bolt ultimate tensile allowable stress | Ftu_bolt := 160000-psi |
| Bolt ultimate shear allowable stress | Fsu_bolt := 0.6-Ftu_bolt |
| Bolt yield Tensile allowable stress | Fty_bolt := 120000-psi |

| Temperature correction factor for bolt modulus | TE_bolt := 0.96 |
| Modulus of elasticity of bolt | E_bolt := \left( 29.1 \times 10^6 \text{psi} \right) |
| Thermal coefficient for bolt | \beta_{\text{bolt_hot}} := 9.2 \times 10^{-6} \text{in}^{-1} \text{deg}^{-1} |
| Data for bending modulus of Rupture of bolt | fm := Ftu_bolt |
| Section factor for bolt | k1 := 1.7 |

Nut

| Temperature correction factor for nut strength | TS_nut := 0.96 |
| Ultimate tensile allowable stress | Ftu_nut := 125000-psi |
Bolt Analysis for Front Sub-Panel/Standoff/Rear Sub-Panel Interface

Ultimate Shear allowable stress: \( F_{\text{uu\_nut}} := 0.6 \cdot F_{\text{tu\_nut}} \)

Ultimate axial strength of nut \( P_{\text{tu\_nut}} := 2460 \text{lbf} \) (Ref. MS21076)

**Washer**

Temperature correction factor for washer modulus \( T_{E_{\text{washer}}} := 0.0 \)

Modulus of elasticity of washer: \( E_{\text{washer}} := \left(0.0 \cdot 10^{-6} \text{psi}\right) \)

**Standoff Data**

Temperature correction factor for standoff modulus \( T_{E_{\text{washer\_ad2}}} := 0.95 \)

Modulus of elasticity of standoff \( E_{\text{washer\_ad2}} := \left(10.3 \cdot 10^{-6} \text{psi}\right) \)

Thermal coefficient for standoff \( \beta_{\text{washer\_ad2\_hot}} := 12.75 \cdot 10^{-6} \text{in} \cdot \text{deg}^{-1} \)

\( \beta_{\text{washer\_ad2\_cold}} := 12.1 \cdot 10^{-6} \text{in} \cdot \text{deg}^{-1} \)

**Flanges**

Stiffness of the joint depends upon number of members in the grip of the fasteners, Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{f1\text{E}} := 0.95 \text{(modulus)} \)

Temperature correction factor for flange 2 \( T_{f2\text{E}} := 0.95 \)

Modulus of elasticity for the parts in the joint \( E_{\text{flange1}} := \left(10.3 \cdot 10^{-6} \text{psi}\right) \)

\( E_{\text{flange2}} := \left(10.3 \cdot 10^{-6} \text{psi}\right) \)

Coefficient of thermal expansion for flanges \( \beta_{\text{flange1\_hot}} := 12.75 \cdot 10^{-6} \text{in} \cdot \text{deg}^{-1} \)

\( \beta_{\text{flange2\_hot}} := 12.75 \cdot 10^{-6} \text{in} \cdot \text{deg}^{-1} \)

\( \beta_{\text{flange1\_cold}} := 12.1 \cdot 10^{-6} \text{in} \cdot \text{deg}^{-1} \)

\( \beta_{\text{flange2\_cold}} := 12.1 \cdot 10^{-6} \text{in} \cdot \text{deg}^{-1} \)

**Torque/Preload data**

Torque coefficient \( k := 0.15 \)

Preload Percentage: \( \text{Per\_Preload} := 0.49 \)

Tensile Area: \( A_t := 0.02 \text{in}^2 \)

Maximum torque \( T_{max} := \text{Fp\_Preload} \cdot k \cdot D \)

Minimum torque \( T_{min} := 0.85 \cdot T_{max} \)
Bolt Analysis for Front Sub-Panel/Standoff/Rear Sub-Panel Interface

Maximum torque \( T_{mx} = 33.516 \text{ in-lbf} \)

Loading plane factor: \( n := 0.5 \)

Minimum torque \( T_{mn} = 28.489 \text{ in-lbf} \)

Preload Uncertainty: \( u := 0.25 \)

Bolt/joint stiffness factor \( = 0.501 \)

Preload due to temperature \( P_{thr} = 202.1 \text{ lbf} \)

Max. preload \( P_{LDM} = 1672.1 \text{ lbf} \)

Min. preload \( P_{LD minimum} = 287.2 \text{ lbf} \)

Uncertainty factor \( u = 0.25 \)

Joint separation load \( P_{sep} = 14.16 \text{ lbf} \)

Torque coefficient \( k = 0.15 \)

Max. load on the bolt(ultimate) \( P_b = 1678.9 \text{ lbf} \)

Loading plane factor \( n = 0.5 \)

Max. load on the bolt(yield) \( P_{by} = 1676.3 \text{ lbf} \)

Thread pullout strength required to develop full strength of bolt \( P_{AS} = 3406 \text{ lbf} \)

Bolt ultimate tensile strength \( P_{At} = 2267.1 \text{ lbf} \)

Nut ultimate tensile strength \( P_{nut} = 2267.1 \text{ lbf} \)

Length_check = "Bolt length should be increased!"

Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Margin</th>
<th>Value</th>
<th>Description</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>22.53</td>
<td>Direct Thread shear Ultimate</td>
<td>6</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>82.53</td>
<td>Total Thread shear Ultimate</td>
<td>7</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>124.5</td>
<td>Shear Ultimate</td>
<td>8</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>0.35</td>
<td>Bending Ultimate</td>
<td>9</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>0.27</td>
<td>Combined shear, tension and bending</td>
<td>10</td>
</tr>
</tbody>
</table>

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[ MS_{bolt} := \min(\text{MS}) \]

\[ MS_{bolt} = 0.07 \]

Failure Mode = "Combined Shear Tension Bending Ultimate"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

<table>
<thead>
<tr>
<th>Fail-safe Loads</th>
<th>Fail-safe Factors of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied tensile load</td>
<td>P_Fs := 23.6 lbf</td>
</tr>
<tr>
<td>Applied shear load</td>
<td>V_Fs := 8.22 lbf</td>
</tr>
<tr>
<td>Applied bending moment</td>
<td>M_Fs := 16.4-in-lbf</td>
</tr>
</tbody>
</table>

- Reference: \Escfl02\2M31 STRUCTURAL ANALYSIS\Projects\AMS\AMS Analysis Files\5.13 Interface Panel A\InterfacepanelBolt4\bolt_stiffnes
- Reference: \Escfl02\2M31 STRUCTURAL ANALYSIS\Projects\AMS\AMS Analysis Files\5.13 Interface Panel A\InterfacepanelBolt4\bolt_stiffnes

Bolt Fail-safe Load data

- Joint separation load          Psep_Fs = 23.6 lbf
- Max. load on the bolt (ultimate) Pb_Fs = 1678.9 lbf

Summary of fail-safe Margins for bolt:

- Joint separation               MS_Fs1 = 13.12  MS_Fs5 = 1.03
- Direct Tension Ultimate        MS_Fs2 = 82.53  MS_Fs6 = 264.36
- Total Tension Ultimate         MS_Fs3 = 0.35   MS_Fs7 = 4.16
- Direct Thread shear Ultimate   MS_Fs4 = 124.5  MS_Fs8 = 0.07

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

MSbolt_Fs := min(MS_Fs)

MSbolt_Fs = 0.07  Failure_Mode_Fs = "Combined Shear Tension Bending Ultimate"
## Bolt Analysis for Base Panel Stiffener to Base Panel

### Base Panel (SDG39137685-001) to Base Panel Stiffener (SDG39137843-001) bolts

**Check Bolts NAS1133E4, 0.190-32UNJF A-286, washer NAS1490332R, Nut Plate MS21076L3E, A-286**

![Diagram of Fasteners connecting Base Panel Stiffener to Base Panel](image)

**Loads**: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[
\text{loads} := \text{READPRN}("58-59.txt")
\]

\[
i := 1, \text{rows}(\text{loads}) = 262, \quad j := 2, \text{cols}(\text{loads}) = 8
\]

\[
\text{ID} := \text{loads}^{(1)}, \quad \text{Fx} := \text{loads}^{(3)} \cdot \text{lbf}, \quad \text{Fz} := \text{loads}^{(5)} \cdot \text{lbf}, \quad \text{My} := \text{loads}^{(7)} \cdot \text{in-lbf}
\]

\[
\text{LC} := \text{loads}^{(2)}, \quad \text{Fy} := \text{loads}^{(4)} \cdot \text{lbf}, \quad \text{Mx} := \text{loads}^{(6)} \cdot \text{in-lbf}, \quad \text{Mz} := \text{loads}^{(8)} \cdot \text{in-lbf}
\]

*Note that "58-59.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.*

\[
\text{Ft}_i := |\text{Fx}_i|, \quad \max(\text{Ft}) = 27.16 \text{lbf} \quad \text{Tensile Load}
\]

\[
\text{Fv}_i := \sqrt{(\text{Fy}_i)^2 + (\text{Fz}_i)^2}, \quad \max(\text{Fv}) = 405.5 \text{lbf} \quad \text{Shear Load}
\]
Base Panel (SDG39137685-001) to Base panel Stiffener (SDG39137843-001) bolts

Check Bolts NAS1133E4, 0.190-32UNJF A-286, washer NAS11490332R, Nut Plate MS21076L3E, A-286

Flange 1: Base Panel Stiffener
Part numbers: SDG39137843
Material: AL ALY 7075-T7351

Flange 2: Base Panel
Part number: SDG39137685
Material: AL ALY 7075-T73

Minimum edge distance of flange one:
\[
\text{edge1} := 0.636 \text{-in}
\]
flange two:
\[
\text{edge2} := 0.969 \text{-in}
\]

Loads

- Applied tensile load
  \[
  P := 27.16 \text{lbf}
  \]
- Applied shear load
  \[
  V := 405.5 \text{lbf}
  \]
- Applied bending moment
  \[
  M := 0 \text{in-lbf}
  \]

Factors of Safety

- Ultimate
  \[
  SFu := 2.0
  \]
- Yield
  \[
  SFy := 1.25
  \]
- Joint Separation
  \[
  SFsep := 1.2
  \]
- Fitting factor
  \[
  FF := 1.15
  \]

Temperature data

- Assembly
  \[
  \text{Temp}_{\text{initial}} := 70 \text{deg}
  \]
- Maximum
  \[
  \text{Temp}_{\text{max}} := 220 \text{deg}
  \]
- Minimum
  \[
  \text{Temp}_{\text{min}} := -180 \text{deg}
  \]

Bolt Data

- Nominal diameter of bolt
  \[
  D := 0.19 \text{-in}
  \]
- Number of threads/inch
  \[
  Nt := 32 \frac{1}{\text{in}}
  \]
- Shank diameter of bolt
  \[
  D_{\text{shank}} := 0.1895 \text{-in}
  \]
- Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area
- Total length of bolt
  \[
  L := 0.526 \text{-in}
  \]
- Threaded length
  \[
  L_t := 0.276 \text{-in}
  \]
  (If bolt is fully threaded, input \( L_t = L \))
- Bolt head dia. across flats
  \[
  d_w := 0.331 \text{-in}
  \]
  (dia of pressure boss if it exists, otherwise dia of head)
- Bolt head height
  \[
  b_h := 0.133 \text{-in}
  \]
  (head height is 0 if bolt is flat head)
Thread data lookup table is hidden

This file uses the data shown in \escfil022\i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength ultimate. \( T_{Su_bolt} := 0.96 \)  
Yield \( T_{Sy_bolt} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{tu_bolt} := 160000 \text{ psi} \)  
Yield \( F_{ty_bolt} := 120000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su_bolt} := 0.6 F_{tu_bolt} \)

Temperature correction factor for bolt modulus \( T_{E_bolt} := 0.96 \)

Modulus of elasticity of bolt \( E_{bolt} := (29.1 \times 10^6 \text{ psi}) \)

Thermal coefficients for bolt  
\[ \beta_{bolt\_hot} := 9.2 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]  
\[ \beta_{bolt\_cold} := 8.0 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg}} \]

Washer Data

Thickness of washers: head \( t_{wh} := 0.032 \text{ in} \)  
these are total washer thickness, if there are more than one  
nut \( t_{wn} := 0.0 \text{ in} \)

Diameter of washer under head, Outer: \( D_{woh} := 0.438 \text{ in} \)  
Inner: \( D_{wh} := 0.203 \text{ in} \)

Diameter of washer under nut, Outer: \( D_{won} := 0.0 \text{ in} \)  
Inner: \( D_{win} := 0.0 \text{ in} \)

Note: If there are no washer tw's, Dw's and Dwi's should be zero

Modulus of elasticity, head: \( E_{washerh} := (29.1 \times 10^6 \text{ psi}) \)  
Temperature correction factor for modulus, head: \( T_{E_{washerh}} := 0.96 \)

Nut Data

Height of nut \( H := 0.250 \text{ in} \)  
Nut dia. across flats \( D_{n} := 0.290 \text{ in} \)

Temperature correction factor for nut strength \( T_{S_{nut}} := 0.96 \)

Ultimate allowable stress, tensile: \( F_{tu_{nut}} := 125000 \text{ psi} \)  
Shear: \( F_{su_{nut}} := 0.6 F_{tu_{nut}} \)

Ultimate axial strength of nut \( P_{tu_{nut}} := 2460 \text{ lbf} \)  
(Reference MS21076)
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

Thickness of flange 1: \( t_{f1} := 0.120 \text{ in} \) flange 2: \( t_{f2} := 0.125 \text{ in} \) Diameter of thru hole \( D_{\text{hole}} := 0.213 \text{ in} \)

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint

\[
E_{\text{flange}1} := \left(10.3 \times 10^6 \text{ psi}\right) \quad E_{\text{flange}2} := \left(10.3 \times 10^6 \text{ psi}\right)
\]

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \) flange 2: \( T_{f2E} := 0.95 \)

Coefficient of thermal expansion for flanges

\[
\beta_{\text{flange}1,\text{hot}} := 12.75 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{\text{flange}2,\text{hot}} := 12.75 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]

\[
\beta_{\text{flange}1,\text{cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}} \quad \beta_{\text{flange}2,\text{cold}} := 12.1 \times 10^{-6} \frac{\text{in}}{\text{deg}}
\]

Torque/Preload data

Maximum torque \( T_{\text{max}} := 35 \text{ in-lbf} \) \((Dwg. \ SEG39137684)\)

Minimum torque \( T_{\text{min}} := 30 \text{ in-lbf} \)

Joint is lubed/dry

Preload Uncertainty \( u := 0.25 \)

Torque coefficient \( k := 0.15 \)

Loading plane factor \( n := 0.5 \)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escf\escfl02\2111_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Bolt Load data

Bolt/joint stiffness factor = 0.35 Preload due to temperature

Max. preload \( \text{PLDmax} := 1659 \text{ lbf} \)

Min. preload \( \text{PLDmin} := 474 \text{ lbf} \)

Nom. preload \( \text{PLDnom} := 1228 \text{ lbf} \)

Preload to yield ratio(nom.) \( \text{PLDratio} := 0.554 \)

Preload to yield ratio \( \text{PLDratio} := 0.554 \)

Joint separation load \( P_{\text{sep}} := 32.592 \text{ lbf} \)
### Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>P = 27.16 lbf</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>V = 405.5 lbf</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>M = 0 in·lbf</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>PAt = 2957 lbf</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>PAs = 2362 lbf</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>Ptu_nut = 2362 lbf</td>
</tr>
</tbody>
</table>

Max. load on the bolt with preload and Factor of safety

- (ultimate) Pb = 1670 lbf
- (yield) Pby = 1666 lbf
- Max. load on the bolt with preload without factor of safety Pbapp = 1664 lbf

### General Checks

- length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

### Summary of Margins for bolt:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>M_{S1} = 14.34</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>M_{S2} = 46.33</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>M_{S3} = 55.8</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>M_{S4} = 0.77</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>M_{S5} = 0.33</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>M_{S6} = 36.8</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>M_{S7} = 0.41</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>M_{S8} = 1.79</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>M_{S9} = 100</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>M_{S10} = 0.6</td>
</tr>
</tbody>
</table>

Smallest margin of safety for the bolt, and the failure mode:

- MSbolt = 0.33
- Failure Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

**Fail-safe Loads**  
Applied tensile load  \( P_{FS} := 54.32 \text{ lbf} \)  
Applied shear load  \( V_{FS} := 811 \text{ lbf} \)  
Applied bending moment  \( M_{FS} := 0 \text{ in-lbf} \)

**Fail-safe Factors of Safety**  
Ultimate  \( SF_{U,FS} := 1.0 \)  
Joint Separation  \( SF_{sep,FS} := 1.0 \)

---

Bolt Fail-safe Load data

Joint separation load  \( P_{sep,FS} = 54.32 \text{ lbf} \)

Max. load on the bolt(ultimate)  \( P_{b,FS} = 1669.9 \text{ lbf} \)

---

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Category</th>
<th>Margin of Safety</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{FS,1} = 8.2 )</td>
<td>Total Thread shear Ultimate</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{FS,2} = 46.33 )</td>
<td>Shear Ultimate</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{FS,3} = 0.77 )</td>
<td>Bending Ultimate</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{FS,4} = 36.8 )</td>
<td>Combined shear, tension and bending ultimate</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt,FS} = 0.41 \)  
Failure Mode FS = "Total Thread Shear Ultimate (Nut)"
Angle Bracket (SEG39137686-705) to C-Channel A Assembly (SEG39137686-701) Bolts

Bolts NAS1133E4, washer NAS1149E0332R, Nut plate MS21076L3E

Loads: Bolt forces were sorted by maximum absolute value on all three axes. The tensile load and shear load were calculated for the worse case. All bolt forces reference the Global Coordinate System.

Read in the external datum from NASPOST results:

\[
\text{loads} := \text{READPRN}("53-57.txt")
\]

\[
\begin{align*}
\text{id} & := 1.. \text{rows(loads)} \quad \text{rows(loads)} = 655 \\
\text{id} & := 2.. \text{cols(loads)} \quad \text{cols(loads)} = 8 \\
\text{ID} & := \text{loads}^{(1)} \\
\text{Fx} & := \text{loads}^{(2)} \cdot \text{lbf} \\
\text{Fz} & := \text{loads}^{(3)} \cdot \text{lbf} \\
\text{My} & := \text{loads}^{(7)} \cdot \text{in-lbf} \\
\text{LC} & := \text{loads}^{(2)} \\
\text{Fy} & := \text{loads}^{(4)} \cdot \text{lbf} \\
\text{Mx} & := \text{loads}^{(6)} \cdot \text{in-lbf} \\
\text{Mz} & := \text{loads}^{(8)} \cdot \text{in-lbf}
\end{align*}
\]

* Note that "1-52.txt" is generated from NASPOST result (.LIS file) by just removing all words and comments.

\[
\begin{align*}
\text{Ft}_i & := \left| \text{Fy}_i \right| \\
\text{Fv}_i & := \sqrt{\left(\text{Fx}_i\right)^2 + \left(\text{Fz}_i\right)^2} \\
\text{max}(\text{Ft}) & = 111.24 \text{ lbf} \\
\text{max}(\text{Fv}) & = 13.68 \text{ lbf}
\end{align*}
\]

Tensile Load

Shear Load
**Angle Bracket (SEG39137686-705) to C-Channel A Assembly (SEG39137686-701) Bolts**

**Bolts NAS1133E4, washer NAS1149E0332R, Nut plate MS21076L3E**

**Flange 1: Angle Bracket**
- Part numbers: SEG39137686-705
- Material: AL ALY 7075-T7351

**Flange 2: C-Channel A assembly**
- Part number: SEG39137686-701
- Material: AL ALY 7075-T7351

Minimum edge distance of flange one: \( e_{1} := 0.312 \text{ in} \)
Minimum edge distance of flange two: \( e_{2} := 0.312 \text{ in} \)

**Loads**
- Applied tensile load \( P := 111.24 \text{lbf} \)
- Applied shear load \( V := 13.68 \text{lbf} \)
- Applied bending moment \( M := 0 \text{in-lbf} \)

**Factors of Safety**
- Ultimate \( SF_{u} := 2.0 \)
- Yield \( SF_{y} := 1.25 \)
- Joint Separation \( SF_{sep} := 1.2 \)
- Fitting factor \( FF := 1.15 \)

**Temperature data**
- Assembly \( Temp_{initial} := 70 \deg \)
- Maximum \( Temp_{max} := 220 \deg \)
- Minimum \( Temp_{min} := -180 \deg \)

**Bolt Data**
- Nominal diameter of bolt \( D := .19 \text{ in} \)
- Number of threads/inch \( N_{t} := 32 \frac{1}{\text{in}} \)
- Shank diameter of bolt \( D_{shank} := .1895 \text{ in} \)
- Total length of bolt \( L := .526 \text{ in} \)
- Threaded length \( L_{t} := 0.276 \text{ in} \)
- Bolt head dia. across flats \( d_{w} := 0.331 \text{ in} \)
- Bolt head height \( b_{h} := .133 \text{ in} \)

---

Note: Figure is for reference only. Not to scale, and actual joint may differ. Washer may be on nut side, head side, or both.

Note, these are maximum temperatures that hardware sees / if maximum load occurs at a different temperature this will be conservative.

Note, if there is a retainer groove in the fastener, this should be the calculated diameter to give an equivalent cross sectional area.

(dia of pressure boss if it exists, otherwise dia of head)

(head height is 0 if bolt is flat head)
Thread data lookup table is hidden

This file uses the data shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\thread_data.mcd

Temperature correction factor for bolt strength ultimate. \( T_{Su_{bolt}} := 0.96 \) Yield \( T_{Sy_{bolt}} := 0.96 \)

Bolt ultimate tensile allowable stress ultimate: \( F_{tu_{bolt}} := 160000 \text{ psi} \) Yield \( F_{ty_{bolt}} := 120000 \text{ psi} \)

Bolt ultimate shear allowable stress \( F_{su_{bolt}} := 0.6 \times F_{tu_{bolt}} \)

Temperature correction factor for bolt modulus \( T_{E_{bolt}} := 0.96 \)

Modulus of elasticity of bolt \( E_{bolt} := \left(29.1 \times 10^6 \text{ psi} \right) \)

Thermal coefficients for bolt
\[
\beta_{bolt_{hot}} := 9.2 \times 10^{-6} \text{ in}^{-1} \text{ in}^{-1} \text{ deg}^{-1} \\
\beta_{bolt_{cold}} := 8.0 \times 10^{-6} \text{ in}^{-1} \text{ in}^{-1} \text{ deg}^{-1}
\]

Washer Data

Thickness of washers: head \( t_{wh} := 0.032 \text{ in} \) nut \( t_{wn} := 0.0 \text{ in} \)

these are total washer thickness, if there are more than one

Diameter of washer under head, Outer: \( D_{woh} := 0.438 \text{ in} \) Inner: \( D_{woi} := 0.203 \text{ in} \)

Diameter of washer under nut, Outer: \( D_{wn} := 0.0 \text{ in} \) Inner: \( D_{win} := 0.0 \text{ in} \)

Note: If there are no washer tw's, Dw's and Dwi's should be zero

Modulus of elasticity, head: \( E_{washerh} := \left(29.1 \times 10^6 \text{ psi} \right) \) nut: \( E_{washern} := (0 \text{ psi}) \)

Temperature correction factor for modulus, head: \( T_{E_{washerh}} := 0.96 \) nut: \( T_{E_{washern}} := 0.96 \)

Nut Data

Height of nut \( H := 0.250 \text{ in} \) Nut dia. across flats \( D_{n} := 0.290 \text{ in} \)

Temperature correction factor for nut strength \( T_{S_{nut}} := 0.96 \)

Ultimate allowable stress, tensile: \( F_{u_{nut}} := 125000 \text{ psi} \) Shear: \( F_{s_{nut}} := 0.6 \times F_{u_{nut}} \)

Ultimate axial strength of nut \( P_{tu_{nut}} := 2460 \text{ lbf} \) \( (Reference \ MS21076) \)
Flange data

Stiffness of the joint depends upon number of members in the grip of the fasteners & their material properties,

Thickness of flange 1: \( tf_1 := 0.120 \text{-in} \)  
flange 2: \( tf_2 := 0.120 \text{in} \)  
Diameter of thru hole \( D_{\text{hole}} := 0.213 \text{-in} \)

Modulus of elasticity of these members, with temperature correction factors

Compressive Modulus of elasticity for the parts in the joint

\[
E_{\text{flange}1} := (10.3 \times 10^6 \text{ psi}) \quad E_{\text{flange}2} := (10.3 \times 10^6 \text{ psi})
\]

Temperature correction factor (modulus) for flange 1: \( T_{f1E} := 0.95 \)  
flange 2: \( T_{f2E} := 0.95 \)

Coefficient of thermal expansion for flanges

\[
\beta_{\text{flange}1\_hot} := 12.75 \times 10^{-6} \text{-in/deg} \quad \beta_{\text{flange}1\_cold} := 12.1 \times 10^{-6} \text{-in/deg}
\]

\[
\beta_{\text{flange}2\_hot} := 12.75 \times 10^{-6} \text{-in/deg} \quad \beta_{\text{flange}2\_cold} := 12.1 \times 10^{-6} \text{-in/deg}
\]

Torque/Preload data

Maximum torque \( T_{\text{max}} := 35\text{-in-lbf} \)  
(Dwg. SEG39137684)  
Minimum torque \( T_{\text{min}} := 30\text{in-lbf} \)

Joint is lubed/dry  
Preload Uncertainty \( u := 0.25 \)  
Loading plane factor \( n := 0.5 \)

Torque coefficient \( k := 0.15 \)

Stiffness and Margin calculations are hidden

This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\Rev_D\bolt_stiffness_nut.mcd

Bolt Load data

Bolt/joint stiffness factor \( = 0.351 \)  
Preload due to temperature \( P_{\text{thr}\_\text{pos}} = 122.9 \text{lbf} \)

Max. preload \( \text{PLD}_{\text{max}} = 1658 \text{lbf} \)  
Uncertainty factor \( u = 0.25 \)

Min. preload \( \text{PLD}_{\text{min}} = 476 \text{lbf} \)  
Torque coefficient \( k = 0.15 \)

Nom. preload \( \text{PLD}_{\text{nom}} = 1228 \text{lbf} \)  
Loading plane factor \( n = 0.5 \)

Preload to yield ratio(nom.) \( \text{PLD}_{\text{ratio}} = 0.554 \)

Joint separation load \( P_{\text{sep}} = 133.488 \text{lbf} \)
Bolt Load data (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Tensile load on the bolt</td>
<td>$P = 111.24 \text{ lbf}$</td>
</tr>
<tr>
<td>Applied shear on the bolt</td>
<td>$V = 13.68 \text{ lbf}$</td>
</tr>
<tr>
<td>Applied bending on the bolt</td>
<td>$M = 0 \text{ in} \cdot \text{lbf}$</td>
</tr>
<tr>
<td>Max. load on the bolt with preload and Factor of safety (ultimate)</td>
<td>$P_b = 1703 \text{ lbf}$</td>
</tr>
<tr>
<td>Max. load on the bolt with preload without factor of safety</td>
<td>$P_{b app} = 1680 \text{ lbf}$</td>
</tr>
<tr>
<td>Bolt ultimate tensile strength</td>
<td>$P_{At} = 2957 \text{ lbf}$</td>
</tr>
<tr>
<td>Thread pullout strength</td>
<td>$P_{As} = 2362 \text{ lbf}$</td>
</tr>
<tr>
<td>Nut ultimate tensile strength</td>
<td>$P_{tu _ nut} = 2362 \text{ lbf}$</td>
</tr>
<tr>
<td>Bolt shear strength</td>
<td>$V_{Au} = 2599 \text{ lbf}$</td>
</tr>
<tr>
<td>Bolt bending strength</td>
<td>$M_{Au} = 61 \text{ in} \cdot \text{lbf}$</td>
</tr>
</tbody>
</table>

**General Checks**

- length_check = "Bolt length should be increased! nut is fully threaded, but does not extend past nut"
- cone_check = "Joint pressure cone does not extend pass flange edge"
- preload_check = "NOTE: Nominal preload < 65% of bolt yield strength"
- washer_check = "Washers under head and nut do not extend past flanges"

**Summary of Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin Description</th>
<th>Margin Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>$M_{S1} = 2.76$</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>$M_{S2} = 10.56$</td>
</tr>
<tr>
<td>Direct Tension Yield</td>
<td>$M_{S3} = 12.87$</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>$M_{S4} = 0.74$</td>
</tr>
<tr>
<td>Total Tension Yield</td>
<td>$M_{S5} = 0.32$</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>$M_{S6} = 8.23$</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>$M_{S7} = 0.39$</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>$M_{S8} = 81.61$</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>$M_{S9} = 100$</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>$M_{S10} = 0.74$</td>
</tr>
</tbody>
</table>

**Smallest margin of safety for the bolt, and the failure mode:**

$M_{S bolt} = 0.32$  Failure Mode = "Total Tension Yield"
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

**Fail-safe Loads**
- Applied tensile load: \( P_{FS} := 222.48 \text{ lbf} \)
- Applied shear load: \( V_{FS} := 27.36 \text{ lbf} \)
- Applied bending moment: \( M_{FS} := 0 \text{-in-lbf} \)

**Fail-safe Factors of Safety**
- Ultimate: \( SFu_{FS} := 1.0 \)
- Joint Separation: \( SF_{Sep_{FS}} := 1.0 \)

Fail Safe Margin calculations are hidden / stiffness & allowable data is not recalculated

This file uses the calculations shown in \( \text{escfl02}\text{\textbackslash}2111\text{\_mathcad}\text{\textbackslash}8307\text{\_bolts}\text{\textbackslash}Rev_D\text{\_bolt\_stiffness\_nut\_FS.mcd} \)

**Bolt Fail-safe Load data**
- Joint separation load: \( P_{sep_{FS}} = 222.48 \text{ lbf} \)
- Max. load on the bolt(ultimate): \( P_{b_{FS}} = 1702.9 \text{ lbf} \)

**Summary of fail-safe Margins for bolt:**

<table>
<thead>
<tr>
<th>Margin</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{FS_1} = 1.26 )</td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{FS_2} = 10.56 )</td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{FS_3} = 0.74 )</td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{FS_4} = 8.23 )</td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( MS_{FS_5} = 0.39 )</td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>( MS_{FS_6} = 81.61 )</td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( MS_{FS_7} = 10 )</td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>( MS_{FS_8} = 0.74 )</td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\( MS_{bolt_{FS}} = 0.39 \)  \( Failure\_Mode\_FS = \"Total Thread Shear Ultimate (Nut)\" \)
6.0 Miscellaneous Analysis
6.1 Vacuum Case Cable Brackets
MINIMUM MARGINS OF SAFETY:

<table>
<thead>
<tr>
<th>PART</th>
<th>Material</th>
<th>Elem ID</th>
<th>Sub case</th>
<th>MSu</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Case Cable Bracket</td>
<td>Al 6061-T651</td>
<td>466</td>
<td>18</td>
<td>5.3</td>
<td>6.1-10</td>
</tr>
</tbody>
</table>

Fasteners Minimum Margin of Safety Summary:

<table>
<thead>
<tr>
<th>PART</th>
<th>Description</th>
<th>Material</th>
<th>Failure Mode</th>
<th>Margin of Safety</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS1351N3-24</td>
<td>Fasteners connecting Integration Cable Bracket to Lower support Ring/Outer Cylinder</td>
<td>A286</td>
<td>Total Tension Yield</td>
<td>0.2 (yield)</td>
<td>6.1-15</td>
</tr>
</tbody>
</table>

Note: The factor of safety for ultimate is 2.0 and the factor of safety for yield is 1.25.

Vacuum Case Cable Bracket

The vacuum case cable bracket is designed to support a short run of electronics cables for the CAB. The designers have estimated that the mass of the supported cables are 0.22 lb (100 grams) as stated in an e-mail from Franck Cadoux on June 23, 2008.

Bracket Characteristics

1. Attached to the lower vacuum case support ring by two fasteners with nuts (NAS1351N3-24).
2. Material: 6061-T651 Aluminum plate
An excerpt from the engineering drawing with the bracket dimensions is shown below:
Loads on the Vacuum Case Cable Bracket

This bracket was analyzed for static load combinations based on the design loads provided in the AMS-02 Structural Verification Plan (JSC 28792, Rev. E) in Table 4-4 for small secondary structures. A load factor of 40 g's was applied in each axis with a simultaneous load of 10 g's in the two orthogonal axes. All positive and negative combinations of the loads were considered.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Nx</th>
<th>Ny</th>
<th>Nz</th>
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</thead>
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<td>40</td>
</tr>
<tr>
<td>24</td>
<td>-10</td>
<td>-10</td>
<td>-40</td>
</tr>
</tbody>
</table>
Math Model of the Vacuum Case Cable Bracket

The finite element model for the bracket consists of plate elements (CQUAD4) with appropriate properties to represent the thickness and materials. The mass of the cable was distributed in a line that lies across the bracket. The holes for the fasteners and the cable ties were omitted because the resulting stresses are very small and the additional detail in the math model is not necessary.

In addition, the radii at the inner and outer corners were not modeled. This is conservative because the model has more surface area and thus the g-loads produce larger body forces.

The fasteners were represented by constraints for the x, y, and z translational degrees of freedom at the two nodes representing the bolt locations. Since the model is free to rotate about a line through the fastener nodes, additional constrains were applied in the z-axis direction at two corners. These constraints represent the physical bearing of the plate against the VC support ring. A second model was used with these corner constraints moved inward on the bracket to the point where the bracket would bear against the VC support ring when the vertical loads are in the opposite direction.

Math Model 1 for contact constraint with force in -Z axis direction (constrain at outer edge):

![Math Model of the Vacuum Case Cable Bracket](image-url)
Math Model 2 for contact constraint with force in +Z axis direction (constraint moved inward):

**Stress Results for the Vacuum Case Cable Bracket**

The stresses for all of the plate elements in the math model were recovered directly from the NASTRAN files and sorted in NASPOST. The peak stresses are summarized below:

\[
\begin{align*}
\sigma_t &= 3830. \text{ psi (maximum principal for ultimate)} \\
\sigma_y &= 3806. \text{ psi (maximum von Mises for yield)} \\
\sigma_s &= 2029. \text{ psi (maximum shear)}
\end{align*}
\]

Note: Due to the symmetry of the bracket and the symmetry of the load cases, more than one load case produces the same maximum value in both models.
The following stress contour shows the maximum principle stress for the worst-case load condition (LC=18, Math Model 2).
The following stress contour shows the maximum Von Mises stress for the worst-case load condition (LC=17, Math Model 2).
The following stress contour shows the maximum shear stress for the worst-case load condition (LC=17, Math Model 2).
Structural Margins for the Vacuum Case Cable Bracket

The material allowables for Al 6061-T651 plate (per Mil. Hdbk. 5J, January 31, 2003) are as follows:

\[
\begin{align*}
F_{u} & := 42000.0 \text{psi} & \text{Tensile ultimate strength} \\
F_{y} & := 35000.0 \text{psi} & \text{Tensile yield strength} \\
F_{s} & := 27000.0 \text{psi} & \text{Shear strength}
\end{align*}
\]

Thermal reduction factor for 140 F:
\[
\beta_{ult} := 0.96 \quad \beta_{yld} := 0.95
\]

Factors of safety for untested hardware:

\[
F_{S_{y}} := 1.25 \quad F_{S_{u}} := 2.0
\]

Maximum stresses:
\[
\begin{align*}
\sigma_{t} & := 3830.0 \\
\sigma_{y} & := 3806.0 \\
\sigma & := 2029.0
\end{align*}
\]

Margins of safety:
\[
\begin{align*}
M_{S_{u}} & := \frac{\beta_{ult} \cdot F_{u}}{\sigma_{t} \cdot F_{S_{u}}} & M_{S_{u}} = 5.264 \text{psi} \\
M_{S_{y}} & := \frac{\beta_{yld} \cdot F_{y}}{\sigma_{y} \cdot F_{S_{y}}} & M_{S_{y}} = 6.989 \text{psi} \\
M_{S_{s}} & := \frac{\beta_{ult} \cdot F_{s}}{\sigma \cdot F_{S_{u}}} & M_{S_{s}} = 6.387 \text{psi}
\end{align*}
\]
Fastener Forces for the Vacuum Case Cable Bracket

The forces in the fasteners that attach the bracket to the support ring were recovered directly from the NASTRAN static analysis as forces of single point constraint. The two constrain forces in the x and y axis directions were combined by RSS to compute the shear in the fastener. The constrain force in the z axis direction was used as the axial force in the fastener.

The maximum fastener forces are:

Faxial = 97.0 lb

Fshear = 24.0 lb

The moments acting on the bracket were reacted by force-couples at the two fastener locations; thus, it is assumed that the fasteners do not sustain any moments.

For the fastener fail safe analysis, the loads previously carried by two fasteners are assumed to now be carried by a single fastener. The moments that are induced on the bracket about the x and y axes are assumed to be reacted by contact of the bracket with the support ring. Any moments induced about the z axis will be reacted by friction between the bracket and the support ring induced by the bolt preload.

The maximum fastener forces for the fail safe analysis are:

Faxial = 194.0 lb

Fshear = 48.0 lb
### Case 1: Model 2A (2 fasteners)

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Element ID</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz (Axial)</th>
<th>Shear</th>
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<tbody>
<tr>
<td>1</td>
<td>212</td>
<td>-10.503</td>
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<td>10.968</td>
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<td>-3.161</td>
<td>-24.029</td>
<td>10.968</td>
</tr>
<tr>
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<td>212</td>
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</tr>
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<td>18.544</td>
</tr>
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<td>-24.029</td>
<td>10.968</td>
</tr>
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**Min** -96.117 3.480  
**Max** 96.117 23.679

### Case 2: Model 2B (2 fasteners)

<table>
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<th>Fz (Axial)</th>
<th>Shear</th>
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<td>18.544</td>
</tr>
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<td>5</td>
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<td>3.992</td>
<td>24.029</td>
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</tr>
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<td>-96.117</td>
<td>3.480</td>
</tr>
</tbody>
</table>

**Min** -96.117 3.480  
**Max** 96.117 23.679
CHECK BOLTS (NAS1351N3-24 0.19"-32 x 1.50 L Material-A-286), Nut NAS1291C3M, Washer NAS1149E 0363R

Flange 1
Part number: SDG39135785/SDG39135779
Material: Al Alloy 7050-T7451

Flange 2
Part number: SDG39135877
Material: Al Alloy 6061-T651

Loads
Applied tensile load \( P := 97.0 \text{lbf} \)
Applied shear load \( V := 24.0 \text{lbf} \)
Applied bending moment \( M := 0.0 \text{in-lbf} \)

Factors of Safety
Ultimate \( SF_u := 2.0 \)
Yield \( SF_y := 1.25 \)
Assembly
Joint Separation \( SF_{sep} := 1.2 \)
Fitting factor \( FF := 1.15 \)
Maximum
Minimum

Temperature data
Temp_initial := 70-deg
Temp_max := 120-deg
Temp_min := -200-deg

Bolt and Nut Data
Nominal diameter of bolt \( D := 0.190 \text{-in} \)
Number of threads/inch \( N_t := 32 \frac{1}{\text{in}} \)
Total length of bolt \( L := 1.50 \text{-in} \)
Height of nut \( H := 0.154 \text{-in} \)
Threaded length \( L_t := 0.875 \text{-in} \)

(If bolt is fully threaded, input \( L_t = L \))

Washer Data
Thickness of washers \( t_w := 0.063 \text{-in} \)
Outer Diameter of washer \( D_w := 0.438 \text{in} \)
Inner Diameter of washer \( D_{wi} := 0.203 \text{-in} \)
Bolt head dia. across flats \( d_w := 0.303 \text{-in} \)

Flange data
Thickness of flange 1 \( t_f1 := 0.75 \text{-in} \)
Thickness of flange 2 \( t_f2 := 0.38 \text{in} \)
Diameter of hole \( D_{\text{hole}} := 0.213 \text{-in} \)

Note: If there is no washer \( t_w \), \( D_w \) and \( D_{wi} \) should be zero
Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate. \( T_{Su_{bolt}} \): 0.98

Yield \( T_{Sy_{bolt}} \): 0.98

Bolt ultimate tensile allowable stress \( F_{tu_{bolt}} \): 160000-psi

Bolt ultimate shear allowable stress \( F_{su_{bolt}} \): 0.6-\( F_{tu_{bolt}} \)

Bolt yield Tensile allowable stress \( F_{ty_{bolt}} \): 120000-psi

Temperature correction factor for bolt modulus \( T_{E_{bolt}} \): 0.99

Modulus of elasticity of bolt\( E_{bolt} := \left(29.1 \cdot 10^6\cdot \text{psi}\right) \)

Thermal coefficient for bolt \( \beta_{bolt_{hot}} := 9.1 \cdot 10^{-6}\frac{\text{in}}{\text{deg}} \)

Nut

Temperature correction factor for nut strength \( T_{S_{nut}} \): 0.94

\( \beta_{bolt_{cold}} := 7.8 \cdot 10^{-6}\frac{\text{in}}{\text{deg}} \)

Ultimate tensile allowable stress \( F_{tu_{nut}} \): 160000-psi

Ultimate Shear allowable stress: \( F_{su_{nut}} := 0.6-F_{tu_{nut}} \)

Ultimate axial strength of nut \( P_{tu_{nut}} := 2460\cdot \text{lbf} \) (Ref. NAS1291, page 2)

Washer

Temperature correction factor for washer modulus \( T_{E_{washer}} := 1.0 \)

Modulus of elasticity of washer: \( E_{washer} := \left(29.1 \cdot 10^6\cdot \text{psi}\right) \)

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners,
Modulus of elasticity of these members, and diameters of the bolt and the washer.

Temperature correction factor for flange 1 \( T_{F1E} := 1.0 \) (modulus)

Temperature correction factor for flange 2 \( T_{F2E} := 1.0 \)

Modulus of elasticity for the parts in the joint \( E_{flange1} := \left(10.6 \cdot 10^6\cdot \text{psi}\right) \)

\( E_{flange2} := \left(10.1 \cdot 10^6\cdot \text{psi}\right) \)

Coefficient of thermal expansion for flanges

\( \beta_{flange1_{hot}} := 12.4 \cdot 10^{-6}\frac{\text{in}}{\text{deg}} \)

\( \beta_{flange2_{hot}} := 12.75 \cdot 10^{-6}\frac{\text{in}}{\text{deg}} \)

\( \beta_{flange1_{cold}} := 12.1 \cdot 10^{-6}\frac{\text{in}}{\text{deg}} \)

\( \beta_{flange2_{cold}} := 11.3 \cdot 10^{-6}\frac{\text{in}}{\text{deg}} \)

Torque/Preload data

Maximum torque \( T_{max} := 40.6\cdot \text{in-lbf} \)

Loading plane factor \( n := 0.5 \)

Minimum torque \( T_{min} := 34.5\cdot \text{in-lbf} \)

Preload Uncertainty \( u := 0.25 \)

Torque coefficient \( k := 0.15 \)

\( 6.1-14 \)
This file uses the calculations shown in \escfil02\2i11_mathcad\8307_bolts\bolt_stiffness__nut_RevC

**Bolt Load data**

- Bolt/joint stiffness factor: \(= 0.164\)
- Preload due to temperature: \(P_{thr\_pos} = 90.2\ lbf\)
- Max. preload: \(PLD_{max} = 1870.9\ lbf\)
- Min. preload: \(PLD_{min} = 244.2\ lbf\)
- Joint separation load: \(P_{sep} = 116.4\ lbf\)
- Max. load on the bolt(ultimate): \(P_b = 1889.2\ lbf\)
- Max. load on the bolt(yield): \(P_{by} = 1882.4\ lbf\)
- Bolt ultimate tensile strength: \(P_{At} = 2312.4\ lbf\)

**Summary of Margins for bolt:**

- Joint separation: \(M_{S1} = 0.99\)
- Direct Tension Ultimate: \(M_{S2} = 9.36\)
- Direct Tension Yield: \(M_{S3} = 15.23\)
- Total Tension Ultimate: \(M_{S4} = 0.22\)
- Total Tension Yield: \(M_{S5} = 0.2\)

Determination of the smallest margin of safety for the bolt, and the failure mode:

\[MS_{bolt} := \min(MS)\]

\[MS_{bolt} = 0.2\]

Failure Mode = “Total Tension Yield”
Fail-safe Analysis  (Conservatively, the loads were doubled to perform fail-safe analysis)

**Fail-safe Loads**
- Applied tensile load \( P_{\text{FS}} := 194\,\text{lbf} \)
- Applied shear load \( V_{\text{FS}} := 48\,\text{lbf} \)
- Applied bending moment \( M_{\text{FS}} := 0\,\text{in-lbf} \)

**Fail-safe Factors of Safety**
- Ultimate \( SF_{\text{Ultimate}} := 1.0 \)
- Joint Separation \( SF_{\text{Joint Separation}} := 1.0 \)

This file uses the calculations shown in \`escfl02\2\11_mathcad\8307_bolts\bolt_stiffness_nut_FS_RevC\`

Bolt Fail-safe Load data
- Joint separation load \( P_{\text{sep,FS}} = 194\,\text{lbf} \)
- Max. load on the bolt(ultimate) \( P_{\text{b,FS}} = 1889.2\,\text{lbf} \)

Summary of fail-safe Margins for bolt:

<table>
<thead>
<tr>
<th>Component</th>
<th>Margins</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint separation</td>
<td>( MS_{\text{FS}1} = 0.19 )</td>
<td></td>
</tr>
<tr>
<td>Direct Tension Ultimate</td>
<td>( MS_{\text{FS}2} = 9.36 )</td>
<td></td>
</tr>
<tr>
<td>Total Tension Ultimate</td>
<td>( MS_{\text{FS}3} = 0.22 )</td>
<td></td>
</tr>
<tr>
<td>Direct Thread shear Ultimate</td>
<td>( MS_{\text{FS}4} = 15.23 )</td>
<td></td>
</tr>
<tr>
<td>Total Thread shear Ultimate</td>
<td>( MS_{\text{FS}5} = 0.92 )</td>
<td></td>
</tr>
<tr>
<td>Shear Ultimate</td>
<td>( MS_{\text{FS}6} = 28.88 )</td>
<td></td>
</tr>
<tr>
<td>Bending Ultimate</td>
<td>( MS_{\text{FS}7} = 10 )</td>
<td></td>
</tr>
<tr>
<td>Combined shear, tension and bending ultimate</td>
<td>( MS_{\text{FS}8} = 0.22 )</td>
<td></td>
</tr>
</tbody>
</table>

Determination of the smallest fail-safe margin of safety for the bolt, and the failure mode:

\[ MS_{\text{bolt,FS}} := \min(MS_{\text{FS}}) \]

\[ MS_{\text{bolt,FS}} = 0.19 \]  
\[ \text{Failure Mode}_{\text{FS}} = \text{"Joint Separation"} \]