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CARLO GAVAZZI

CARLO GAVAZZI SPACE SpA

RICH SYSTEM

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REGISTRAZIONE DELLE MODIFICHE / *CHANGE RECORD*

EDIZIONE *ISSUE*	DATA *DATE*	AUTORIZZAZIONE *CHANGE AUTHORITY*	OGGETTO DELLA MODIFICA E SEZIONI AFFETTE *REASON FOR CHANGE AND AFFECTED SECTIONS*
1	29/06/04		First emission
2	09/11/05		Change Design: Debris shield added Reflector thickness; Reflector support material;

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LIST OF ACRONYMS

AD	APPLICABLE DOCUMENT
AMS	ALPHA MAGNETIC SPECTROMETER
CLA	COUPLED LOAD ANALYSIS
CFRP	CARBON FIBER-REINFORCED PLASTIC
DoF	DEGREE of FREEDOM
FEM	FINITE ELEMENT MODEL
LC	LOAD CASE
LMSO	LOCKHEED MARTIN SPACE OPERATION
MC	MAXIMUM COMBINED
MoS	MARGINS of SAFETY
NA	NOT AVAILABLE
RD	REFERENCE DOCUMENT
RICH	RING IMAGING CHERENKOV
SF	SAFETY FACTOR
SPC	SINGLE POINT CONSTRAIN
USS	UNIQUE SUPPORT STRUCTURE
VM	VON MISES

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1. INTRODUCTION

1.1 SCOPE OF THE DOCUMENT

This document describes the models and methodologies utilized to verify by analysis the structural requirements of the RICH assembly.

The result of these analyses will demonstrate that RICH assembly is compliant with all structural requirements:

- The first natural frequency greater than 50Hz (AD 1) (see Chapter 8).
- All the MoS of the structure positive, under applicable design loads (see Chapters 9.2.9 , 9.3.10 and 9.4)

In the ANNEX 2 Fracture Classification table for AMS-02 RICH is presented.

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2. RELEVANT DOCUMENTS

2.1 APPLICABLE DOCUMENTS

AD # (ID)	Doc Number	Issue	Date	Rev	Title
AD 1	JSC-28792		August, 2003	C	AMS-02 STRUCTURAL VERIFICATION PLAN

2.2 REFERENCE DOCUMENTS

RD # (ID)	Doc Number	Issue	Date	Rev	Title
RD. 1	MIL-HDBK-5	H	Dec, 1998		Metallic Materials and Elements for Aerospace Vehicle Structures
RD. 2					LMSO bolt verification guidelines
RD. 3	NSTS 1700.7B		13/01/89		Safety policy and requirements for payloads using the space transportation system
RD. 4	NSTS 1700.7B ISS ADD		Dec, 1995		Safety Policy and Requirements
RD. 5	NTS08307		July 6, 1998	A	Criteria for preloaded bolt
RD. 6			June, 1973		E. F. BRUHN – Analysis Design of Flight Vehicle Structures
RD 7	RICH-OHB-TN-0001	1	08/03/05		MOD shield for RICH Detector

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3. RICH POSITION

In the following figure the position of the RICH in the AMS-02 Exploded view is presented.

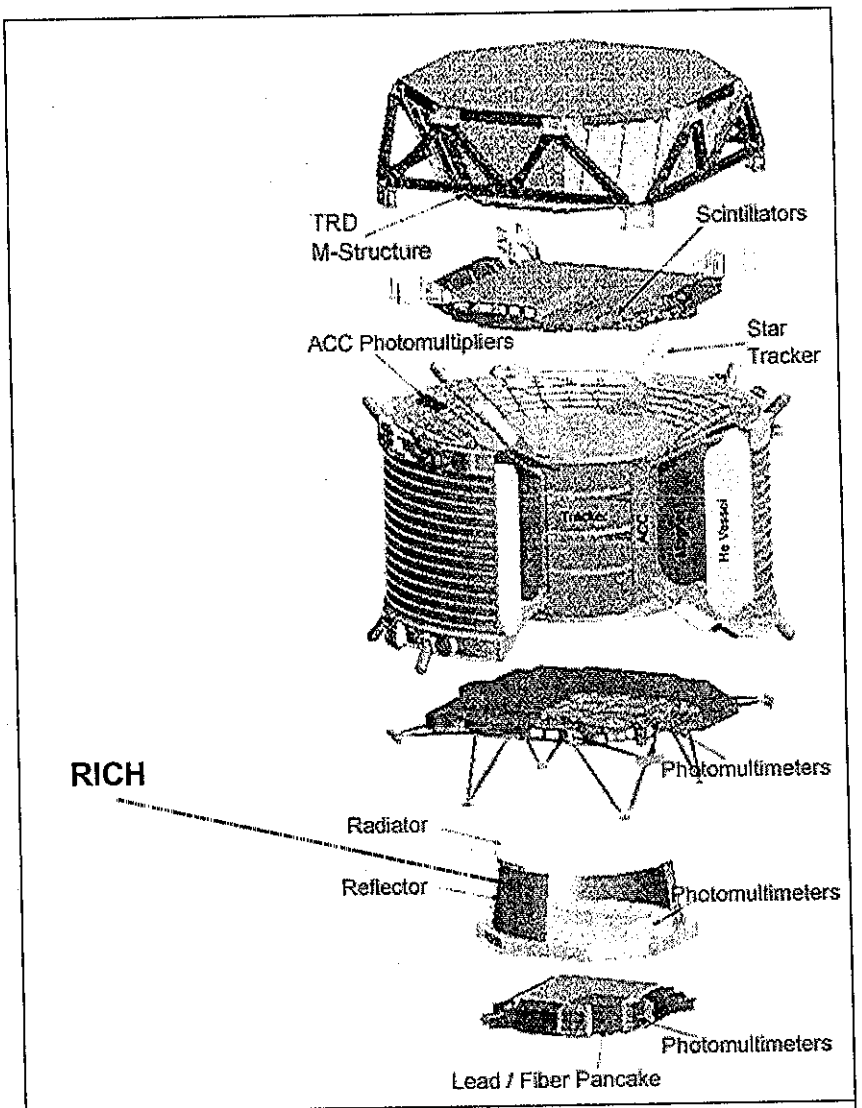

Figure 3-1: Exploded view of AMS-02 subcomponents

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4. VERIFIED ITEMS OF RICH

In the following tables the verified items are showed:

RICH VERIFIED ITEMS				
ITEM	PART NUMBER	MATERIAL	FAILURE	REFERENCE PAGE
EXTERNAL STRUCTURE	13-RICSYS-00.001 13-RICSYS-00.002 13-RICSYS-00 003 13-RICSYS-00.004 13-RICSYS-00 005 13-RICSYS-00.006 13-RICSYS-00.007	AL 7075 T7351	Strength (part+lugs)	
			Buckling	
INTERNAL STRUCTURE (7075)	12-RICSYS-10.001 12-RICSYS-10.002 12-RICSYS-10.003 12-RICSYS-10.004 12-RICSYS-10 005 12-RICSYS-10.006 12-RICSYS-10.007 12-RICSYS-10.008 12-RICSYS-20.001 12-RICSYS-30 001 12-RICSYS-30.002 12-RICSYS-30.003	AL 7075 T7351	Strength (part+lugs)	49
			Buckling	77
INTERNAL STRUCTURE (6061)	12-RICSYS-10 009 12-RICSYS-20.002 12-RICSYS-30.004	AL 6061T6	Strength (part+lugs)	49
			Buckling	77
REFLECTOR	12-RICSYS-40.001	CFRP	Strength	50
REFLECTOR SUPPORT	14-RICSYS-00.001 14-RICSYS-00 002	AL 6061T6	Strength (part+lugs)	51
			Buckling	76
DEBRIS SHIELD	12-RICSYS-00.00567	CFRP / HONEYCOMB	Strength	52
DEBRIS STIRRUP	12-RICSYS-00.004008	AL 7075 T7351	Strength (part+lugs)	53
			Buckling	
JOINT 1	NAS 1351N4	A286 (160ksi)	Strength, bearing	59
JOINT 2	M3	A4-70	Strength, bearing	61
JOINT 3	NAS 1351N5	A286 (160ksi)	Strength, bearing	63
JOINT 4	MAXIBOLT	A286 (95ksi)	Strength, bearing	65
JOINT 5	NAS 1351N3	A286 (160ksi)	Strength, bearing	67
JOINT 6	NAS 1351N3	A286 (160ksi)	Strength, bearing	69
JOINT 7	NAS 1351N3	A286 (160ksi)	Strength, bearing	71
JOINT 8	NAS 1351N3	A286 (160ksi)	Strength, bearing	73

Table 4-1: Verified Items

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FAILURE	VERIFICATION APPLIED
Strength	Von Mises on shells
	Maximum combined on bars
	TSAI WU on CFRP
	Combined/ Intracell Buckling / Wrinkling for Honeycomb
Bolt	Separation / Tension / Thread shear / Shear / Bending / Combined
Rivet	Combined
Buckling	Local Buckling

Table 4-2: Verification Applied

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5. RICH MODEL DESCRIPTION

In the following images a view of the entire RICH model is presented.

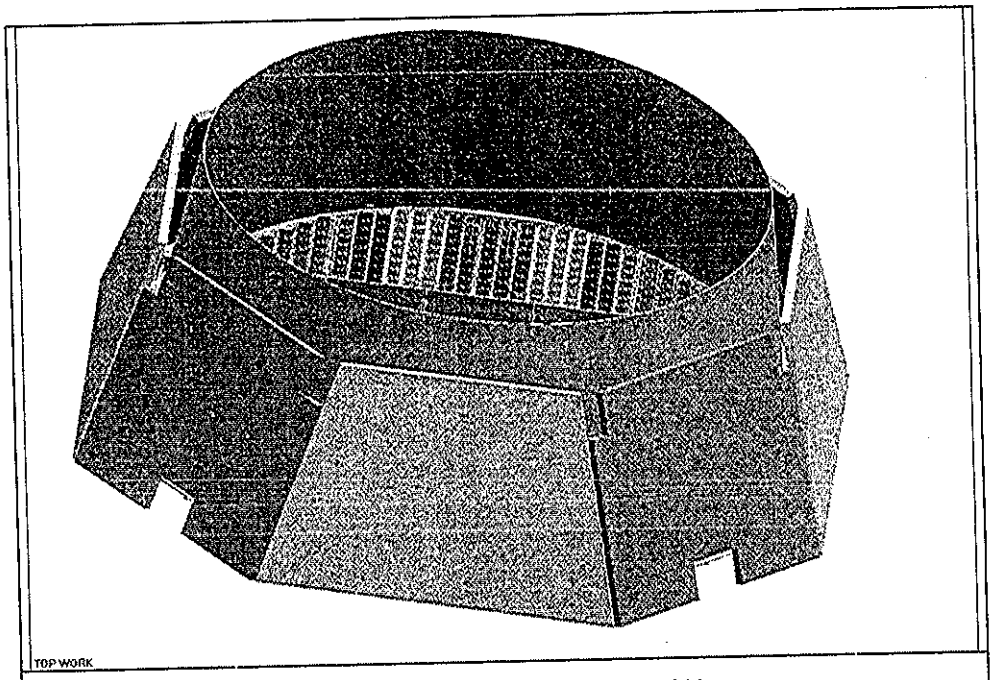

Figure 5-1: General view of RICH

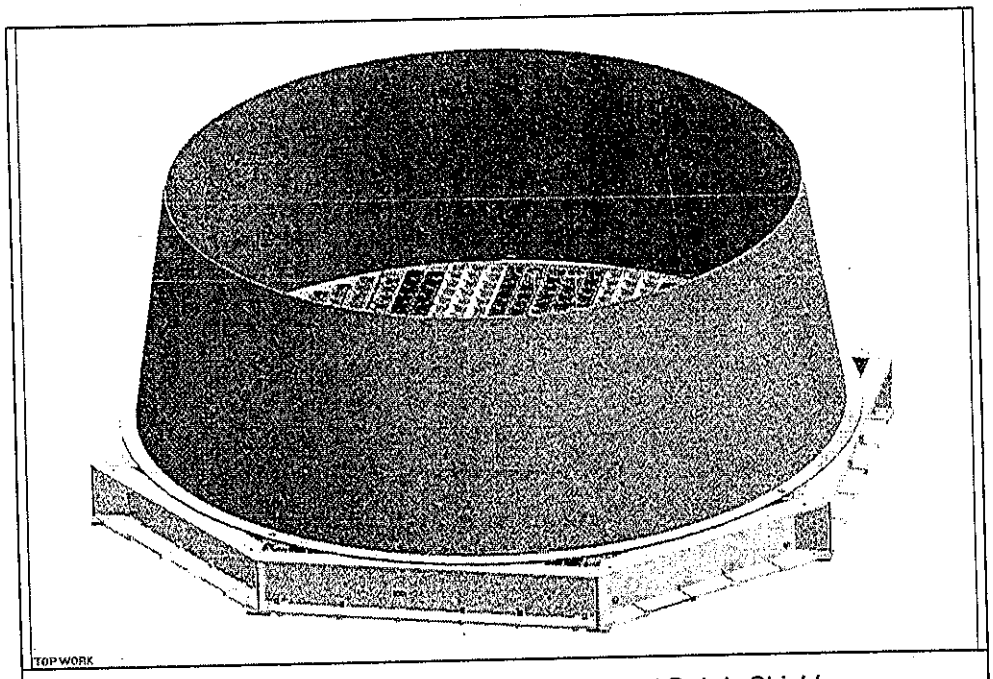

Figure 5-2: General view of RICH without Debris Shields

In the following chapters the structural Finite Element Model is described (the model used is "RICH_050908.bdf").

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5.1 USED SOFTWARE

The software used for FEM pre and post processing is MSC/PATRAN 2005.
The software used for Finite Element analysis is MSC/NASTRAN V2005.

5.2 MODEL UNITS

Default FEM units (otherwise specified) are:

- Length [m]
- Masses [Kg]
- Forces [N]
- Moments [Nm]
- Materials densities [Kg/m^3]
- Young's modules [N/m^2]
- Stresses [N/m^2]
- Displacements [m]

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5.3 MODEL COORDINATE SYSTEM

For the RICH model, the AMS-02 coordinate system (Coord 0 in Figure 5-3) is used:

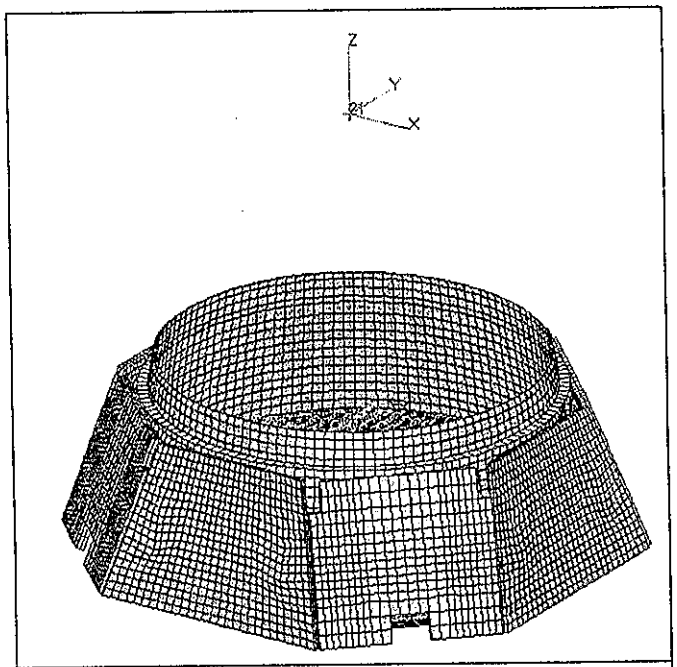

Figure 5-3: AMS-02 coordinate system

In the following figure two views of the position of the AMS-02 CoG are presented:

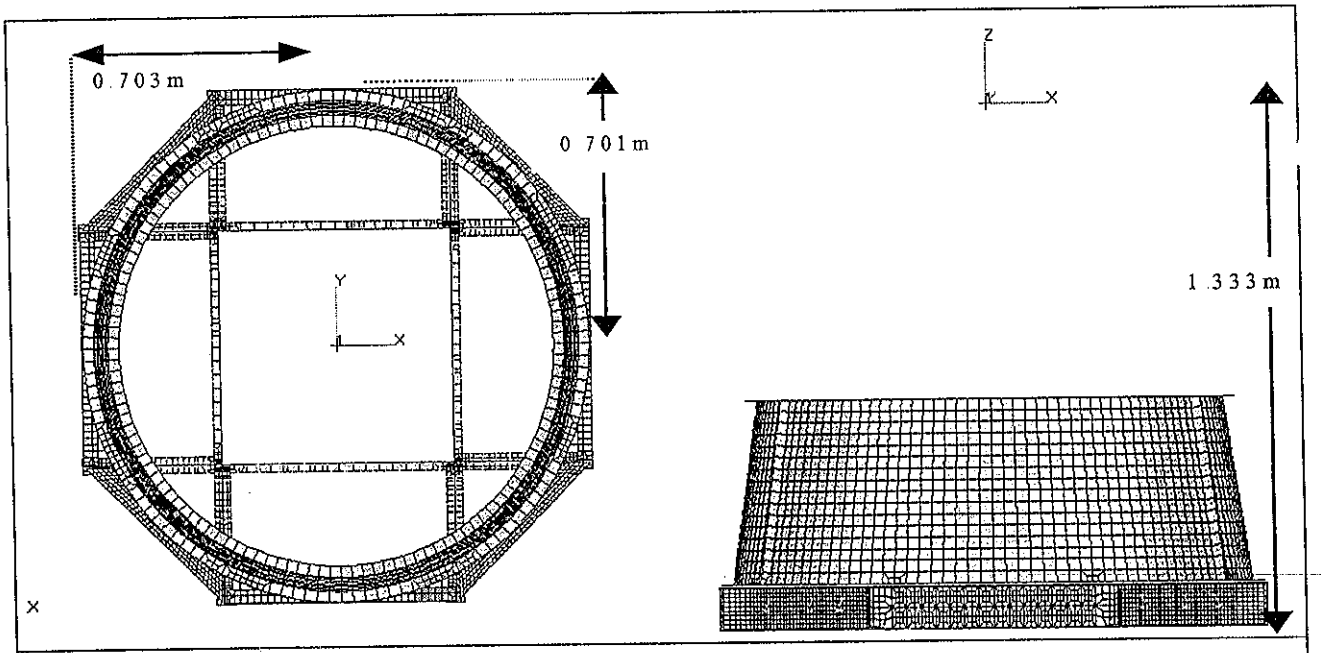

Figure 5-4: AMS-02 coordinate system

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5.4 MODEL MATERIALS

In the following tables

- the properties of each materials
- the items
- the corresponding NASTRAN card

are shown.

In the evaluation of the MoS, all allowable stresses have been reduced by a factor of 6% in order to account for thermal effect.

5.4.1 AL 7075 T7351

7075 Aluminium Alloy		
Source	MIL-HDBK-5H	
Specification	AMS 4078 and AMS-QQ-A-250/12	
Form	Plate	
Temper	T7351	
Thickness [in]	0.250 - 0.499	
Mechanical Properties		
	[MPa]	**[ksi]**
Ftu L	468.84	68
Fty L	393.00	57
Fcy L	386.11	56
Fsu	262.00	38
Fbru (e/d=1.5)	703.27	102
Fbry (e/d=1.5)	544.69	79
E	71016.00	10300
Ftu LT	475.74	69
Fty LT	393.00	57
Fcy LT	406.79	59
Fbru (e/d=2)	903.21	131
Fbry (e/d=2)	655.00	95
Physical Properties		
	[kg/m^3]	**[lb/in^3]**
ρ	2796	0.101
ν	0.33	

Table 5-1: AL 7075 T7351 properties

NASTRAN CARD:	MAT1 1 7.1+10 .33 2790.
ITEMS:	External and internal structures

Table 5-2: AL 7075 T7351 in FE model

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5.4.2 AL 6061 T6

6061 Aluminium Alloy		
Source	MIL-HDBK-5H	
Specification	AMS 4025, AMS 4027 and AMS-QQ-A-250/11	
Form	Sheet	
Temper	T6	
Thickness [in]	0.010 - 0.249	
Mechanical Properties		
	[MPa]	**[ksi]**
Ftu	289.58	42
Fty	241.32	35
Fcy	241.32	35
Fsu	186.16	27
Fbru	461.95	67
Fbry	344.74	50
E	68258	9900
Physical Properties		
	[kg/m^3]	**[lb/in^3]**
ρ	2713	0.098
ν	0.33	

Table 5-3: AL 6061 T6 properties

NASTRAN CARD:	MAT1 400006 6.82+10 .33 2713.
ITEMS:	Internal structures and reflector support

Table 5-4: AL 6061 T6 in FE model

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5.4.3 CFRP / REFLECTOR

CFRP / REFLECTOR		
Source	Vendor	
Fibre	M55J	
Resin	EX-1515	
Form	Quasi Isotropic	
Thickness [in]	0.0025 +/- 10%	
Mechanical Properties		
	[MPa]	**[ksi]**
Ftu	503	73
Fcu	241	35
Fsu	200	29
Et	103421	15000
Ec	87563	12700
G	33853	4910
Physical Properties		
	[kg/m^3]	**[lb/in^3]**
ρ	1500	0.0542
ν	0.2	

Table 5-5: CFRP properties

NASTRAN CARD:	MAT8.....9.....1.05+11.1.05+11..2.....3.43+10.....1500. *.....5.03317+8 *.....2.41317+8.....5.03317+8.....2.41317+8.....1.99948+8
ITEMS:	Reflector

Table 5-6: CFRP / REFLECTOR in FE model

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5.4.4 CFRP / DEBRIS SHIELDS

CFRP / DEBRIS SHIELDS		
Source	Vendor	
Fibre	T300	
Resin	Vicotex 1454	
Form	Plain Weave fabric	
Thickness [in]	0.021 +/- 10%	
Mechanical Properties		
	[MPa]	**[ksi]**
Ftu	850	123
Fcu	700	102
Fsu	105	15
Et	75000	10878
Ec	70000	10153
Ebend	950	138
G	12000	1740
Physical Properties		
	[kg/m^3]	**[lb/in^3]**
ρ	1400	0.051
ν	0.28	

Table 5-7: CFRP properties

NASTRAN CARD:	MAT8.....7.....7.+10....7.+10.....28.....1.2+10..9.5+8....9.5+8....1400. .....8.5+8...7.+8....8.5+8...7.+8....1.05+8
ITEMS:	Debris Shields

Table 5-8: CFRP / DEBRIS SHIELDS in FE model

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5.4.5 HONEYCOMB

HEXCEL CR III-3/16-5056-.007-2.0		
Source	HexWeb product data	
Material	5056 Aluminium Alloy	
Form	Honeycomb	
Cell size [in]	3/16	
Nominal foil thickness [in]	0.0007	
Mechanical Properties		
	[MPa]	**[ksi]**
Fty (L direction)	0.72	0.11
Fty (W direction)	0.34	0.05
E11	0.00	0.00
E22	0.00	0.00
E33	310.26	45.00
G13	186.16	27.00
G23	89.63	13.00
G12	0.00	0.00
Physical Properties		
	[kg/m^3]	**[lb/ft^3]**
ρ	32	2

Table 5-9: Honeycomb properties

NASTRAN CARD:	MAT9.....3.....1000.....1000. .....3 1+8 .....1000.....1.86+8.....8.9+7...36.4
ITEMS:	Debris shields

Table 5-10: Honeycomb in FE model

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5.4.6 DUMMY STEEL FOR BOLTED CONNECTIONS

A dummy material with reference properties of steel is used for beam elements that represent bolted connections:

The corresponding NASTRAN BULK data card is:

```
MAT1     400007  2.01+11          .3       1.
```

5.5 FE MODEL DESCRIPTION

In this chapter the components of RICH Finite Element Model are presented:

GRID POINTS	65808
ELEMENTS	
CBAR	7128
CONM2	28
CQUAD4	42318
CTRIA3	52
RBE2	1844
HEX	7232

Table 5-11: Model summary

RICH NASTRAN model subcomponents are presented in the following chapters:

- EXTERNAL STRUCTURE
- INTERNAL STRUCTURE (7075)
- INTERNAL STRUCTURE (6061)
- REFLECTOR
- REFLECTOR SUPPORT
- DEBRIS SHIELDS
- DEBRIS STIRRUP

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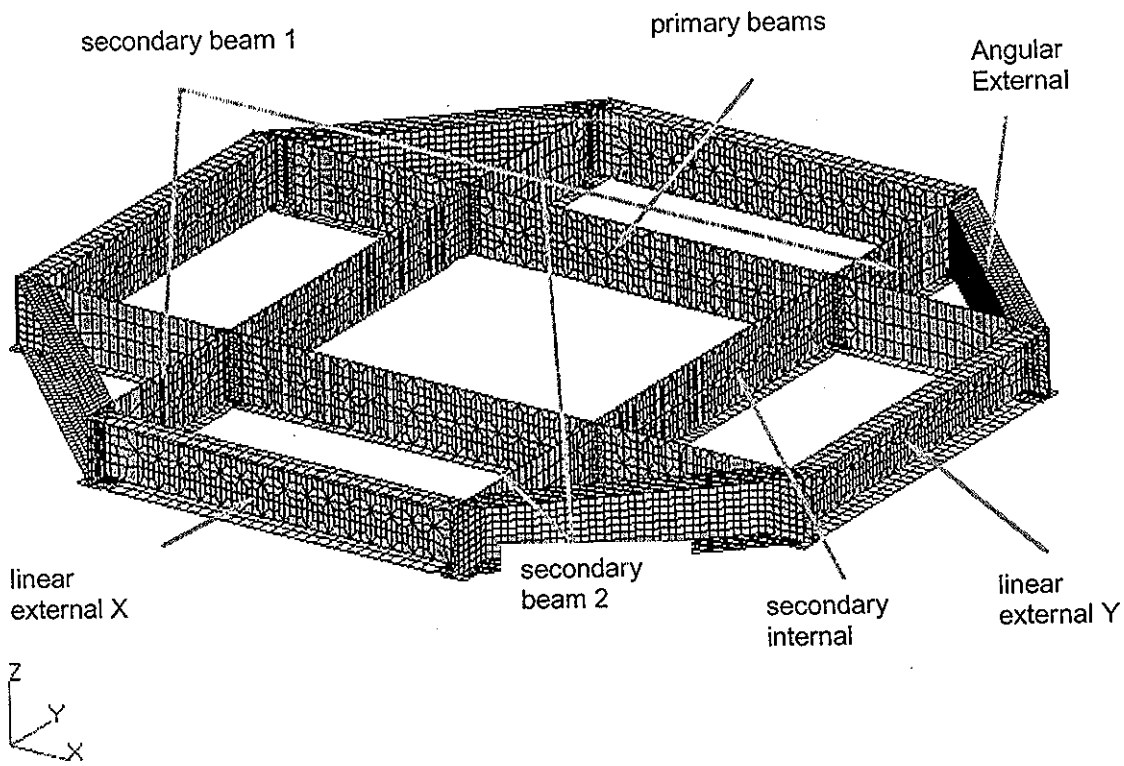
5.5.1 EXTERNAL STRUCTURE

The external structure of the RICH is presented in the following figure:



Main Dimensions [m]	Length: 1.407	Width: 1.402	Height: 0.108
Mass [kg]	Total: 20.8		
Material	AL 7075 T7351		
Thickness range [m]	[0.003, 0.008]		
FEM elements	Shell		
Connection	RBE2, Bar		

Figure 5-5: External structure

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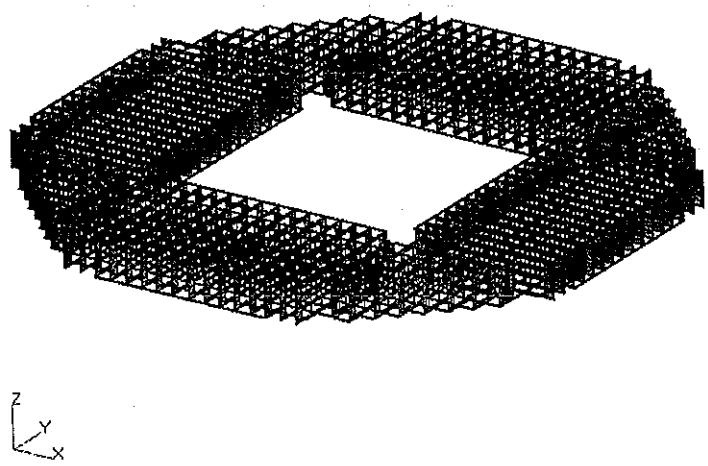
5.5.2 INTERNAL STRUCTURE (7075)

The internal structure made by 7075 T7351 of the RICH is presented in the following figure:



Main Dimensions [m]	Length: 1.324	Width: 1.319	Height: 0.08
Mass [kg]	Total: 55.8		
Material	AL 7075 T7351		
Thickness range [m]	[0.0042, 0.010]		
FEM elements	Shell, Bar		
Connection	RBE2, Bar		

Figure 5-6: Internal structure

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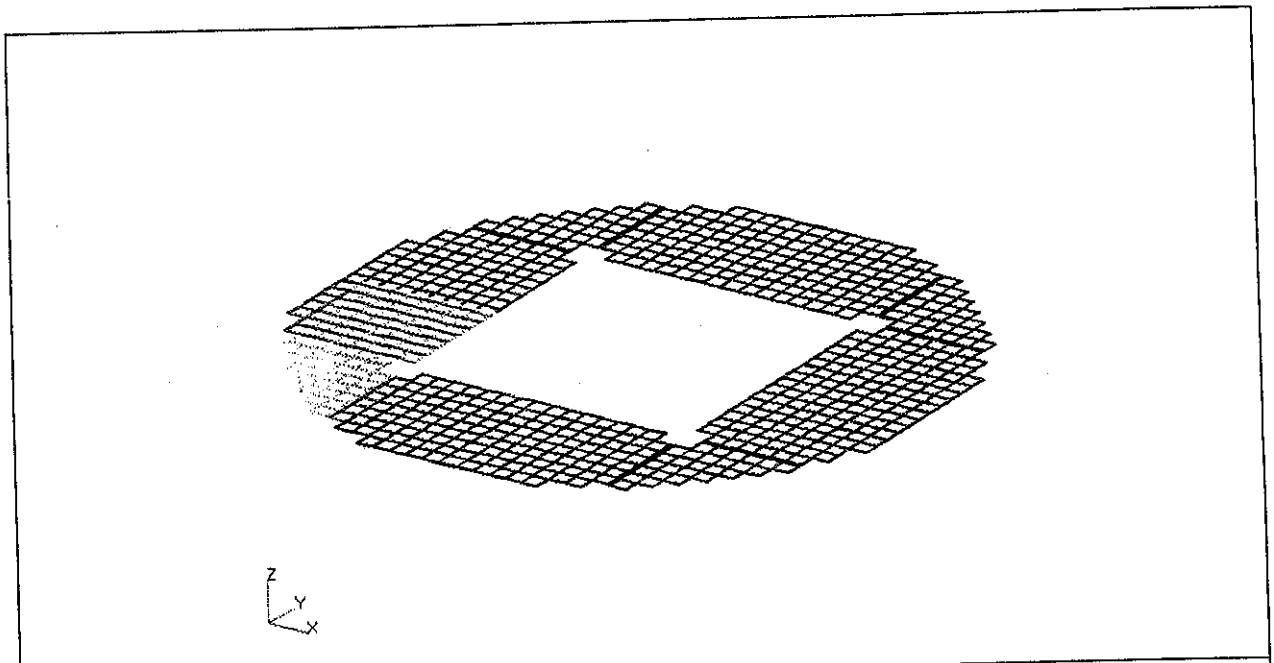
5.5.3 INTERNAL STRUCTURE (6061)

The internal structure made by 6061 T6 of the RICH is presented in the following figure:



Main Dimensions [m]	Length: 1.324	Width: 1.319	Height: 0.001
Mass [kg]	Total: 0.8		
Material	AL 6061 T6		
Thickness range [m]	[0.002]		
FEM elements	Bar		
Connection	RBE2, Bar		

Figure 5-7: Internal structure

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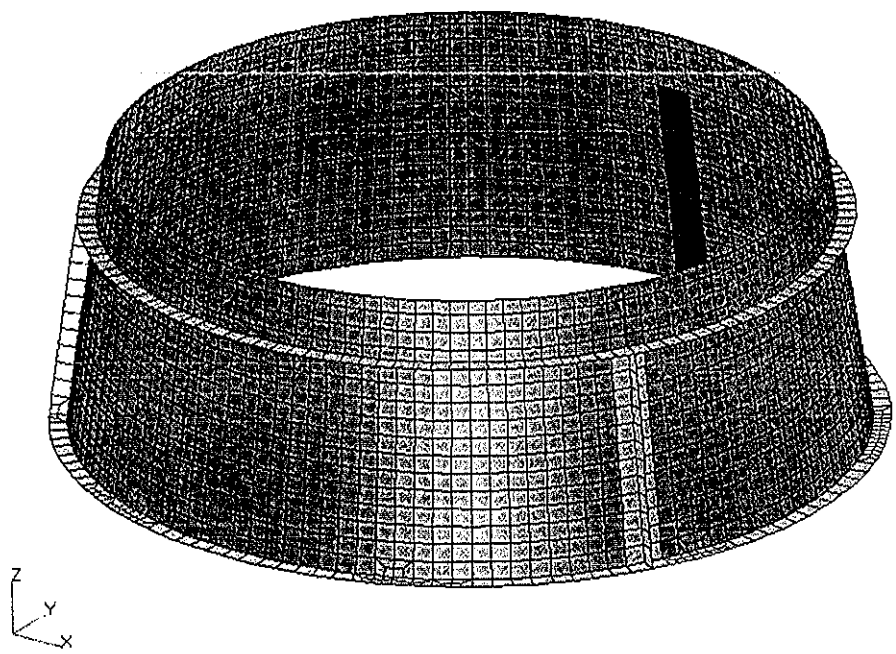
5.5.4 REFLECTOR

The reflector of the RICH is presented in the following figure:



Main Dimensions [m]	Max diameter: 1.4	Min diameter: 1.25	Height: 0.468
Mass [kg]	Total: 8.2		
Material	CFRP		
Thickness range [m]	[0.0022, 0.0052]		
FEM elements	Shell		
Connection	RBE2, Bar		

Figure 5-8: Reflector

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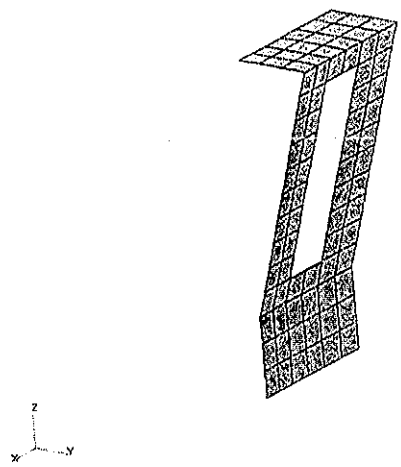
5.5.5 REFLECTOR SUPPORT

One of the reflector supports of the RICH is presented in the following figure:



Main Dimensions [m]	Length: 0.046	Width: 0.024	Height: 0.104
Mass [kg]	Total: 0.12		
Material	AL 6061 T6		
Thickness range [m]	[0.002]		
FEM elements	Shell		
Connection	RBE2, Bar		

Figure 5-9: Reflector support

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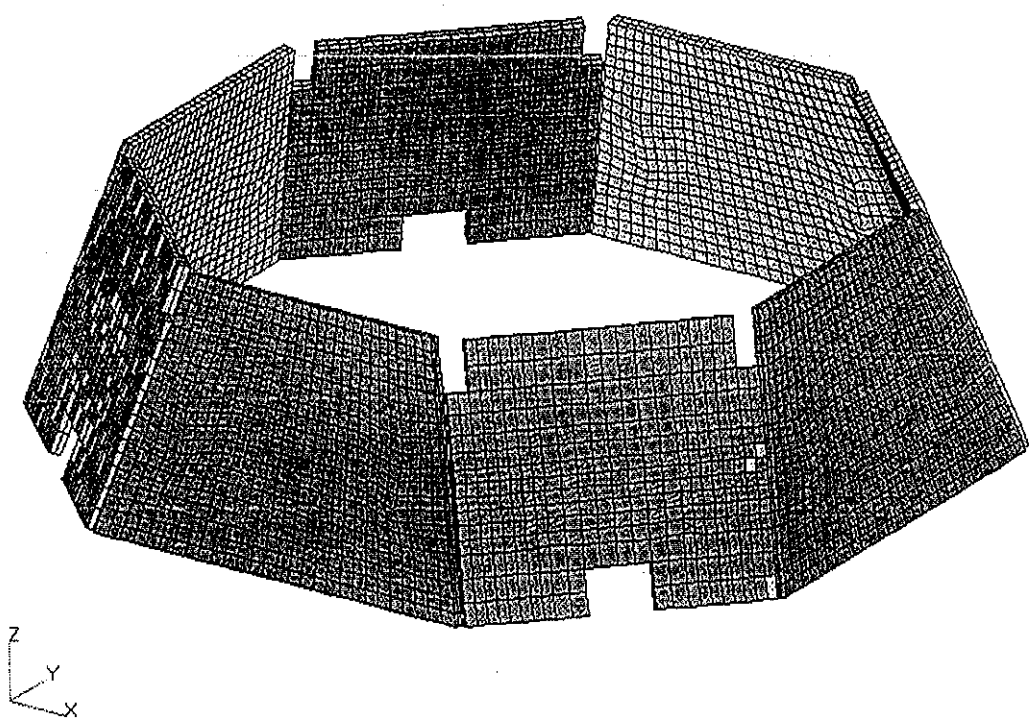
5.5.6 DEBRIS SHIELDS

The debris shields of the RICH are presented in the following figure:



Main Dimensions [m]	Length: 1.68	Width: 01.68	Height: 0.47
Mass [kg]	Total: 6.38		
Material	CFRP, Honeycomb		
Thickness range [m]	[0.025]		
FEM elements	Shell, Solid		
Connection	RBE2, Bar		

Figure 5-10: Debris Shields

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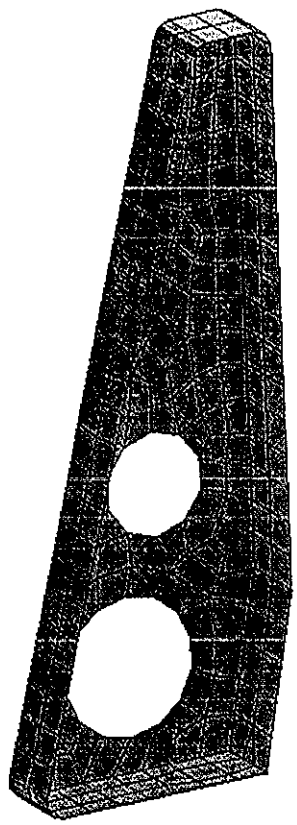
5.5.7 DEBRIS STIRRUP

One of the debris shields brackets of the RICH is presented in the following figure:



Main Dimensions [m]	Length: 0.076	Width: 0.021	Height: 0.21
Mass [kg]	Total: 0.15		
Material	AL 7075 T7351		
Thickness range [m]	[0.002 - 0.003]		
FEM elements	Shell		
Connection	RBE2, Bar		

Figure 5-11: Debris Shields Brackets

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5.6 MODEL BOUNDARY CONDITIONS

The RICH external structure is connected to the USS through 16 bolts. In the Finite Element Model it is simulated by 16 SPC (with the three translation constrained) directly positioned on the structure.

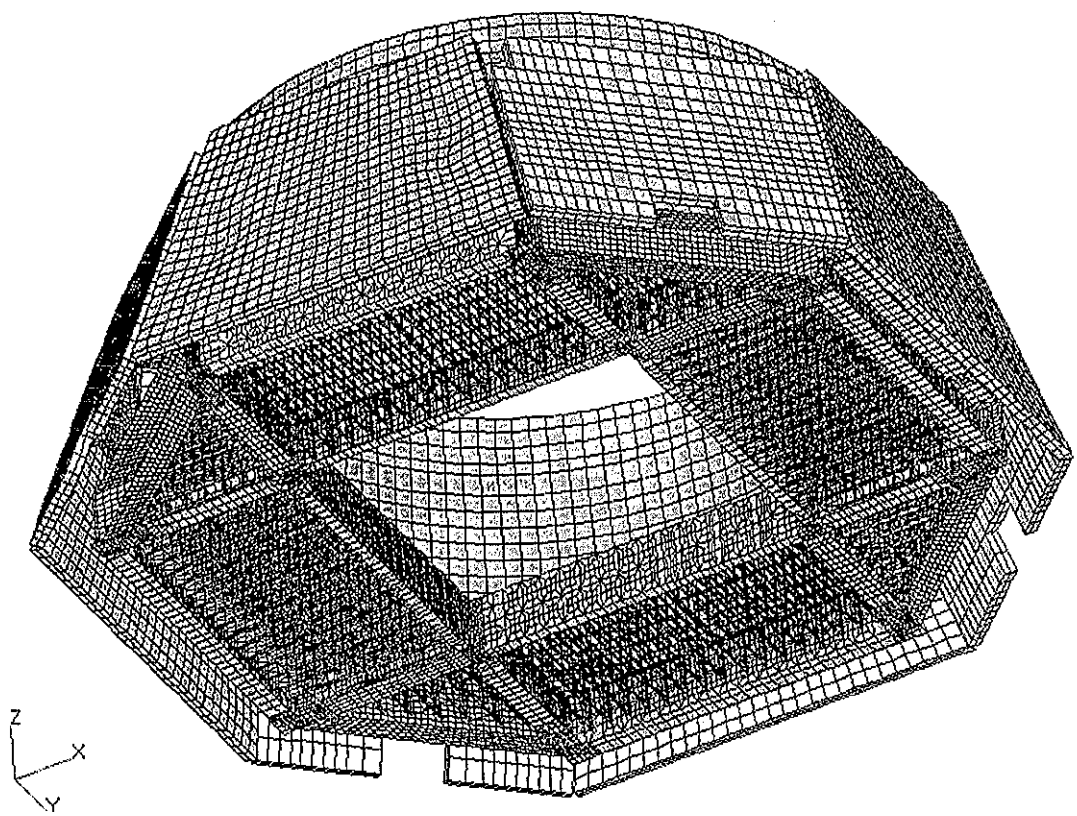

Figure 5-12: Model boundary conditions

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5.7 MODEL MASS BUDGET

The total mass has been considered without any contingency.

RICH MASS BUDGET		ITEM	CAD MASS [Kg]	FEM MASS [Kg]	REMARKS
	EXTERNAL STRUCTURE	MAIN STRUCTURE PARTS	20,8	44,2	
		DEBRIS SHIELD & BKTs	8,9	8,9	
		OCTAGON COVER PANELS	1,5	1,5	
		LOWER PANEL & LIGHT SEALING	3,3	3,3	
		BOLTS & NUTS	6,2		Added on the main structure parts
		FIXATION TO USS	0,3		
		ELECTRONICS	4,5		
		CABLES & CONNECTORS	12,4		
		TOTAL	**58,0**	**58,0**	
	INTERNAL STRUCTURE	STRUCTURE PARTS	56,5	58,7	
		PMT ASSEMBLY	53,3	53,3	
		CABLE & CONNECTORS	2,1		Added on the structure parts
		TOTAL	**112,0**	**112,0**	
	REFLECTOR	MIRROR ASSEMBLY	8,4	8,4	
		TOTAL	**8,4**	**8,4**	
	TOTAL		**178,3**	**178,3**	

Table 5-12: Model mass budget

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5.8 MODEL CHECK

5.8.1 MODEL SIZE AND GEOMETRY

In the following tables the summary of the check runs that verify the mathematical correctness of the assembly model is shown:

MATHEMATICAL MODEL VERIFICATION RESULTS
GEOMETRY CHECK

MODEL FILE NAMES :
RICH_ 050809.bdf

RUN FILE NAMES
AMS_RICH_050908_1g_check.dat, RICH_param.blk

MODEL UNITS
Length=m, mass=Kg, density=Kg/m^3, Young mod.=N/m^2, Stress=N/m^2, Deformation=m, Strain En=N*m=Joule.

M O D E L S U M M A R Y

NUMBER OF GRID	POINTS =	65808
NUMBER OF CBAR	ELEMENTS =	7128
NUMBER OF CHEXA	ELEMENTS =	7232
NUMBER OF CONM2	ELEMENTS =	28
NUMBER OF CQUAD4	ELEMENTS =	42318
NUMBER OF CTRIA3	ELEMENTS =	52
NUMBER OF RBE2	ELEMENTS =	1844

E L E M E N T G E O M E T R Y T E S T R E S U L T S S U M M A R Y

TOTAL NUMBER OF TIMES TOLERANCES WERE EXCEEDED

ELEMENT TYPE	ASPECT/ SKEW ANGLE	MINIMUM TAPER RATIO	MAXIMUM INTER. ANGLE	SURFACE/FACE INTER. ANGLE	WARP FACTOR	EDGE POINT OFFSET RATIO	JACOBIAN LENGTH RATIO	DETERMINANT
BAR	N/A	N/A	N/A	N/A	N/A	0	N/A	N/A
HEXA	N/A	0	N/A	N/A	0	N/A	0	0
QUAD4	0	253	449	458	0	N/A	N/A	N/A
TRIA3	0	N/A	N/A	0	N/A	N/A	N/A	N/A

N/A IN THE ABOVE TABLE INDICATES TESTS THAT ARE NOT APPLICABLE TO THE ELEMENT TYPE AND WERE NOT PERFORMED.
FOR ALL ELEMENTS WHERE GEOMETRY TEST RESULTS HAVE EXCEEDED TOLERANCES

QUAD4	ELEMENT ID	456094	PRODUCED LARGEST	TAPER RATIO	OF	0.67	(TOLERANCE = 0.50)
QUAD4	ELEMENT ID	403042	PRODUCED SMALLEST	INTERIOR ANGLE	OF	16.35	(TOLERANCE = 30.00)
QUAD4	ELEMENT ID	429609	PRODUCED LARGEST	INTERIOR ANGLE	OF	163.64	(TOLERANCE = 150.00)

Table 5-13: FEM Geometry Check

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5.8.2 FREE-FREE AND HARDMOUNTED MODES

MATHEMATICAL MODEL VERIFICATION RESULTS
MASS PROPERTIES, FREE-FREE MODES, HARDMOUNTED MODES

MODEL FILE NAMES
RICH_ 050809.bdf

RUN FILE NAMES
AMS_RICH_050908_constrain.dat, AMS_RICH_050908_free.dat, RICH_param.blk

MODEL UNITS
Length=m, mass=Kg, density=Kg/m^3, Young mod.=N/m^2, Stress=N/m^2, Deformation=m, Strain En=N*m=Joule.

PARAMETERS:

PARAM,POST,0
PARAM,AUTOSPC,YES
PARAM,PRGPST,NO
PARAM,K6ROT,1.
PARAM,PRTMAXIM,YES
PARAM,GRDPNT,0
PARAM,COUPMASS,1

MASS PROPERTIES

```
O U T P U T   F R O M   G R I D   P O I N T   W E I G H T   G E N E R A T O R
                                                  REFERENCE POINT =        0
 0
                                    M O
*  1.784490E+02 -4.821159E-18  2.768824E-17  6.017575E-18 -2.242088E+02  7.823995E-01 *
* -4.821159E-18  1.784490E+02 -4.797832E-17  2.242088E+02  6.324237E-18  1.337726E-03 *
*  2.768824E-17 -4.797832E-17  1.784490E+02 -7.823995E-01 -1.337726E-03 -1.219065E-17 *
*  6.017575E-18  2.242088E+02 -7.823995E-01  3.141474E+02 -7.605821E-03  1.797941E-03 *
* -2.242088E+02  6.324237E-18 -1.337726E-03 -7.605821E-03  3.136921E+02 -8.701828E-01 *
*  7.823995E-01  1.337726E-03 -1.219065E-17  1.797941E-03 -8.701828E-01  6.208774E+01 *
                                    S
                        *  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 *
                                    DIRECTION
                                                X-C.G.        Y-C.G.        Z-C.G.
MASS AXIS SYSTEM (S)      MASS
   X                   1.784490E+02        3.372154E-20 -4.384444E-03 -1.256431E+00
   Y                   1.784490E+02        7.496408E-06  3.544003E-20 -1.256431E+00
   Z                   1.784490E+02        7.496408E-06 -4.384444E-03 -6.831449E-20
                                    I(S)
                        *  3.244104E+01  7.611686E-03 -1.171807E-04 *
                        *  7.611686E-03  3.198918E+01 -1.128482E-01 *
                        * -1.171807E-04 -1.128482E-01  6.208431E+01 *
                                    I(Q)
                        *  3.244116E+01                             *
                        *                3.198863E+01               *
                        *                             6.208474E+01  *
                                    Q
                        *  9.998585E-01  1.682330E-02  0.000000E+00 *
                        * -1.682318E-02  9.998515E-01  3.749637E-03 *
                        *  6.308127E-05 -3.749106E-03  9.999930E-01 *
```

RIGID BODY NORMAL MODE CHECK

R E A L E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	4.337581E+04	2.082686E+02	3.314698E+01	1.000000E+00	4.337581E+04
2	2	6.983170E+04	2.642569E+02	4.205779E+01	1.000000E+00	6.983170E+04
3	3	7.692294E+04	2.773499E+02	4.414160E+01	1.000000E+00	7.692294E+04
4	4	8.302999E+04	2.881493E+02	4.586038E+01	1.000000E+00	8.302999E+04
5	5	1.095902E+05	3.310441E+02	5.268730E+01	1.000000E+00	1.095902E+05
6	6	1.109946E+05	3.331584E+02	5.302381E+01	1.000000E+00	1.109946E+05
7	7	1.658777E+05	4.072809E+02	6.482076E+01	1.000000E+00	1.658777E+05
8	8	1.722322E+05	4.150087E+02	6.605069E+01	1.000000E+00	1.722322E+05
9	9	1.817562E+05	4.263287E+02	6.785233E+01	1.000000E+00	1.817562E+05
10	10	2.166695E+05	4.654777E+02	7.408308E+01	1.000000E+00	2.166695E+05

HARDMOUNTED NORMAL MODE CHECK

R E A L E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	-1.453569E-06	1.205640E-03	1.918836E-04	1.000000E+00	-1.453569E-06
2	2	-8.450973E-07	9.192917E-04	1.463098E-04	1.000000E+00	-8.450973E-07
3	3	-6.149197E-07	7.841682E-04	1.248042E-04	1.000000E+00	-6.149197E-07
4	4	1.458028E-07	3.818414E-04	6.077194E-05	1.000000E+00	1.458028E-07
5	5	6.464577E-07	8.040259E-04	1.279647E-04	1.000000E+00	6.464577E-07
6	6	1.010818E-06	1.005395E-03	1.600135E-04	1.000000E+00	1.010818E-06
7	7	1.643311E+04	1.281917E+02	2.040234E+01	1.000000E+00	1.643311E+04
8	8	2.882044E+04	1.697658E+02	2.701907E+01	1.000000E+00	2.882044E+04
9	9	4.321870E+04	2.078911E+02	3.308689E+01	1.000000E+00	4.321870E+04
10	10	6.962116E+04	2.638582E+02	4.199434E+01	1.000000E+00	6.962116E+04

Table 5-14: FEM mass properties, free-free modes, hardmounted modes

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5.8.3 1 G CHECK

MATHEMATICAL MODEL VERIFICATION RESULTS
1g CHECK

MODEL FILE NAMES :
RICH_ 050809.bdf

RUN FILE NAMES
AMS_RICH_050908_1g_check.dat, grav_1gchk.blk, AMS_ subcases_1gchk.blk, RICH_param.blk

PARAMETERS:	
PARAM,POST,0	PARAM,K6ROT,1.
PARAM,AUTOSPC,YES	PARAM,PRTMAXIM,YES
PARAM,PRGPST,NO	PARAM,GRDPNT,0
	PARAM,COUPMASS,1

UNITY GRAVITY LOADING CHECK
(COORD 0)
M=178.3 Kg
g=9.81
Fxyz=1750.5 N

OLOAD RESULTANT

TYPE	T1	T2	T3	R1	R2	R3
10001	1.750585E+03	-4.760698E-17	2.716217E-16	5.863597E-17	-2.199489E+03	7.675340E+00
10002	-4.754715E-17	1.750585E+03	-4.706673E-16	2.199489E+03	6.235049E-17	1.312310E-02
10003	2.716218E-16	-4.706673E-16	1.750585E+03	-7.675340E+00	-1.312310E-02	-1.195903E-16

SPCFORCE RESULTANT

	T1	T2	T3	R1	R2	R3
10001	-1.750585E+03	3.421690E-10	-1.497824E-10	2.651035E-10	2.199489E+03	-7.675340E+00
10002	8.109780E-11	-1.750585E+03	-6.492868E-10	-2.199489E+03	-1.372484E-09	-1.312310E-02
10003	-2.214051E-11	-6.167369E-10	-1.750585E+03	7.675340E+00	1.312310E-02	0.000000E+00

EPSILON

LOAD SEQ. NO.	EPSILON	EXTERNAL WORK
1	-4.0296937E-12	1.6290901E-02
2	-4.0178026E-12	1.7307693E-02
3	-1.4268127E-12	1.6224964E-02

Table 5-15: FEM 1g check

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5.8.4 STRAIN ENERGY CHECK

MATHEMATICAL MODEL VERIFICATION RESULTS
STRAIN ENERGY CHECK

MODEL FILE NAMES :
RICH_ 050809.bdf

RUN FILE NAMES
AMS_RICH_050908_strain_energy.dat, RICH_param.blk

COMAND:
GROUNDCHECK(SET=ALL,THRESH=1.E-3,DATAREC=YES,1.E-3) = YES

PARAMETERS:

PARAM,POST,0
PARAM,AUTOSPC,YES
PARAM,PRGPST,NO
PARAM,K6ROT,1.
PARAM,PRTMAXIM,YES
PARAM,GRDPNT,0
PARAM,COUPMASS,1

STRAIN ENERGY CHECK [J]

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	2.254268E-06	PASS
2	3.305265E-05	PASS
3	1.400187E-04	PASS
4	4.581722E-06	PASS
5	1.730945E-05	PASS
6	2.182810E-05	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	1.452013E-05	PASS
2	3.543712E-05	PASS
3	1.390970E-04	PASS
4	2.219586E-06	PASS
5	1.999033E-05	PASS
6	2.692790E-05	PASS

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-03

DIRECTION	STRAIN ENERGY	PASS/FAIL
1	1.452013E-05	PASS
2	3.543712E-05	PASS
3	1.390970E-04	PASS
4	2.219586E-06	PASS
5	1.999033E-05	PASS
6	2.692790E-05	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	1.452013E-05	PASS
2	3.543712E-05	PASS
3	1.390970E-04	PASS
4	2.219586E-06	PASS
5	1.999033E-05	PASS
6	2.692790E-05	PASS

Table 5-16: FEM Strain Energy check

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6. DIMENSIONING LOADS

The dimensioning loads are based on the results of the CLA performed by LMSO (and provided by the mail "RICH to USS-02 Interface Forces and Displacements 2-042.xls"), using the FEM Model of the entire AMS-02. The Dimensioning Loads used (series 1000, 2000 and 4000) are composed by both inertial loads and enforced displacement of the constraints. In the following table the set of the load cases used for the analysis is presented: in the first table the entire set is showed with the inertial loads applied; in the second table the enforced displacements of load case 4001 are presented

Load Case	Nx (g)	Ny (g)	Nz (g)	Rx (rad/sec^2)	Ry (rad/sec^2)	Rz (rad/sec^2)
1001-1064	+3.7	+1.4	+1.4	+4.5	+8.4	+3.9
	-0.4	-1.6	-1.5	-4.1	-11.0	-4.1
2001-2064	+1.2	+0.7	+2.1	+5.2	+10.7	+6.0
	-1.3	-0.6	-5.6	-4.7	-13.9	-4.8
4001-4064	+1.7	+1.1	+2.7	+12.5	+14.7	+12.1
	-2.0	-1.1	-7.4	-11.1	-18.1	-10.0

Table 6-1: Applied set of load cases

Sets 1000 and 2000 are applied in AMS-02 center of gravity in launch configuration.
Set 4000 is applied in AMS-02 Center of gravity in landing configuration (with empty tank)

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LOAD CASE 4001 DISPLACEMENTS						
GRID	Tx [m]	Ty [m]	Tz [m]	Tx [in]	Ty [in]	Tz [in]
985591	0.0035	0.0017	0.0011	1.37E-04	6.54E-05	4.49E-05
985697	0.0035	0.0017	0.0011	1.36E-04	6.61E-05	4.45E-05
156082	0.0034	0.0020	0.0019	1.34E-04	7.87E-05	7.60E-05
155446	0.0034	0.0020	0.0020	1.34E-04	7.91E-05	7.68E-05
156173	0.0036	0.0021	0.0022	1.42E-04	8.31E-05	8.70E-05
156280	0.0037	0.0021	0.0022	1.44E-04	8.39E-05	8.82E-05
998097	0.0050	0.0022	0.0030	1.96E-04	8.58E-05	1.20E-04
997661	0.0050	0.0022	0.0031	1.97E-04	8.50E-05	1.20E-04
998180	0.0052	0.0020	0.0029	2.06E-04	8.03E-05	1.16E-04
998286	0.0052	0.0020	0.0029	2.06E-04	7.99E-05	1.15E-04
1010653	0.0053	0.0017	0.0023	2.07E-04	6.65E-05	9.21E-05
1010054	0.0052	0.0017	0.0023	2.06E-04	6.57E-05	9.02E-05
1010736	0.0050	0.0014	0.0015	1.96E-04	5.67E-05	5.94E-05
1010842	0.0050	0.0014	0.0015	1.95E-04	5.59E-05	5.71E-05
985508	0.0038	0.0014	0.0011	1.50E-04	5.43E-05	4.25E-05
984909	0.0038	0.0014	0.0011	1.49E-04	5.47E-05	4.29E-05

Table 6-2: Load case 4001 displacements

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7. DIMENSIONING RULES

7.1 SAFETY FACTORS

The RICH system has to show positive MoS applying the following SF:

SAFETY FACTORS	Yield	Ultimate
Metallic structures	1.25	2.0
Non metallic structures	NA	2.0
Fasteners (Nominal)	1.25	2.0
Joint separation	1.2	NA
Joints fitting factor	1.15	1.15
Buckling	NA	2.0
Fasteners (Fail safe)	NA	1.0

Table 7-1: Safety Factors for structure

7.2 TEMPERATURE DERATING FACTOR

For all the material the temperature degradation factor is considered, as per RD 1 at 60°C (140°F) (landing temperature) the worst temperature degradation factor for the material is 6% with respect to the material nominal mechanical characteristics. This temperature degradation factor is applied to all the material

7.3 MARGINS OF SAFETY FOR STRUCTURE

The MoS is defined as:

$$MoS_Y = \frac{\sigma_y}{SF_Y \cdot \sigma_{Load}} - 1.0$$ for the yield strength, and

$$MoS_U = \frac{\sigma_u}{SF_U \cdot \sigma_{Load}} - 1.0$$ for the ultimate strength, where:

- σ_Y the yield strength of the material,
- σ_U the ultimate strength of the material,
- SF_Y the safety factor for yield strength,
- SF_U the safety factor for ultimate strength,
- σ_{Load} the maximum Von Mises equivalent stress due to external loads.

The MoS for stresses indicates the amount by which the allowable stress, defined by the material characteristics, exceeds the actual stress due to the applied loads, taking into account the applicable SF, defined in Chapter 7.1.

It is required that MoS are positive for all load cases, for all structural elements
Additional MoS can be defined to evaluate margins for generic results.

$$MoS = \frac{A}{SF \cdot B} - 1.0$$

- A allowable
- B actual value
- SF applicable safety factor

It is required that Margins of Safety are positive for all load cases and operative conditions, for all elements.

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7.4 MARGINS OF SAFETY FOR COMPOSITE (CFRP)

The MoS is defined as:

$$MoS_u = \frac{1}{SF_u \cdot fl} - 1.0$$

fl = failure index

7.5 FAILURE INDEX CALCULATION FOR COMPOSITE (CFRP)

For the reflector, TSAI WU verification for composite materials is used:

TSAI WU Failure Index: $$fi = F_{11}\sigma_1^2 + F_{22}\sigma_2^2 - F_{12}(\sigma_1\sigma_2) + F_{66}\tau_{12}^2 + F_1\sigma_1 + F_2\sigma_2$$

Where:

$$\begin{cases} F_1 = \left(\frac{1}{f_T}\right) - \left(\frac{1}{f_C}\right) \\ F_2 = \left(\frac{1}{f_T}\right) - \left(\frac{1}{f_C}\right) \\ F_{11} = \frac{1}{(f_T \cdot f_C)} \\ F_{22} = \frac{1}{(f_T \cdot f_C)} \\ F_{66} = \frac{1}{f_s^{\,2}} \\ F_{12} = -0.5\sqrt{F_{11} \cdot F_{22}} \end{cases}$$

7.6 HONEYCOMB VERIFICATION

For the honeycomb panels the following verifications are performed:

- Combined load strength
- Intracell buckling
- Wrinkling

These verifications are performed in according to chapter 12 of the RD. 6

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7.7 MARGINS OF SAFETY FOR MAXIBOLT

Defining:

$$Rs := \frac{FF \cdot FSu \cdot Fshear}{fsu} \quad \text{and} \quad Rt := \frac{Ften \cdot FF \cdot FSu}{ftu};$$

$$MoScombU := \left[\frac{1}{\left(Rs^2 + Rt^2\right)^{\frac{1}{2}}} \right] - 1$$

7.8 BOLT VERIFICATION

For the bolt verification the formula are presented in ANNEX 1.

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8. DYNAMIC ANALYSIS

In this section, results in terms of frequencies, mode shapes and effective masses are included.

8.1 EIGENFREQUENCIES AND MODE SHAPES

In the following table the first two modes (that have an associated mass lower that the 1%) and all the ones with associated mass greater than 5% of the constrained RICH system are shown.

MODE	FREQ [Hz]	% EFFECTIVE MASS		
		X Dir	Y Dir	Z Dir
1	33.2	<1%	<1%	<1%
2	42.1	<1%	<1%	<1%
11	76.2	<1%	<1%	13%
12	79.2	<1%	12%	<1%
13	81.1	<1%	16%	<1%
15	83.4	17%	<1%	<1%
22	91.4	<1%	<1%	17%
42	93.2	<1%	<1%	6%
169	159.3	5%	<1%	<1%
171	161.3	<1%	5%	<1%
172	163.5	12%	<1%	<1%
338	277.0	<1%	<1%	10%

Table 8-1: RICH system natural frequencies

In the following figures the shapes of the first two modes (reflector modes) and the ones with effective mass greater than 5% (showed with all structure and without reflector) are presented:

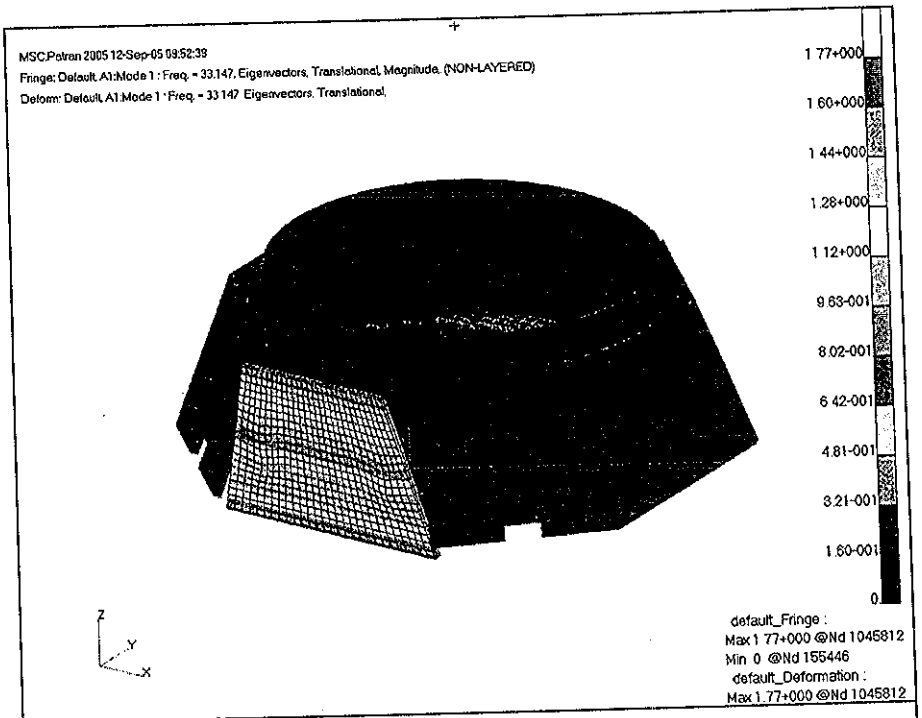

Figure 8-1: mode 1 at 33.15 Hz

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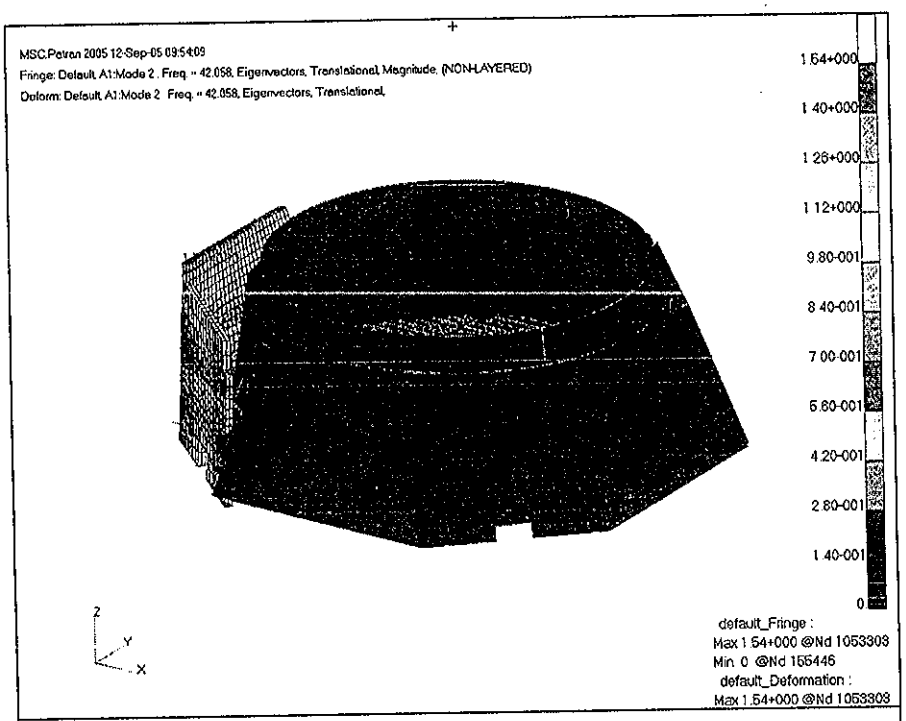

Figure 8-2: mode 2 at 42.06 Hz

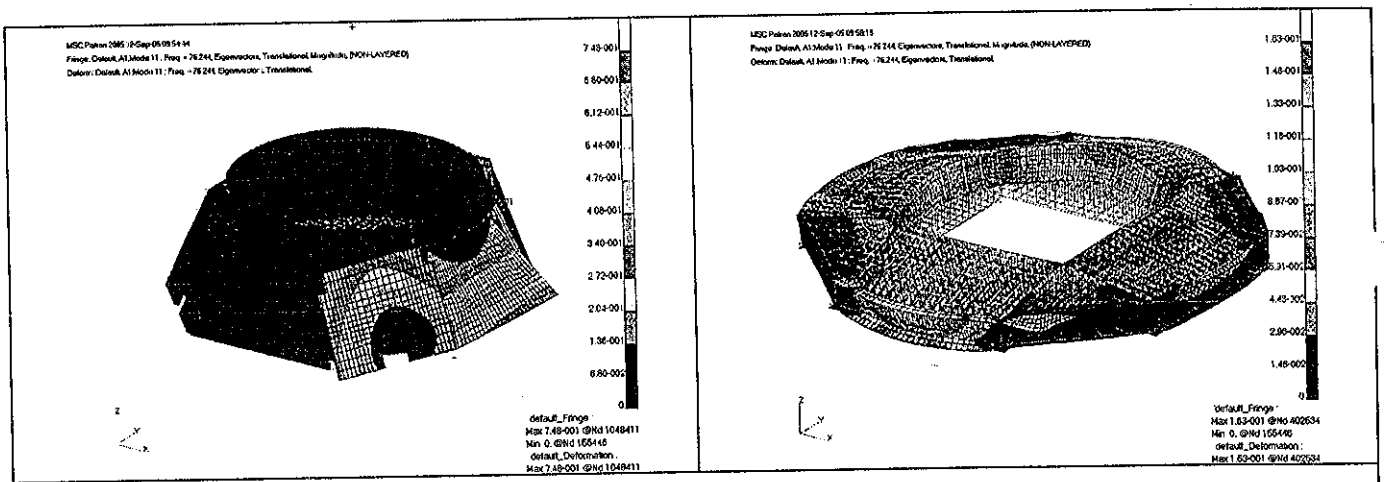

Figure 8-3: mode 11 at 76.24 Hz

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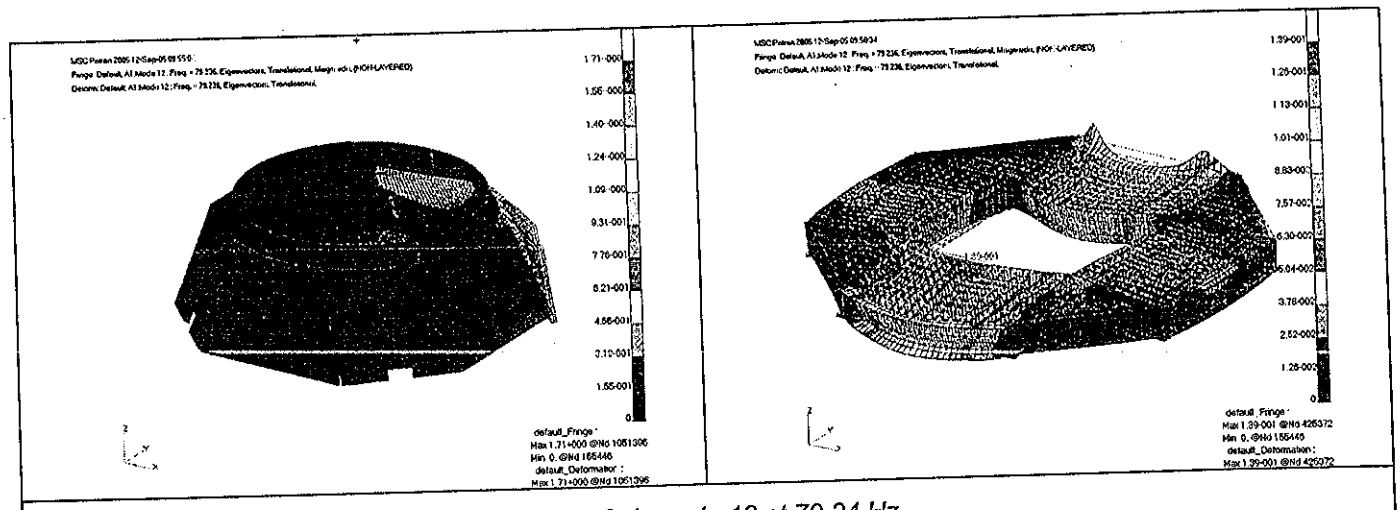

Figure 8-4: mode 12 at 79.24 Hz

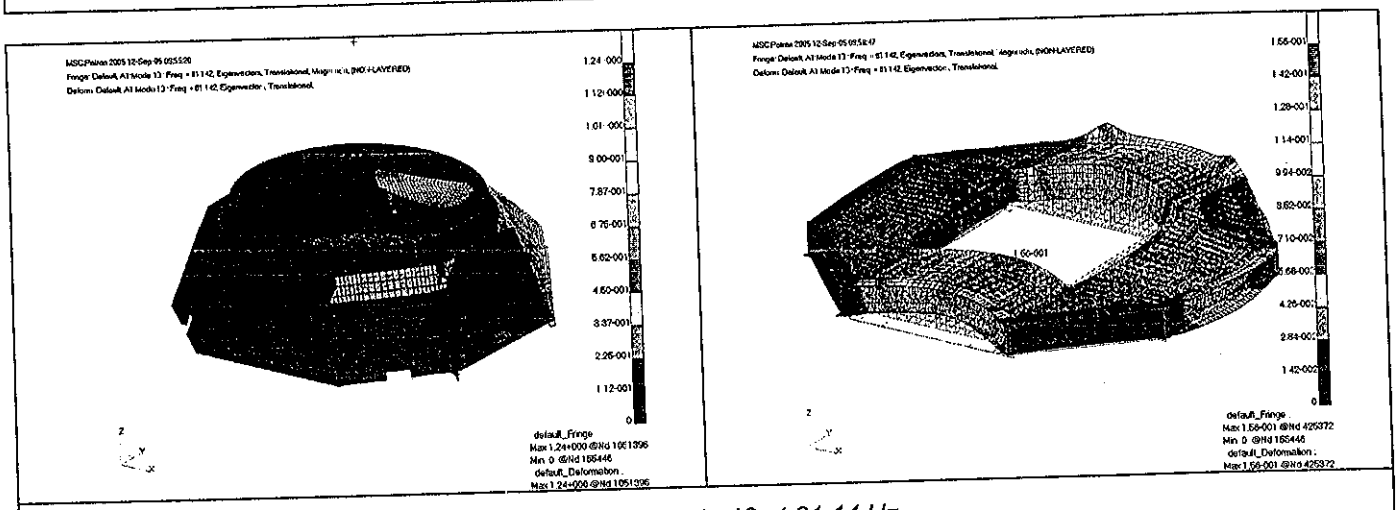

Figure 8-5: mode 13 at 81.14 Hz

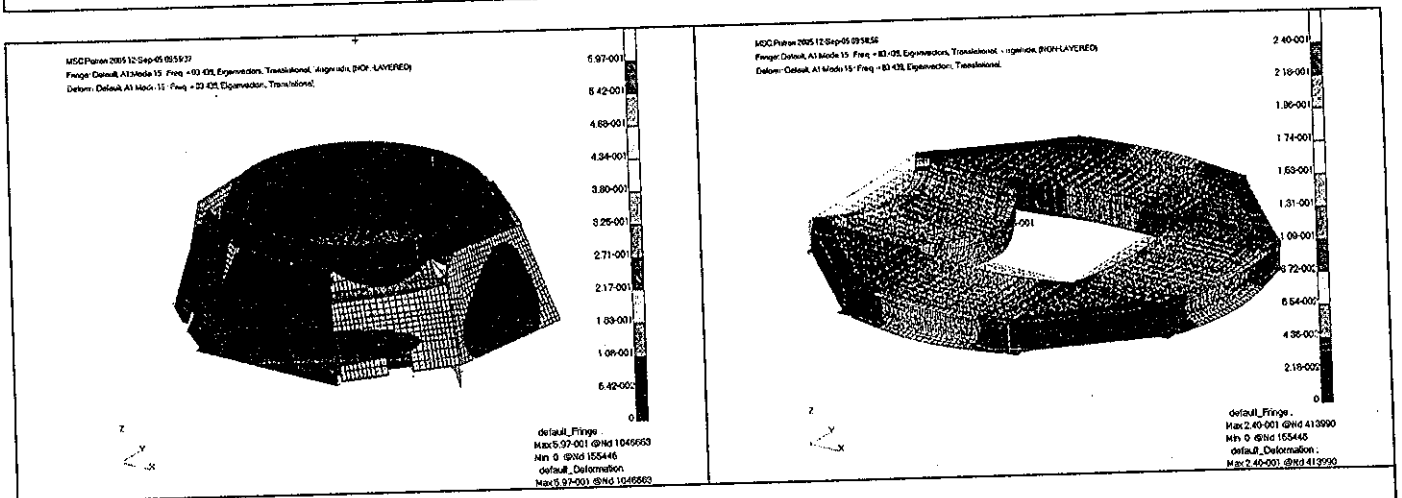

Figure 8-6: mode 15 at 83.15 Hz

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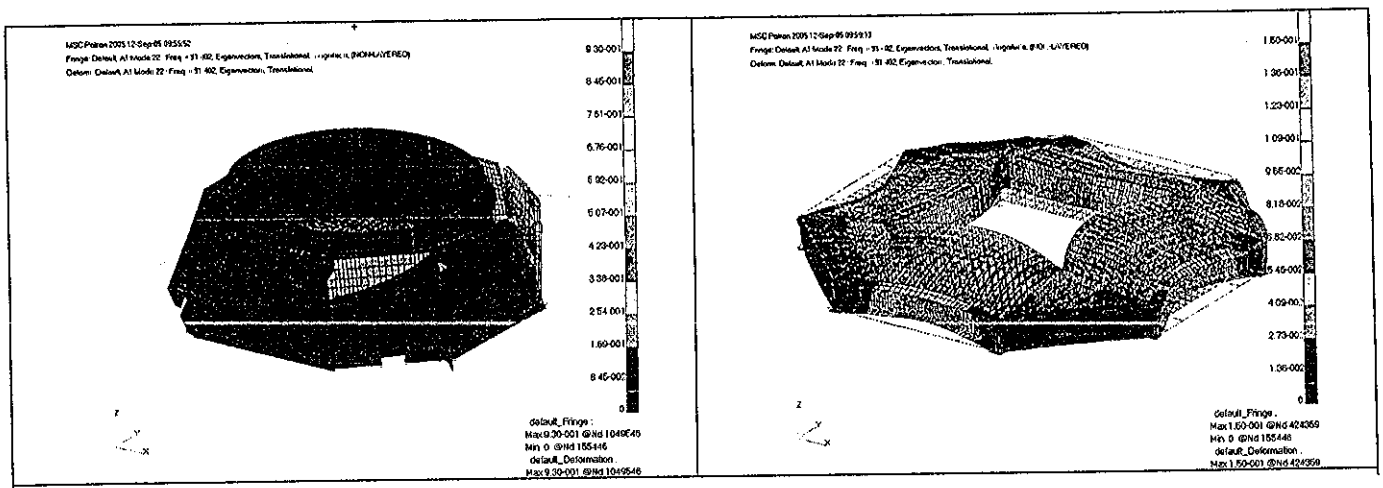

Figure 8-7: mode 22 at 91.40 Hz

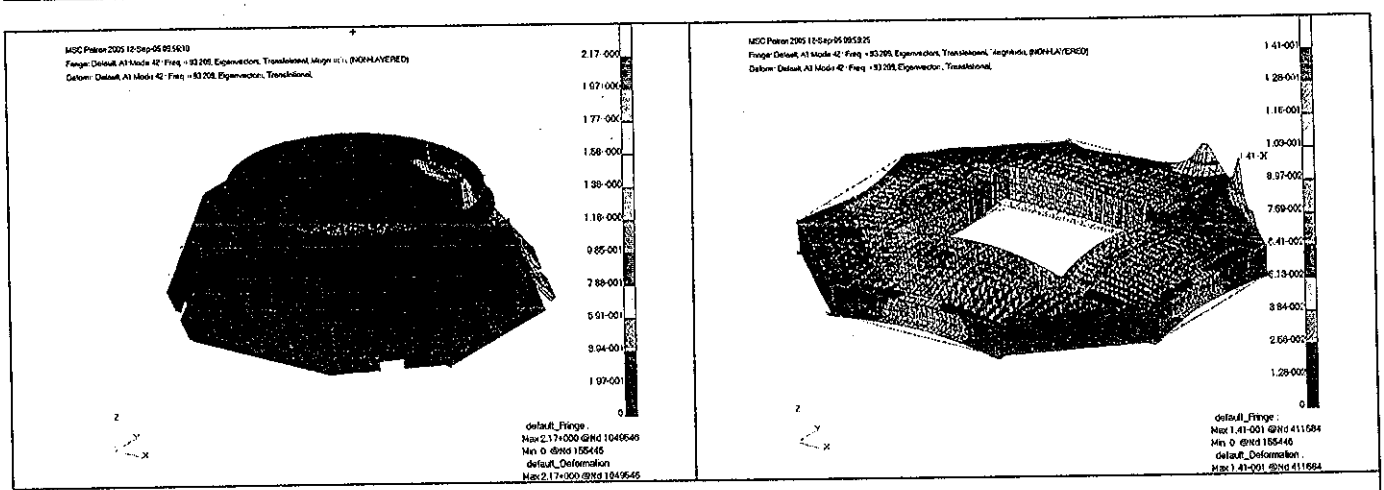

Figure 8-8: mode 42 at 93.21 Hz

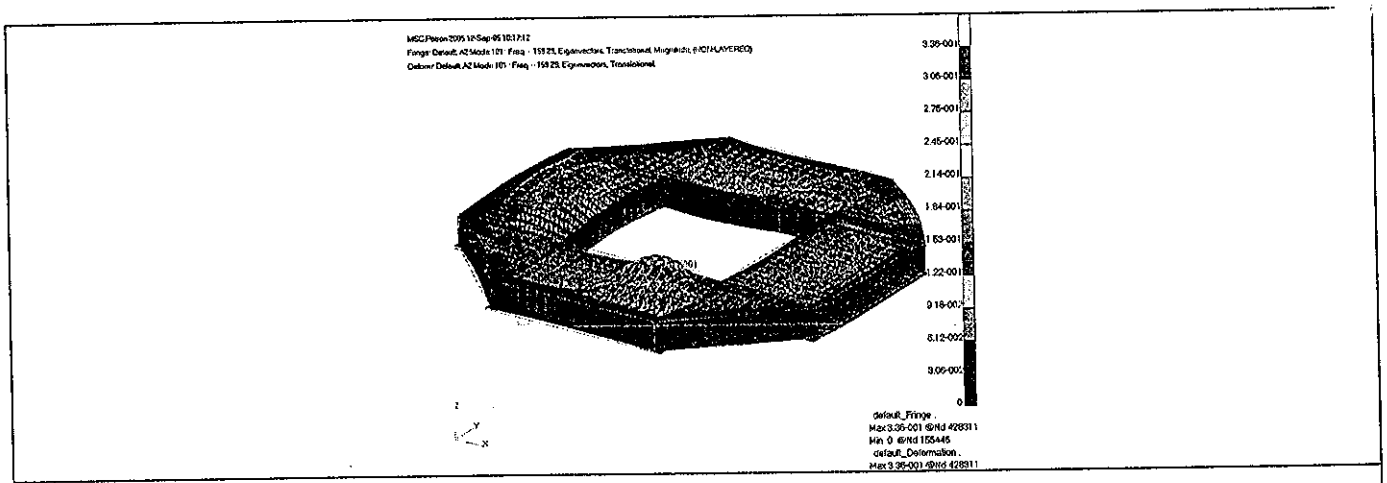

Figure 8-9: mode 169 at 159.29 Hz

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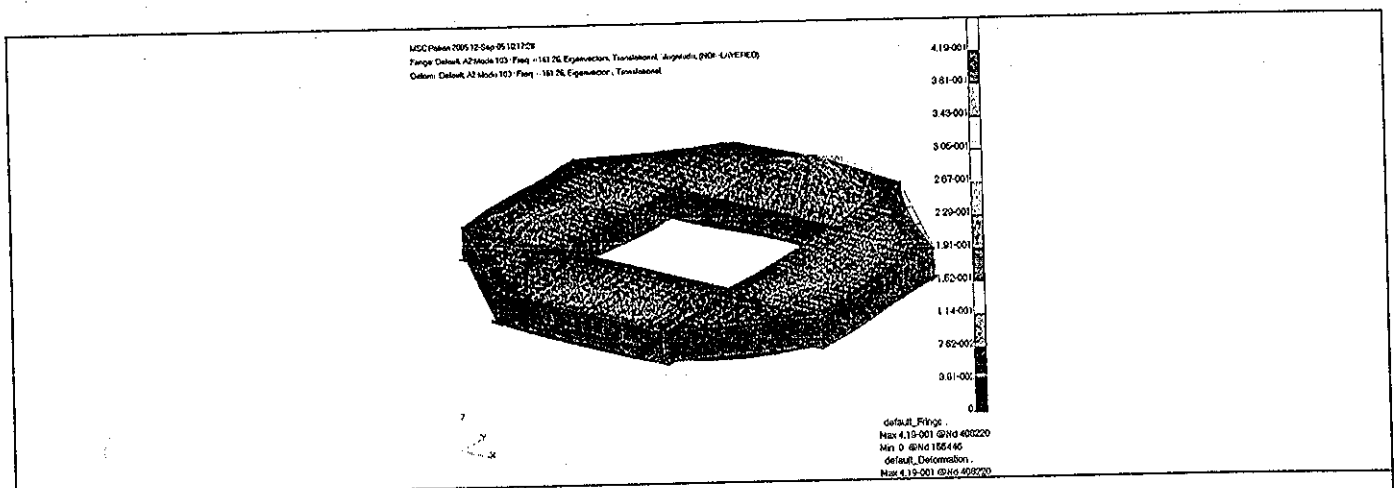

Figure 8-10: mode 171 at 161.26 Hz

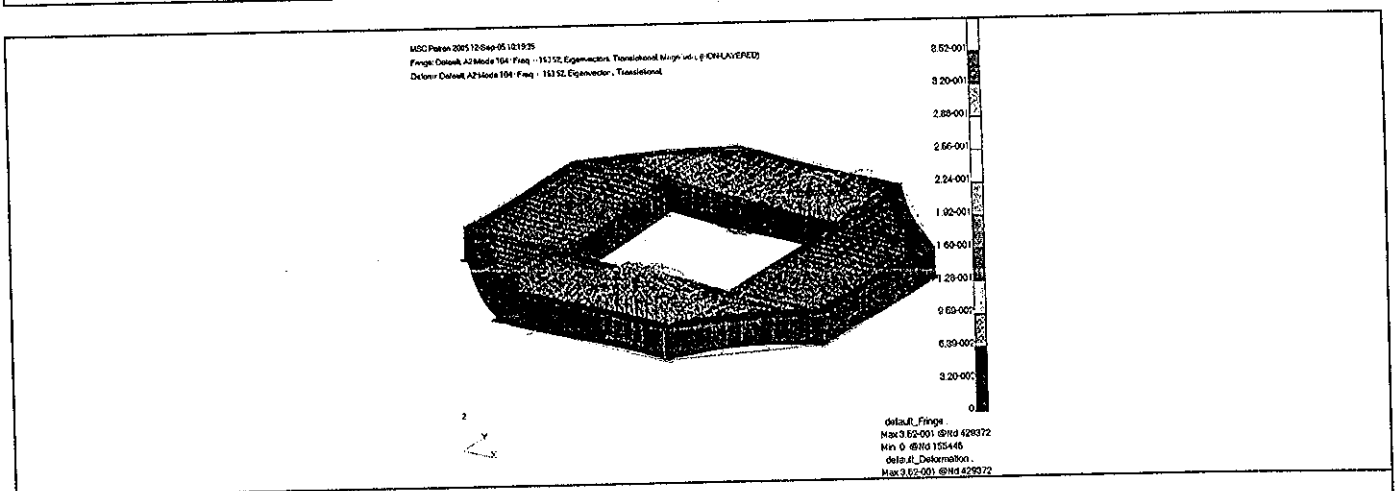

Figure 8-11: mode 172 at 163.5 Hz

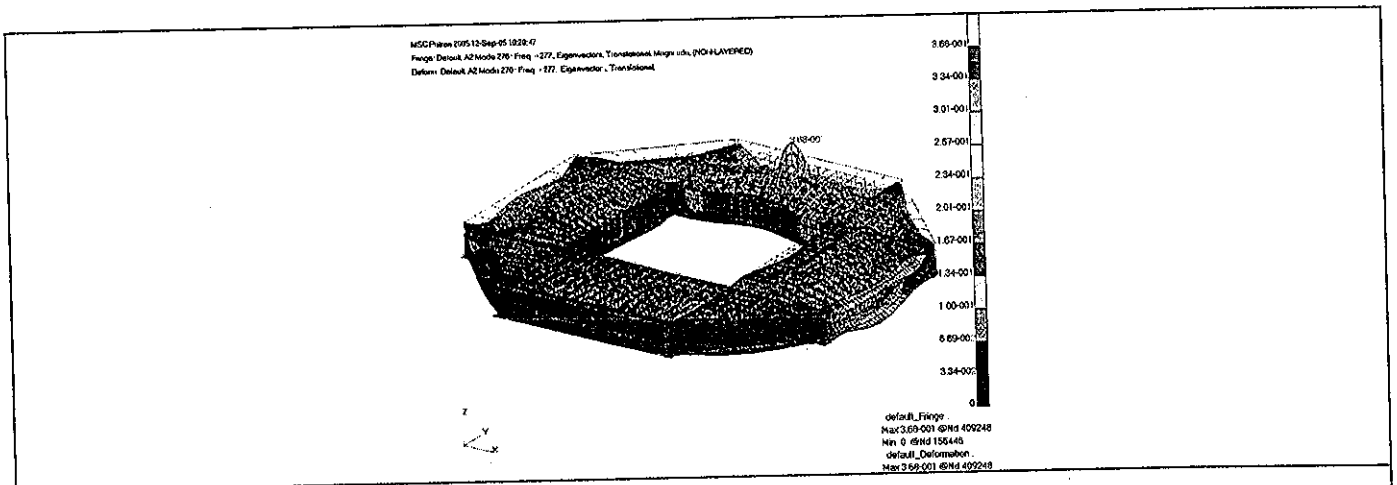

Figure 8-12: mode 368 at 277 Hz

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8.2 EFFECTIVE MASS

Effective masses are reported; in the figures only for the spectrum from 0 to 500Hz are showed:

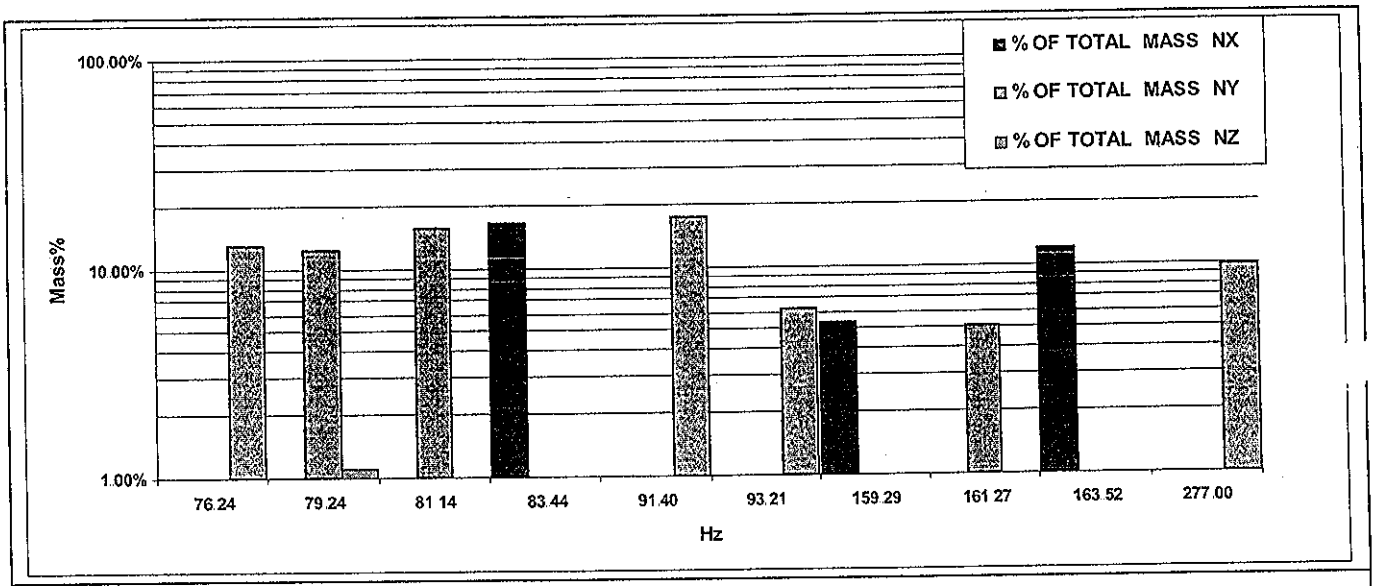

Figure 8-13: Effective masses for all axes

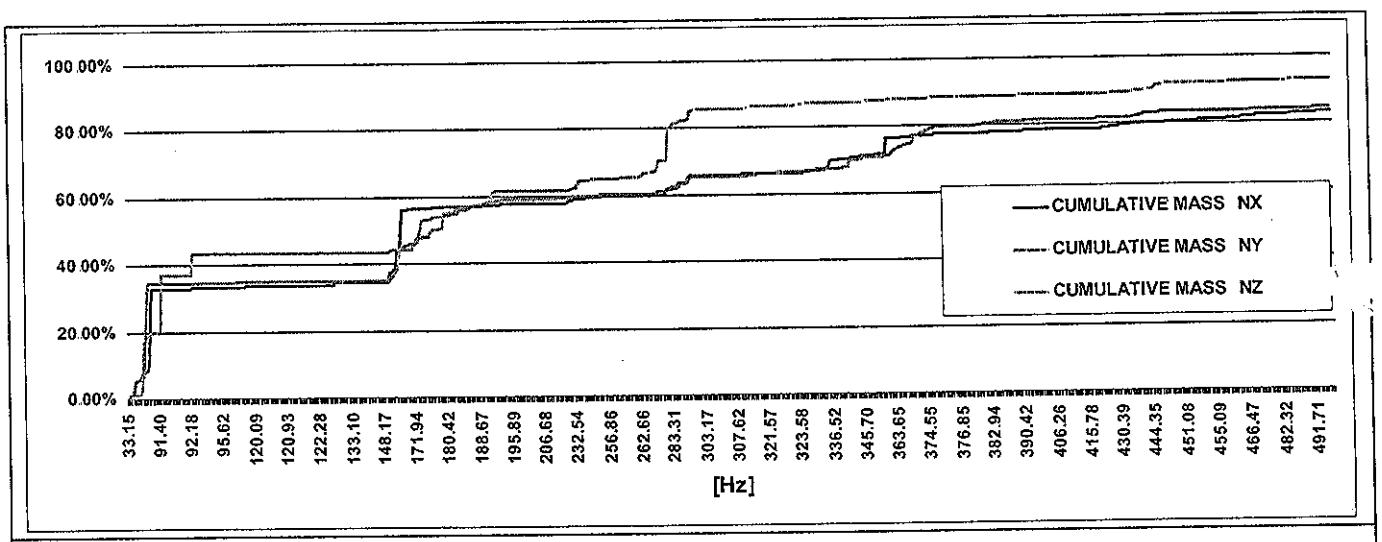

Figure 8-14: Cumulative effective masses for all axes

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9. STATIC ANALYSIS

In the following sections, static analysis results are described for nominal configuration.

Four different types of analyses are performed:

- 9.1 DISPLACEMENT ANALYSIS
- 9.2 STRESS ANALYSIS
- 9.3 JOINT ANALYSIS
- 9.4 BUCKLING ANALYSIS

9.1 DISPLACEMENT ANALYSIS

The worst condition if for **NODE 401129** for **Load Case 1024**. This value include the motion of the USS interface.
The resulting maximum displacement is **1.52E-2 m**.
Following figure shows displacements for this subcase

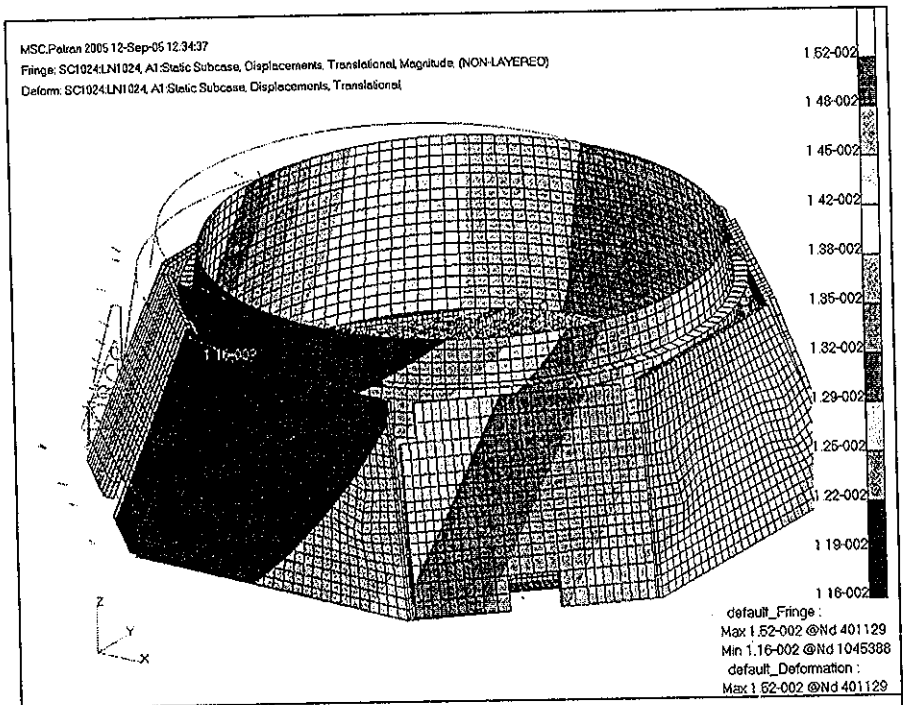

Figure 9-1: Maximum displacement – Load case 1024

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9.2 STRESS ANALYSIS

For each safety critical item the stress contour and MoS calculation is shown in the next pages.
The structure is divided in the following items:

9.2.1 EXTERNAL STRUCTURE VON MISES
9.2.2 INTERNAL STRUCTURE (7075) VON MISES
9.2.3 INTERNAL STRUCTURE (7075) MAXIMUM COMBINED
9.2.4 INTERNAL STRUCTURE (6061) MAXIMUM COMBINED
9.2.5 REFLECTOR
9.2.6 REFLECTOR SUPPORT
9.2.7 DEBRIS SHIELD
9.2.8 DEBRIS STIRRUP

Summary of stress analysis results are shown in 9.2.9 (MARGINS OF SAFETY).

9.2.1 EXTERNAL STRUCTURE VON MISES

The worst condition is for **ELEMENT 428415** for **Load Case 4062** at **Layer Z1**.
The resulting Von Mises stress is: **f_{VM} = 100.9 MPa**.
Following figure shows stress distribution for this subcase.

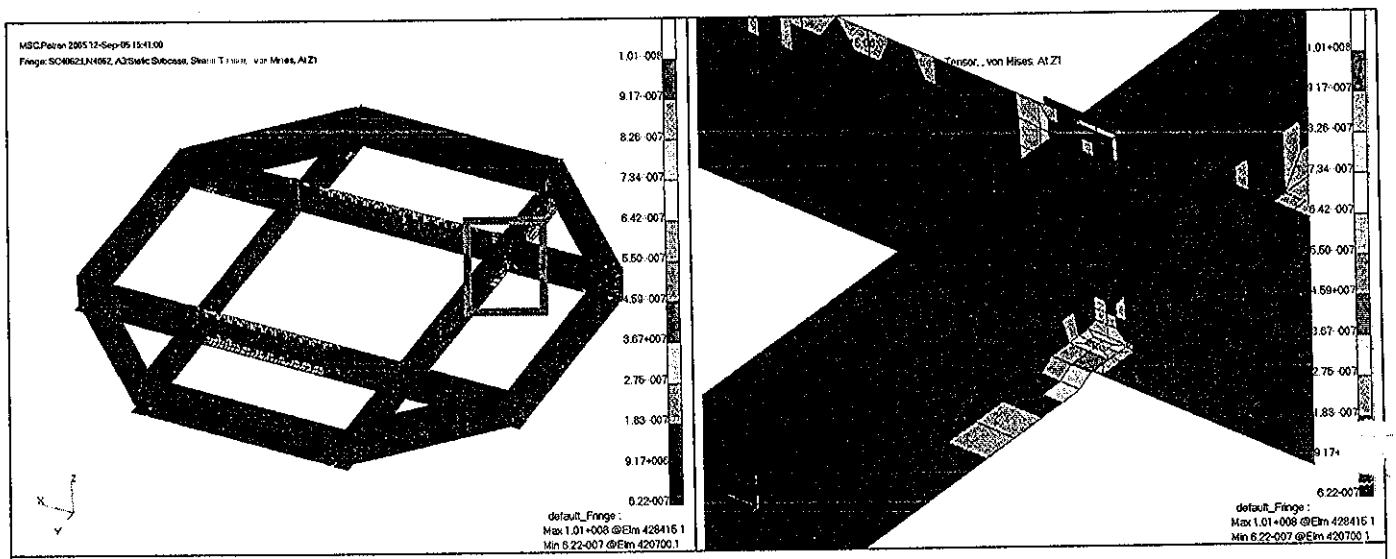

Figure 9-2: External structure, Load Case 4062, Layer Z1

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9.2.2 INTERNAL STRUCTURE (7075) VON MISES

The worst condition is for **ELEMENT 416526** for **Load Case 1024** at **Layer Z1**.
The resulting Von Mises stress is: **f_{VM} = 37.2 MPa**
Following figures show stress distribution for this subcase.

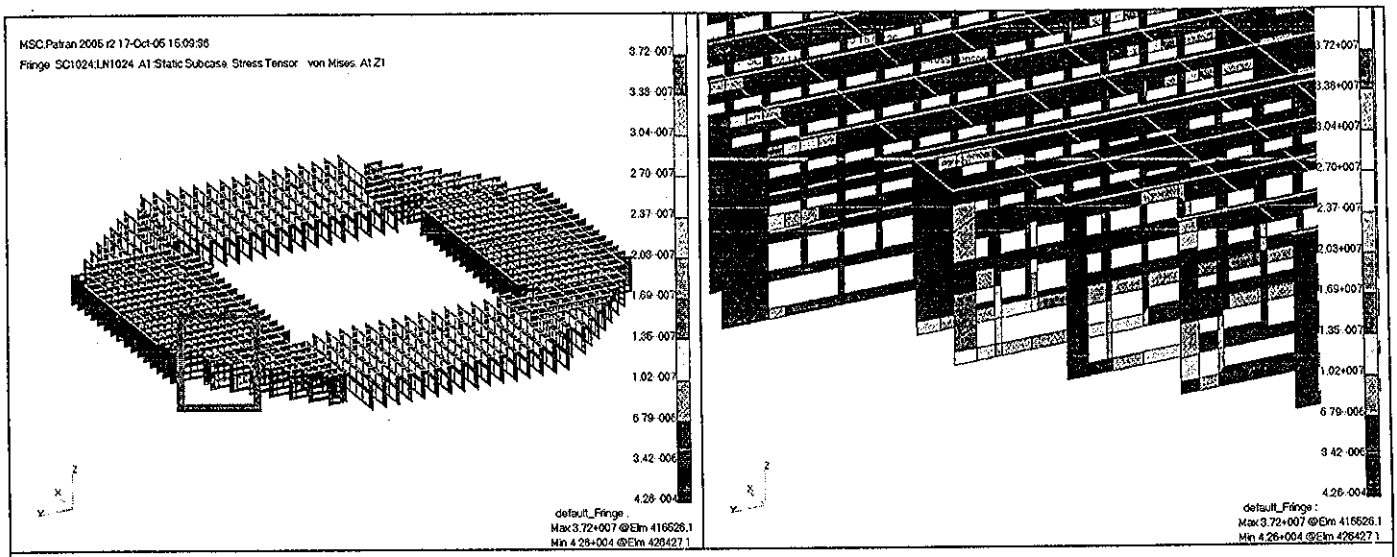

Figure 9-3: Internal structure7075), Load Case 1024, Layer Z1

9.2.3 INTERNAL STRUCTURE (7075) MAXIMUM COMBINED

The worst condition is for **ELEMENT 436191** for **Load Case 4061**.
The resulting stress is: **f = 78.7 MPa**.
Following figure shows stress distribution for this subcase.

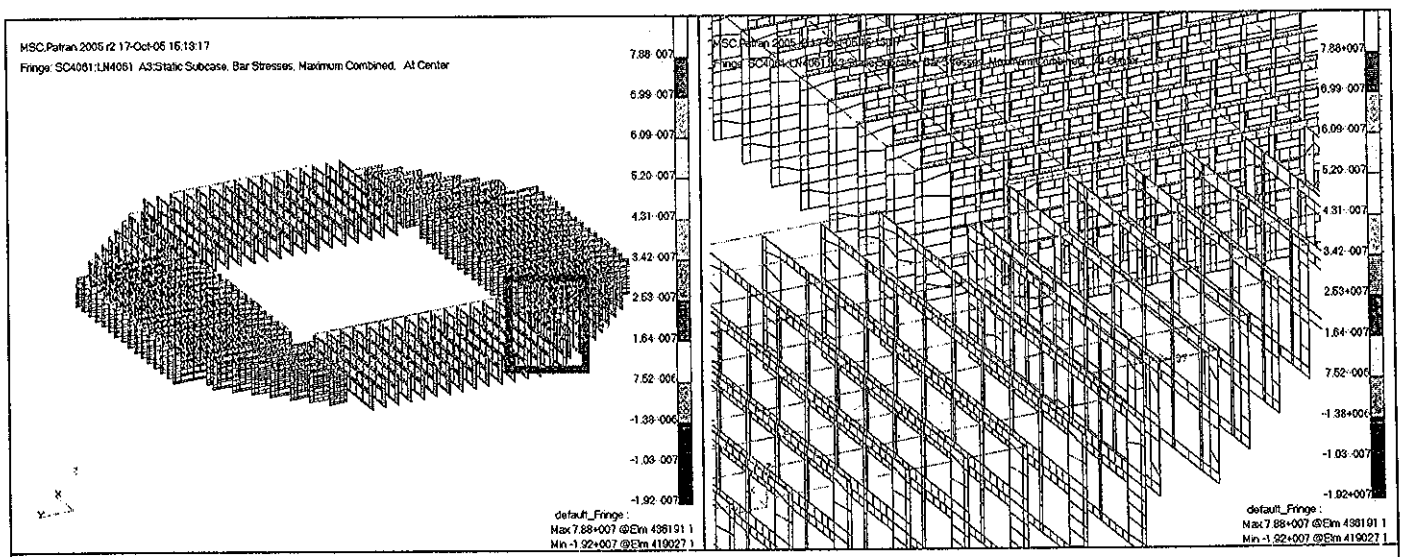

Figure 9-4: Internal structure (7075), Load Case 4061

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9.2.4 INTERNAL STRUCTURE (6061) MAXIMUM COMBINED

The worst condition is for **ELEMENT 418847** for **Load Case 1024**.
The resulting stress is: **f = 93.1 MPa**.
Following figure shows stress distribution for this subcase

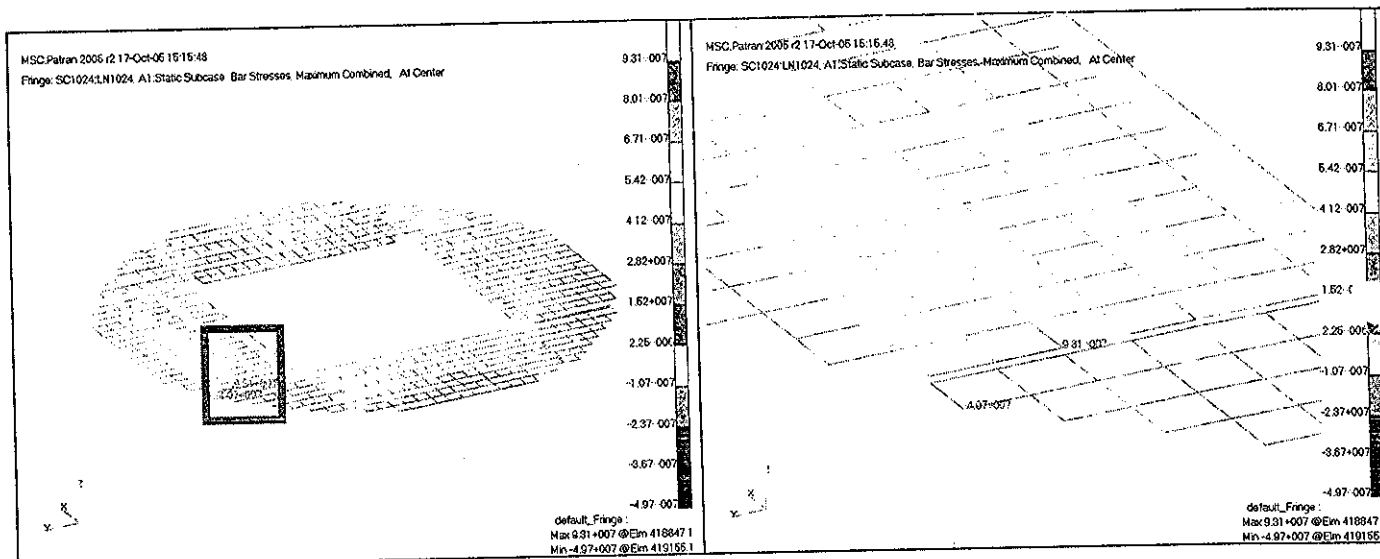

Figure 9-5: Internal structure (6061), Load Case 1024

9.2.5 REFLECTOR

The worst condition is for **ELEMENT 410940** for **Load Case 1024**.
The resulting stress is: **fi = 0.074**.
Following figure shows failure index distribution for this subcase.

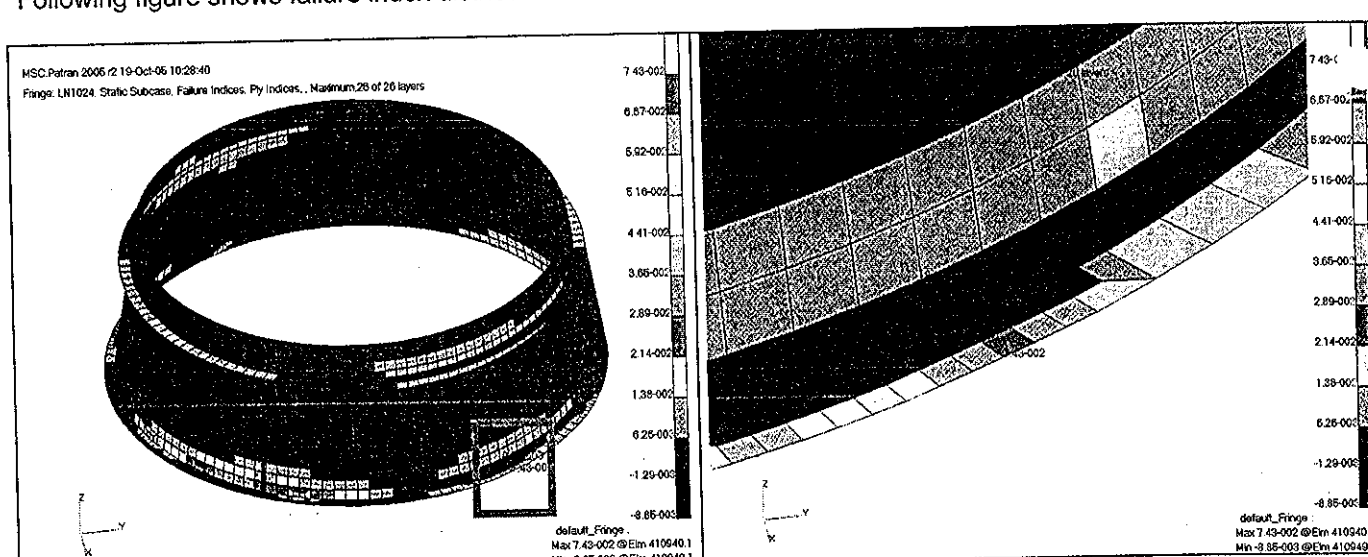

Figure 9-6: MIRROR CFRP PLY Load Case 1024

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9.2.6 REFLECTOR SUPPORT

The worst condition is for **ELEMENT 437263** for **Load Case 4046** at **Layer Z1**.
The resulting stress is: f_{VM} = **77.8 MPa**.
Following figure shows stress distribution for this subcase.

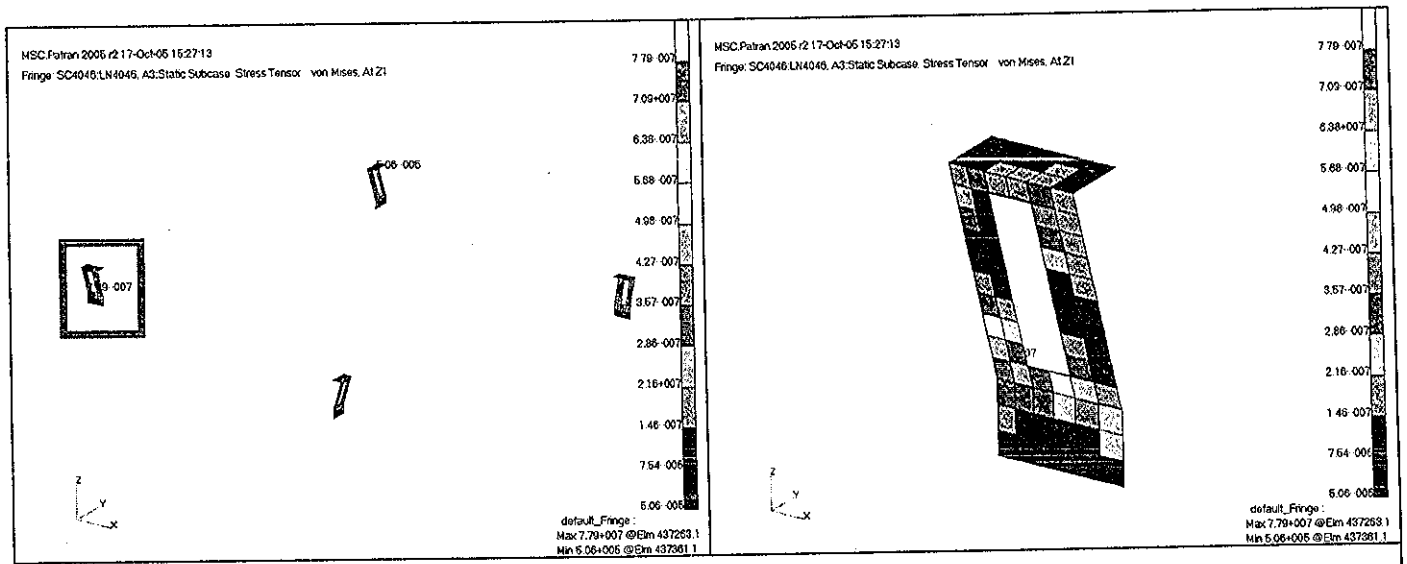

Figure 9-7: Reflector support, Load Case 4046, Layer Z1

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9.2.7 DEBRIS SHIELD

9.2.7.1 CFRP

The worst condition is for **ELEMENT 466207** for **Load Case 1007**.
The resulting stress is: **fi = 0.0034**
Following figure shows failure index distribution for this subcase

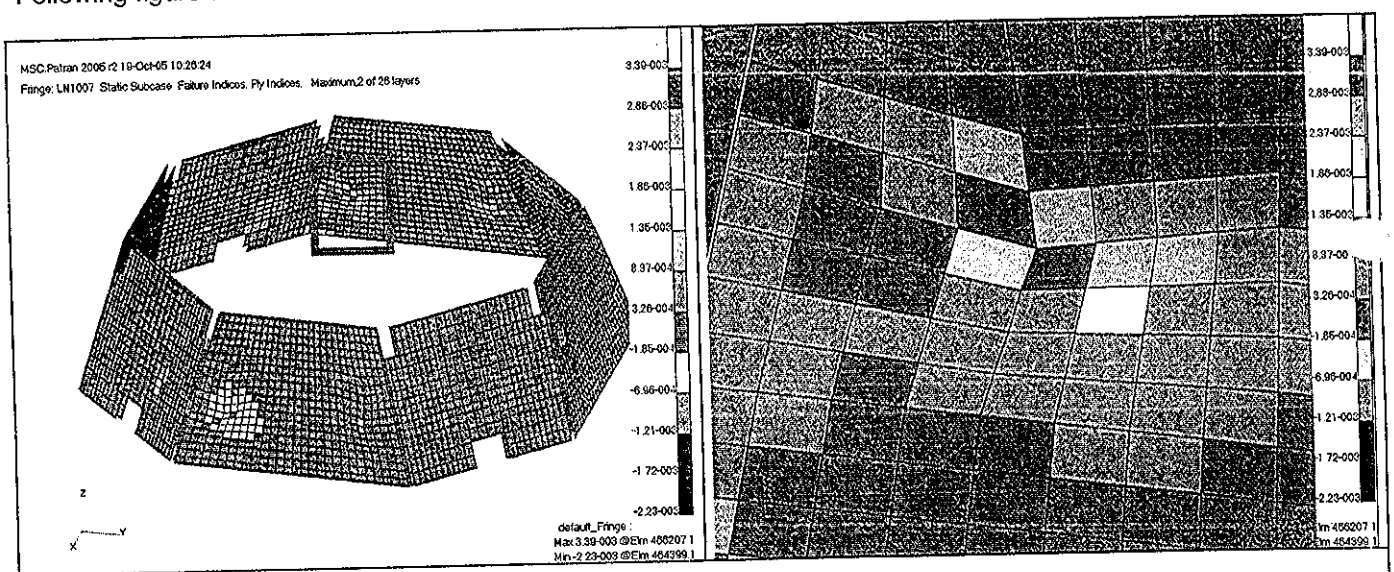

Figure 9-8: DEBRIS SHIELD CFRP PLY Load Case 1007

9.2.7.2 HONEYCOMB

The worst condition is for **ELEMENT 472400** for **Load Case 1032**.
Following figure shows stress distribution for this subcase.

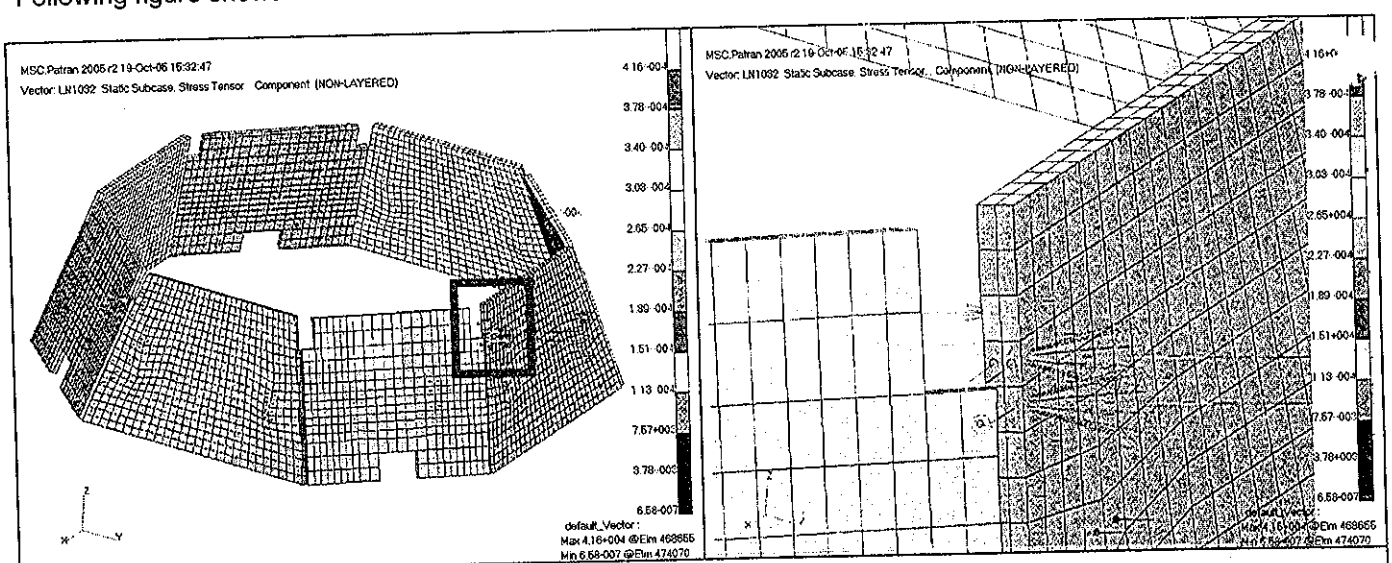

Figure 9-9: HONEYCOMB Load Case 1032

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9.2.8 DEBRIS STIRRUP

The worst condition is for **ELEMENT 454355** for **Load Case 4031** at **Layer Z2**.
The resulting stress is: f_{VM} = **35.78 MPa**.
Following figure shows stress distribution for this subcase.

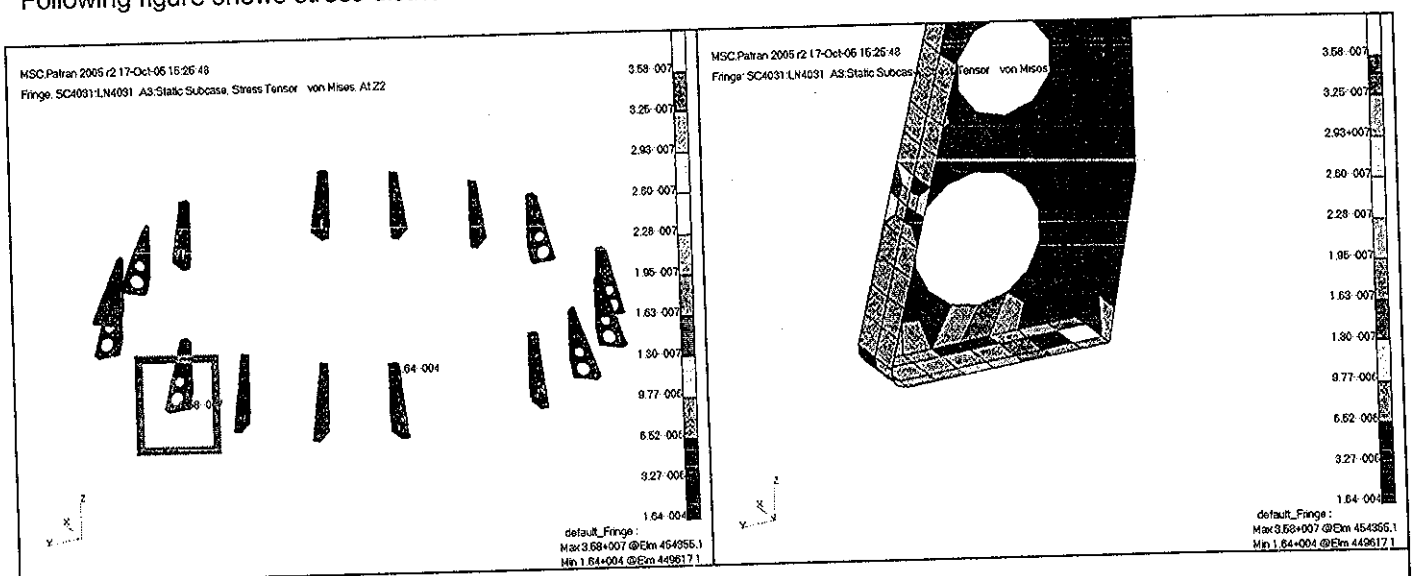

Figure 9-10: Reflector support, Load Case 4062, Layer Z2

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9.2.9 MARGINS OF SAFETY SUMMARY

In the following tables MoS of the entire structure are showed:

MARGINS OF SAFETY FOR STRENGHT FAILURE (STRESS)

ITEM	DRAWING NUMBERS	LC	EID	MATERIAL	F_{ty} [MPa] (*)	F_{tu} [MPa] (*)	Limit stress [MPa]	$S.F._y$	$S.F._u$	MoS_y	MoS_u	REMARKS	REFERENCE PAGE
Primary Beam	13-RICSYS-00.001	4062 At Z2	428473	Al 7075 T7351	369	441	91	1.25	2	>2	1.42	Von Mises	48
Secondary Beam 1	13-RICSYS-00.002	4062 At Z1	429041	Al 7075 T7351	369	441	56	1.25	2	>2	>2		
Secondary Beam 2	13-RICSYS-00.003	1024 At Z1	411062	Al 7075 T7351	369	441	53	1.25	2	>2	>2		
Secondary Internal	13-RICSYS-00.004	4062 At Z1	428415	Al 7075 T7351	369	441	101	1.25	2	1.92	1.18		
Linear External X	13-RICSYS-00.005	4058 At Z1	429481	Al 7075 T7351	369	441	57	1.25	2	>2	>2		
Linear External Y	13-RICSYS-00.006	4033 At Z2	411836	Al 7075 T7351	369	441	47	1.25	2	>2	>2		
Angular External	13-RICSYS-00.007	4045 At Z2	417274	Al 7075 T7351	369	441	41	1.25	2	>2	>2		
INTERNAL STRUCTURE (7075)	12-RICSYS-10.001 12-RICSYS-10.002 12-RICSYS-10.003 12-RICSYS-10.004 12-RICSYS-10.005 12-RICSYS-10.006 12-RICSYS-10.007 12-RICSYS-10.008 12-RICSYS-10.009 12-RICSYS-20.001 12-RICSYS-30.001 12-RICSYS-30.002 12-RICSYS-30.003	1024 (At Z1)	416526	Al 7075 T7351	369	441	37.2	1.25	2	>2	>2	Von Mises	49
INTERNAL STRUCTURE (7075)		4061	436191	Al 7075 T7351	369	441	78.7	1.25	2	>2	1.8	Maximum Combined	49
INTERNAL STRUCTURE (6061)	12-RICSYS-20.002 12-RICSYS-30.004	1024	418847	Al 6061 T6	227	272	93.1	1.25	2	0.95	0.46	Maximum Combined	50
REFLECTOR SUPPORT	12-RICSYS-40.001	4046 At Z1	437263	Al 6061 T6	227	272	77.8	1.25	2	1.33	0.74	Von Mises	51
DEBRIS STIRRUP	12-RICSYS-00.004008	4031 At Z2	454355	Al 7075 T7351	369	441	35.78	1.25	2	>2	>2	Von Mises	53

Table 9-1: MoS for stress analysis for the structure

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MARGINS OF SAFETY FOR CFRP FAILURE

ITEM	DRAWING NUMBERS	LC	EID	MATERIAL	F_{tu} [MPa]	F_{cu} [MPa]	F_{su} [MPa]	FAILURE INDEX	$S.F._u$	MoS	REMARKS	REFERENCE PAGE
REFLECTOR	13-RICSYS-00.008	4045	410950	CFRP	503	241	200	0.049	2	>2		50
DEBRISSHIELD		4061	457105	CFRP	850	700	105	0.002	2	>2		52

Table 9-2: MoS for CFRP analysis

MARGINS OF SAFETY FOR HONEYCOMB

INTRACELL BUCKLING (Biaxial and Shear Loading)

ITEM	Ef [MPa]	Fcy [MPa]	tf [m]	s [m]	Sf	LC	EID	APPLIED STRESS FACE SHEET			VERIFICATION	MoS	REFERENCE PAGE
								fx [Mpa]	fy [Mpa]	fs [Mpa]			
HCOMB	70000	400	0.0007	0.005	2	1023	464405	7.1	-0.8	1.5	0.03	30.1	52

WRINKLING (Biaxial and Shear Loading)

ITEM	Ef [MPa]	G'c [MPa]	E'c [MPa]	Fcy [MPa]	Sf	LC	EID	APPLIED STRESS FACE SHEET			VERIFICATION	MoS	REFERENCE PAGE
								fx [Mpa]	fy [Mpa]	fs [Mpa]			
HCOMB	70000	89	310	400	2	1023	464399	9.1	3.6	-4.6	0.05	20.7	52

COMBINED LOAD STRENGTH

ITEM	SIZE	ALLOWABLE STRESS CORE			APPLIED STRESS CORE			SF	SHEAR [MPa]		AXIAL [MPa]	VERIFICATION		MoS	REFENCE PAGE
		SHEAR [MPa]		AXIAL [MPa]	SHEAR [MPa]		AXIAL [MPa]								
		F'SL	F'SW	F'C	F'sL	F'sW	F'c		RsL	RsW	Ra	$RsL+Ra^2<1$	$RsW+Ra^2<1$	(1/VER)-1	
HCOMB	3/16 5056 .007 2.0	2.30	1.50	1.44	LC 1032	ELM 472400		2	0.0048	-0.0008	-0.0550	0.008	0.002	126.2	52
					0.0056	-0.0006	-0.0396								

Table 9-3: MoS for Honeycomb analysis

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9.3 JOINT ANALYSIS

The analysis of the joints shall be divided in eight different kinds of connections:

JOINT #	Description	Material	BOLT TYPE				Torque[1]	Pg
			Name	Diam.	Pitch	Length [mm]		
JOINT 1	External Structure	A 286 160KSi	NAS 1351N4	0.25 in	28 1/In	19.05	10.2Nm[2]	59
JOINT 2	External-Internal Structure	A4-70	M3	3 mm	0.5mm	8	0 65Nm[2]	61
JOINT 3	External	A 286 160KSi	NAS 1351N5	0.3125 in	24 1/In	38.1	20.4Nm[2]	63
JOINT 4	External Structure Hi-Lock	A286-95KSi	CR7620 dash 06	5 mm	NA	NA	NA	65
JOINT 5	External Structure-Reflector BKT	A 286 160KSi	NAS 1003	0.19 in	32 1/In	15.39	4.2Nm[2]	67
JOINT 6	Reflector BKT-Reflector	A 286 160KSi	NAS 1351N3	0.19 in	32 1/In	12.7	4.2Nm[2]	69
JOINT 7	External Structure-Debris Shield BKT	A 286 160KSi	NAS 1351N3	0.19 in	32 1/In	12.7	4.2Nm[2]	71
JOINT 8	Debris Shield BKT- Debris Shield	A 286 160KSi	NAS 1351N3	0.19 in	32 1/In	38.1	4.2Nm[2]	73

[1] *The installation torque is obtained by the sum of the torque necessary for the self locking device (running torque) and the Torque defined here*
[2] *The defined torque is obtained by the analysis as per Table 9-8*

Table 9-4: Joints definition

Summary of joint analysis results are shown in 9.3.10 (MOS SUMMARY FOR JOINT ANALYSIS).
The value of Fsy is evaluated according to RD. 1, par. 1.4.6.5.
For each joint, bolt separation has been verified using the maximum axial force acting on the bolts.
Other MoS have been calculated using the worst load case for the most loaded bolt (where most loaded means that the forces acting on the selected bolts results in lower MoS, with respect to other bolts).
Used formulas are shown in Annex 1.
Also a Fail Safe analysis of bolts have been made; Summary of joint analysis results for Fail Safe configuration are shown in paragraph 9.3.11.

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The MoS definition for bolts analysis is reported in the next table.

MOS	DESCRIPTION
MS 1	Joint separation
MS 2	Direct Tension Ultimate
MS 3	Direct Tension Yield
MS 4	Total Tension Ultimate
MS 5	Total Tension Yield
MS 6	Direct Thread shear Ultimate
MS 7	Total Thread shear Ultimate
MS 8	Shear Ultimate
MS 9	Bending Ultimate
MS 10	Combined shear, tension and bending ultimate

Table 9-5: MoS definition for bolt analysis

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9.3.1 JOINT GEOMETRY INPUT

In the following table the inputs for the joint verification are presented:

JOINT #	Type of bolted connections	Threaded length [mm]	Washer		Flange 1		Flange 2		Friction Coeff (1)	Fitting factor
			Thk [mm]	Outer Diam [mm]	Thk [mm]	Material	Thk [mm]	Material		
JOINT 1	NUT	19.05	1.6	11.88	3	Al 7075	3	Al 7075	0.2	1.15
JOINT 2	INSERT	4.5	0.5	6	1.5	Al 7075	4.5	Al 7075	0.2	1.15
JOINT 3	NUT	28.6	1.6	15.06	8	Al 7075	17	Al 7075	0.2	1.15
JOINT 4	MAXI BOLT	NA	NA	NA	NA	NA	NA	NA	NA	1.15
JOINT 5	NUT	15.39	1.6	8	3	Al 7075	2	Al 6061	0.2	1.15
JOINT 6	NUT	12.7	1.6	8	5	CFRP	2	Al 6061	0.2	1.[illegible]
JOINT 7	INSERT	12.7	1.6	9	3	Al 7075	8	Al 7075	0.2	1.15
JOINT 8	INSERT	38.1	1.6	9	2	Al 7075	8	Al 6061	0.2	1.15

Note:
(1) 0 2 for non lubricated joint
0.15 for lubricated joint

Table 9-6: Joint Geometry Input

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9.3.2 JOINT 1: EXTERNAL STRUCTURE

RICH external structure joints are NAS 1351N4 bolts, made of stainless steel A286-160 KSi. In the following figure positions of the bolts are shown:

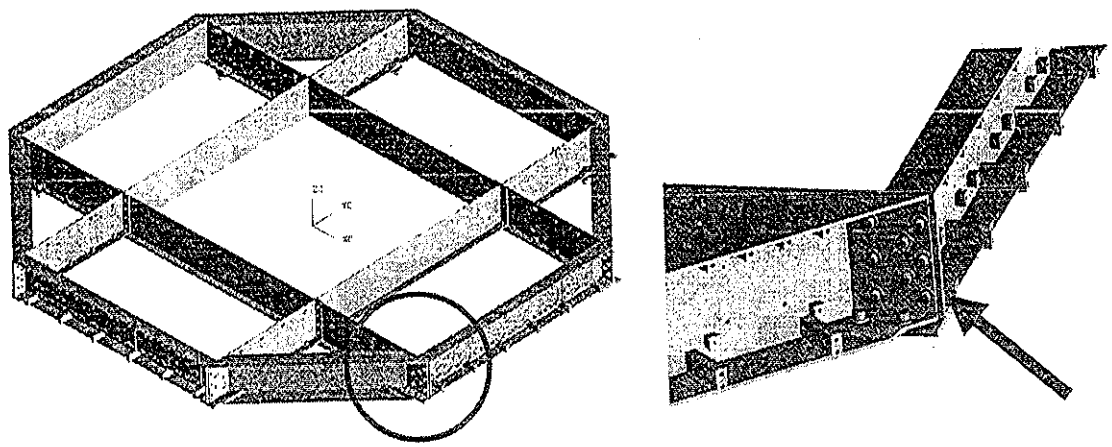

Figure 9-11: JOINT 1: External structure bolts

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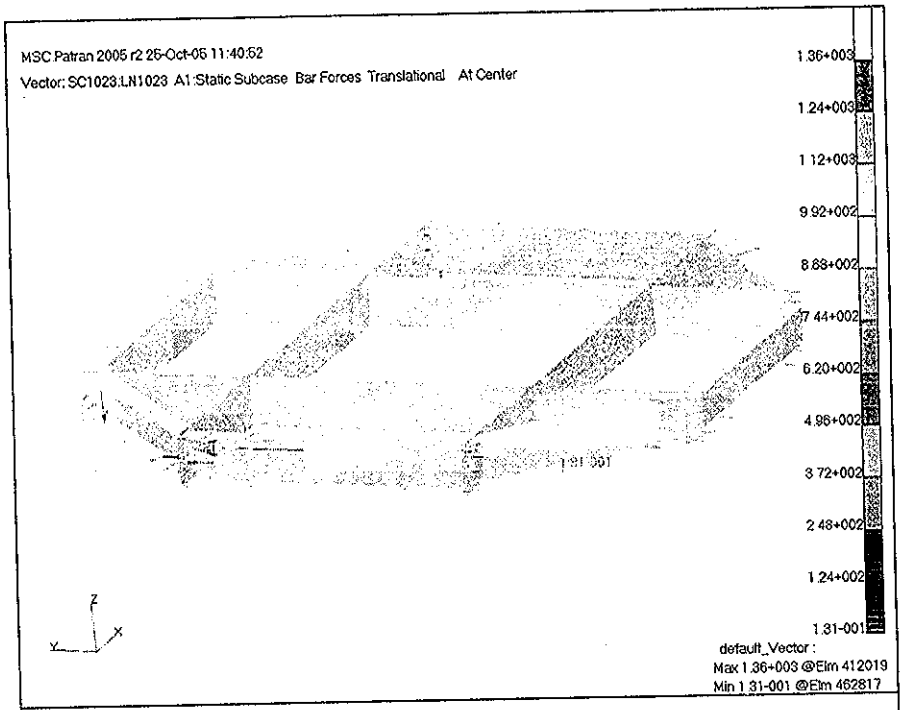

Figure 9-12: JOINT 1: Maximum axial force, load case 1023

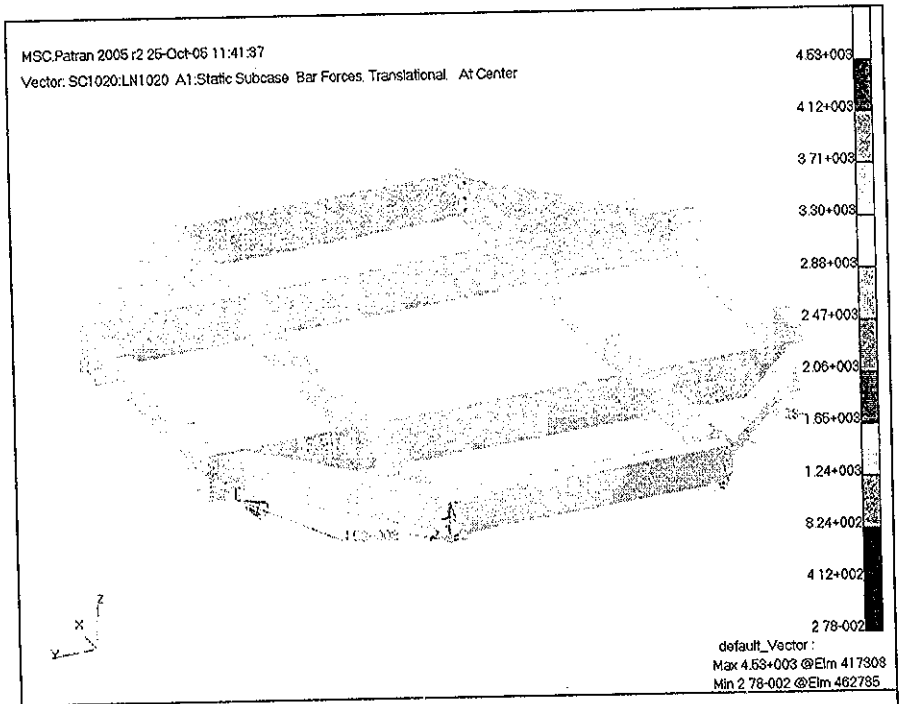

Figure 9-13: JOINT 1: Maximum resultant force, load case 1020

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9.3.3 JOINT 2: EXTERNAL-INTERNAL STRUCTURE

RICH external-internal structure joints are M3 bolts, made of stainless steel INOX A4-70: in the following figure positions of some bolts are shown.

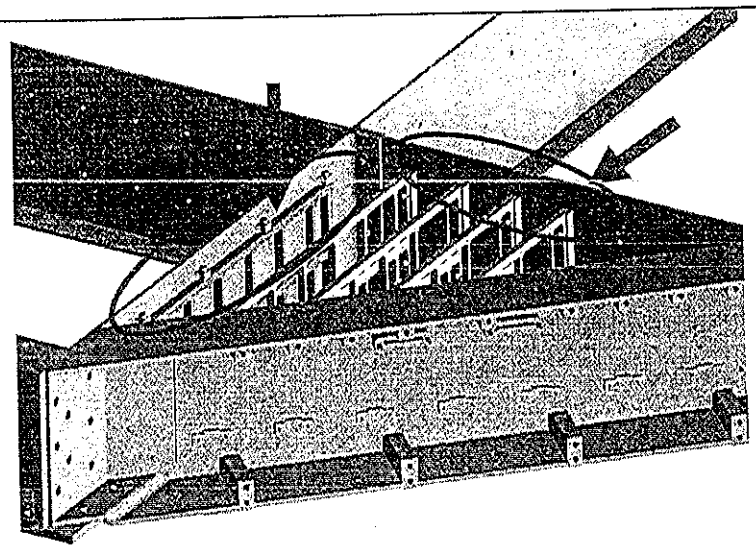

Figure 9-14: JOINT 2: External-internal structure bolts

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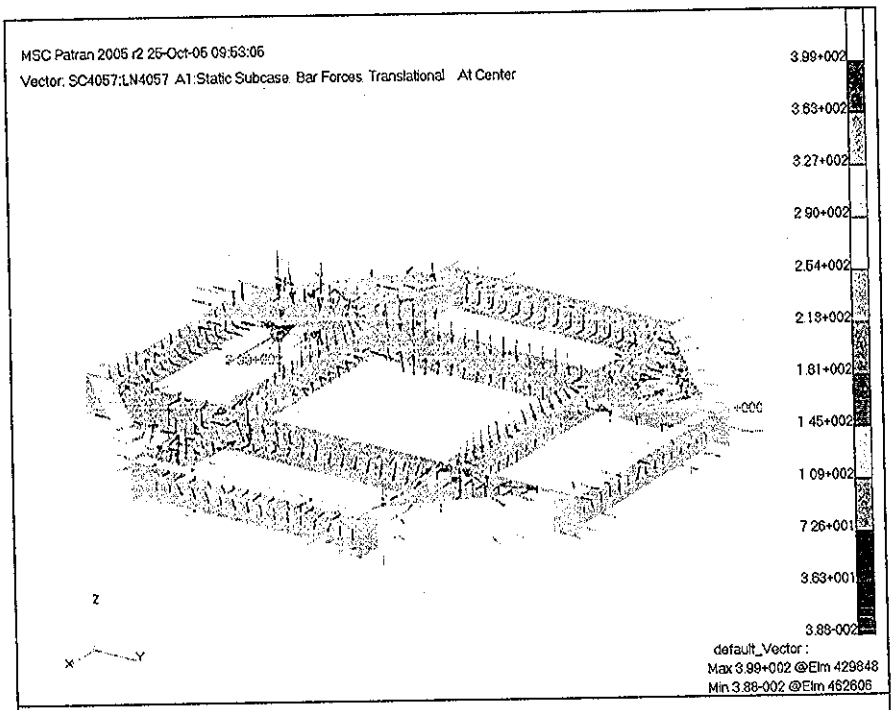

Figure 9-15: JOINT 2: Maximum axial force, load case 4057

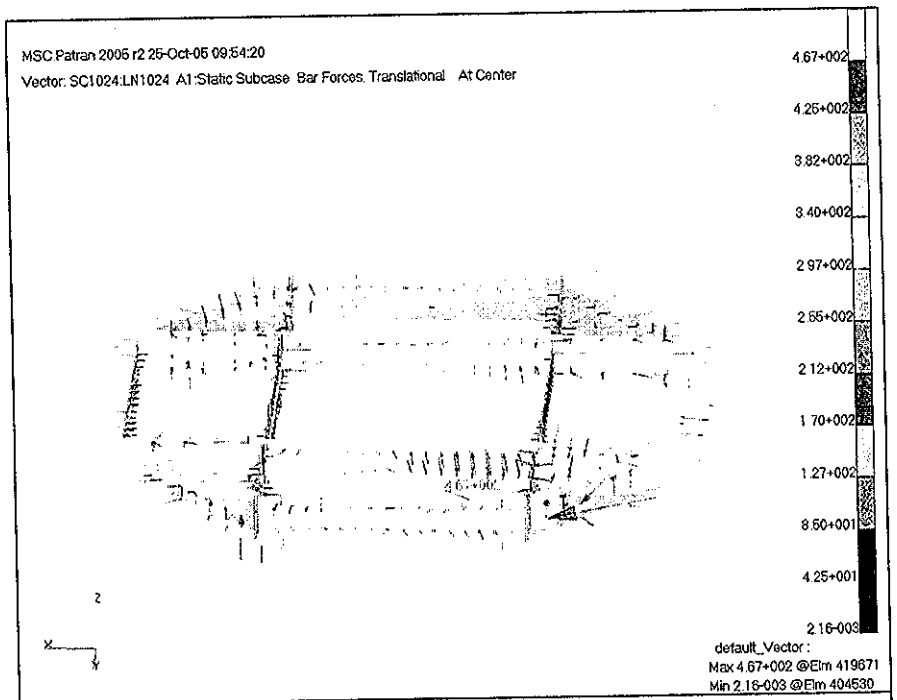

Figure 9-16: JOINT 2: Maximum resultant force, load case 1024

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9.3.4 JOINT 3: EXTERNAL

RICH external joints are NAS 1351N5 bolts, made of stainless steel A286-160 KSi: in the following figure positions of some of the bolts are shown.

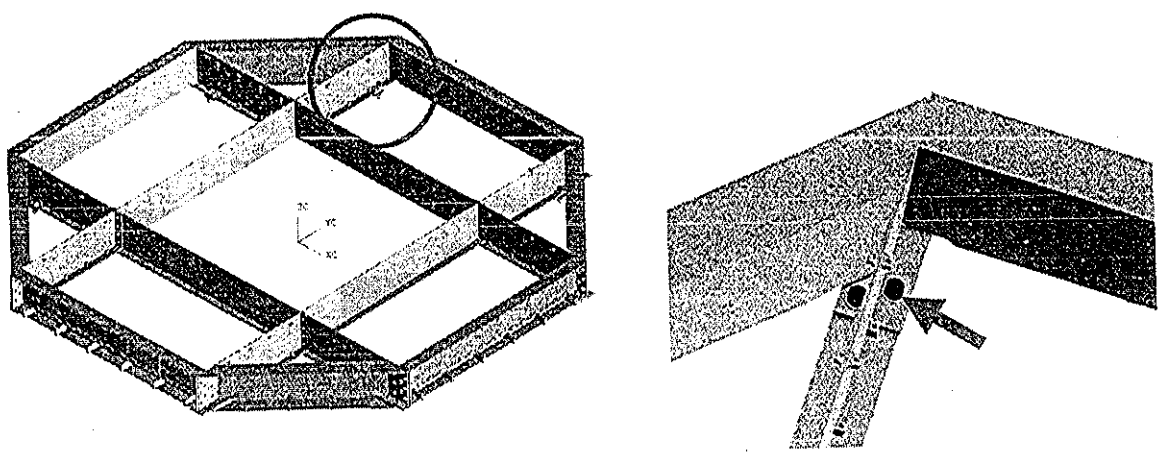

Figure 9-17: JOINT 3: External bolts

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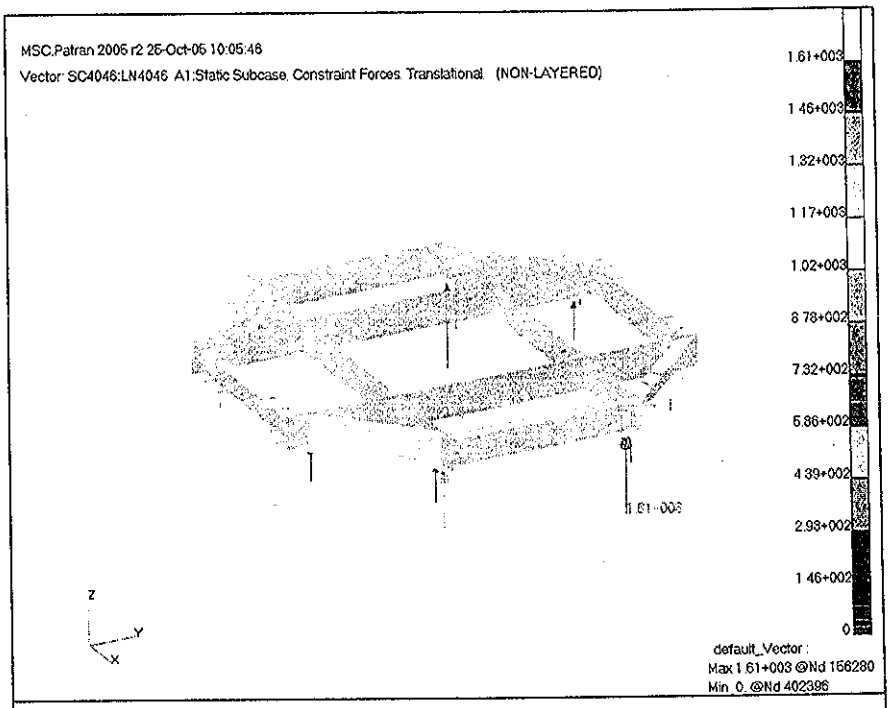

Figure 9-18: JOINT 3: Maximum axial force, load case 4026

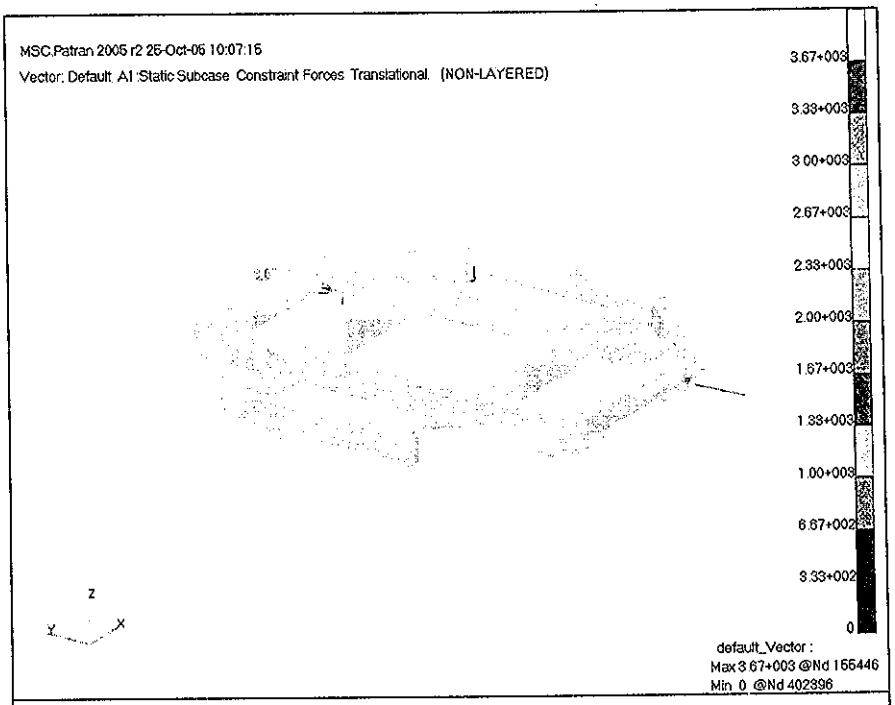

Figure 9-19: JOINT 3: Maximum resultant force, load case 1007

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9.3.5 JOINT 4: EXTERNAL STRUCTURE HI-LOCK

RICH external structure joints are Maxi Bolt CR7620 dash 06, made of stainless steel A286-95 KSi: in the following figure positions of the bolts are shown.

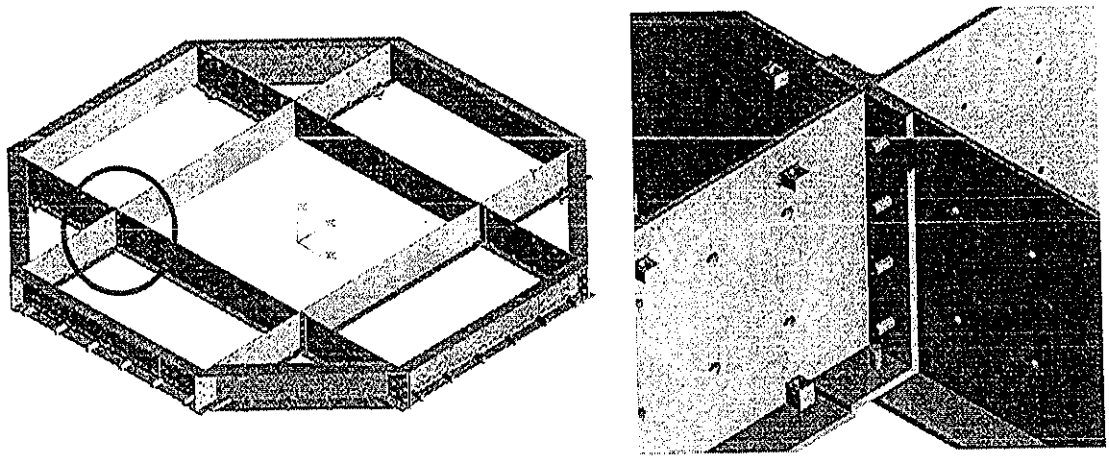

Figure 9-20: JOINT 4: External structure Hi-Lock

Allowable for Maxi Bolt CR7620 dash 06	
Tensile [N]	7500
Single SHEAR [N]	13000
Reference	TEXTRON Aerospace Fasteners

Table 9-7: Allowable for Maxi Bolt CR7620 dash 06

For this analysis the maximum Axial and shear values are used as conservative assumption.

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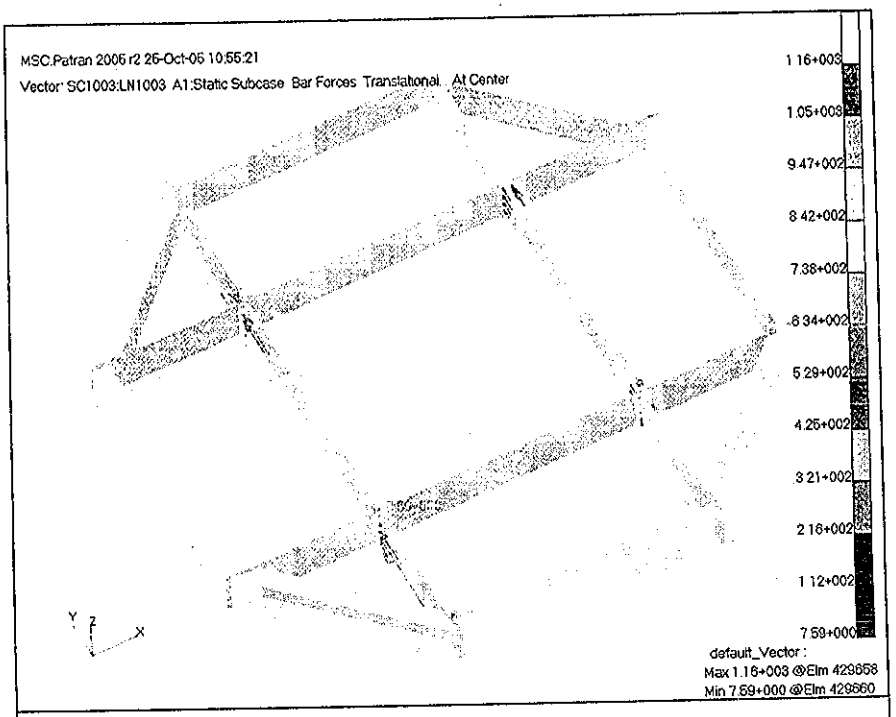

Figure 9-21: JOINT 4: Maximum Axial force

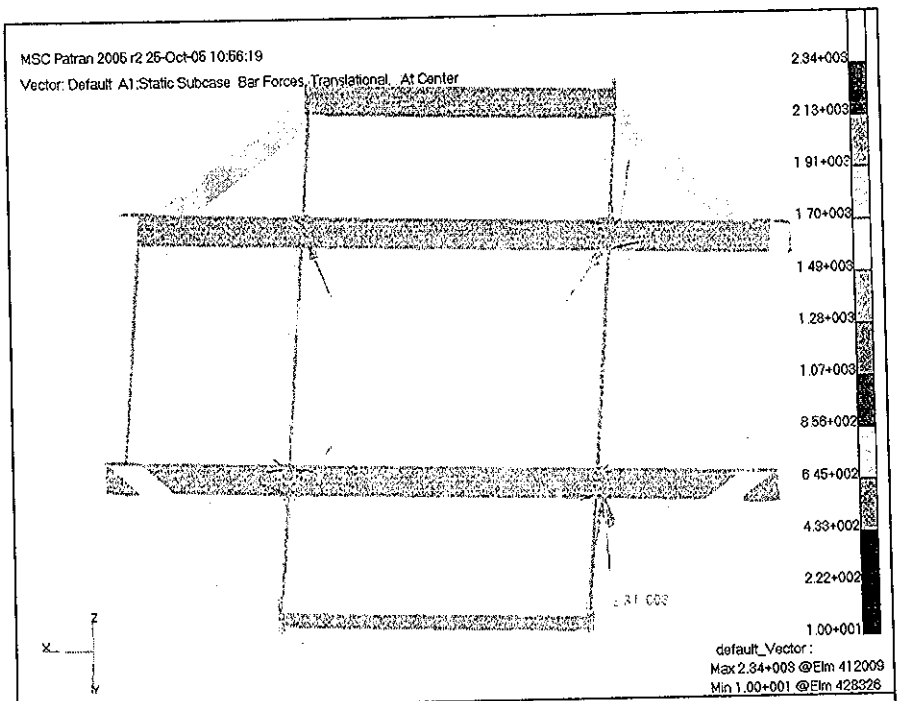

Figure 9-22: JOINT 4: Maximum shear force

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9.3.6 JOINT 5: EXTERNAL STRUCTURE- REFLECTOR BKT

RICH external structure to reflector bracket joints are NAS 1351N3 bolts, made of stainless steel A286-160 KSi: in the following figure positions of some of the bolts are shown.

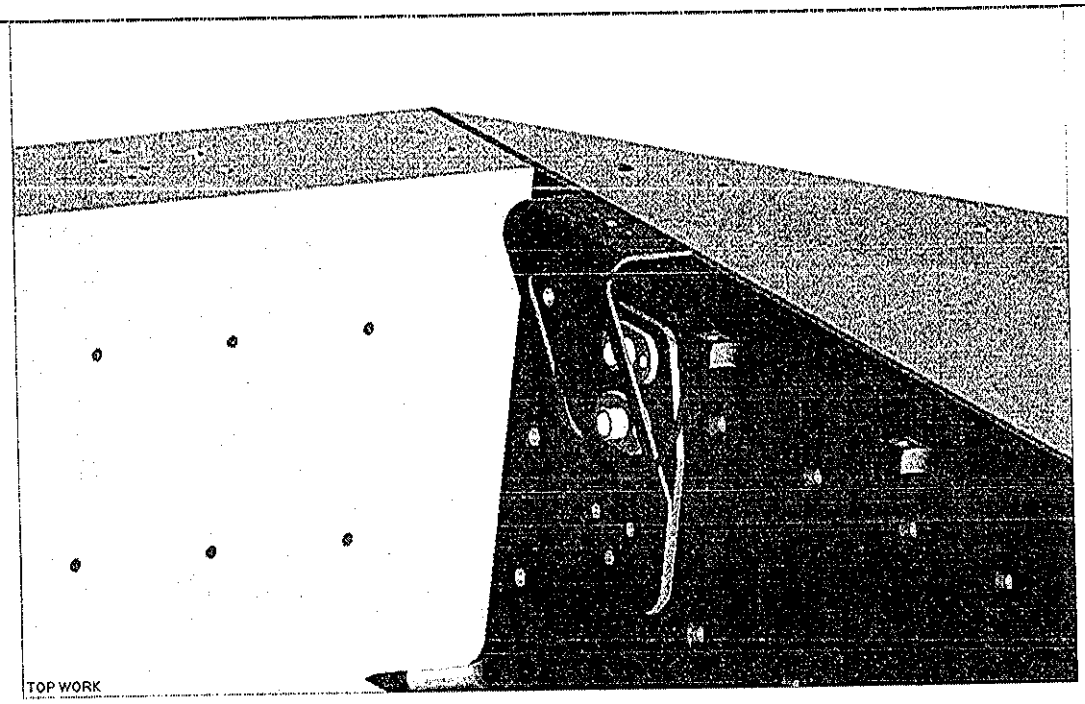

Figure 9-23: JOINT 5: External Structure – Reflector Bracket

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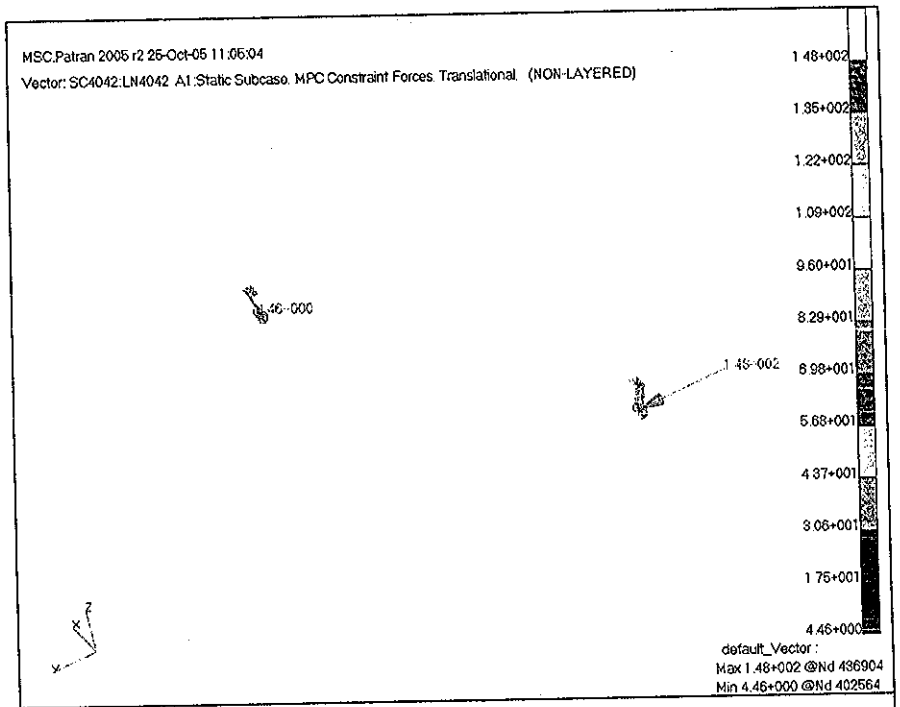

Figure 9-24: JOINT 5: Maximum axial force, load case 4042

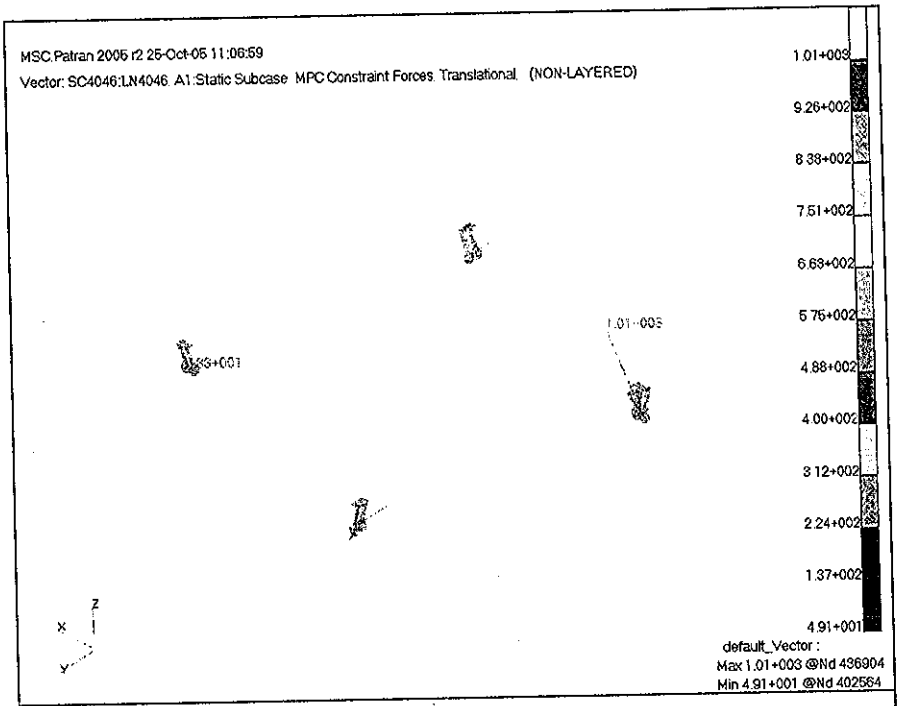

Figure 9-25: JOINT 5: Maximum resultant force, load case 4046

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9.3.7 JOINT 6: REFLECTOR BKT-REFLECTOR

RICH reflector bracket to reflector joints are NAS 1351N3 bolts, made of stainless steel A286-160 KSi: in the following figure positions of some of the bolts are shown

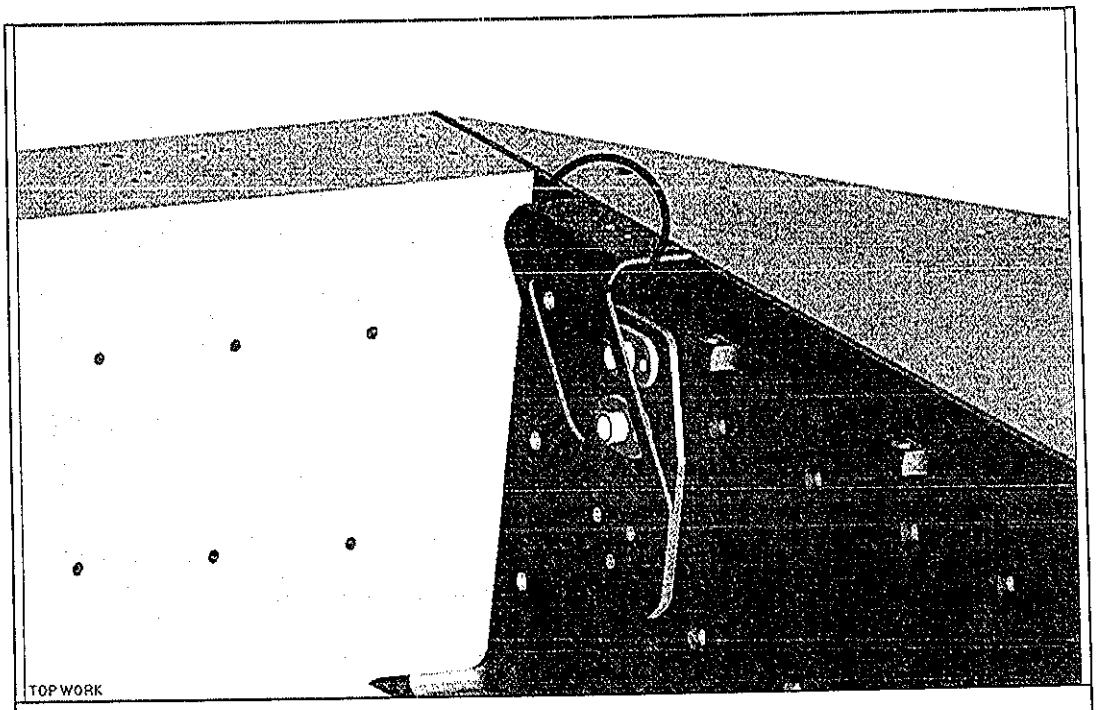

Figure 9-26: JOINT 6: Reflector Bracket - Reflector

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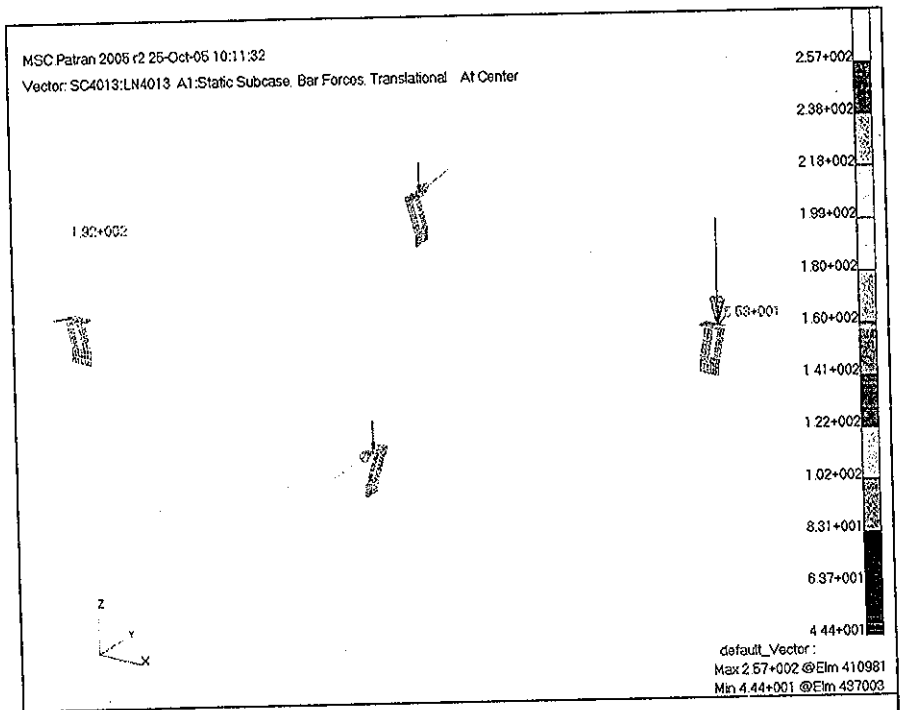

Figure 9-27: JOINT 6: Maximum axial force, load case 4013

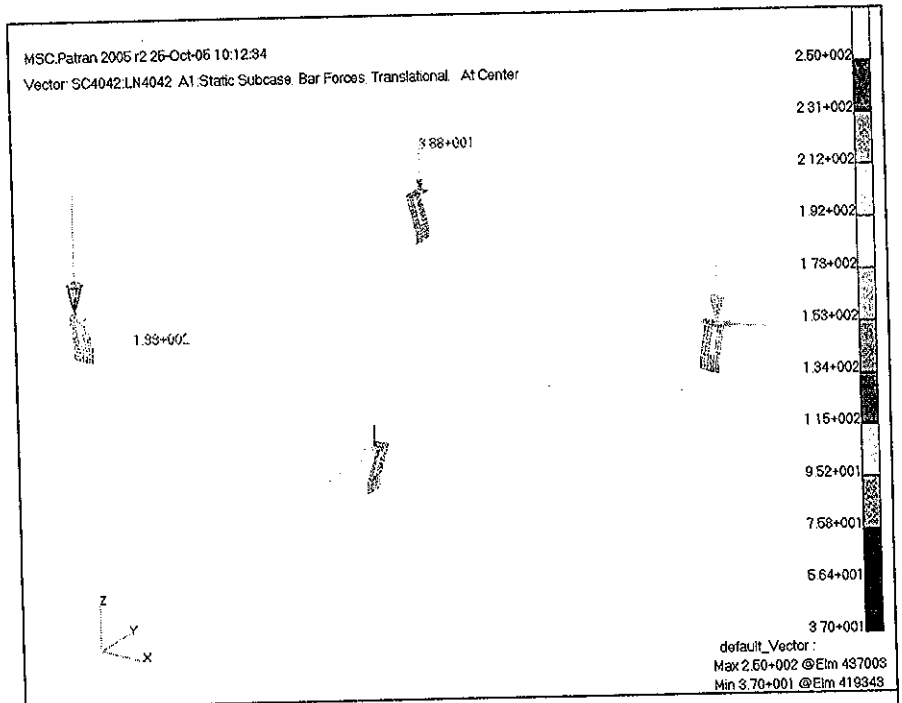

Figure 9-28: JOINT 6: Maximum resultant force, load case 4042

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9.3.8 JOINT 7: EXTERNAL STRUCTURE- DEBRIS SHIELD BKT

RICH external structure to debris shield bracket joints are NAS 1351N3 bolts, made of stainless steel A286-160 KSi: in the following figure positions of some of the bolts are shown.

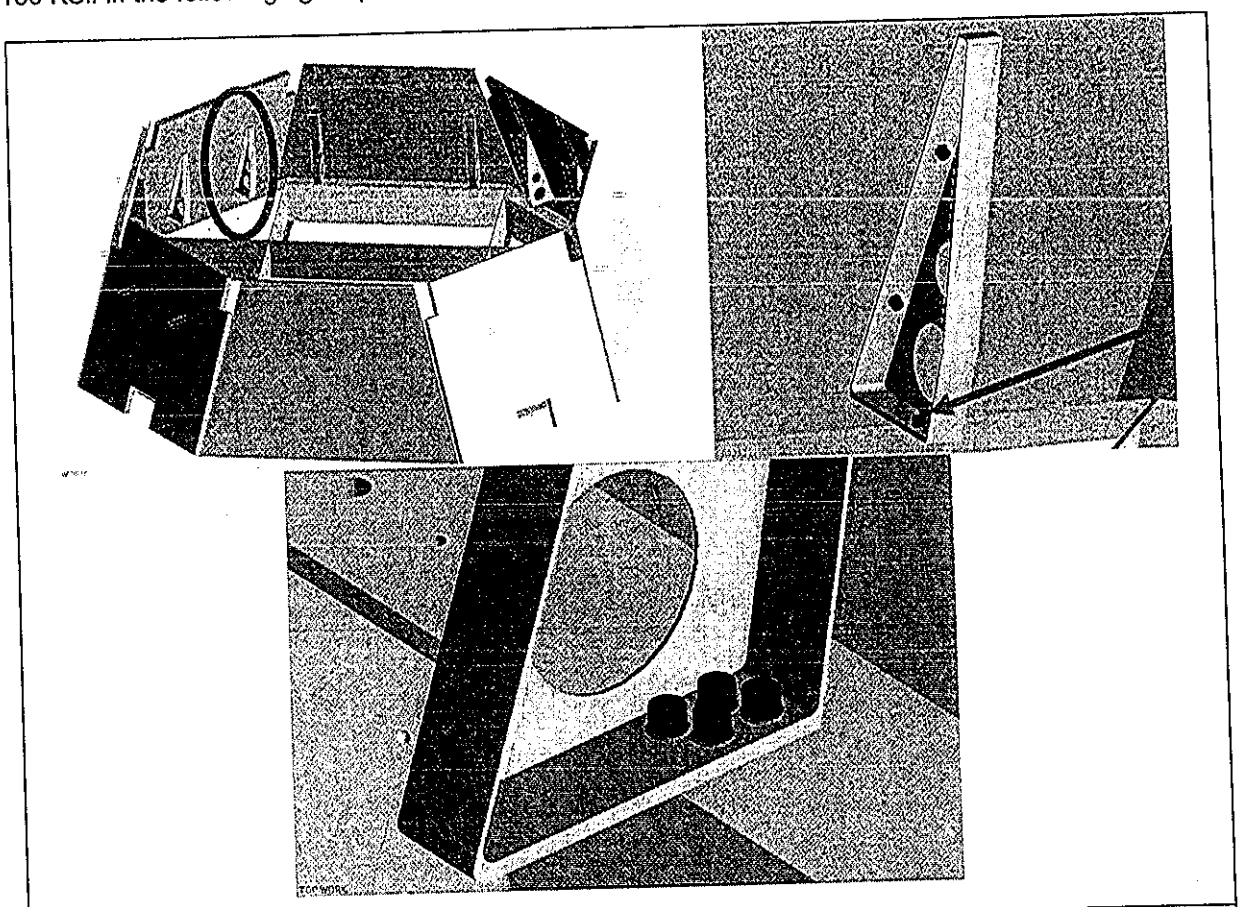

Figure 9-29: JOINT 7: External Structure – Debris Shield Bracket

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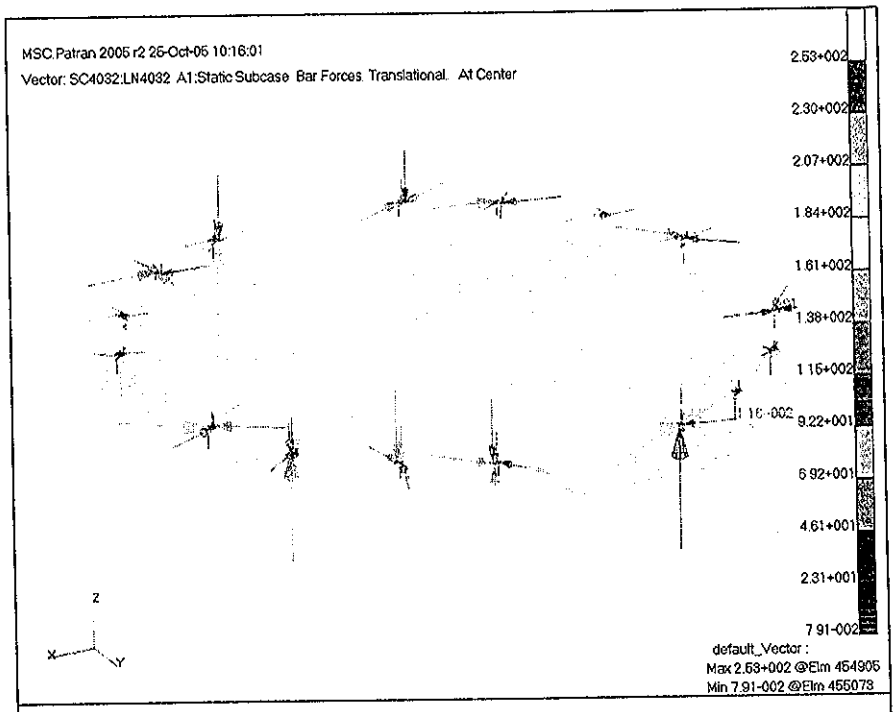

Figure 9-30: JOINT 7: Maximum axial force, load case 4032

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9.3.9 JOINT 8: DEBRIS SHIELD BKT- DEBRIS SHIELD

RICH debris shield bracket to debris shield joints are NAS 1351N3 bolts, made of stainless steel A286-160 KSi: in the following figure positions of some of the bolts are shown.

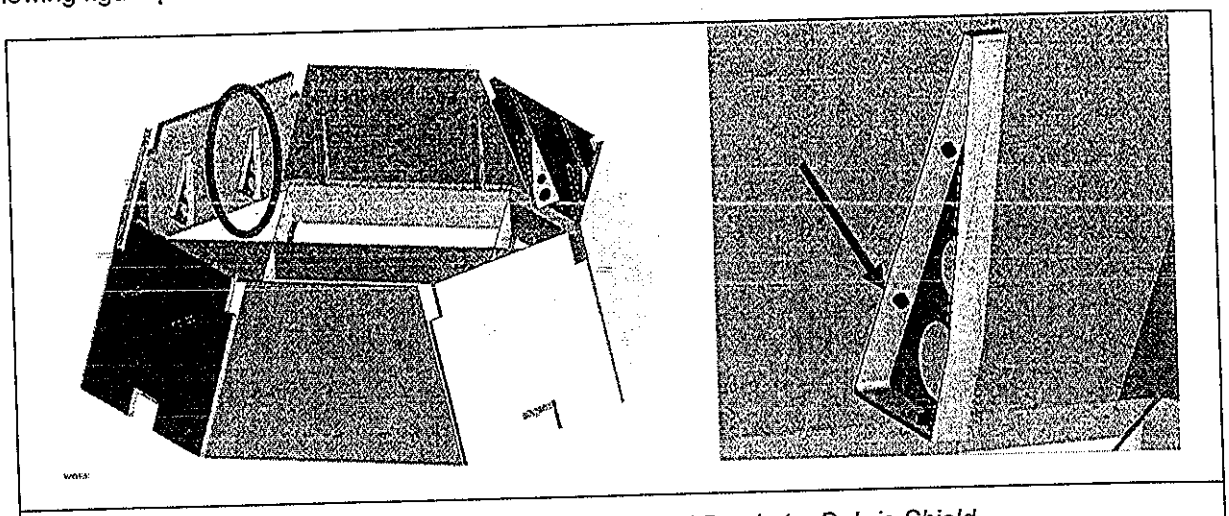

Figure 9-31: JOINT 8: Debris Shield Bracket – Debris Shield

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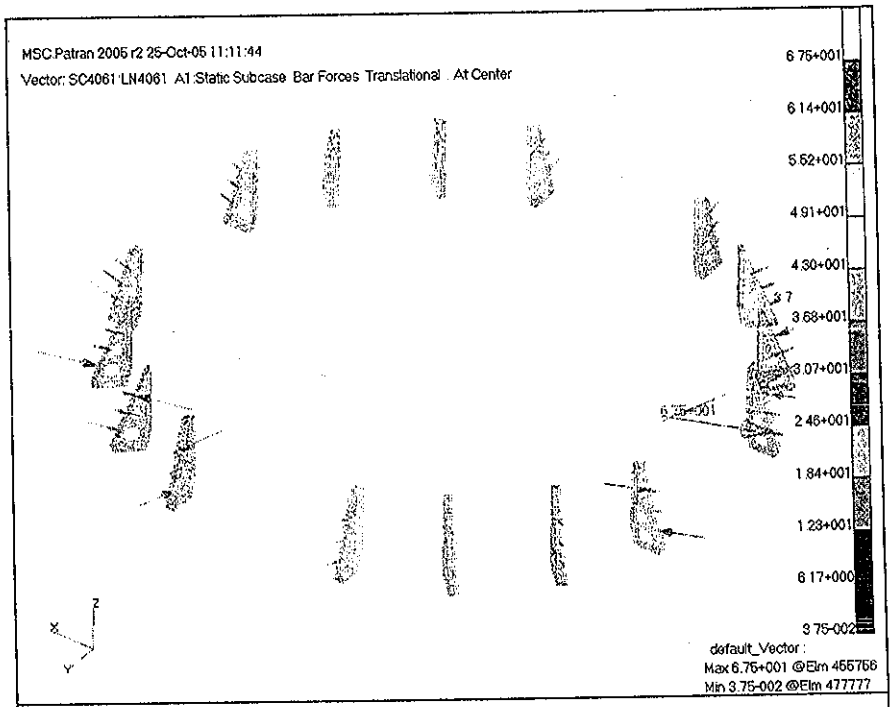

Figure 9-32: JOINT 8: Maximum axial force, load case 4061

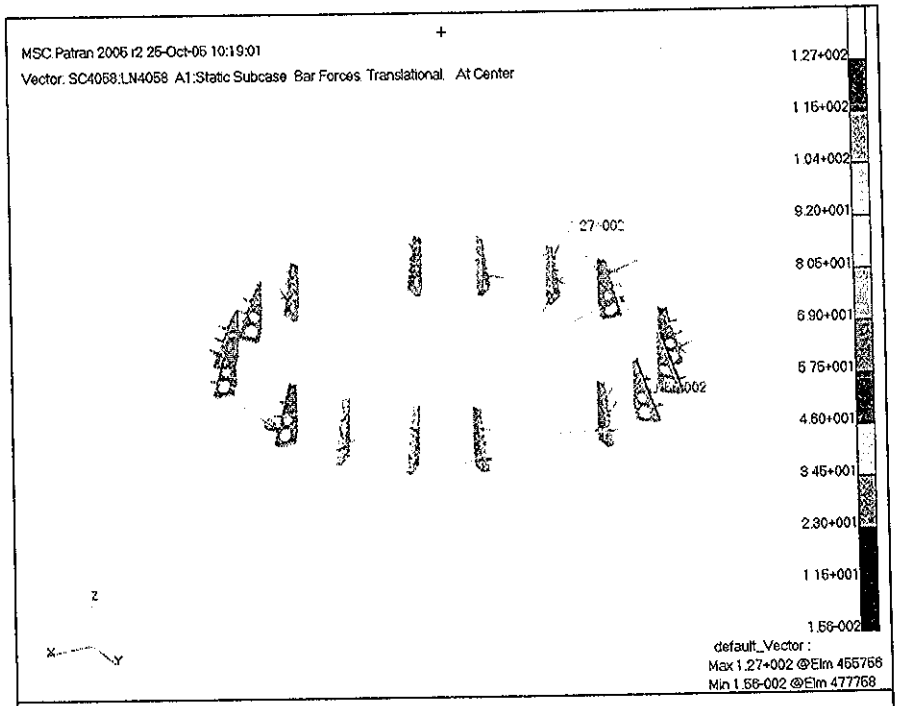

Figure 9-33: JOINT 8: Maximum resultant force, load case 4058

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9.3.10 MOS SUMMARY FOR JOINT ANALYSIS

In the following tables MoS summary for joint analysis is presented.

RICH

NOMINAL CONFIGURATION

Worst case for MS10=combined ultimate

JOINT #	position	BOLT	MATERIAL	TORQUE AVERAGE	APPLIED FORCES AXIAL [N]	APPLIED FORCES SHEAR [N]	MOS RESULTS MS1	MS2	MS3	MS4	MS5	MS6	MS7	MS8	MS9	MS10	Msmin	REMARKS
JOINT 1	External Structure	NAS 1351N4	A286 160KSi	10.2 Nm	386	4532	9.6	25.5	30	1.05	0.55	30	1.44	0.24	10	0.11	0.11	
JOINT 2	External-Internal Structure	M3	A4-70	0.65 Nm	33	467	13	41	43	0.96	0.263	58	1.71	0.48	10	0.245	0.245	
JOINT 3	External	NAS 1351N5	A286 95KSi	20.4 Nm	503	3666	11	22	38	0.46	0.54	37	1.43	1.47	10	0.34	0.34	
JOINT 4	External Structure Hi-Lock	Maxi Bolt CR7620 (06)	A286 160KSi	NA	1155	2337	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.72	0.72	
JOINT 5	External Structure- Reflector BKT	NAS 1351N3	A286 160KSi	4.2 Nm	105	1013	20	52	62	1.07	0.56	62	1.46	1.99	10	0.82	0.56	
JOINT 6	Reflector BKT-Reflector	NAS 1351N3	A286 160KSi	4.2 Nm	250	187	7.8	21	25	1.05	0.54	25	1.43	15	10	1.05	0.54	
JOINT 7	External Structure- Debris Shield BKT	NAS 1351N3	A286 160KSi	4.2 Nm	253	115	7.2	21	25	1.02	0.521	18	0.75	25	10	1.01	0.521	
JOINT 8	Debris Shield BKT- Debris Shield	NAS 1351N3	A286 160KSi	4.2 Nm	65	126	31	85	102	1.04	0.531	73	0.77	23	10	1.04	0.531	

Worst case for MS1=separation

JOINT #	position	BOLT	MATERIAL	TORQUE AVERAGE	APPLIED FORCES AXIAL [N]	APPLIED FORCES SHEAR [N]	MOS RESULTS MS1	MS2	MS3	MS4	MS5	MS6	MS7	MS8	MS9	MS10	Msmin	REMARKS
JOINT 1	External Structure	NAS 1351N4	A286 160KSi	10.2 Nm	1319	1866	2.01	6.5	8.1	0.99	0.52	7.9	1.36	25	10	0.99	0.52	
JOINT 2	External-Internal Structure	M3	A4-70	0.65 Nm	399.2	284.5	0.19	2.55	2.66	0.81	0.199	3.92	1.5	1.43	10	0.553	0.19	
JOINT 3	External	NAS 1351N5	A286 95KSi	20.4 Nm	1663	1846	2.6	6.07	10.8	0.43	0.52	10.7	1.38	3.91	10	0.42	0.42	
JOINT 4	External Structure Hi-Lock	Maxi Bolt CR7620 (06)	A286 160KSi	NA	1155	2337	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.72	0.72	
JOINT 5	External Structure- Reflector BKT	NAS 1351N3	A286 160KSi	4.2 Nm	148	906	14	36	44	1.07	0.56	43	1.46	2.34	10	0.88	0.56	
JOINT 6	Reflector BKT-Reflector	NAS 1351N3	A286 160KSi	4.2 Nm	257	55	7	20	25	1.05	0.54	24	1.43	54	10	1.05	0.54	
JOINT 7	External Structure- Debris Shield BKT	NAS 1351N3	A286 160KSi	4.2 Nm	253	115	7.2	21	25	1.02	0.521	18	0.75	25	10	1.01	0.521	
JOINT 8	Debris Shield BKT- Debris Shield	NAS 1351N3	A286 160KSi	4.2 Nm	68	95	29	81	97	1.04	0.53	70	0.77	30	10	1.039	0.53	

Table 9-8: Joint analysis MoS summary

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9.3.11 MOS SUMMARY FOR FAIL SAFE JOINT ANALYSIS

In order to check the integrity of the joints under failing of the most stressed joints. For such analysis, a new static FEA has been carried out. The most stressed joint (one for each type of connection) have been removed from the model. All the analyses for each joint set have been newly performed. In the following table the results are reported.

FAIL SAFE CONFIGURATION

Worst case

JOINT #	position	BOLT	MATERIAL	TORQUE AVERAGE	APPLIED FORCES AXIAL [N]	APPLIED FORCES SHEAR [N]	MAX PRELOAD [N]	STIFFNESS FACTOR	LOAD IN PLANE FACTOR	MOS RESULTS MS2	MS4	MS6	MS7	MS8	MS10	Msmin	REMARKS
JOINT 1	External Structure	NAS 1351N4	A286 160KSi	10.2 Nm	292	4295	11300 N	0.329	0.5	69	1.07	82	1.46	1.62	0.74	0.74	
JOINT 2	External-Internal Structure	M3	A4-70	0.65 Nm	391	306	1650 N	0.337	0.5	6.2	0.89	9.04	1.61	3.52	0.825	0.825	
JOINT 3	External	NAS 1351N5	A286 95KSi	20.4 Nm	125	1151	18300 N	0.264	0.5	187	0.47	311	1.44	14.7	0.47	0.47	
JOINT 4	External Structure Hi-Lock	Maxi Bolt CR7620 (06)	A286 160KSi	NA	2362	1939	NA	NA	NA	NA	NA	NA	NA	NA	1.34	1.34	
JOINT 5	External Structure- Reflector BKT	NAS 1351N3	A286 160KSi	4.2 Nm	91	1309	6100 N	0.378	0.5	122	1.08	145	1.47	3.63	1.00	1.00	
JOINT 6	Reflector BKT-Reflector	NAS 1351N3	A286 160KSi	4.2 Nm	350	123	6100 N	0.357	0.5	30	1.06	36	1.44	48	1.06	1.06	
JOINT 7	External Structure- Debris Shield BKT	NAS 1351N3	A286 160KSi	4.2 Nm	248	130	6300 N	0.305	0.5	44	1.03	38	0.77	45	1.03	0.77	
JOINT 8	Debris Shield BKT- Debris Shield	NAS 1351N3	A286 160KSi	4.2 Nm	65	37	6300 N	0.324	0.5	171	1.04	148	0.78	162	1.04	0.78	

Table 9-9: Joint Fail Safe analysis MoS summary

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9.4 BUCKLING ANALYSIS

For external structure and reflector supports buckling verification, the following equation is used:

$$\sigma_{CR} = \frac{\pi^2 k_c E}{12(1-\nu^2)} \cdot \left(\frac{t}{b}\right)^2 \quad \text{(RD 6 chp. C.6.2)}$$

Where:

- k_c: buckling coefficient;
- E: material Young modulus in compression;
- v: material elastic Poisson's ratio;
- b: short dimension of plate or loaded edge
- t: sheet thickness

In the following figures stress on external structure and support reflector are shown:

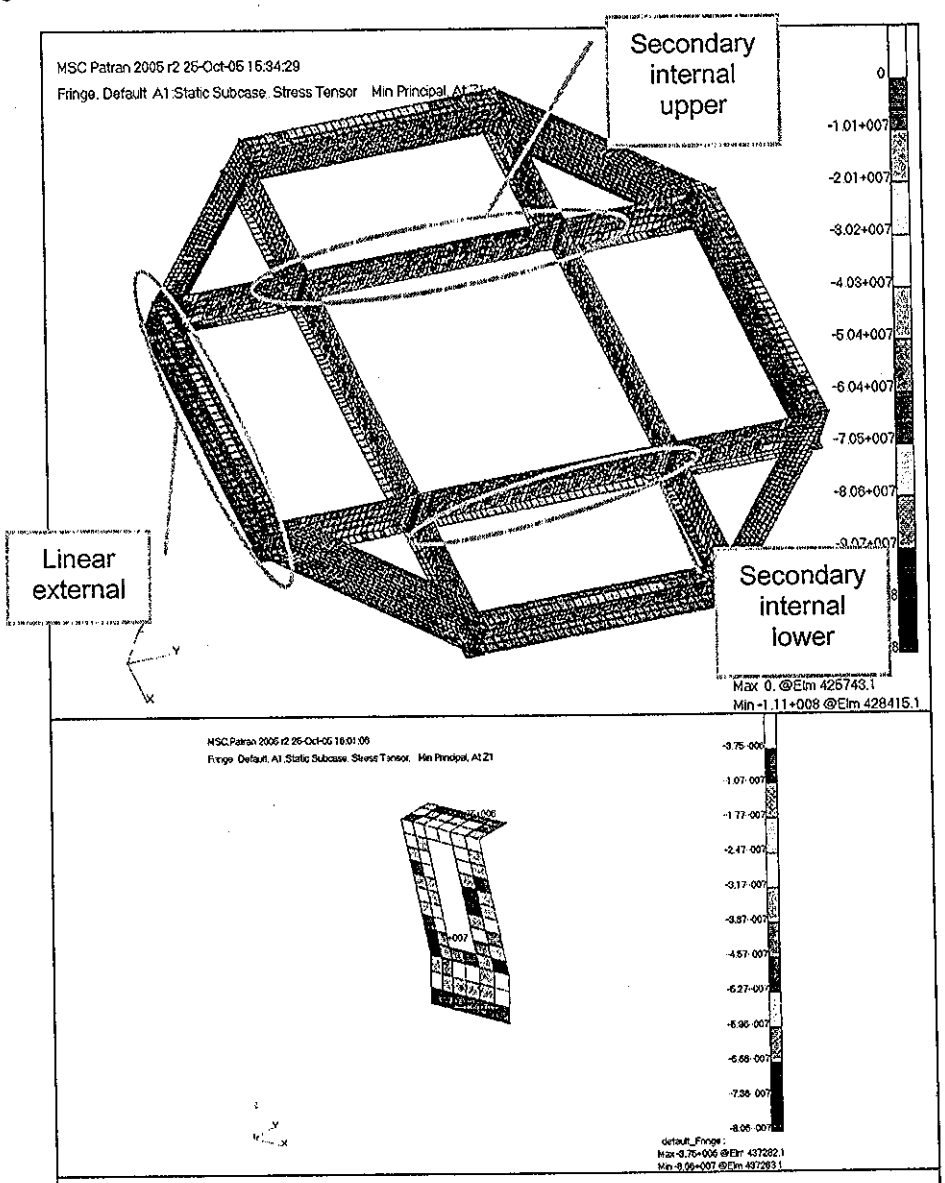

Table 9-10: Buckling verification, external structure and reflector support

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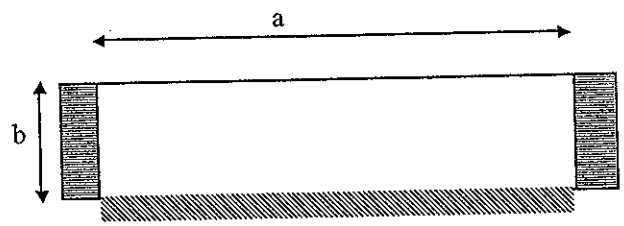
For the main structure three equivalent beams are considered:

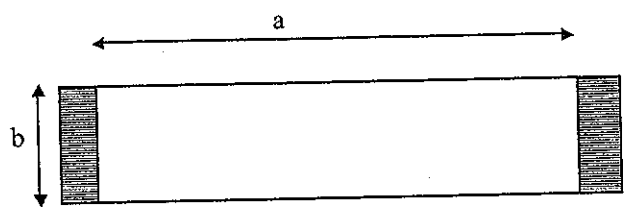


for this equivalent section the k_c defined in RD6 Chapter C6.1 is used:

k_c=0.43

The values of a and b are depending on the item.

For the reflector support the equivalent beam considered is:



f
or this equivalent section the k_c defined in RD6 Chapter C6.1 is used:

k_c=0.43

In the following table MoS of buckling verification are shown:

MOS SUMMARY FOR BUCKLING VERIFICATION								
ITEM	k_c	b	t	MATERIAL	F_{cr} [MPa]	Limit stress [MPa]	$S.F._u$	MoS_u
EXTERNAL STRUCTURE (SECONDARY INTERNAL LOWER)	0.43	0.025	0.003	Al 7075 T7351	405	111	2	0.83
EXTERNAL STRUCTURE (SECONDARY INTERNAL UPPER)	0.43	0.05	0.003	Al 7075 T7351	101	40	2	0.27
EXTERNAL STRUCTURE (LINEAR EXTERNAL)	0.43	0.1	0.005	Al 7075 T7351	70.4	30	2	0 17
REFLECTOR SUPPORT	0.43	0.017	0.002	AL 6061T6	375	80	2	1.34

Table 9-11: Buckling verification MoS summary

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10.CONCLUSIONS AND COMMENTS

All the performed analyses show the following results:

- the 1st natural frequency of the assembly is 76.2Hz, (see chapter 8.1) there are some modes with frequency lower than 50Hz but they are not considered because they have an effective mass lower than1%.
- all MoS are positive for all applied loads; see chapters 9.2.9 for the stress verification, chapters 9.3.10 for joints verification, chapter 9.4 for buckling analysis in nominal conditions
- in fail safe condition the MoS for joints verification are positive for all applied loads; see chapters 9.3.11

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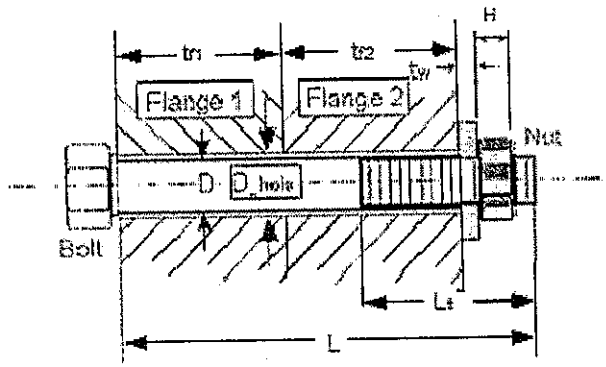
ANNEX 1. BOLTS VERIFICATION FORMULA

AMS-02 RICH
JOINT 1

NAS1351N4 0.25"-28 x 1.0" L Material-A-286 @ 160KSi
Nut NAS 1291 C4M
Washer NAS 620C416

Flange 1
Part number:
Material:

Flange 2
Part number:
Material:



Loads

Applied tensile load $P := 386\ N$

Applied shear load $V := 4532\ N$

Applied bending moment $M := 0\ N \cdot m$

Factors of Safety

Ultimate $SFu := 2.0$ Yield $SFy := 1.25$

Joint Separation $SFsep := 1.2$ Fitting factor $FF := 1.15$

Temperature data

Assembly $Temp_initial := 68 \cdot deg$

Maximum $Temp_max := 122 \cdot deg$

Minimum $Temp_min := 32 \cdot deg$

Bolt and Nut Data

Nominal diameter of bolt $D := 0.25\ in$

Number of threads/inch $Nt := 28 \frac{1}{in}$

Total length of bolt $L := 19.05\ mm$

Height of nut $H := 0.21\ in$

Threaded length $Lt := 19.05\ mm$

(If bolt is fully threaded, input Lt = L)

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Washer Data

Thickness of washers $tw := 1.6\ mm$

Outer Diameter of washer $Dw := 11.88\ mm$

Inner Diameter of washer $Dwi := 6.47\ mm$

Bolt head dia across flats $dw := 9.271\ mm$ (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 $tf1 := 3\ mm$

Thickness of flange 2 $tf2 := 3\ mm$

Diameter of hole $D_hole := 6.6\ mm$

Material Property Data

Bolt

Temperature correction factor for bolt strength ultimate $TSu_bolt := 0.94$ Yield $TSy_bolt := 0.94$

Bolt ultimate tensile allowable stress $Ftu_bolt := 1103\ 10^6\ Pa$

Bolt ultimate shear allowable stress $Fsu_bolt := 655\ 10^6\ Pa$

Bolt yield Tensile allowable stress $Fty_bolt := 827\ 10^6\ Pa$

Temperature correction factor for bolt modulus $TE_bolt := 0.94$

Modulus of elasticity of bolt $E_bolt := (29.1\ 10^6\ psi)$ Thermal coeffecient for bolt $\alpha_bolt_hot := 8.7\ 10^{-6}\ \frac{\frac{in}{in}}{deg}$

Nut

Temperature correction factor for nut strength $TS_nut := 0.94$ $\alpha_bolt_cold := 8.5\ 10^{-6}\ \frac{\frac{in}{in}}{deg}$

Ultimate tensile allowable stress $Ftu_nut := 160000\ psi$

Ultimate Shear allowable stress $Fsu_nut := 0.6 \cdot Ftu_nut$

Ultimate axial strength of nut $Ptu_nut := 6470\ lbf$ (Ref NAS3350 page 10)

Washer

Temperature correction factor for washer modulus $TE_washer := 1.0$

Modulus of elasticity of washer: $E_washer := (29.1 \cdot 10^6\ psi)$

Flanges

Stiffness of the joint depends upon number of members in the grip of the fasteners, Moculus of elasticity of these members and diameters of the bolt and the washer

Temperature correction factor for flange 1 $Tf1E := 1.0$ (modulus)

Temperature correction factor for flange 2 $Tf2E := 1.0$

Modulus of elasticity for the parts in the joint $E_flange1 := (10.5 \cdot 10^6\ psi)$ $E_flange2 := (10.5\ 10^6\ psi)$

Coefficient of thermal expansion for flanges $\alpha_flange1_hot := 12.15\ 10^{-6}\ \frac{\frac{in}{in}}{deg}$ $\alpha_flange2_hot := 12.15\ 10^{-6}\ \frac{\frac{in}{in}}{deg}$

$\alpha_flange1_cold := 12\ 10^{-6}\ \frac{\frac{in}{in}}{deg}$ $\alpha_flange2_cold := 12\ 10^{-6}\ \frac{\frac{in}{in}}{deg}$

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Torque/Preload data Maximum torque $T_{max} := 11.10\ m\ N$ Loading plane factor $n := 0.5$

Minimum torque $T_{min} := 9.43\ m\ N$ Preload Uncertainty $\Gamma := 0.25$

Torque coefficient $k := 0.15$

Torque check

Minimum pitch diameter of bolt $E_{smin} := E_{max} - 0.5\ tol_b$ Max inner diameter of nut $K_{nmax} := K_{nmin} + 0.5\ tol_n$

Max pitch diameter of nut $E_{nmax} := E_{max} + 0.5\ tol_n$ Min outer diameter of bolt $D_{smin} := D - 0.5\ tol_b$

Bolt tension allowable ultimate $F_{tu_bolt} := F_{tu_bolt} \cdot SF_{u_bolt}$

Bolt tension allowable yield $F_{ty_bolt} := F_{ty_bolt} \cdot SF_{y_bolt}$

Bolt shear allowable ultimate $F_{su_bolt} := F_{su_bolt} \cdot SF_{u_bolt}$

Bolt shear allowable yield $F_{sy_bolt} := \frac{F_{ty_bolt}}{F_{tu_bolt}} \cdot F_{su_bolt}$

Modulus of elasticity of bolt $E_{_bolt} := E_{_bolt} \cdot TE_{_bolt}$

Nut tension allowable ultimate $F_{tu_nut} := F_{tu_nut} \cdot TS_{_nut}$

Nut shear allowable $F_{su_nut} := F_{su_nut} \cdot TS_{_nut}$

Nut axial tension allowable $P_{tu_nut} := P_{tu_nut} \cdot TS_{_nut}$

Modulus of elasticity of washer $E_{_washer} := E_{_washer} \cdot TE_{_washer}$

Modulus of elasticity of parts in the joint $E_{_flange1} := E_{_flange1} \cdot Tf1E$

$E_{_flange2} := E_{_flange2} \cdot Tf2E$

Grip length (assumes fastener fully engages the nut) $LG := t_w + t_{f1} + t_{f2}$

Unthreaded length(shank) $l_d := L - l_t$

If the bolt is fully threaded the unthreaded shank length l_d is zero and the program will check it by the if statement

$$l_d := \begin{cases} 0.0\ in & \text{if } l_t \geq L \\ l_d & \text{otherwise} \end{cases}$$

Length of threaded portion $l_t := LG - l_d$

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Unthreaded tensile area:

$$Ad := \pi \cdot \left(\frac{D}{2}\right)^2$$

$$At1 := 0.7854 \left(D - \frac{0.9743}{Nt}\right)^2$$ (Ref 4, page 1325)

$$At2 := \pi \cdot \left(\frac{Esmin}{2} - \frac{0.16238}{Nt}\right)^2$$

Tensile area:

$$At := \begin{cases} At1 & \text{if } Ftu_bolt \le 100000\ psi \\ At2 & \text{otherwise} \end{cases}$$

Shear area:

$$As := \pi \cdot \left(\frac{D - 1.299038 \frac{1}{Nt}}{2}\right)^2$$

Shank area

$$Ash := \frac{\pi \cdot D^2}{4}$$

Moment of inertia of bolt cross section:

$$I := \frac{\pi \cdot \left(D - 0.9743 \frac{1}{Nt}\right)^4}{64}$$

Distance to outer fiber:

$$c := \frac{D - 0.9743 \frac{1}{Nt}}{2}$$

Bolt ultimate tensile strength: $PAt := Ftu_bolt \cdot At$

Bolt yield tensile strength: $PAy := Fty_bolt \cdot At$

Bolt ultimate shear strength at threads: $VAu := Fsu_bolt \cdot As$

Bolt ultimate shear strength at shank: $VAsh := Fsu_bolt \cdot Ash$

Check if shear is in the shank

$$VAu := \begin{cases} VAsh & \text{if } ld > (tw + tfl) \\ VAu & \text{otherwise} \end{cases}$$

Bending moment allowable ultimate: $MAu := Ftu_bolt \cdot \frac{I}{c}$

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Joint load factor:

The joint load factor (ϕ) is specified by Ref 1 as: $\phi = \frac{Kb}{Kb + Kj}$

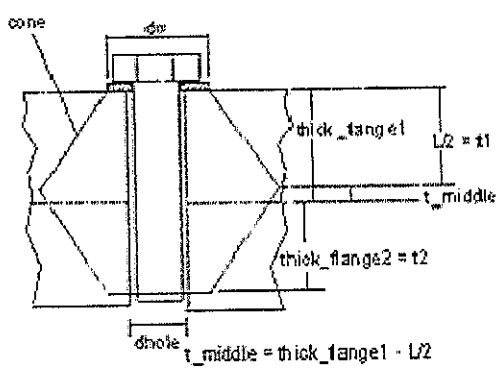
where Kb is the stiffness of the bolt and Kj the stiffness of the joint. Ref 1, does not give a method for calculating these stiffnesses. Kb and Kj will be calculated using the method described in Ref 2, page 458

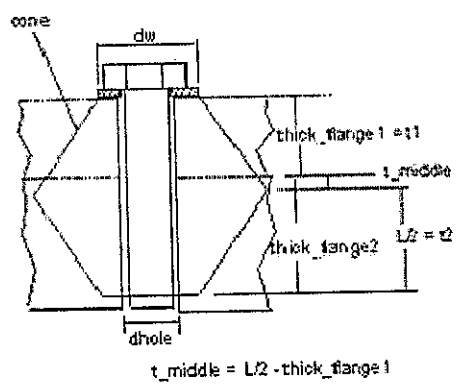
$$k_bolt := \frac{Ad \cdot At \cdot E_bolt}{Ad \cdot lt + At \cdot ld}$$ (Ref 2, page 461)

This gives the washer area as: $A_washer := \pi \cdot \frac{(Dw^2 - Dwi^2)}{4}$

(Ref 2, page 463 uses a pressure-cone method for the stiffness calculation. When loading is applied using a washer-face annulus the apex cone angle they recommend is 30 degrees

$\alpha_cone := 30 \cdot deg$





$Lthick := tf1 + tf2$

The mid-plane of the frustrum may lie in either flange1 or flange 2. If the material properties of the two are different then this must be accounted for

$$t1 := if\left[\left(\frac{Lthick}{2} > tf1\right), tf1, \frac{Lthick}{2}\right]$$ thickness of flange1 frustum

$$t2 := if\left[\left(\frac{Lthick}{2} > tf1\right), \frac{Lthick}{2}, tf2\right]$$ thickness of flange2 frustum

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Properties for middle of flange1 and flange 2 frustum

$$Dw := \begin{cases} dw & \text{if } Dw = 0.0\ in \\ Dw & \text{otherwise} \end{cases}$$

$$E_middle := if\left[\left(\frac{Lthick}{2} > tfl\right), E_flange2, E_flange1\right]$$

$$D_middle := if\left[\left(\frac{Lthick}{2} > tfl\right), Dw + 2\ t1\ \tan(\alpha_cone), Dw + 2\ t2\ \tan(\alpha_cone)\right]$$

$$t_middle := if\left[\left(\frac{Lthick}{2} > tfl\right), \frac{Lthick}{2} - tfl, tfl - \frac{Lthick}{2}\right]$$

The stiffness for each of the members is then given by

$$k_flange1 := \frac{\pi\ E_flange1\ D_hole\ \tan(\alpha_cone)}{\ln\left[\frac{(2\ t1\ \tan(\alpha_cone) + Dw - D_hole)\ (Dw + D_hole)}{(2\ t1\ \tan(\alpha_cone) + Dw + D_hole)\ (Dw - D_hole)}\right]}$$

$$k_flange2 := \frac{\pi\ E_flange2\ D_hole\ \tan(\alpha_cone)}{\ln\left[\frac{(2\ t2\ \tan(\alpha_cone) + Dw - D_hole)\ (Dw + D_hole)}{(2\ t2\ \tan(\alpha_cone) + Dw + D_hole)\ (Dw - D_hole)}\right]}$$

$$k_middle := if\left[t_middle = 0\ in, 10^{15}\ \frac{lbf}{in}, \frac{\pi\ E_middle\ D_hole\ \tan(\alpha_cone)}{\ln\left[\frac{(2\ t_middle\ \tan(\alpha_cone) + D_middle - D_hole)\ (D_middle + D_hole)}{(2\ t_middle\ \tan(\alpha_cone) + D_middle + D_hole)\ (D_middle - D_hole)}\right]}\right]$$

NOTE: If statement to check if thick_flange1 = thick_flange2

The stiffness for the washer, treating it as a cylinder, is

$$k_washer := \begin{cases} 10.0\ \frac{lbf}{in} & \text{if } tw = 0.0\ in \\ \frac{A_washer\ E_washer}{tw} & \text{otherwise} \end{cases}$$

The joint stiffness will be

$$Kj := \begin{cases} \dfrac{1}{\frac{1}{k_flange1} + \frac{1}{k_flange2} + \frac{1}{k_middle}} & \text{if } tw = 0\ in \\ \dfrac{1}{\frac{1}{k_flange1} + \frac{1}{k_flange2} + \frac{1}{k_middle} + \frac{1}{k_washer}} & \text{otherwise} \end{cases}$$

The joint load factor will then be

$$\varphi := \frac{k_bolt}{Kj + k_bolt}$$

stiffness of joint

$$K_therm := \frac{k_bolt\ Kj}{(k_bolt + Kj)}$$

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Calculation of Preload on the Bolt:

Increase in preload due to increase in temperature

$$Pthr_1 := \left[\begin{array}{l}((tf1)\,(Temp_max - Temp_initial)\,(\alpha_flange1_hot - \alpha_bolt_hot)) \\ +(tf2)\,(Temp_max - Temp_initial)\,(\alpha_flange2_hot - \alpha_bolt_hot)\end{array}\right] K_therm$$

Decrease in preload due to reduction in temperature:

$$Pthr_2 := \left[\begin{array}{l}(tf1)\,(Temp_min - Temp_initial)\,(\alpha_flange1_cold - \alpha_bolt_cold) \\ -(tf2)\,(Temp_min - Temp_initial)\,(\alpha_flange2_cold - \alpha_bolt_cold)\end{array}\right] K_therm$$

$$Pthr_pos := \begin{cases} Pthr_1 & \text{if } (Pthr_1 \ge 0\,N)\,(Pthr_2 \le 0\,N) \\ Pthr_2 & \text{if } (Pthr_1 \le 0\,N)\,(Pthr_2 \ge 0\,N) \\ \max\left(\begin{bmatrix} Pthr_1 \\ Pthr_2 \end{bmatrix}\right) & \text{if } (Pthr_1 > 0\,N)\,(Pthr_2 > 0\,N) \\ 0\,lbf & \text{otherwise} \end{cases}$$

$$Pthr_neg := \begin{cases} Pthr_2 & \text{if } (Pthr_1 \ge 0\,N)\,(Pthr_2 \le 0\,N) \\ Pthr_1 & \text{if } (Pthr_1 \le 0\,N)\,(Pthr_2 \ge 0\,N) \\ 0\,lbf & \text{if } (Pthr_1 > 0\,N)\,(Pthr_2 > 0\,N) \\ \min\left(\begin{bmatrix} Pthr_1 \\ Pthr_2 \end{bmatrix}\right) & \text{otherwise} \end{cases}$$

Maximum preload at max temp $\quad PLDmax := (1 + \Gamma)\,\frac{Tmax}{k\,D} + Pthr_pos$

Max preload at room temp $\quad PLDmaxRT := (1 + \Gamma)\,\frac{Tmax}{k\,D}$

Preload loss will be 5% of max preload at Room temp: $\quad Ploss := PLDmaxRT \cdot 0.05$

Minimum preload $\quad PLDmin := (1 - \Gamma)\,\frac{Tmin}{k\,D} + Pthr_neg - Ploss$

Check to see if Min preload is negative $\quad PLDmin := \begin{cases} PLDmin & \text{if } PLDmin > 0.0\,lbf \\ (0.0\,lbf) & \text{if } PLDmin \le 0.0\,lbf \end{cases}$

Calculation for shear pullout strength

The pullout strength of the nut depends on whether the Nut material is stronger, equal to or weaker than the bolt material. The minimum engagement length required to develop the full strength of the bolt is calculated

The shear area for the 3 cases are calculated as follows: Ref 5, page 67-68

Nut and Bolt are same strength

Thread engagement length $\quad Le1 := \frac{4\,At}{\pi\,Emax}$

Shear pullout area $\quad Ats1 := \frac{\pi\,Emax\,Le1}{2}$

Nut stronger than Bolt

Thread engagement length $\quad Le2 := \frac{2\,At}{\pi\,Nt\,Knmax\left[\left(\frac{1}{2\,Nt}\right) + 0.57735\,(Esmin - Knmax)\right]}$

Shear pullout area $\quad Ats2 := \pi\,Nt\,Le2\,Knmax\left[\left(\frac{1}{2\,Nt}\right) + 0.57735\,(Esmin - Knmax)\right]$

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Nut weaker than Bolt

Thread engagement length $Le3 := \dfrac{Ftu_bolt \cdot 2 \cdot At}{Ftu_nut \cdot \pi \cdot Nt \cdot Dsmin \cdot \left[\left(\frac{1}{2 \cdot Nt}\right) + 0.57735 \cdot (Dsmin - Enmax)\right]}$

Shear pullout area $Ats3 := \pi \cdot Nt \cdot Le3 \cdot Dsmin \left[\left(\frac{1}{2 \cdot Nt}\right) + 0.57735 \cdot (Dsmin - Enmax)\right]$

Determine if nut is stronger , equal or weaker than bolt

$PAs1 := Fsu_bolt \cdot Ats1$ (Bolt and nut equal strength)

$PAs2 := Fsu_bolt \cdot Ats2$ (Nut stronger than bolt)

$PAs3 := Fsu_nut \cdot Ats3$ (Nut weaker than bolt)

Minimum thread shear strength required to develop full strength of bolt:

$$PAs := \begin{cases} PAs2 & \text{if } Fsu_nut > Fsu_bolt \\ PAs3 & \text{if } Fsu_nut < Fsu_bolt \\ PAs1 & \text{otherwise} \end{cases}$$

Compare bolt and nut tensile strength and use the smaller value

$$PAt := \begin{cases} Ptu_nut & \text{if } Ptu_nut \le PAt \\ PAt & \text{otherwise} \end{cases}$$

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Margins of Safety on the bolt

Check for length of bolt

$$Length_check := \begin{cases} \text{"Bolt length is sufficient"} & \text{if } L \ge \left(tw + tf1 + tf2 + H + \frac{2}{Nt}\right) \\ \text{"Bolt length should be increased!"} & \text{otherwise} \end{cases}$$

Total tensile load on bolt $Pb := PLDmax + n\,\phi\,(SFu\,P\,FF)$

Total Yield tensile load on bolt $Pby := PLDmax + n\,\phi\,(SFy\,P\,FF)$

Joint Separation load $Psep := P\,SFsep$

Margin of safety on joint separation

$$MS_1 := \begin{cases} 100 & \text{if } P = 0\,N \\ \dfrac{PLDmin}{(1 - n\,\phi)\,Psep\,FF} - 1 & \text{otherwise} \end{cases}$$

Margin of safety on applied tension load ultimate:

$$MS_2 := \begin{cases} 100 & \text{if } P = 0\,N \\ \dfrac{PAt}{(SFu\,P)\,FF} - 1 & \text{otherwise} \end{cases}$$

Ratio on applied tension ult $Rau_1 := \dfrac{SFu\,P\,FF}{PAt}$

Margin of safety on applied tension load yield:

$$MS_3 := \begin{cases} 100 & \text{if } P = 0\,N \\ \dfrac{PAy}{(SFy\,P)\,FF} - 1 & \text{otherwise} \end{cases}$$

Ratio on applied tension ult $Ray_1 := \dfrac{SFy\,P\,FF}{PAy}$

Margin of safety on total tension load ultimate: $MS_4 := \dfrac{PAt}{(Pb)} - 1$

Ratio on total tension: $Rau_2 := \dfrac{Pb}{PAt}$

Margin of safety on total tension load Yield $MS_5 := \dfrac{PAy}{Pby} - 1$

Ratio on total tension (Yield) $Ray_2 := \dfrac{Pby}{PAy}$

Ratio on preload (Yield): $Ray_3 := \dfrac{PLDmax}{PAy}$

Margin of safety on thread shear using direct tension only

$$MS_6 := \begin{cases} 100 & \text{if } P = 0\,N \\ \dfrac{PAs}{SFu\,P\,FF} - 1 & \text{otherwise} \end{cases}$$

Margin is based upon the total tension load $MS_7 := \dfrac{PAs}{Pb} - 1$

Margin of safety on applied shear load ultimate:

$$MS_8 := \begin{cases} 100 & \text{if } V = 0\,N \\ \dfrac{VAu}{(SFu\,|V|)\,FF} - 1 & \text{otherwise} \end{cases}$$

Shear ratio: $Rsu := \dfrac{SFu\,|V|\,FF}{VAu}$

Margin of safety on applied moment ultimate

$$MS_9 := \begin{cases} 100 & \text{if } M = 0\,N\,m \\ \dfrac{MAu}{SFu\,|M|\,FF} - 1 & \text{otherwise} \end{cases}$$

Moment ratio $Rbu := \dfrac{SFu\,|M|\,FF}{MAu}$

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Guess K $Kru := 1.0$

Given

$$(Kru \cdot Rsu)^3 + (Kru \cdot (\max(Rau) + Rbu))^2 = 1 \qquad Kru := Find(Kru)$$

Margin of safety on combined loading ultimate: $MS_{10} := Kru - 1$

Summary of Margins for bolt: $MSbolt := \min(MS)$

$$Failure_Mode := \begin{cases} \text{"Joint Separation"} & \text{if } MS_1 = \min(MS) \\ \text{"Direct Tension Ultimate"} & \text{if } MS_2 = \min(MS) \\ \text{"Direct Tension Yield"} & \text{if } MS_3 = \min(MS) \\ \text{"Total Tension Ultimate"} & \text{if } MS_4 = \min(MS) \\ \text{"Total Tension Yield"} & \text{if } MS_5 = \min(MS) \\ \text{"Direct Thread Shear Ultimate"} & \text{if } MS_6 = \min(MS) \\ \text{"Total Thread Shear Ultimate"} & \text{if } MS_7 = \min(MS) \\ \text{"Shear Ultimate"} & \text{if } MS_8 = \min(MS) \\ \text{"Bending Ultimate"} & \text{if } MS_9 = \min(MS) \\ \text{"Combined Shear Tension Bending Ultimate"} & \text{if } MS_{10} = \min(MS) \end{cases}$$

References:

1. Criteria for preloaded bolts, NSTS 08307, Rev. A
2. Mechanical Engineering Design, Shigley and Mischke, 6th edition
3. Marks Mechanical Engineers Handbook, 8th edition
4. Machinery's handbook, 24th edition
5. An Introduction to Design and Behavior of Bolted Joints, John Bickford, 3rd edition
6. Metallic Materials and Elements for Aerospace Vehicle Structures, MIL-HDBK-5H

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Bolt Load data

Bolt/joint stiffness factor	$\phi = 0.329$	Preload due to temperature	Pthr_pos = 95.2 lbf
Max. preload	PLDmax = 14990.3 N		Pthr_neg = -64.4 lbf
Min. preload	PLDmin = 6410.5 N	Uncertainty factor	$\Gamma = 0.25$
Joint separation load	Psep = 104132 lbf	Torque coefficient	k = 0.15
Max. load on the bolt(ultimate)	Pb = 3402.8 lbf	Loading plane factor	n = 0.5
Max. load on the bolt(yield)	Pby = 3390.5 lbf	Thread pullout strength required to develop full strength of bolt	PAs = 6301.5 lbf
Bolt ultimate tensile strength	PAt = 5305.8 lbf	Nut ultimate tensile strength	Ptu_nut = 6081.8 lbf

Length_check = "Bolt length is sufficient"

Summary of Margins for bolt:

Joint separation	$MS_1 = 13.41$	Direct Thread shear Ultimate	$MS_6 = 30.57$
Direct Tension Ultimate	$MS_2 = 25.58$	Total Thread shear Ultimate	$MS_7 = 0.85$
Direct Tension Yield	$MS_3 = 30.89$	Shear Ultimate	$MS_8 = 0.24$
Total Tension Ultimate	$MS_4 = 0.56$	Bending Ultimate	$MS_9 = 10$
Total Tension Yield	$MS_5 = 0.17$	Combined shear, tension and bending ultimate	$MS_{10} = 0.03$

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ANNEX 2. RICH TABLE FOR SAFETY REVIEW

Item	Drawing number	Material and Temper	Max. tensile (ksi)	Ratio of applied limit stress to allowable stress	Margin of safety (ult) S.F.=2	Fracture Classification	Rationale	Comments
Primary Beam	13-RICSYS-00.001	AL 7075 T7351	13.1	0.21	1.42			Near bolt
Secondary Beam 1	13-RICSYS-00.002	AL 7075 T7351	8.1	0.13	>2			Near bolt
Secondary Beam 2	13-RICSYS-00.003	AL 7075 T7351	7.6	0.12	>2			Near bolt
Secondary Internal	13-RICSYS-00.004	AL 7075 T7351	14.6	0.23	1.18			Near bolt
Linear External X	13-RICSYS-00.005	AL 7075 T7351	8.2	0.13	>2			Near bolt
Linear External Y	13-RICSYS-00.006	AL 7075 T7351	6.8	0.11	>2			Near bolt
Angular External	13-RICSYS-00.007	AL 7075 T7351	5.9	0.09	>2			Near bolt

Item	Material	Ftu [Ksi]	Fty [Ksi]	Fsu [Ksi]	Margin of safety (Comb) Fail Safe S.F.=1	Fracture Classification	Rationale	Comments
Joint 1	A286	160	119	96	0.43	Fail Safe		
Joint 2	A4-70	116	87	69	0.68	Fail Safe		
Joint 3	A286	160	119	96	0.12	Fail Safe		
Joint 4	A286	95	75	57	1.34	Fail Safe		
Joint 5	A286	160	119	96	0.51	Fail Safe		
Joint 6	A286	160	119	96	0.53	Fail Safe		
Joint 7	A286	160	119	96	0.53	Fail Safe		
Joint 8	A286	160	119	96	0.54	Fail Safe		

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