NSTX Upgrade

TF to Umbrella Structure Aluminum Block Connection

NSTXU-CALC-12-06-00

Rev 0

October18 2011

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Mark Smith, NSTX Cognizant Engineer

Reviewed By:

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PPPL Calculation Form

Calculation # **NSTXU-CALC-12-04-00** Revision # 00 WP #, 0029,0037 (ENG-032)

Purpose of Calculation: **(Define why the calculation is being performed.)**

Qualify the Aluminum Block and Bolting for upgrades and modifications proposed for the NSTX CS Upgrade FDR

References **(List any source of design information including computer program titles and revision levels.)**

-See the reference list in the section 5.3 of the calculation

Assumptions **(Identify all assumptions made as part of this calculation.)**

Originally and conservatively, the OOP loads on the aluminum block were derived from a simple model of the outer leg that did not include the knuckle clevis restraint/support. This has been updated with loads based on the stiffer struts, from [1] and [2]. Loads from the TF flex joint have been considered. There is some variation in loading, and it is assumed that the choice of loads has adequately enveloped the actual loading. Global model and local model displacements were compared. To get better consistency in the rotational stiffness, the global model should improve modeling of reinforcements, but the behavior of the two models is deemed sufficient to assess the aluminum block hardware with the global model loads.

Calculation **(Calculation is either documented here or attached)**

Attached in the body of the calculation

Conclusion **(Specify whether or not the purpose of the calculation was accomplished.)**

With recommended reinforcements, and modest preloads, the 3/4 inch 316 SS bolts are acceptable for the upgrade loads. DCPS input has been generated and provided to the DCPS Cognizant Engineer. The vertically split "wing" reinforcement is adequate but the split must be welded. Weld details of the recommended reinforcement are acceptable - previously reported high weld stresses were improved by "turning the corners" at the weld ends. The aluminum blocks appear to be cast material rather than the wrought material called out in the drawings. Reinforcements are proposed both on the inside of the umbrella structure, and outside the umbrella structure to help support the load and capture the block.

Cognizant Engineer's printed name, signature, and date

Mark Smith ____

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Irving Zatz Irving Zatz Digitally signed by Irving Zatz DN: cn=Irving Zatz, o=PPPL, ou, email=zatz@pppl.gov, c=US Date: 2011.11.10 11:24:04 -05'00'

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3.0 Executive Summary:

The aluminum blocks at the top and bottom ends of the TF outer legs react part of the loads from the outer legs of the TF coils. The aluminum blocks are split and clamp the TF coil end with an epoxy glass filler. This calculation is intended to investigate the aluminum block stress and the stresses in the 3/4 inch bolts that connect the block to the umbrella shell. This analysis initially uses conservatively derived OOP loads and moments from the TF outboard leg based on soft struts at the knuckle clevis. These loads have been updated for the latest stiff struts. Loads have come from references [1], [2] and [9] .

Analysis has progressed through a number of iterations of recommended reinforcements. The last set of modifications is intended to address the uncertainty in the material properties of the aluminum blocks. Outer bar clamps have been added. If tests or documentation shows adequate properties, the last set of additions may not be needed. Photos of the blocks support the belief that the blocks are sand cast. The biggest concern with cast material is that the ductilities are low. If fit-up isn't perfect, the blocks may have been deformed close to their ultimate during assembly or could be when the upgrade components are added. The uncertainty in the properties, particularly the ductility, argues for some additional reinforcements to provide redundancy in the block flange. Consequently, the full complement of reinforcements is recommended.

With recommended reinforcements, and a preload to 25 ksi, stress levels in the 3/4 inch bolting remain close to the preload stress. This satisfies the stress limits for the 316 bolts specified, which is 33.6 ksi for the "generic" 316 bar stock assumed for the existing bolts. A better grade of bolt with a proper pedigree is recommended, but preloads, discussed next, should not be exceeded to protect the block flange. The bolts are expected to be preloaded with the recommended reinforcements. The bolts are expected to be preloaded beyond the design stress and will be isolated from the cyclic loading. The pre-tension needed is 8375 lbs. The torque needed for this is .2*F*D = .2*8375*.75/12= 104 ft-lbs.

Bolt stresses are strongly affected by the flexibility of the umbrella structure shell. Reinforcing the shell has improved stresses in the shell as well as the bolt stress. Also lateral loads are assumed taken by a good fit between the aluminum blocks and umbrella structure cut-out. This requires shimming. If shimming is to be avoided, the preload would have to be increased and the aluminum block flange would be more highly stressed.

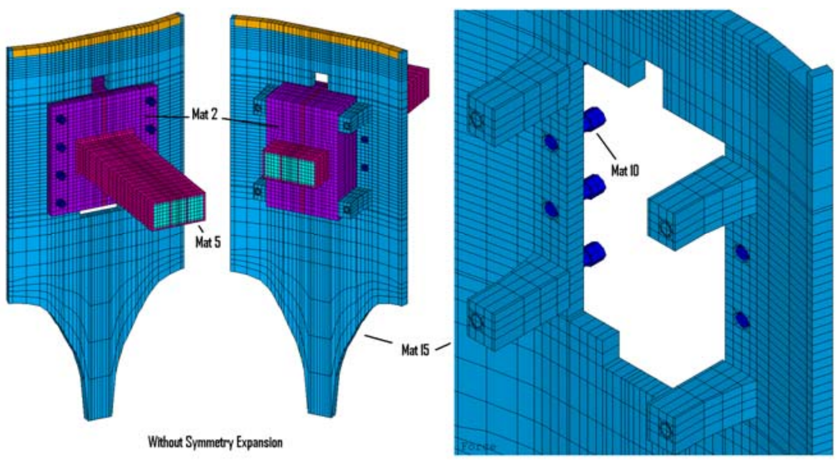


Figure 3.0-1 Initial Model Representing the Current (2010) configuration

While this calculation is not intended to address umbrella structure arch stresses, or TF outer leg bending and insulation bond shear, these areas are included in the models and stress values for these areas are consistent with those reported in other analyses [1] [2].

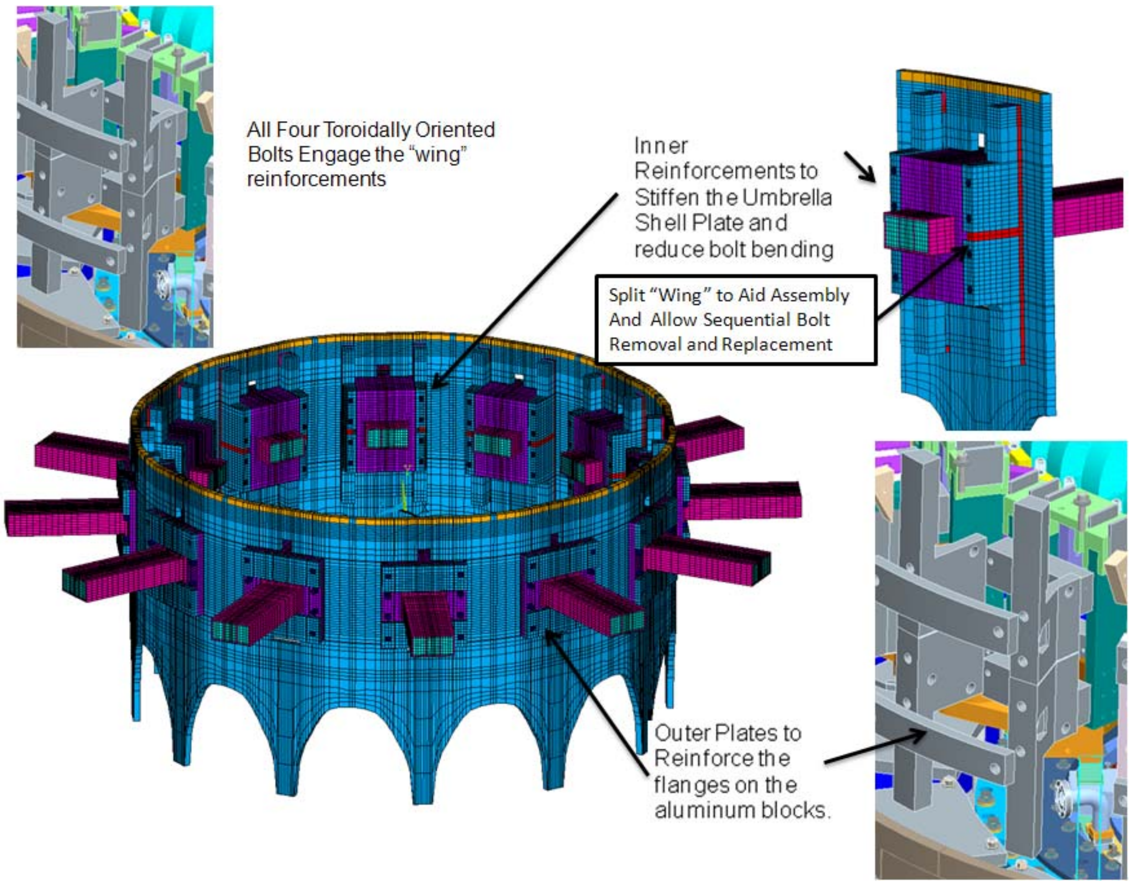


Figure 3.0-2 Symmetry expansion of the model with recommended reinforcements added

The external bars or outer plates are 1 inch thick, 4.25 high and 13.5 inches wide. There are two, one above the TF conductor and one below, held by 3/4 inch bolts that thread into the reinforcing bars on the inside of the umbrella structure. The modeling in this calculation shows the TF leg protruding straight out of the conductor. Actually it is angled downward. This was done to simplify meshing. The inclined TF should allow the top bar to be positioned one pair of bolts downward.

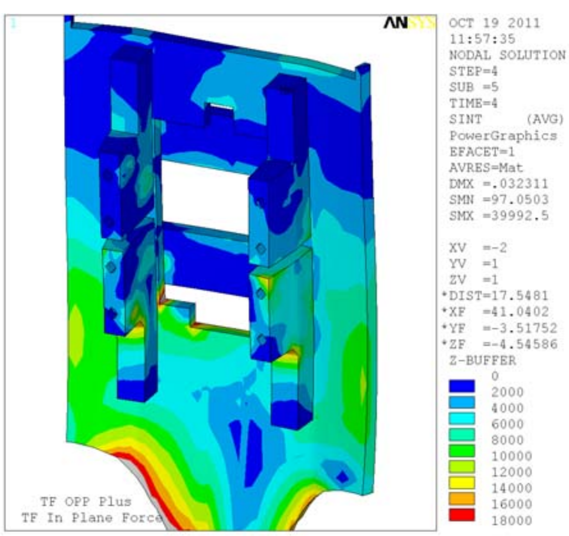


Figure 3.0-4 Stresses in the reinforcement components

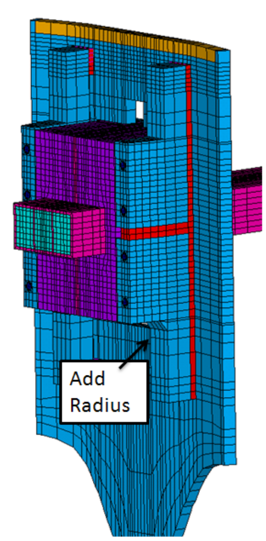


Figure 3.0-3 Add Radius to Lower Corner of "Wing"

The "wing" reinforcements on the inside of the umbrella structure are cut or stepped on the top to fit the TF Strap Finger ring. At the bottom they are also similarly stepped. The corner in the lower wing was highly stressed without a radius. The addition of a radius is recommended. Stresses in the upper corner are not as bad and the radius would interfere with the finger support ring.

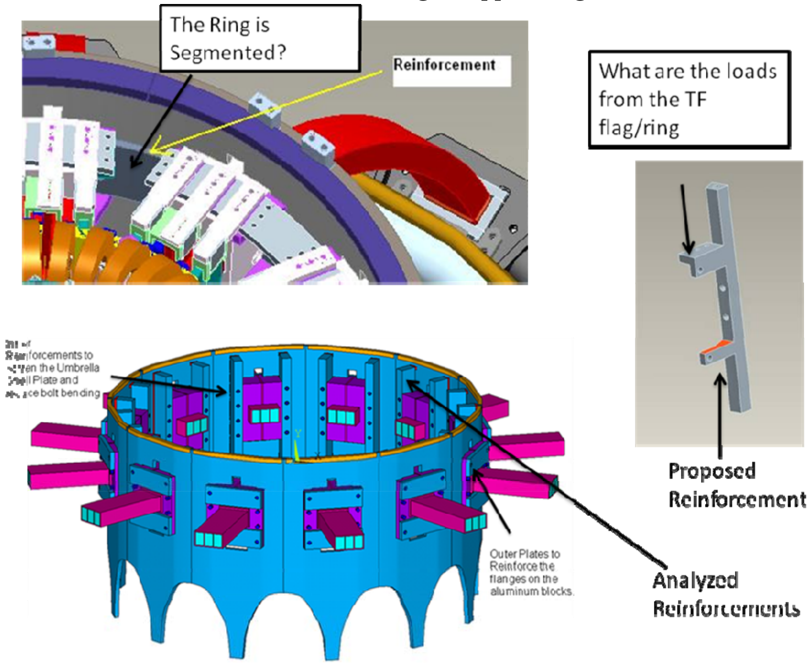


Figure 3.0-5 TF Flex Joint Support "Fingers" and One of the Initial Reinforcement Concepts

Loading from the fingers was obtained from [9] and post processed by Yuhu Zhai, but a review of the source of these loads determined that they were already included in the loading extracted from the global model [2]. This is discussed in section 5.5. The fingers help react the moment caused by the cantilevered extension of the outer leg between the umbrella structure and the flex strap.

The local model analysis is divided into four load steps. Figure 3.0-6 shows the results for each of the load steps with a consistent contour range (in psi) for comparison.

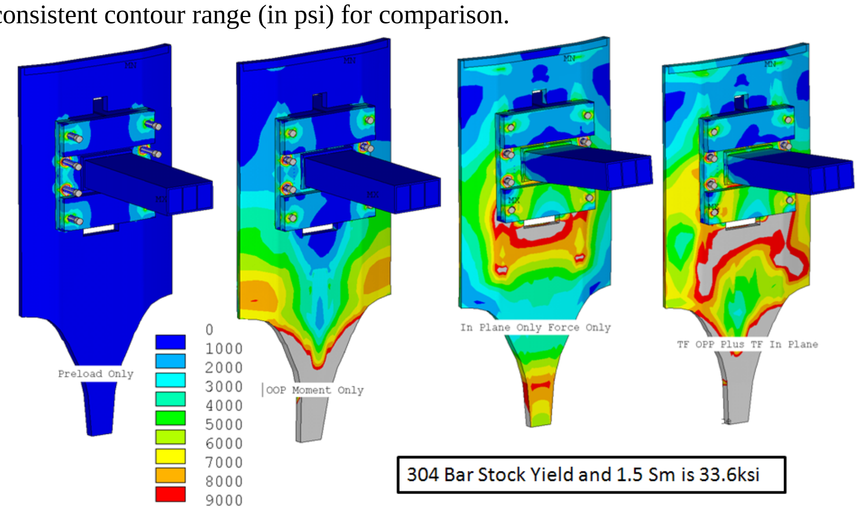


Figure 3.0-6 TF Stresses in the Local Model With the Same Contours (in psi) for Comparison of the Four Load Cases Considered.

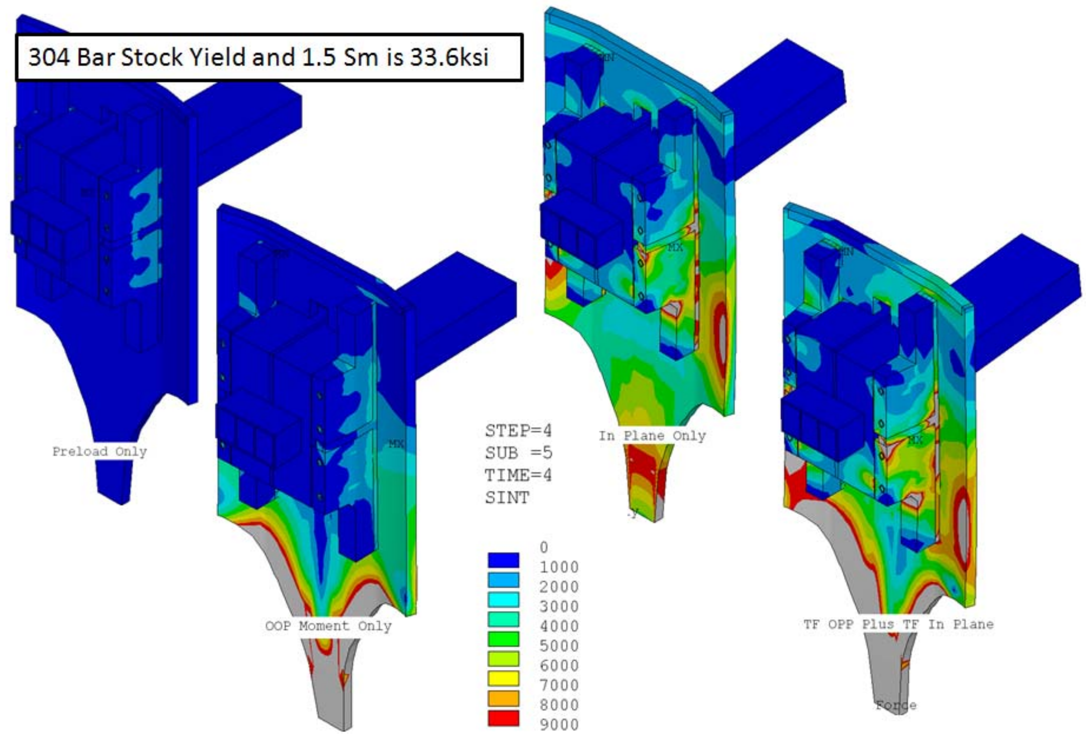


Figure 3.0-7 TF Stresses in the Local Model With the Same Contours (in psi) for Comparison of the Four Load Cases Considered.

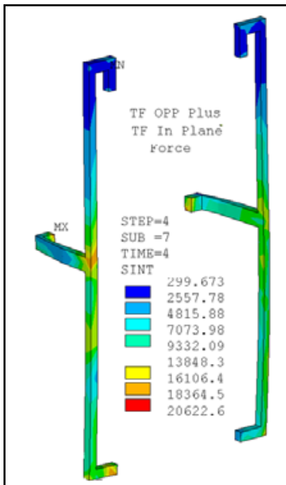


Figure 3.0-8

Weld stresses in the latest analyses based on ref [2] loads and the vertically split reinforcement, are acceptable. Local stress concentrations are 18 ksi and 20 ksi with the lower preload, but the bulk is below 14 ksi. In earlier analyses, the weld ends had stress concentrations. In the latest modeling of the weld, the weld "turns the corner" and puts the weld start/stop in a better location. Weld stresses are discussed in more detail ion section 9.3.

4.0 DCPS Algorithm

The out-of-plane (OOP) component of the critical stresses in the aluminum block and associated hardware will scale with the upper and lower half outer leg net moments. These are available from Bob Woolley's equations in NSTXU CALC 132-03-00 [5], and are implemented in Charlie Neumeyer's Design Point [4]. The in-plane component of the critical stress will scale with the square of the TF current.

4.1 Bolt Stress on Net section at threads

Bolt Stress Axial = (69.8MPa*single leg upper half moment/252 N-m + 82MPa*(TF current /130 kA)^2)
This should be kept below the allowable of 184 MPa.
Note that this excludes pre-tensioning which is intended to offload the bolts from cyclic loads. The pre-tension should be (69.8+82)/275.8 = 55% of yield as a minimum, but no greater than 75% of yield.

Bolt Stress Axial plus Bending = (15360psi*single leg upper half moment/252 N-m + 18,045 psi*(TF current /130 kA)^2)

Bolt Stress Axial plus Bending = (106MPa*single leg upper half moment/252 N-m + 125MPa*(TF current /130 kA)^2)
This should be kept below the bending allowable of 275.8 MPa.

4.2 TF Outer Leg Copper Stress at Aluminum Block:

TF Outer Leg Stress = (26,625psi*single leg upper half moment/252 N-m + 6112psi *(TF current /130 kA)^2)
or, in consistent SI units:
TF Outer Leg Stress = (183MPa*single leg upper half moment/252 N-m + 42MPa*(TF current /130 kA)^2)

This should be kept below the allowable of 238 MPa.

5.0 Design Input

5.1 Criteria

Criteria may be found in reference [3], NSTX Structural Design Criteria Document, I. Zatz

5.2 Design Point Spreadsheet Loads

Reference [6] is the design point spreadsheet for the upgrade project. This includes a load combination table that includes moment summations for the upper half vs. lower half of the coil arrays. These summations are recommended as a basis for scaling the loads and stresses calculated in this calculation in the DCPS. The loading employed in this calculation comes from equilibrium #79 and is the maximum reported in the design point spreadsheet.

5.3 References

[1] NSTXU-CALC-132-04-00 ANALYSIS OF TF OUTER LEG, Han Zhang, August 31, 2009
[2] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus December 2010
[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz
[4] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE GENERAL REQUIREMENTS DOCUMENT NSTX_CSU-RQMTS-GRD Revision 0 March 30, 2009 Prepared By: Charles Neumeyer NSTX Project Engineering Manager
[5] OOP PF/TF Torques on TF , R. Woolley, NSTXU CALC 132-03-00
[6] NSTX Design Point Sep 8 2009 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[7] http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html Dated 2 -17- 2009
[8] "Estimated and Compiled Properties of Glass/101K Epoxy/Kapton Composite Properties at Room Temperature" Report to Jim Chrzanowski Princeton Plasma Physics Laboratory July 15, 2009 R. P. Reed Cryogenic Materials, Inc. Boulder, CO
[9] "TF Flex Joint and TF Bundle Stub" T. Willard, NSTX-CALC-132-06-00
[10] Loads post-processed from the TF flex calculation analysis model, [9]
[11] ANSYS Structural Analysis Program, Revision 10.0 Swanson Analysis Systems
[12] email from Han Zhang transmitting Strap stiffnesses from Tom Willard:
Mark, Following is the number from Tom.
> The force required to deflect the 31 lamination assembly .3" vertically is 76.2 lbf.
> The flex assembly rotates 2.57 degrees with a torque of 100 in-lbf applied.

If you want to know the E and G to use in an ANSYS model, they depends on how you model the flex strap (I used two solid arch) and the dimensions. Anyway, I can check my model and tell you the numbers. But you still need to compare with your model dimensions.

Han.

[13] Umbrella Reinforcement Details, by P. Titus NSTXU CALC 12-07-00

[14] WBS 1.1.2 Lid/Spoke Assembly, Upper & Lower NSTX-CALC-12-08-00 Rev 0 May 2011 Prepared by: Peter Titus, Reviewed By: Irving Zatz, Cognizant Engineer: Mark Smith,
[15] NSTX Ring Bolted Joint, NSTX-U Calc 132-11 March 2011, Peter Rogoff, Reviewed by I. Zatz
[16] NATIONAL SPHERICAL TORUS EXPERIMENT CENTER STACK RESEARCH AND DEVELOPMENT FINAL REPORT No. 13-970430-JHC Prepared By: James H. Chrzanowski April 30, 1997 PRINCETON UNIVERSITY PLASMA PHYSICS LABORATORY (PPPL)
[17] "Mechanical, Electrical and Thermal Characterization of G10CR and G11CR Glass Cloth/Epoxy Laminates Between Room Temperature and 4 deg. K", M.B. Kasen et al , National Bureau of Standards, Boulder Colorado.
[18] Final Test Report, PPPL Purchase Order PE010925-W Fabrication and Testing of Cyanate Ester - Epoxy /Glass Fiber/Copper Laminates, October 7 2011, Prepared for Princetoin Plasma Physics Laboratory Forrestal Campus by Composite Technology Development Inc. 2600 Campus Drive Suite D Lafayette CO 80026
[19] "General Electric Design and Manufacture of a Test Coil for the LCP", 8th Symposium on Engineering Problems of Fusion Research, Vol III, Nov 1979
[20] "Handbook on Materials for Superconducting Machinery" MCIC- HB-04 Metals and Ceramics Information Center, Battelle Columbus Laboratories 505 King Avenue Columbus Ohio 43201

5.4 Photos and Drawings of Existing and Upgrade Components

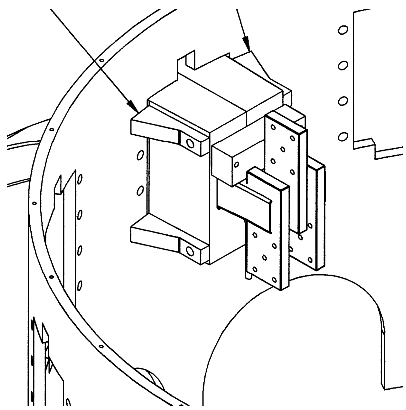


Figure 5.4-1 Isometric From the Drawing Series of the Existing Umbrella Structure

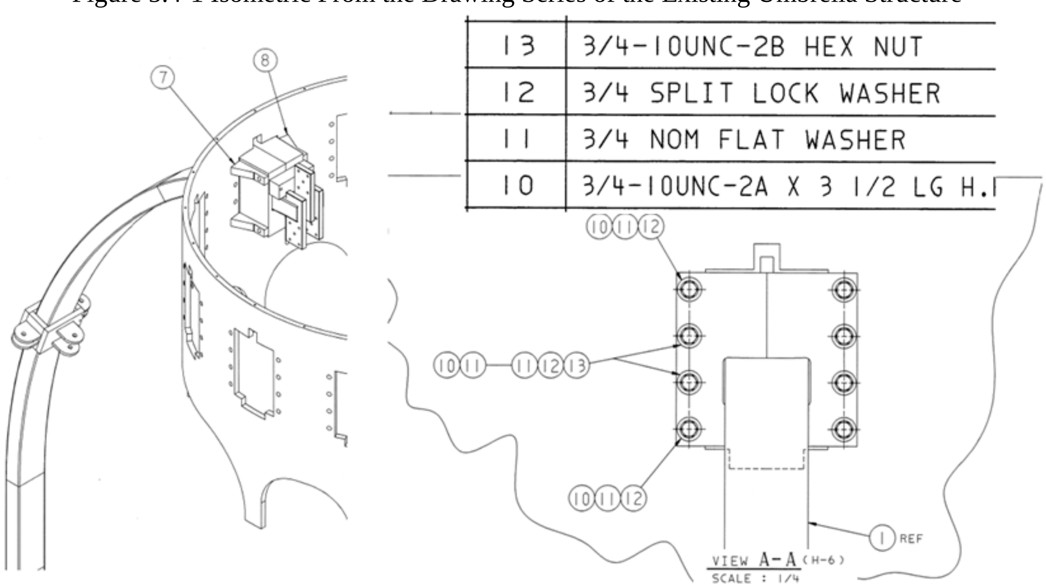


Figure 5.4-2 Excerpts from NSTX drawings ¾ inch bolts are used which have a stress area of .335 in^2

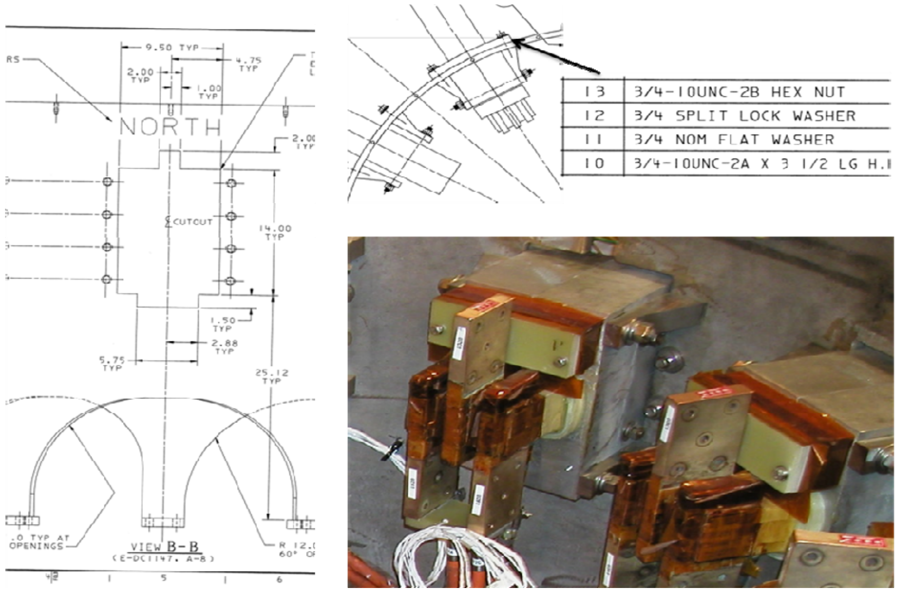


Figure 5.4-3 Excerpts from NSTX drawings, Photo of the blocks from inside the umbrella structure

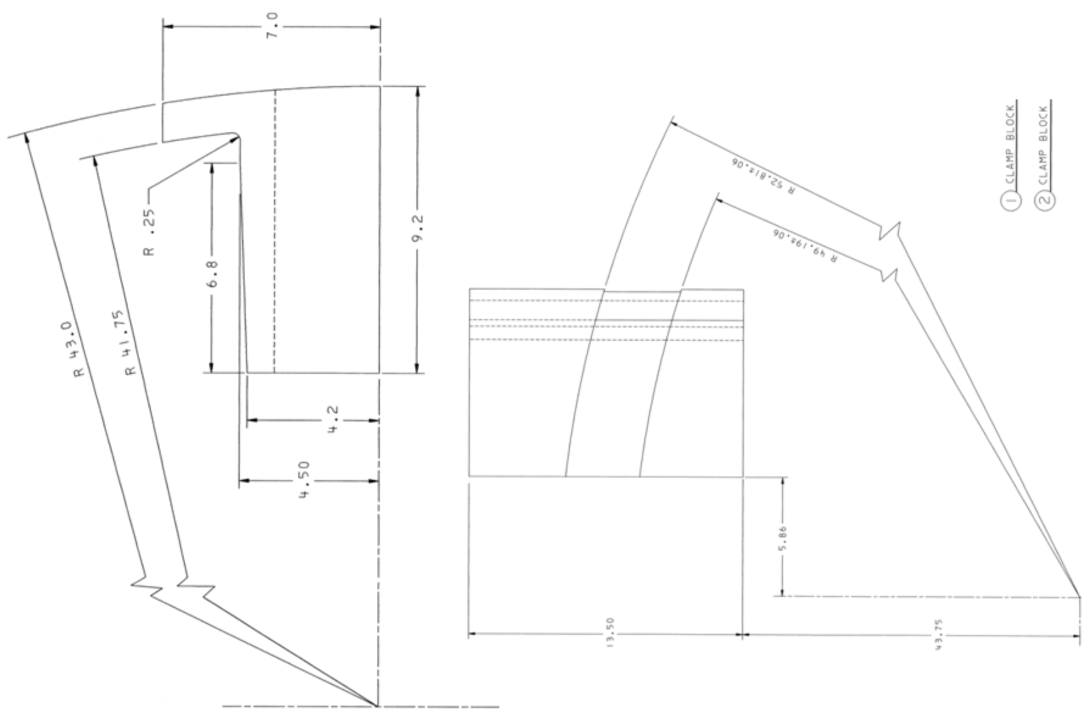


Figure 5.4-4 Excerpts from NSTX drawings,

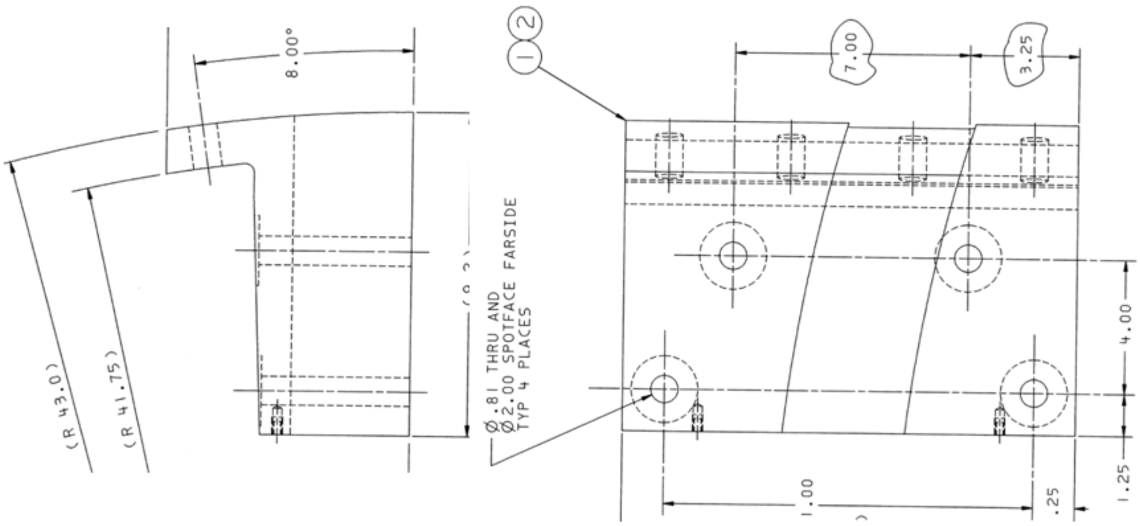


Figure 5.4-5 Excerpts from NSTX drawings

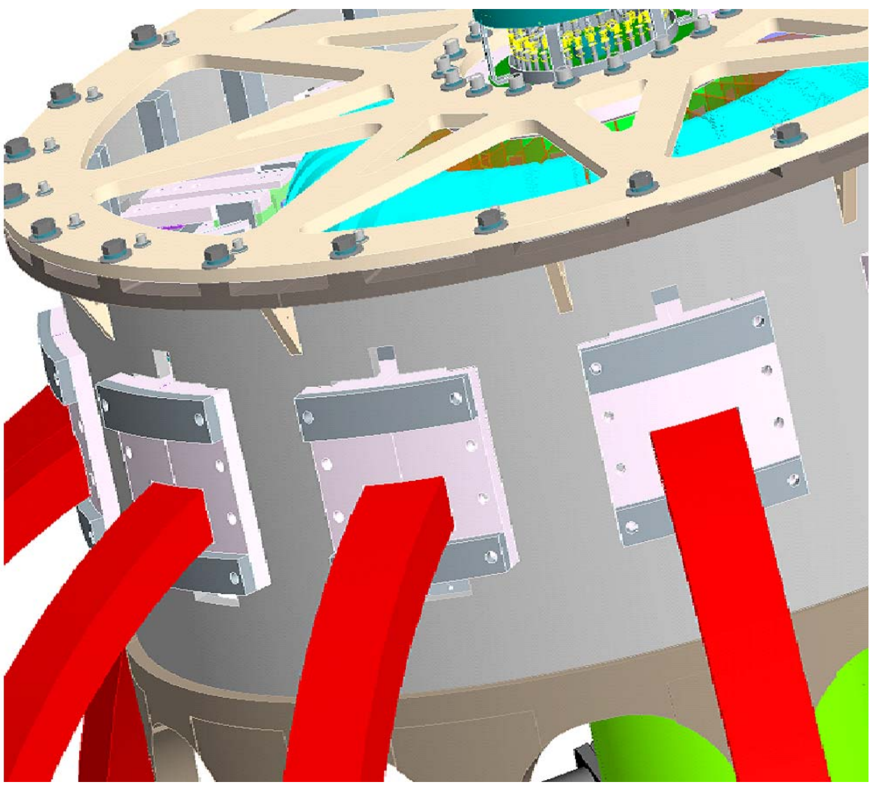


Figure 5.4-6 Screen Shot of the ProE Model of the Upgrade Components

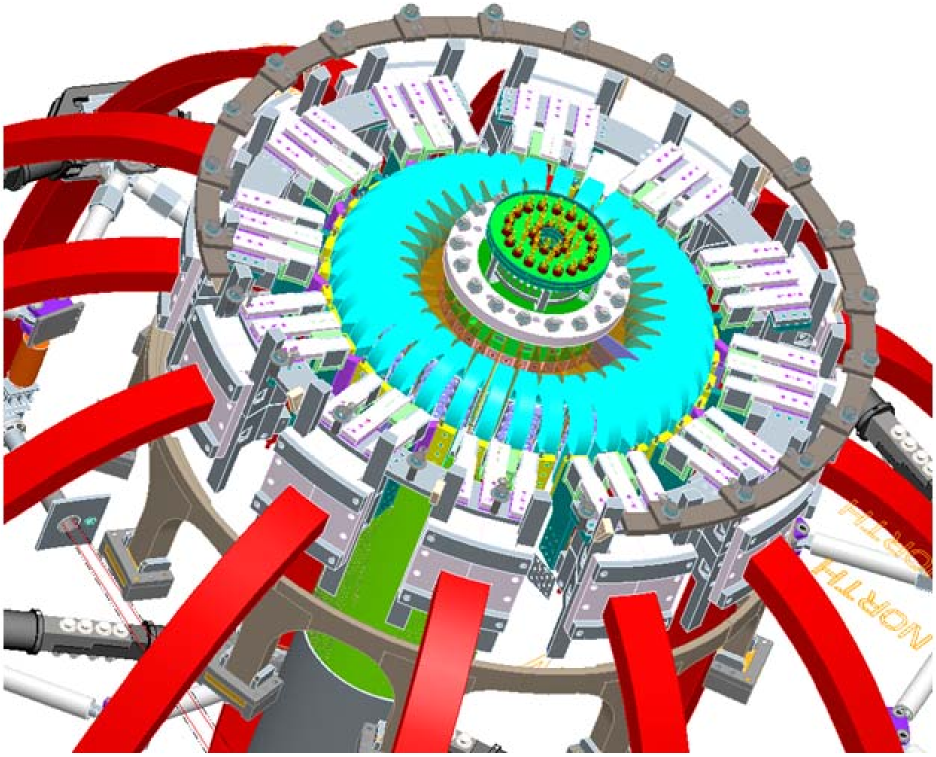


Figure 5.4-7 Screen Shot of the ProE Model

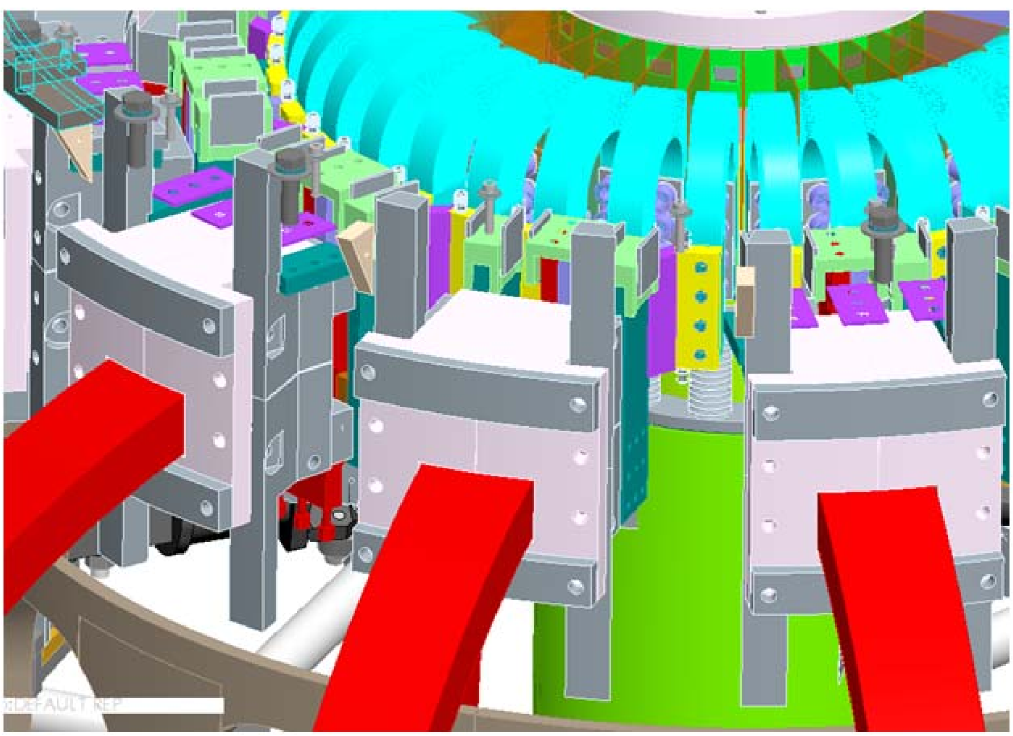


Figure 5.4-8 Screen Shot of the ProE Model

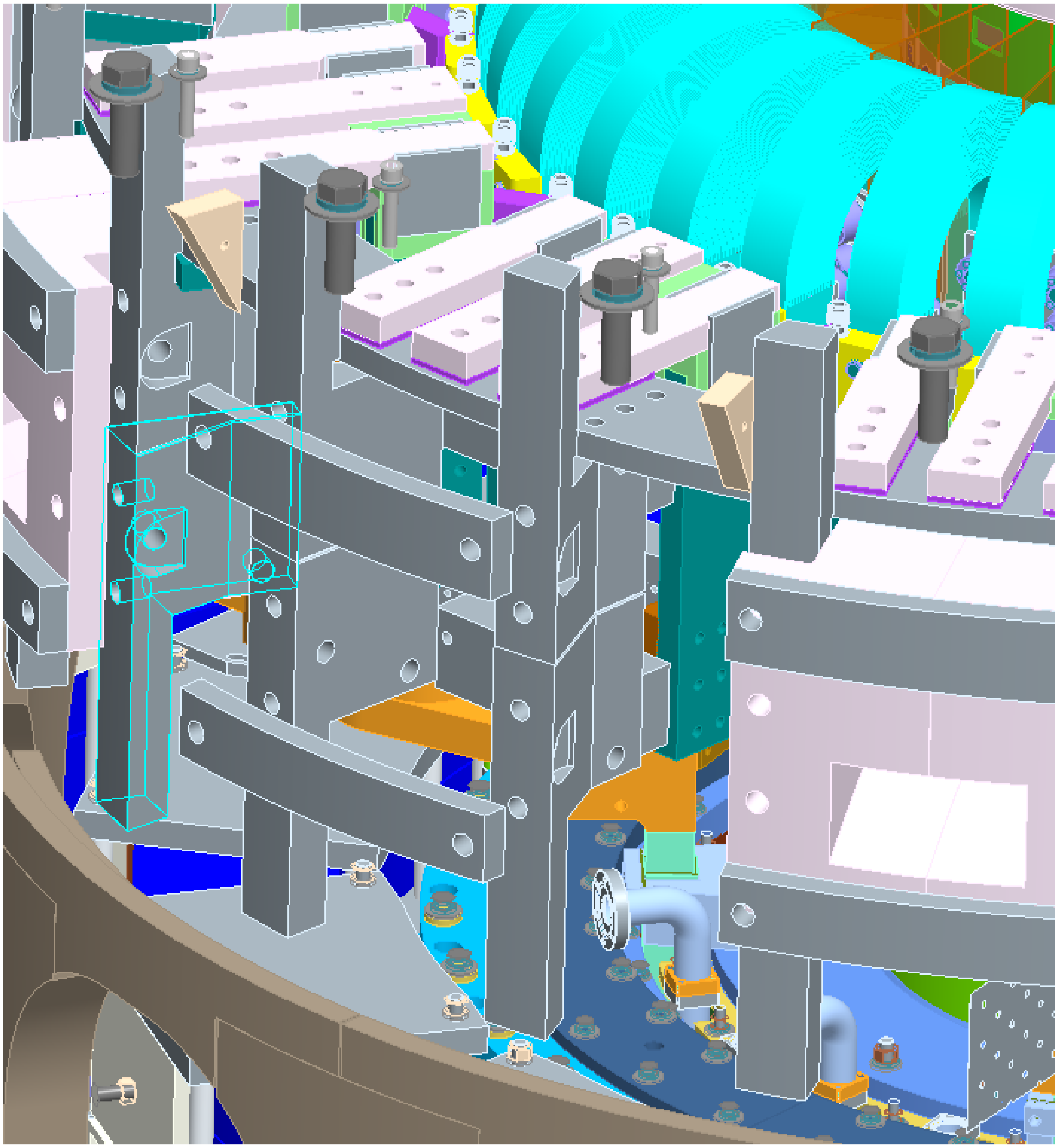


Figure 5.4-9 Screen Shot of the ProE Model

5.5 Loading

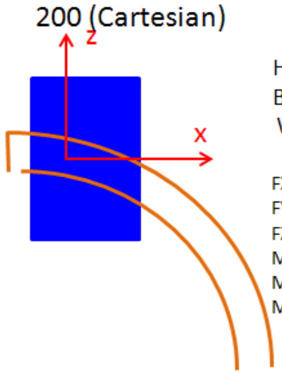
The aluminum blocks appear in a number of models. Han Zhang's model of the outer leg structures is the analysis of record for the outer legs, and, as of this writing, Han's loading from the worst of the 96 equilibria and for the stiff struts, is used along with ref [2] results. Figure 5.5-1 summarizes and compares the loading from the two global models [1] and [2] and loads derived for the PDR concept of using soft springs instead of the stiff knuckle struts currently planned. There is some load inventory from the length of TF current between the middle of the flex strap and the inside of the umbrella structure. The reference [2] global model summation includes this inventory. Reference [1] includes this up to the flex but not the contributory length of strap conductor loads that would be transmitted to the aluminum block. Earlier loads derived in this analysis are from a calculation of a single TF coil with fixity at the umbrella structure and no support from the knuckle clevis or ring. The single leg analysis uses scenario #79 to compute the loads. This has been extensively checked by D. Mangra, and T. Willard, and is consistent with the net upper half-outer leg torque calculated by Bob Woolley and included in the design point spreadsheet. Load comparisons are shown in figure 5.5-1

The aluminum blocks and bolting are also addressed in the global model calculation [2] in an approximate modeling. It was difficult to model the individual bolts and gapped interfaces in the large model. The global model does provide an indication of the relative magnitudes of the bolt loads for the 96 scenarios.

Load in Aluminum block (in coordinate system 200)

TFInPlane=242058
TFInPlane=TFInPlane*.2248
TFInPlaney=-25516.9
TFInPlaney=tfinplaney*.2248
momy=254831 IN-M
momy=momy*.2248*39.37
TFOOPForce=168311.2*.2248

coordinate system 200 (Cartesian)



Han EQ 16
Ball End Struts,
Welded Clevis

FX = -203828.1 N
FY = -111829.7 N
FZ = -17760.17 N
MX = 169.0026 N-m
MY = -5506.380 N-m
MZ = -12044.77 N-m

Titus Calc, EQ16
Ball End Struts,
Welded Clevis

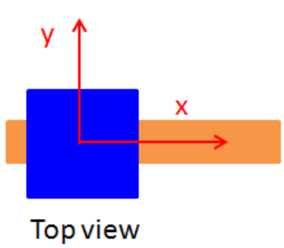
```
**** SUMMATION OF TOTAL FORCES
AND MOMENTS IN COORDINATE
SYSTEM 5
   NOTE: THE SUM IS DONE IN
COORDINATE SYSTEM 5
 FX = 139580.7
 FY = 90927.03
 FZ = 133837.8
 MX = -1362.338
 MY = 32135.61
 MZ = 9598.212

SUMMATION POINT= 1.0624    2.4824
0.28466
```

Titus Calc, EQ 79
Spring Struts,
Bolted Clevis
Hand Calc

FX = 242058 N
FY = 184800 N
FZ = -25500 N
MX = 0 N-m
MY = 0 N-m
MZ = 254831 N-m

	Han EQ 16	Titus Calc, EQ16	Titus Calc, EQ 79
Vector Sum of FX and FZ	204,600N	193,377N	243,340N
Mz at Alum Block	12044.77 N-m	9598 N-m	254831 N-m
My at Alum Block	5506.38N-m	32135N-m	0



	Fradial	Fvertical	Ftheta
Han's Early Loads	224-297 kN	10-44 kN	100 - 170 kN
Titus (This Calc), Scenario 79	242.1 kN	-25.5 kN	184.8*
Sri's 2009 Calc	256.3 kN	21.3	

* this is 168*1.1 intended to apply the 10% headroom in PF current
The 6 3/4 bolts should be preloaded to a minimum of 92 ft-lbs or 7375 lbs each to avoid cyclic loading. This produces a frictional restraint of 6*7373*.3 = 13275 lbs or 59052 N frictional restraint. Not enough to support the 184.8kN

Figure 5.5-1 Aluminum Block Load Comparisons

The summation point used in the ref [2] loads is 1.0624 m or 41.82 inches.

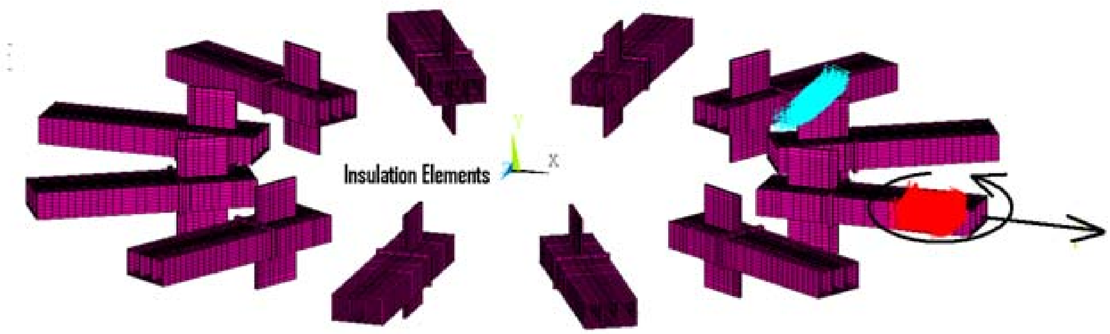


Figure 5.5-2 Application of Moments

Moments are applied by applying the forces at a point outboard of the center of the aluminum block.

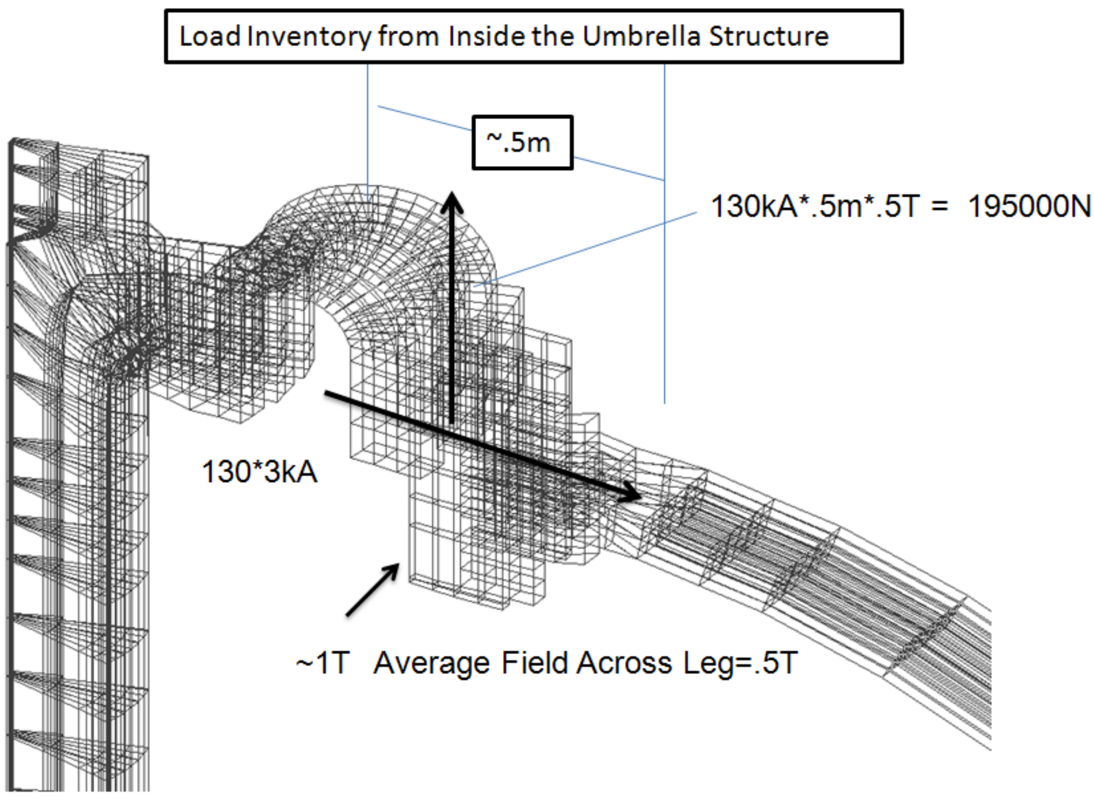


Figure 5.5-3 Load Inventory from Inside the Umbrella Structure

Forces and moments from the TF components inside the umbrella structure are also applied to the aluminum block. Additional loads from the flex strap will occur when the TF inner legs expand. This is as much as 8 mm or about .31 inches per reference [12]. The force required to deflect the 31 lamination assembly .3" vertically is 76.2 lbf. So, the flex elastic thermal deformation will not add significantly to the total forces.

From Ref [1]

The loading of record from Han Zhang's calculation is shown in figure 5.5-1, with comparisons of the EQ 16 loading from [2]. The radial and vertical loads vary based on the line of action of the tensile load in the outer leg. Temperature variations in the leg, PF and vacuum loads on the vessel, fit-up and uncertainties in the stiffness of the structures can vary the loads. The soft spring loading was the loading used in the PDR analyses and predates improvements in the outer leg supports.

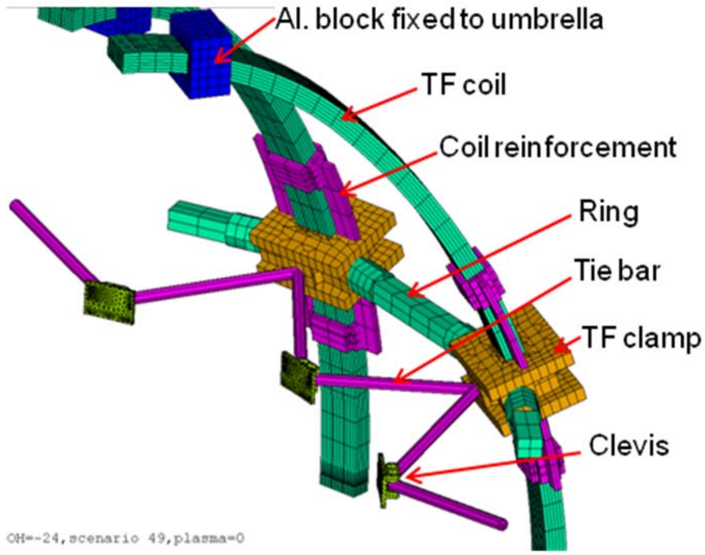


Figure 5.5-4 Ref [1] Model

Differences between ref [1] and [2] may relate to how much of the vertical loads from the TF inside of the umbrella structure is included. The ref [1] model included a portion of the TF leg inside the umbrella structure. Ref [2] includes the load inventory including the flex. The flex joint was analyzed by T. Willard [9]. Y Zhai post-processed these results and provided the load inventory imposed on the three fingers that support the paddles or flags.

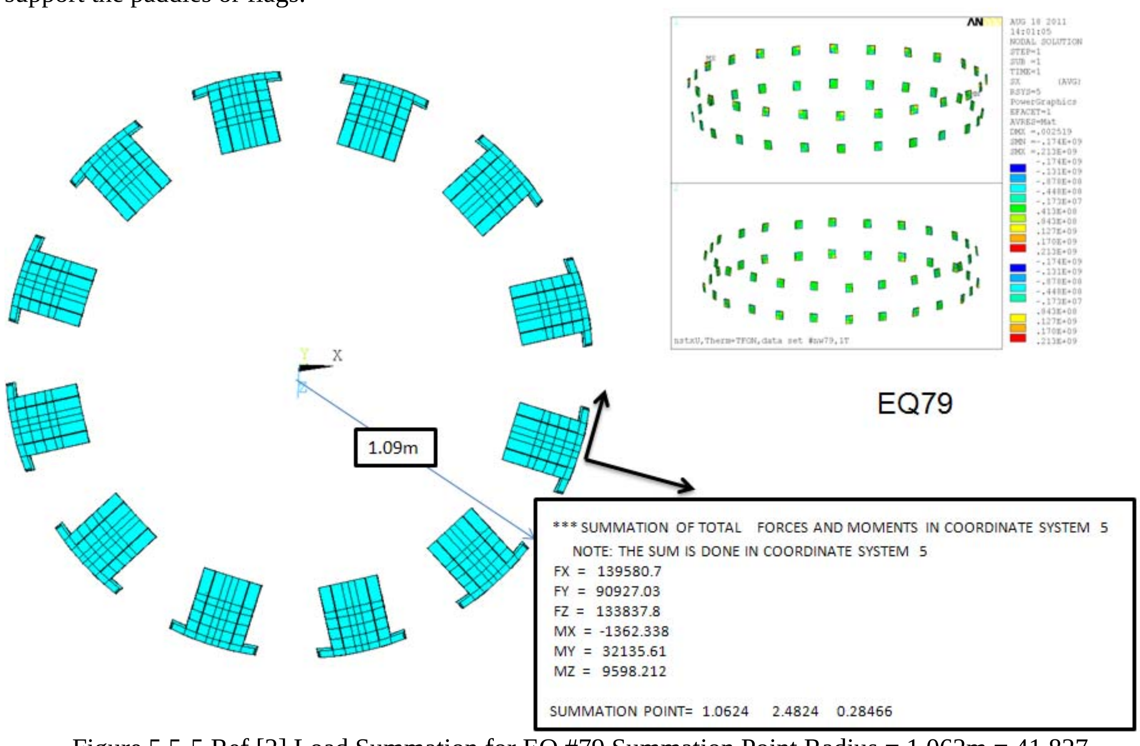


Figure 5.5-5 Ref [2] Load Summation for EQ #79 Summation Point Radius = 1.062m = 41.827

The global model [2], section 9.6, also is a source of loading. Loads shown above were extracted from the global model by selecting mat, 14, then selecting the nodes connected to mat, 14, then selecting the upper half of these nodes then graphically "reselecting" the pad nodes that are connected to the umbrella shell. A summation point at the center of the TF leg at the surface of the umbrella structure was selected using the ANSYS SPOINT command. RSYS,5 was used. Then the FSUM,RSYS command was issued.

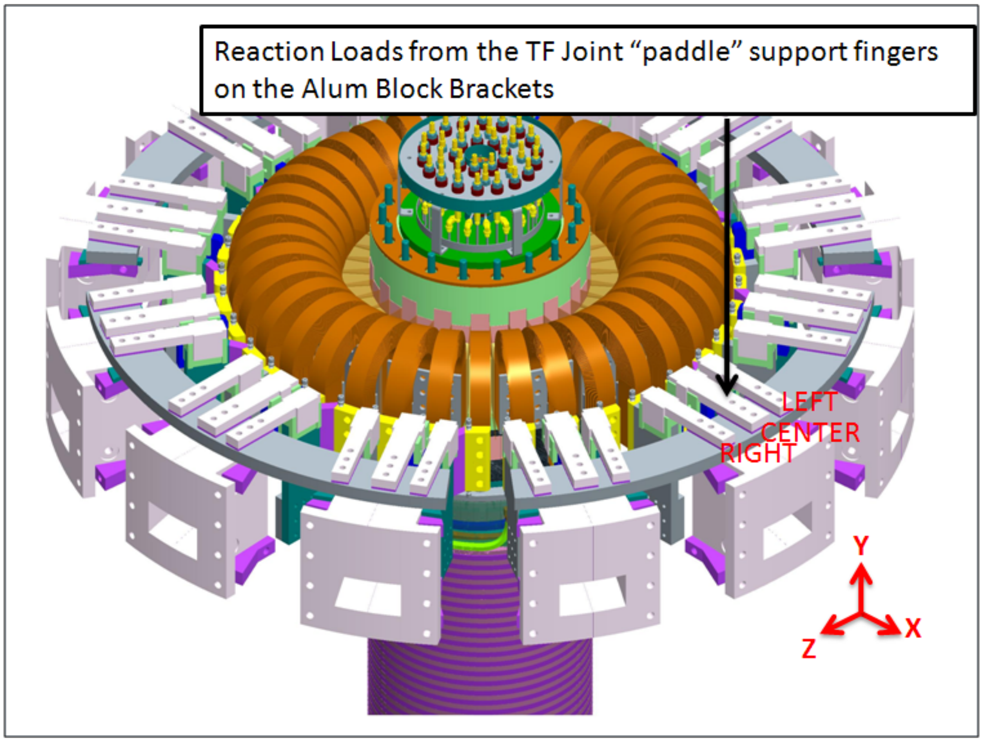


Figure 5.5-6 Paddle Support Fingers

Hi Pete, Mon 7/25/2011 4:21 PM

Please find attached the reaction loads at TF joint support fingers (LEFT, CENTER, RIGHT). The results are extracted via post-processing from Tom Willard Flex Strap model – with imported body temperature from transient thermal analysis and body force density from Maxwell.

Let me know if you have any questions.

Regards,
Yuhu

Reaction Forces

	Fx (kN)	Fy (kN)	Fz (kN)	Net Force (kN)
LEFT	-19.9	3.35	4.56	20.7
CENTER	-18.0	0.46	-0.46	18.0
RIGHT	-27.6	-12.6	2.42	30.4

Reaction Moments

	Tx (kNm)	Ty (kNm)	Tz (kNm)	Net Moment (kNm)
LEFT	0.03	-1.54	0.036	1.54
CENTER	0.05	0.54	0.29	0.62
RIGHT	0.14	1.2	1.78	2.15

Moment is given at the center of the Flex Strap global model

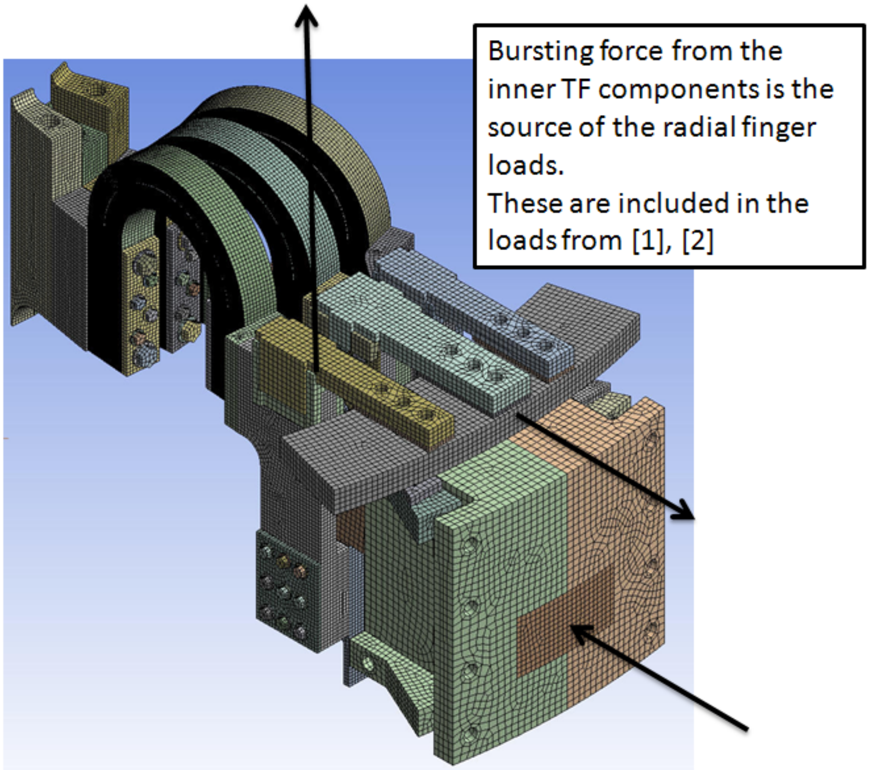


Figure 5.5-7 Bursting Load Inventory from Components Inside the Umbrella Structure

It was the original intention to add the finger loads to the loads from the global models but after reviewing the loads on the fingers it was concluded that these were part of the load inventory already included from the global models. The section of TF leg inside the umbrella structure is cantilevered from the aluminum blocks and the moment on this length of conductor results in a radially outward load at the fingers and a radially inward load on the TF conductor.

	Radial	Vertical	Theta
TF Outer Leg Loads	203.8	17.76	111.8
TF Finger Loads	65.5	-8.64	6.52

Loads other than the radial loads are small compared with the global loads

Table 1: Calculated force on Aluminum block when adding stainless steel case, rings and tie bars.

	ss case no effective			link to vacuum vessel: bar1, 2 and 3 have different orientations		
	no truss	adding case (0.5" thick, 12" wide)	adding ring (0.5x12" rect, welded)	adding bar1 (3x3" rect, pin connected)	adding bar2 (3x3" rect, pin connected)	adding bar3 (3x3" rect, pin connected)
Total end reaction force (kN)	**297**	**294**	**269**	**239**	**249**	**224**
End reaction force r (kN)	245.71	245.96	223.2	212.98	225	192.09
End reaction force theta (kN)	166.49	161.03	149.95	105.98	105.95	106.05
End reaction force z (kN)	11.956	10.3	10.155	19.366	9.2544	44.565

Prior to stiffening the knuckle truss struts, a simple estimate of the loading for Scenario 79 would be:
The total OOP load on one upper half of a TF outer leg - mid plane to aluminum block is 127,000N = 28,550 lbs. Five kips is assumed reacted by the knuckle clevis leaving 23,550 lbs to be split between the aluminum block and shear in the TF outer leg mid-plane or 11,775 lbs at each end.

The worst moment about a vertical axis is 22.8% of the total OOP moment.

	Fradial	Fvertical	Ftheta
Han's Loads	224-297 kN	10-44 kN	100 - 170 kN
Titus (This Calc), Scenario 79	242.1 kN	-25.5 kN	184.8*
Sri's 2009 Calc	256.3 kN	21.3	

* This is 168*1.1 intended to apply the 10% headroom in PF current

```
TFInPlane=242058
TFInPlane=TFInPlane*.2248
TFInPlaney=-25516.9
TFInPlaney=tfinplaney*.2248
momy=254831   !N-M
momy=momy*.2248*39.37
TFOOPForce=168311.2*.2248
```

Sri's Input to Umbrella Structure Analysis

Fx(Radial)	Fz(Vertical)
25628 N*	21314 N

*This must have been a typo. He probably meant 256.3 kN.

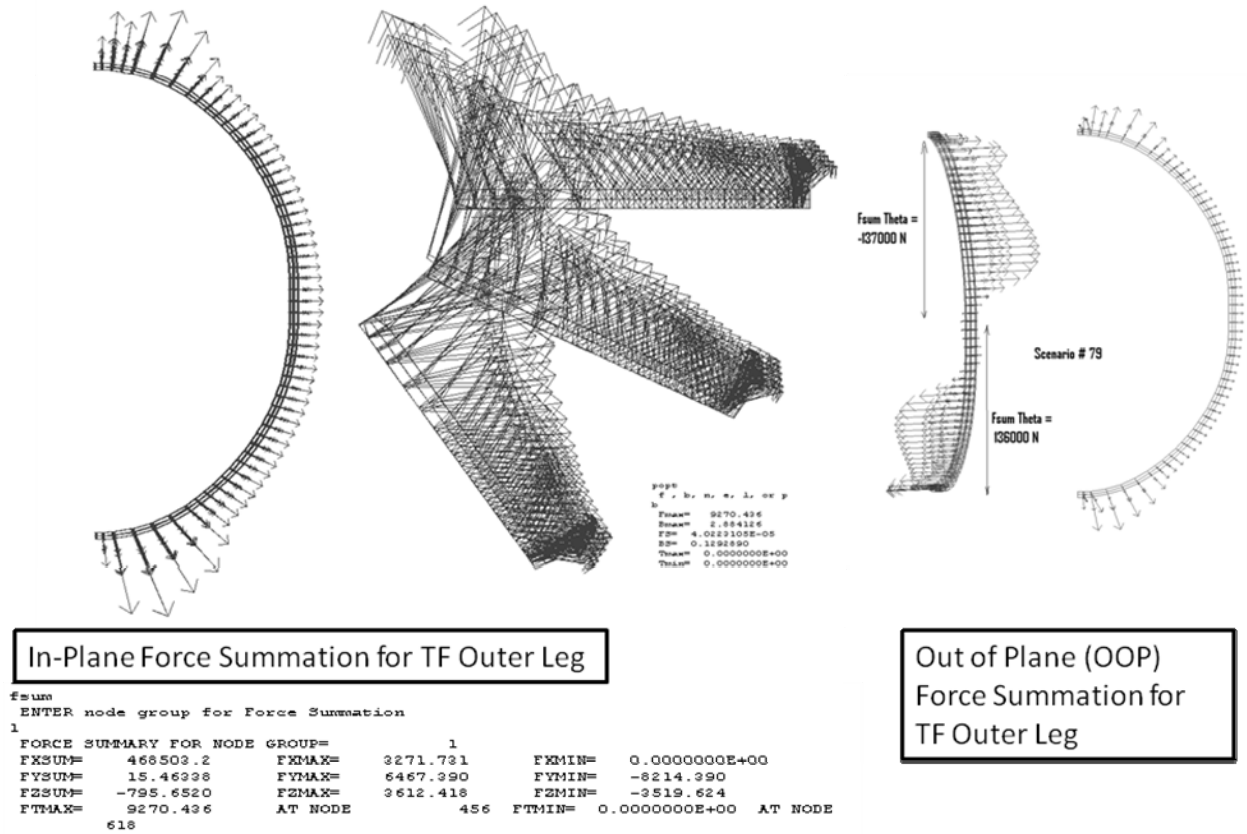


Figure 5.5-8

In addition to the forces at the aluminum blocks, there are moments as well. These are applied by calculating an effective radius at which to apply the theta and vertical forces on the "stub" of the TF leg in the model.

```
esel,mat,1
nelem
nrsel,x,52,53
f,all,fy,TFOOPForce/(378/2)*1.1
esel,mat,1
nelem
```

```
esel,mat,1
nelem
nrsel,x,46.1,47
f,all,fz,TFInPlaney/(378/2)
```

Reaction forces and moments applied to the aluminum block are from a single TF outer leg analysis conservatively modeled with no knuckle clevis or ring. This is intended to produce a worst set of loads for sizing the aluminum block bolting.

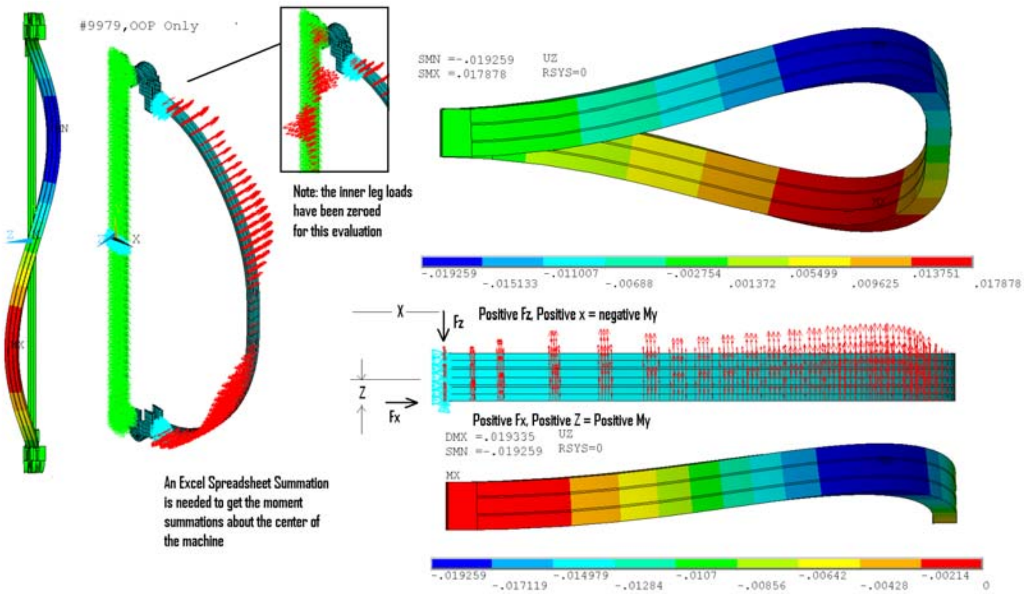


Figure 5.5-9 Single TF Coil Model Used to Study Load Distributions

Reactions at the Umbrella Structure from the Singe TF Model									Local Mom	Shear*Rac	Total Moment	Local Mom About a Theta Axis		
									at Alum Block		About Vert Axis	Fy*(y-2.652547)		
									MY Reaction	MyReaction				
NODE	FX	FY	FZ	NODE	X	Y	Z		FX*Zccor	Fz*Xcoor				
51	29898	20094	23805	51	0.93959	2.5401	-7.62E-02		-2.28E+03	-22366.9	-2.46E+04	-2259.51		
52	25841	-44986	28500	52	0.95035	2.6155	-7.62E-02		-1.97E+03	-27085	-2.91E+04	1666.596		
56	-2743.6	-7566.3	-18402	56	0.95035	2.6155	1.63E-07		-4.48E-04	17488.34	1.75E+04	280.3087		
58	51042	-14350	51044	58	0.94497	2.5778	-7.62E-02		-3.89E+03	-48235	-5.21E+04	1072.619		
59	-27388	-15822	20958	59	0.93959	2.5401	7.62E-02		-2.09E+03	-19691.9	-2.18E+04	1779.136		
60	-28730	36819	24633	60	0.95035	2.6155	7.62E-02		-2.19E+03	-23410	-2.56E+04	-1364.03		
64	-49979	15236	44656	64	0.94497	2.5778	7.62E-02		-3.81E+03	-42198.6	-4.60E+04	-1138.85		
790	698.6	382.74	-11560	790	0.94497	2.5778	1.55E-07		1.08E-04	10923.85	1.09E+04	-28.6087		
3717	53383	-12343	53937	3717	0.94766	2.5967	-7.62E-02		-4.07E+03	-51113.9	-5.52E+04	689.3195		
3719	31770	-8935.2	-9004.2	3719	0.94497	2.5778	-3.10E-02		-9.86E+02	8508.699	7.52E+03	667.8794		
3721	33381	-7220.8	-17049	3721	0.94766	2.5967	-3.10E-02		-1.04E+03	16156.66	1.51E+04	403.26		
3723	14762	-28259	-11996	3723	0.95035	2.6155	-3.10E-02		-4.58E+02	11400.4	1.09E+04	1046.911		
3725	12105	-2424	-6690.5	3725	0.94497	2.5778	-2.54E-02		-3.07E+02	6322.322	6.01E+03	181.1867		
3727	22153	-3822.4	-14331	3727	0.94766	2.5967	-2.54E-02		-5.63E+02	13580.92	1.30E+04	213.4696		
3729	14888	-16097	-10085	3729	0.95035	2.6155	-2.54E-02		-3.78E+02	9584.28	9.21E+03	596.3456		
3731	-1499	555.51	-25949	3731	0.94766	2.5967	1.17E-07		-1.75E-04	24590.83	2.46E+04	-31.0236		
3733	51146	-10304	49965	3733	0.94228	2.5589	-7.62E-02		-3.90E+03	-47081	-5.10E+04	964.9387		
3735	19078	11215	7374.6	3735	0.93959	2.5401	-3.10E-02		-5.92E+02	-6929.1	-7.52E+03	-1261.09		
3737	33413	-5269.5	-1221.2	3737	0.94228	2.5589	-3.10E-02		-1.04E+03	1150.712	1.14E+02	493.4729		
3741	2689.1	1460.1	-638.67	3741	0.94228	2.5589	-2.54E-02		-6.83E+01	601.806	5.34E+02	-136.734		
3743	3841.1	5386.4	7430.7	3743	0.94228	2.5589	8.27E-08		3.18E-04	-7001.8	-7.00E+03	-504.42		
3745	-12517	2331.9	-6886.2	3745	0.94497	2.5778	2.54E-02		-3.18E+02	6507.252	6.19E+03	-174.303		
3747	-22689	3787.7	-14512	3747	0.94766	2.5967	2.54E-02		-5.76E+02	13752.44	1.32E+04	-211.532		
3749	-15348	14032	-10182	3749	0.95035	2.6155	2.54E-02		-3.90E+02	9676.464	9.29E+03	-519.844		
3751	-32169	8894.1	-9110.9	3751	0.94497	2.5778	3.10E-02		-9.98E+02	8609.527	7.61E+03	-664.807		
3753	-33902	7202.6	-17099	3753	0.94766	2.5967	3.10E-02		-1.05E+03	16204.04	1.52E+04	-402.244		
3755	-15204	26370	-11981	3755	0.95035	2.6155	3.10E-02		-4.72E+02	11386.14	1.09E+04	-976.929		
3757	-54266	12933	46993	3757	0.94766	2.5967	7.62E-02		-4.14E+03	-44533.4	-4.87E+04	-722.269		
3761	-2571.3	22.023	-245.62	3761	0.94228	2.5589	2.54E-02		-6.53E+01	231.4428	1.66E+02	-2.06239		
3763	-18075	-8484.5	7319.1	3763	0.93959	2.5401	3.10E-02		-5.61E+02	-6876.95	-7.44E+03	954.0566		
3765	-33385	5716.7	-1016.2	3765	0.94228	2.5589	3.10E-02		-1.04E+03	957.5449	-7.81E+01	-535.352		
3767	-49167	12253	44513	3767	0.94228	2.5589	7.62E-02		-3.75E+03	-41943.7	-4.57E+04	-1147.46		
5121	67150	-20118	-14778	5121	0.94497	2.5778	-5.36E-02		-3.60E+03	13964.77	1.04E+04	1503.76		
5123	80308	-18047	-21589	5123	0.94766	2.5967	-5.36E-02		-4.31E+03	20459.03	1.62E+04	1007.871		
5125	33697	26918	801.25	5125	0.93959	2.5401	-5.36E-02		-1.81E+03	-752.846	-2.56E+03	-3026.85		
5127	60447	-13078	-9292	5127	0.94228	2.5589	-5.36E-02		-3.24E+03	8755.666	5.52E+03	1224.715		
5337	42432	-66816	-14537	5337	0.95035	2.6155	-5.36E-02		-2.27E+03	13815.24	1.15E+04	2475.332		
	Fradial	Fvert	Ftheta			95.4917			Loca Bend Mor	Mom fro Shear				
Totals	**242058**	**-25517**	**168311**			2.652547			-5.82E+04	-144592	-2.03E+05	2.11E+03		
										-2.03E+05			-4.66E+01	
									254831	254831	254831	-8.28E-02	-3.26E+00	Vertical Lc
									-2.28E-01	-5.67E-01	-7.96E-01		-5736.21	Net Vertic

The summation above is from the single coil model shown in Figure 5.5-9. The summation is at the fixed nodes modeling the interface with the umbrella structure. 254831 N-m is the total sum of the TF OOP loads about the machine central axis. This is compared with the reactions at the umbrella structure. 79.6% of the outer leg moment appears at the umbrella structure - the rest is reacted by TF equatorial plane shear. The loads from this analysis formed the basis of early analyses when the truss at the vessel knuckle was considerably softened to almost eliminate the loads at the bolted cantilevered clevis. The discussion of this loading is retained to emphasize the value of a stiff structure at the knuckle clevis. Comparisons of these loads and those from the global model are shown in Figure 5.5-1

6.0 Materials

6.1 Stainless Steel Properties

Table 6.1-1Tensile Properties for Stainless Steels

Material	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	275.8[19]	613[19]
316 LN SST Weld	324[19]	482[19] 553[19]
316 SST Sheet Annealed	275[20]	596[20]
316 SST Plate Annealed		579
304 Stainless Steel (Bar,annealed)	234 33.6ksi	640 93ksi
304 SST 50% CW	1089	1241 180ksi

Table 6.1-2 Coil Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm
316 Stainless Steel	184*	276
316 Weld	161	241
304 Stainless Steel (Bar,annealed)	156MPa(22.6ksi)	234 MPa (33.9ksi)

*The yield criteria governs and Sm = 26.6 ksi or 184 MPa

6.2 Fatigue Data

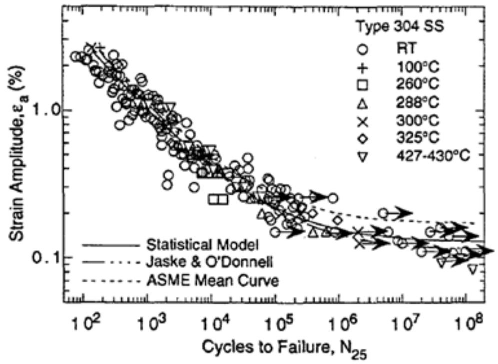


Figure 6.2-1 From Tom Willard's Collection of SST Fatigue Data
"Estimation of Fatigue Strain-Life Curves for Austenitic in Light Water Reactor Environments Stainless Steels", Argonne Nat. Lab, 1998

6.3 Bolt Strength Data

ASTM A193 Bolt Specs from PortlandBolt.com

B8M	Class 1 Stainless steel, AISI 316, carbide solution treated.
B8	Class 2 Stainless steel, AISI 304, carbide solution treated, strain hardened
B8M	Class 2 Stainless steel, AISI 316, carbide solution treated, strain hardened

Mechanical Properties

Grade	Size	Tensile ksi, min	Yield, ksi, min	Elong, %, min	RA % min
B8M Class 1	All	75	30	30	50
B8 Class 2	Up to 3/4	125	100	12	35
	7/8 - 1	115	80	15	35
	1-1/8 - 1-1/4	105	65	20	35
	1-3/8 - 1-1/2	100	50	28	45
B8M Class 2	Up to 3/4	110	95	15	45
	7/8 - 1	100	80	20	45
	1-1/8 - 1-1/4	95	65	25	45
	1-3/8 - 1-1/2	90	50	30	45

6.4 Insulation Strength Data

There will be two types of TF outer leg coil insulation. The original system was a pre-preg system which used DZ-80 primer. This was tested [16] when the original NSTX was under construction. The new system is CTD 425 with a CTD 450 primer.

6.4.1 Original Insulation system (CTD 12P) Capacities

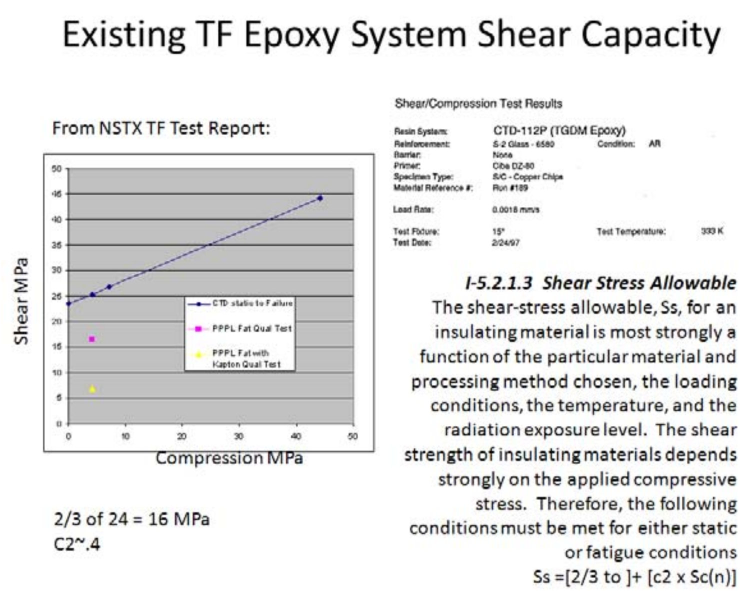


Figure 6.4.1-1 Existing TF Outer Leg Shear Compression Data

NSTX FINAL REPORT No. 13-970430-JHC
CENTER STACK R&D

Table No. 2-4
BI-AXIAL SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (Lbs.)	Shear Load (psi) *	Compressive Load (psi)	Specimen Temp (°C)
11	3125	6250	600	60
12	3125	6250	600	60
13	3000	6000	600	60
14	3000	6000	600	60
19	3350	6750	600	60
20	3350	6750	600	60
21	2625	5250	600	60
22	2625	5250	600	60
3	3100	6200	2000	60
4	3100	6200	2000	60
9	3525	7050	1000	60
10	3525	7050	1000	60

* Destructive load

Figure 6.4.1-2 Existing TF Outer Leg Shear Compression Data

Table No. 2-6
SHEAR/COMPRESSION FATIGUE TEST RESULTS
(TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (psi)	Compressive Load (psi)	Specimen Temp (°C)	Cycles Completed
11	2400	600	60	1,000,000
12	2400	600	60	1,000,000
13	2400	600	60	1,000,000
14	2400	600	60	1,000,000
19	2400	600	60	1,000,000
20	2400	600	60	1,000,000

=2400*6895/1000000 = 16.548MPa

Figure 6.4.1-3 Existing TF Outer Leg Shear Compression Fatigue Test Data

The epoxy system was qualified for 2400*6895/1,000,000 = 16.55MPa at 1e6 cycles. NSTX has been operating for nearly 10 years and recently (July 2011) experienced a fault in the central column. The failure analysis included assessments of insulation stresses as well as other failure causes including chemistry of the flux used. There were no indications of insulation mechanical damage, even though the torsional shear was calculated to be 20 MPa for the High TF current shots rather than the allowed 16.5 MPa and the tokamak operated for about 20,000 shots at full OH field and the lesser TF current (53 vs. 71 kA).

6.4.2NSTX Upgrade Insulation System (CTD 425 with CTD 450 Primer) capacities

Two replacement coils are planned for the upgrade. These will be VPI'ed with the new epoxy materials that have been tested and qualified for service in the TF inner leg. The allowable shear capacity of the new system is between 22 and 25 MPa, [1] [18], depending on the cyclic requirements in the GRD. It is in excess of the existing epoxy capacity of 16 MPa.

6.5 Aluminum Block Properties

The aluminum blocks appear to be cast material rather than the wrought material called out in the drawings. Figure 6.5-1 includes some close-ups of the block which show porosity more like would be found in a sand casting. Appendix B shows the range of properties expected for cast material. There are some large tensile yields and some as low as 6 to 7 ksi. The biggest concern is that the ductilities are low. If fit-up isn't perfect, the blocks may have been deformed close to their ultimate during assembly or could be when the upgrade components are added. The uncertainty in the properties, particularly the ductility, argues for some additional reinforcements to provide redundancy in the block flange.

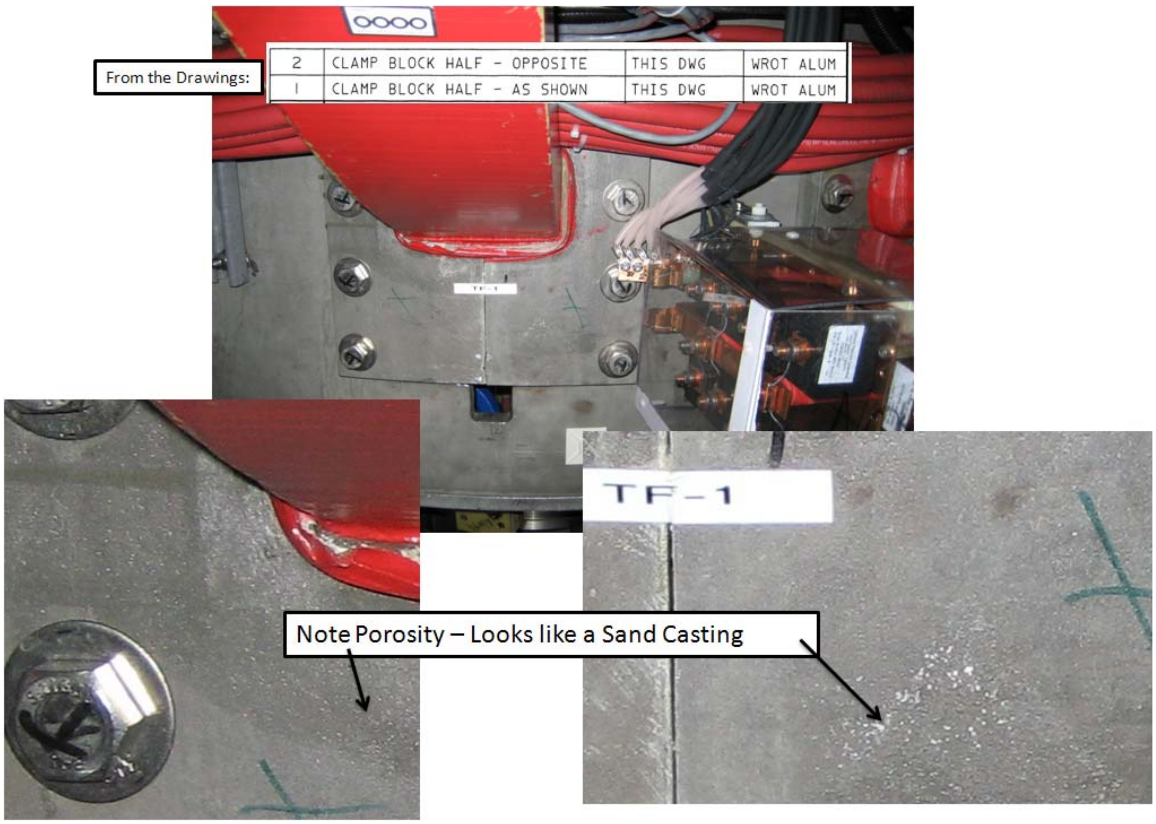


Figure 6.5-1Photos of existing Block Components

6.6 TF Conductor Properties

The TF copper ultimate is 39,000 psi or 270 MPa [16]. The yield is 38 ksi (262 MPa) [16]. Sm is 2/3 yield or 25.3 ksi or 173 MPa with adequate ductility, which is the case with this copper which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor per [3] (it is for other structural materials). These stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10%. So, the Sm value is 156 MPa or 23 ksi, and the bending allowable is 34.6 ksi.

6.7 Weld Allowable

From the NSTX Criteria:

Weld Allowable

For welds in steel, the design Tresca stress shall be the lesser of:
2/3 of the ***minimum*** specified yield if the weld at temperature, or
1/3 of the ***minimum*** specified tensile strength of the weld at temperature.

From the AISC Criteria:

Reference and Weld	Rod or weld wire	Parent Material	Allowable Stress (Exclusive of Weld Efficiency)
AISC Stress on cross section of full penetration Welds		All	Same as Base material
AISC Shear Stress on Effective Throat of fillet weld	AWS A5.1 E60XX	A36 -	21 ksi

For shear on an effective throat of a fillet, For 304 Stainless, the weld metal is annealed, or the base metal in the heat effected zone is annealed. and Estimate 241*21/36 = 140 MPa = 20 ksi (without weld efficiency)
This is consistent with NSTX Criteria of 2/3 yield or 2/3 of 30ksi for annealed 304
With a weld efficiency of .7 the allowable is 14ksi, or 96 MPa
For fillets divide weld area by sqrt(2)

7.0 FEA Models and Analyses

There are a number of analyses available to address the loads in the aluminum blocks and the umbrella structure around the blocks. Early upgrade analyses were done be S. Avasarala in 2009. These were based on a 5/8-inch shell thickness for the umbrella structure. In early 2010, the umbrella structure models were updated to the 1 inch thickness.

```
csys,5
nrotate,all
cpdele,all,all
cpcyc,ux,.001,5,0,30,0
cpcyc,uy,.001,5,0,30,0
cpcyc,uz,.001,5,0,30,0
nsel,z,-40,-33.5
d,all,all,0.0
```

The model used in this calculation is a 30 degree cyclic symmetry model. This is reasonably representative of the symmetry of the TF coils and aluminum blocks, but the umbrella structure is a bit more complex. At this writing, the effect of the double arch and the non-uniformity of the umbrella structure is considered in the global model and in other referenced calculations and analyses.

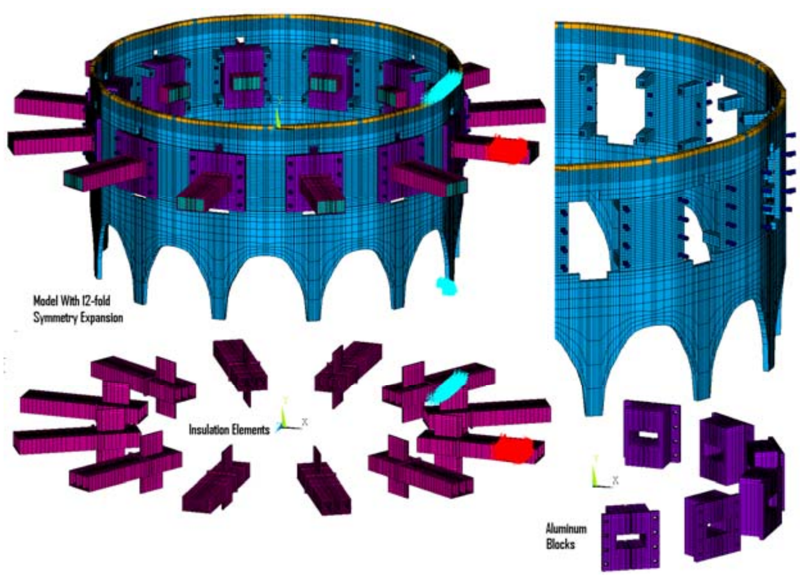


Figure 7.0-1 Model elements with Symmetry Expansion and Displacement Constraints Shown.

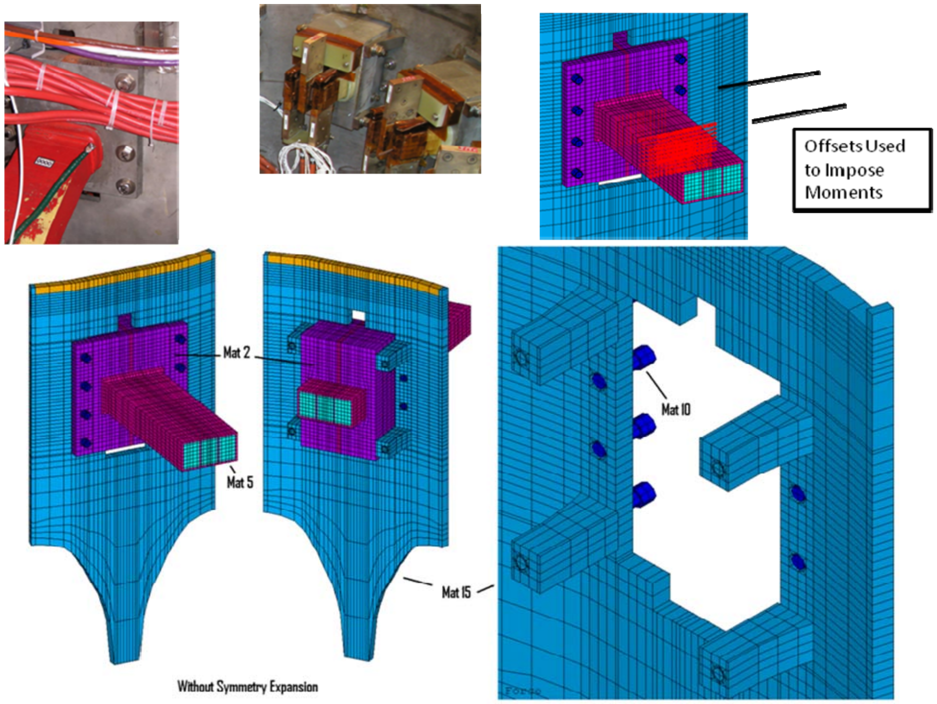


Figure 7.0-2 Model Plots and Comparisons with the Actual Components. Loads are applied with offsets to apply the appropriate moments concurrent with the loads.

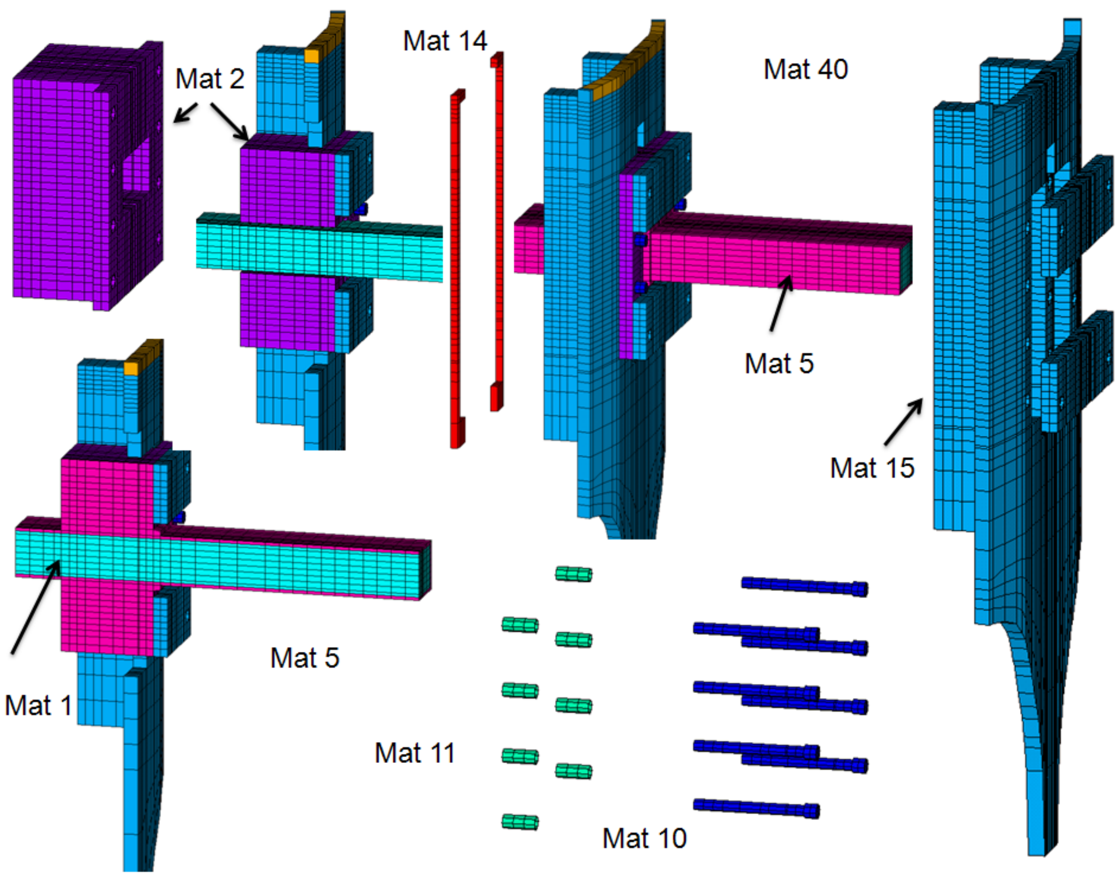


Figure 7.0-3 Modeling Elements

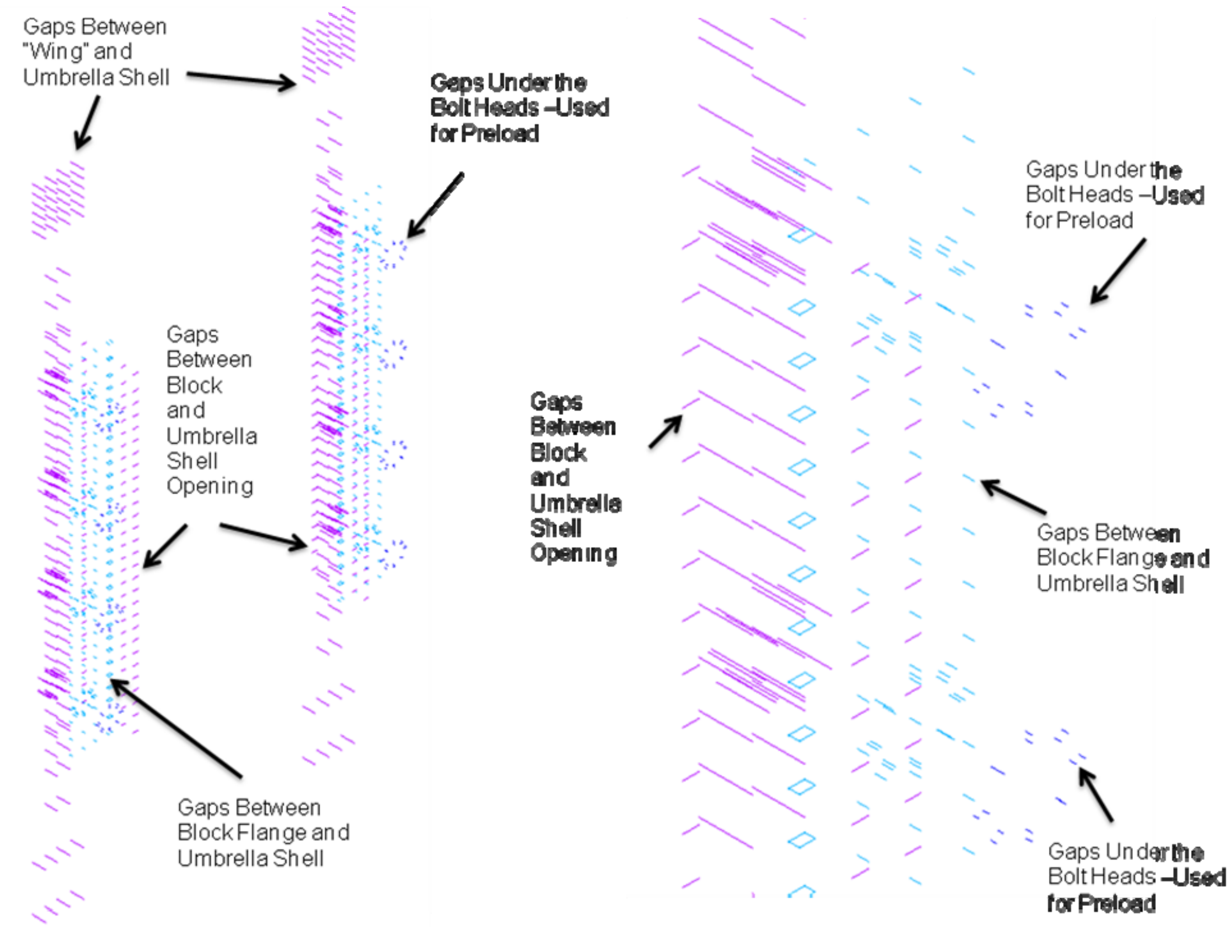


Figure 7.0-4 Gap Elements Used in the Model

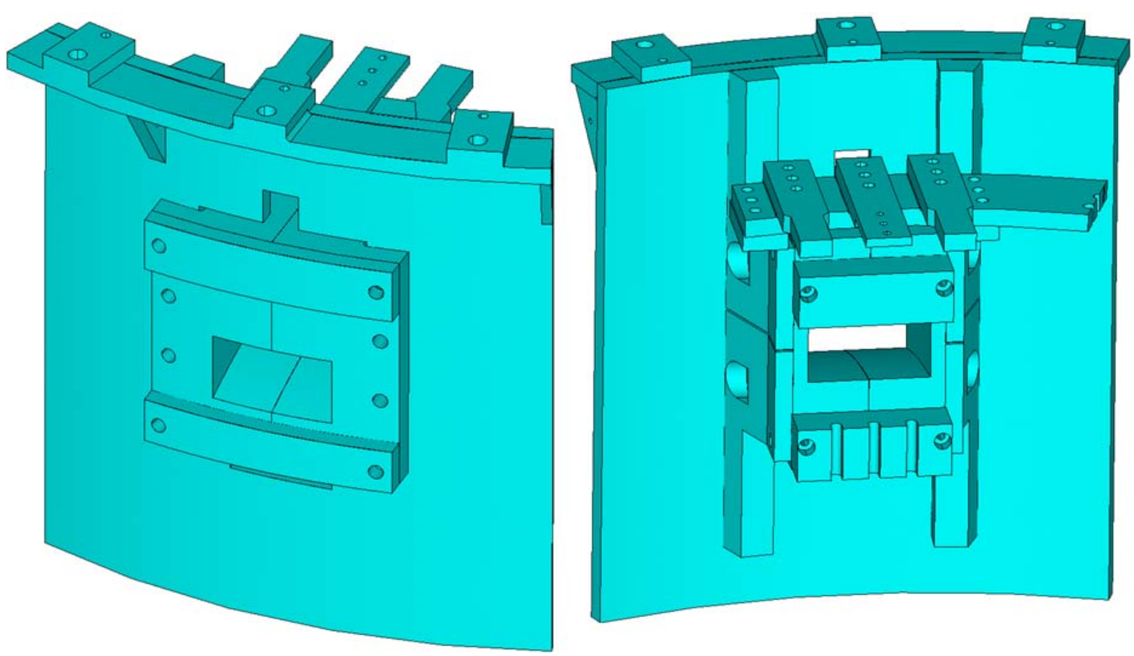


Figure 7.0-5 Aluminum Block Solid Model Imported into ANSYS from ProE/Wildfire by M. Mardenfeld

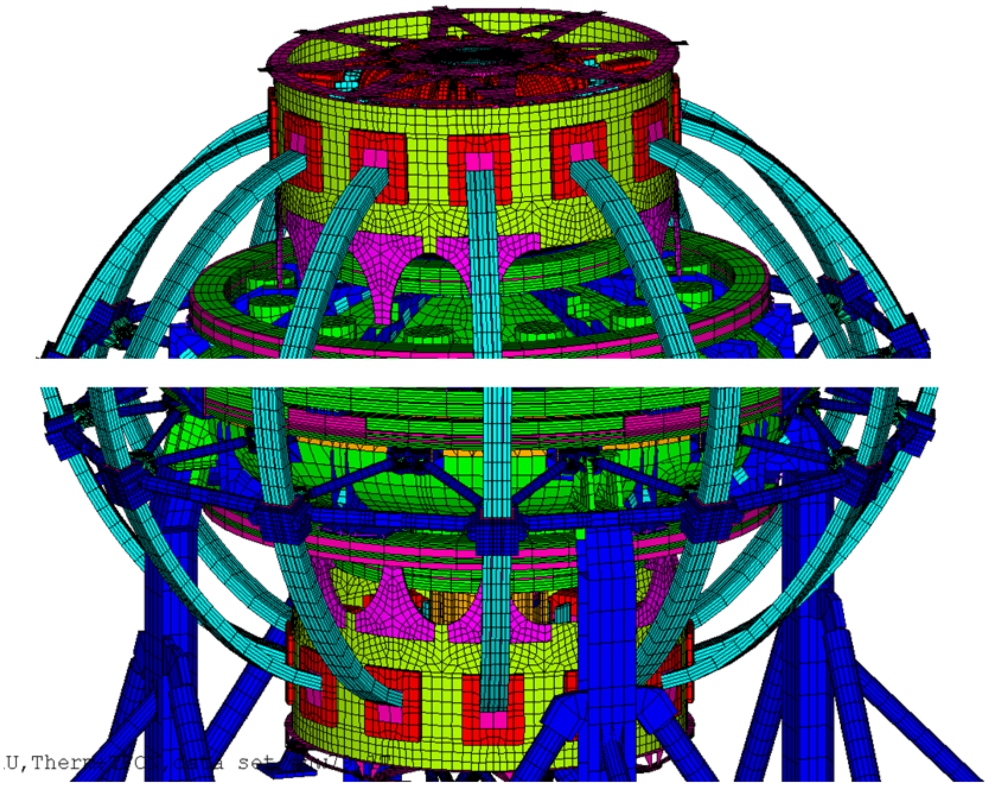


Figure 7.0-5 Global Model [2] Representation of the Aluminum Blocks

8.0 Global Model Results

Reference [2] includes a representation of the aluminum blocks. This modeling of the aluminum blocks is overly simplified in the global model, but this analysis [2] may be used to identify a limiting case to apply to the sub-model of the block. In Figure 8.0-1, the worst stress is for EQ 79 with no plasma. There is an earlier equilibria that looks comparable (Han Zhang reports 16v as being most severe), but the difference doesn't appear significant.

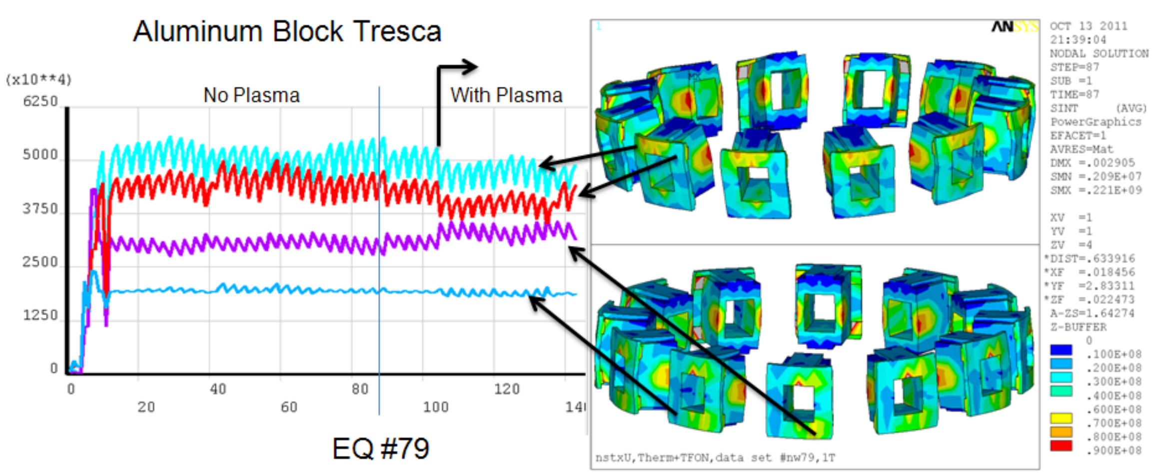


Figure 8.0-1 Aluminum Block Stress for the 96 equilibria - plus some of the 'with plasma' results

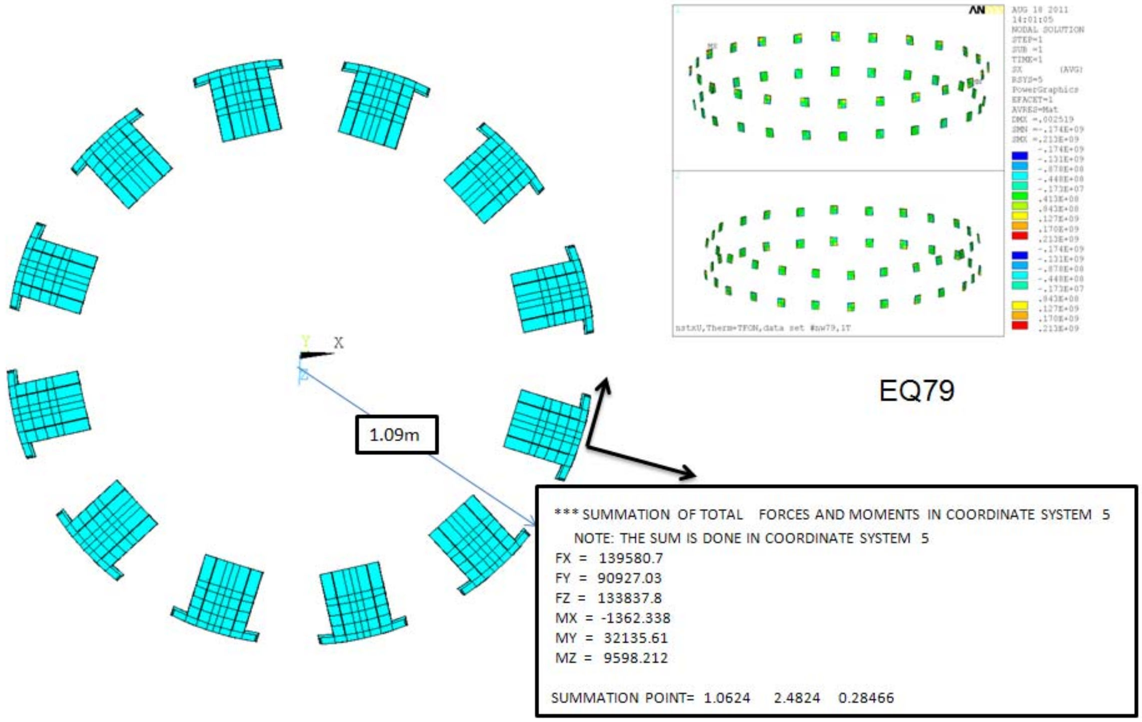


Figure 8.0-2 Aluminum Block Loads for EQ 79

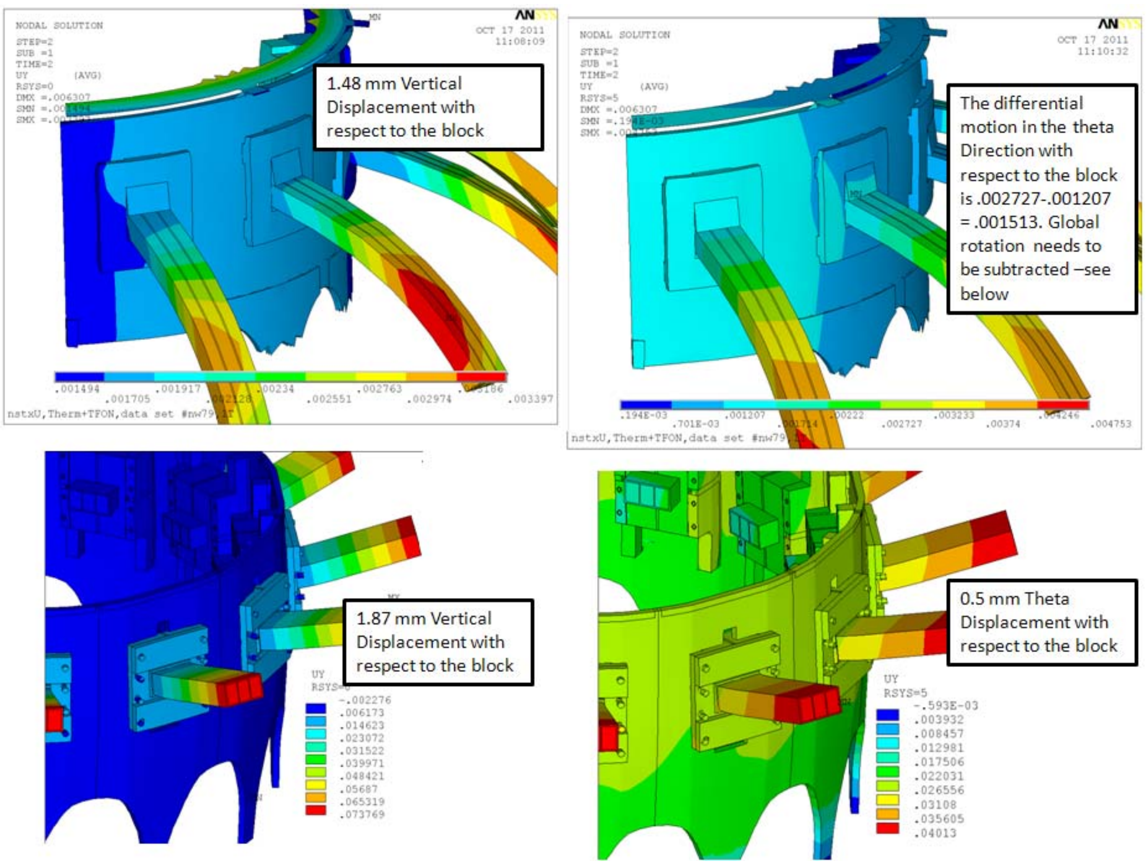


Figure 8.0-3 Comparison of Displacements -Global Model (Above) Local Model (Below)

As a qualitative check between the global and local model results, the vertical and theta direction deflections of the TF are compared. The models are different in terms of loading and geometry of the TF leg, and the global model does not include the reinforcements or the non-linear behavior of the bolted connections. Displacements should be reasonably close if loads from the global model are to be used.

In the local model, the radial distance to the end of the conductor is 62 inches, or 1.57 m, from the machine centerline and the surface of the umbrella structure is 42 inches or 1.0624 m. For the theta displacement comparison, the global rotation of the umbrella structure needs to be subtracted out. In the global model the umbrella structure rotates .001207/1.0624 = .001136 radians and the global displacement difference just from the global rotation is 1.57/1.0624*.001207 = 0.00187 m and the difference is .00187-.00127 = .000606m or 0.6 mm. The comparison is then 1.513-.6 = 0.9 mm vs. 0.5 mm for the local model. To get better consistency in the rotational stiffness, the global model should include the reinforcements, but the behavior of the two models is deemed sufficient to assess the aluminum block hardware with the global model loads.

9.0 Local Model Results

9.1 Reinforcement Design


Figure 9.1-1

In the early evolution of the analyses of the aluminum block and its bolting, the flexibility of the edge of the opening that accepts the aluminum block caused bending of the flange and bolting. In the analysis, the "wings" on the inside of the umbrella structure were changed to large bars that were welded to the umbrella structure shell to suppress the flexing of the edge. These interfered with the TF strap finger support ring and needed to be stepped. In order to install the large bars, all the clamping bolts needed to be loosened. This was considered risky in that it could disturb the existing bond. The bar or wing was split. In the ProE CAD model it does not show a weld, but to supply the needed rigidity it should be welded.

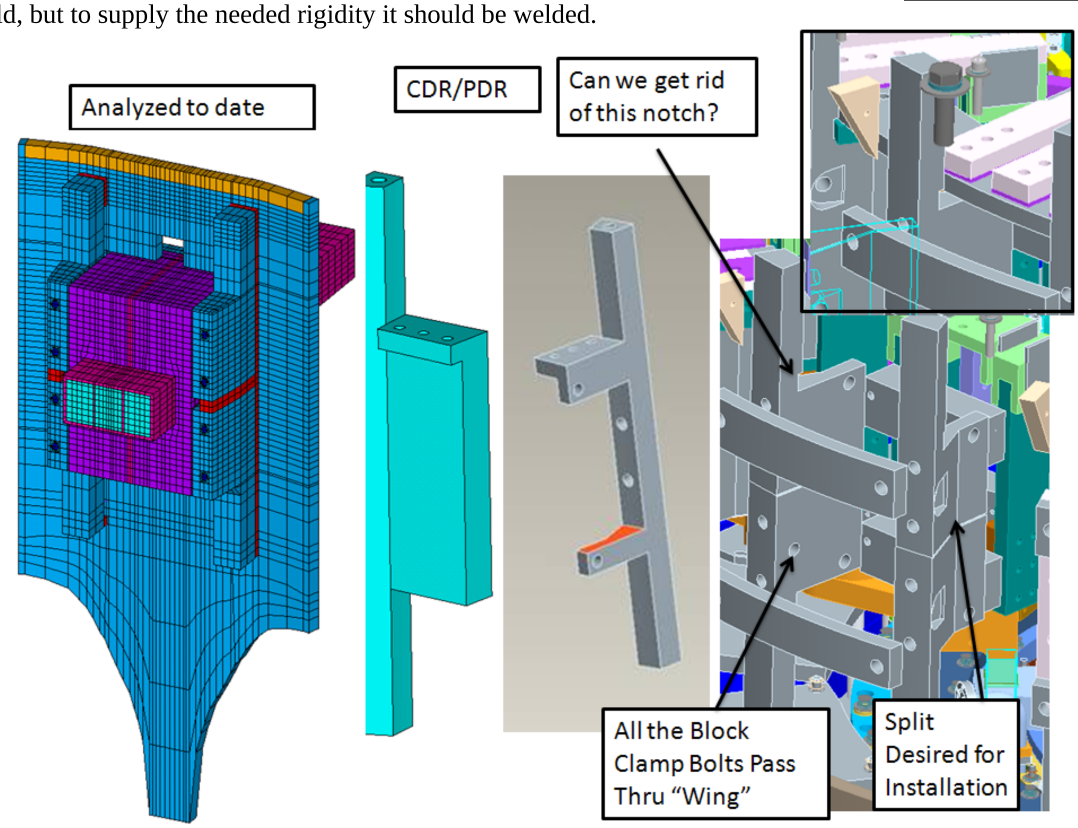


Figure 9.1-2

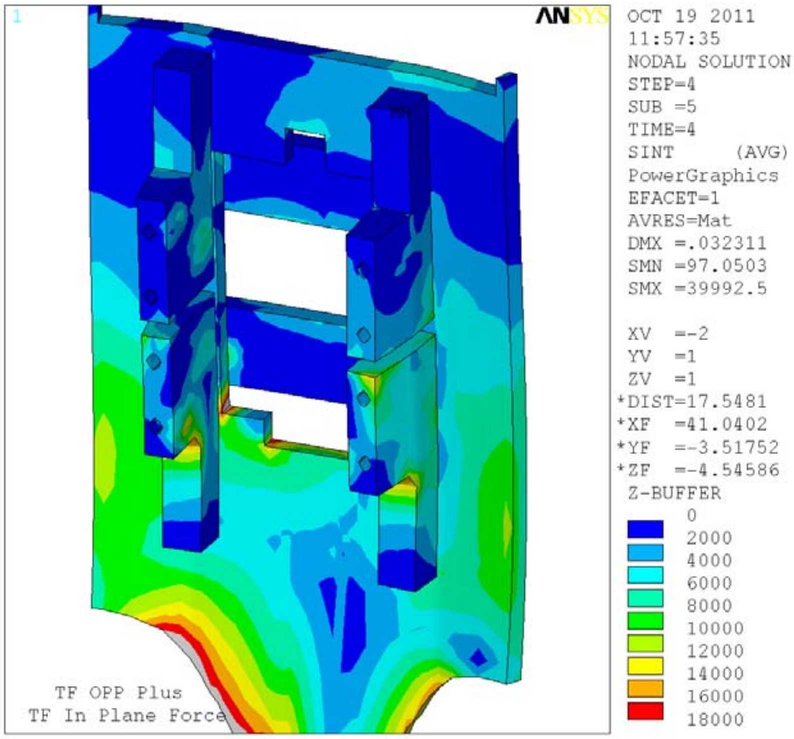


Figure 9.1-3

The corner in the lower wing step was highly stressed without a radius. The addition of a radius is recommended. Stresses in the upper corner are not as bad and the radius would interfere with the finger support ring.

9.2 Aluminum Block Stress

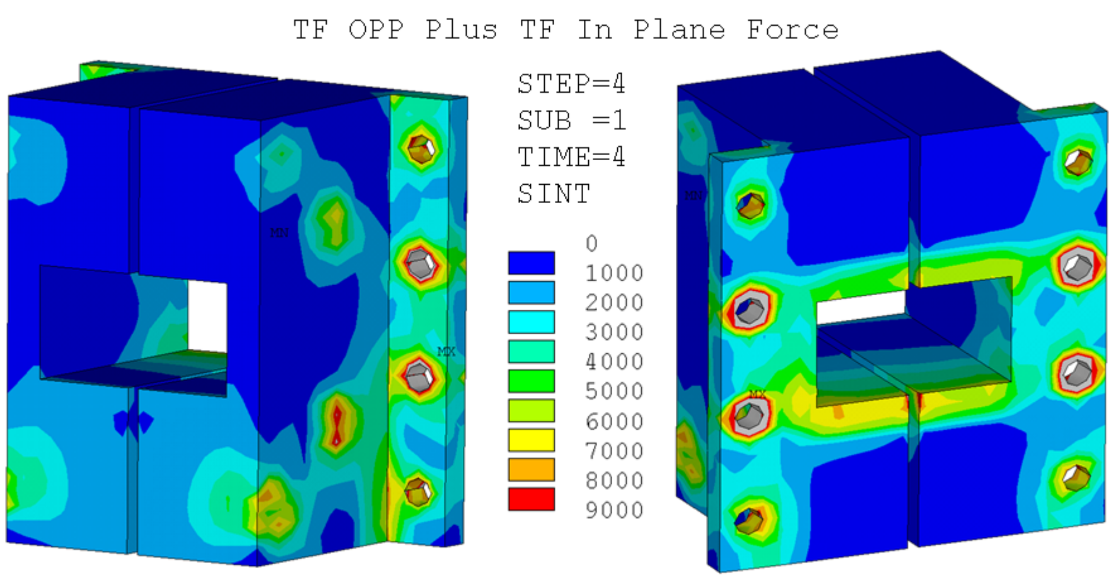


Figure 9.2-1Aluminum Block Stresses , run ablk11, Ref [2] Loads

Figure 9.2-1 includes preload compression around the holes. The bending stress at the corner of the block peaks at 8 ksi.

9.3 Weld Evaluations

The weld of the wing extension to the umbrella shell is highly stressed. This is modeled with finite elements as a .5 in rectangular cross section, and the stresses can be scaled. A 3/8 inch bevel with a 3/8 inch fillet would be consistent with this size.

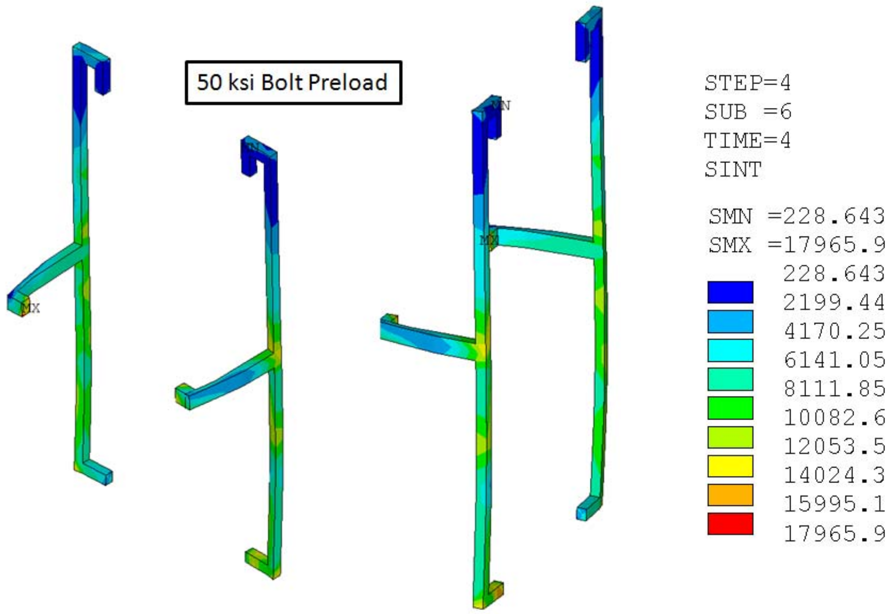


Figure 9.3-1 Weld Stress run #ablk11 with ref [2] loads, and split "wing" reinforcement

Weld stresses in the latest analyses, based on ref [2] loads and the vertically split reinforcement, are acceptable. Local stress concentrations are 18 ksi and 20 ksi with the lower preload, but the bulk is below 14 ksi. In earlier analyses the weld ends had concentrations of stress. In the latest modeling of the weld, the weld "turns the corner" and puts the weld start/stop in a better location.

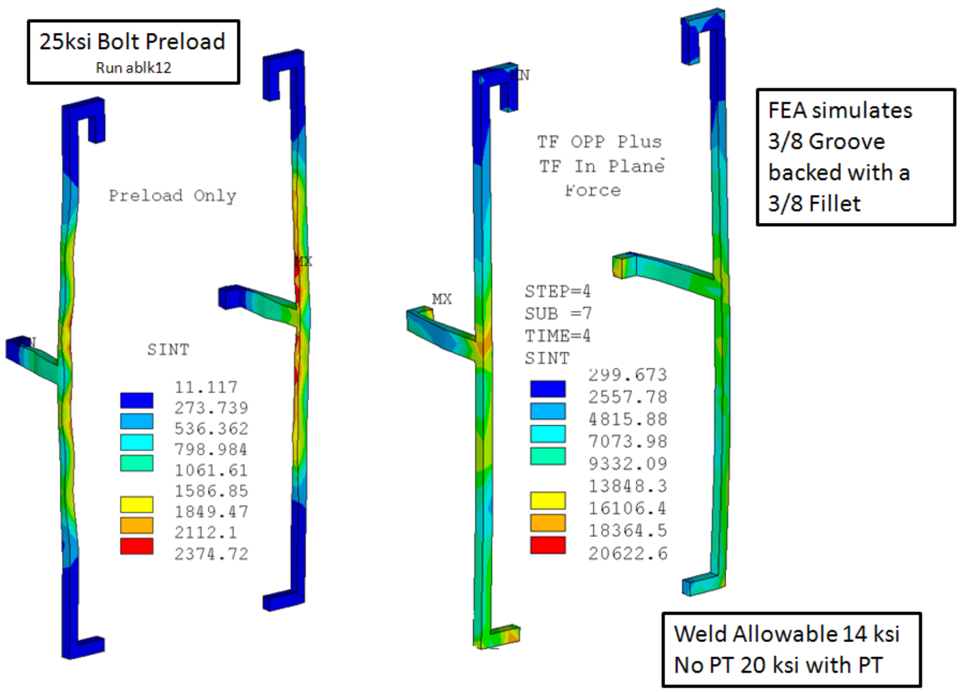


Figure 9.3-2 Weld Stress run #ablk12 with ref [2] loads, and split "wing" reinforcement, 25 ksi Bolt Preload

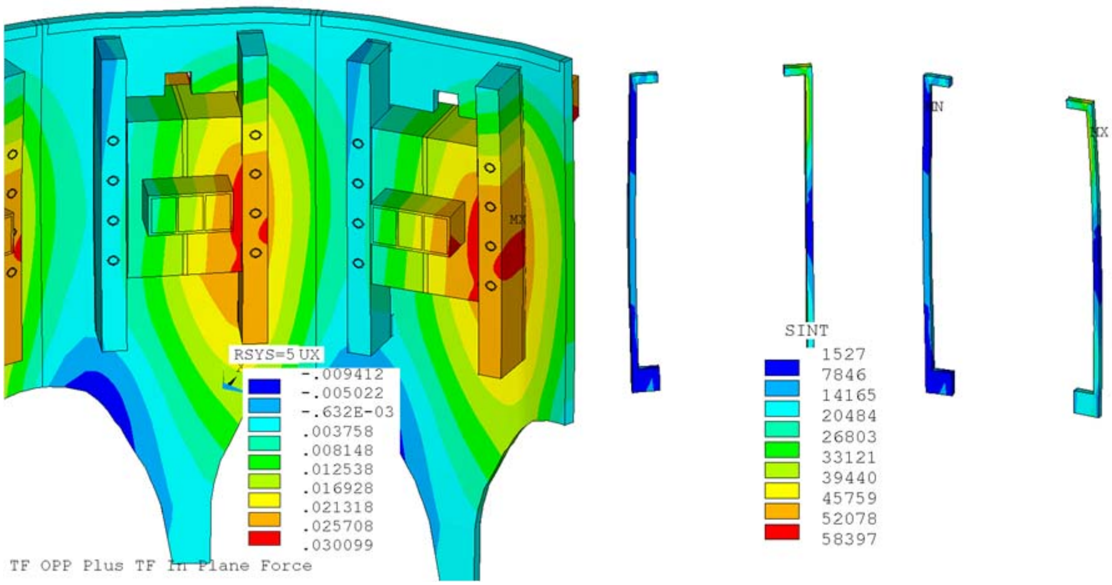


Figure 9.3-3

The inner reinforcement weld was overstressed at 58 ksi, with the larger loads. This was very localized and in the latest runs, the welds have been lengthened around the corners to reduce the local peak.

9.4 Bolting Evaluations

The aluminum block is secured to the umbrella structure with 12 bolts; 8 on the outward face of the block, and four oriented toroidally that provide the clamping force on the TF outer leg. These toroidally oriented

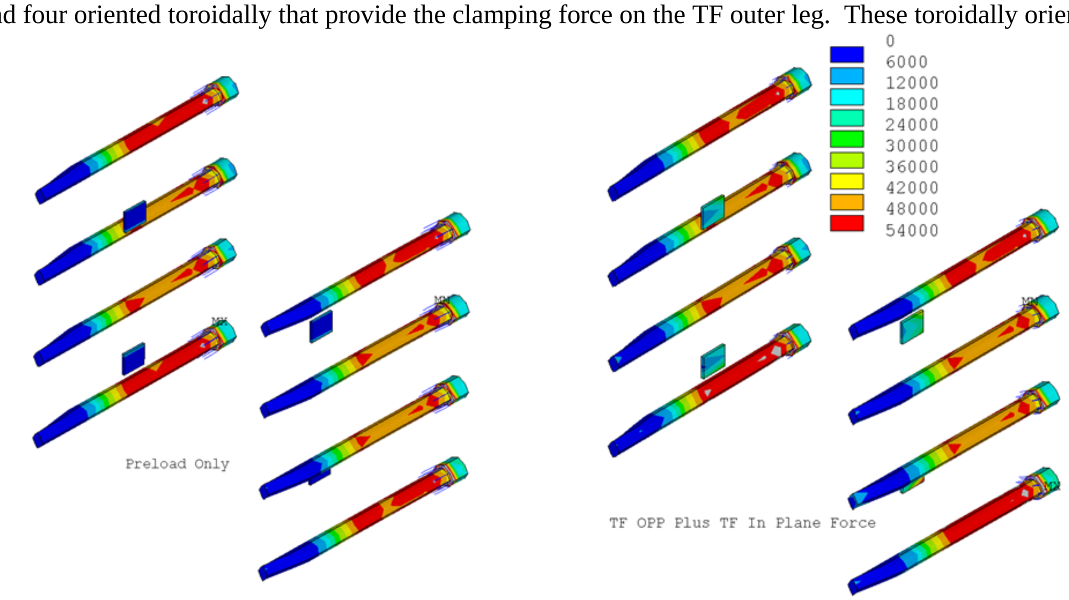


Figure 9.4-1 3/4 in bolt stress at Preload and Full Operating Load, 50 ksi Initial Preload

bolts are ¾ inch bolts which have a stress area of .335 in^2. The 8 bolts on the flanges of the block are intended to take the outward tension from the outer TF leg.

The eight 3/4 inch bolts on the block flange should be preloaded The pre-tension shown in figure 9.4-1 is 16750 lbs for the 50 ksi bolt preload case analyzed and 8375 lbs for the 25 ksi bolt preload case analyzed (Figure 9.4-2). The bolt stress range is small for both pretensions. The lower preload has a bit more percentage change, but this is still essentially a static stress when considering fatigue.

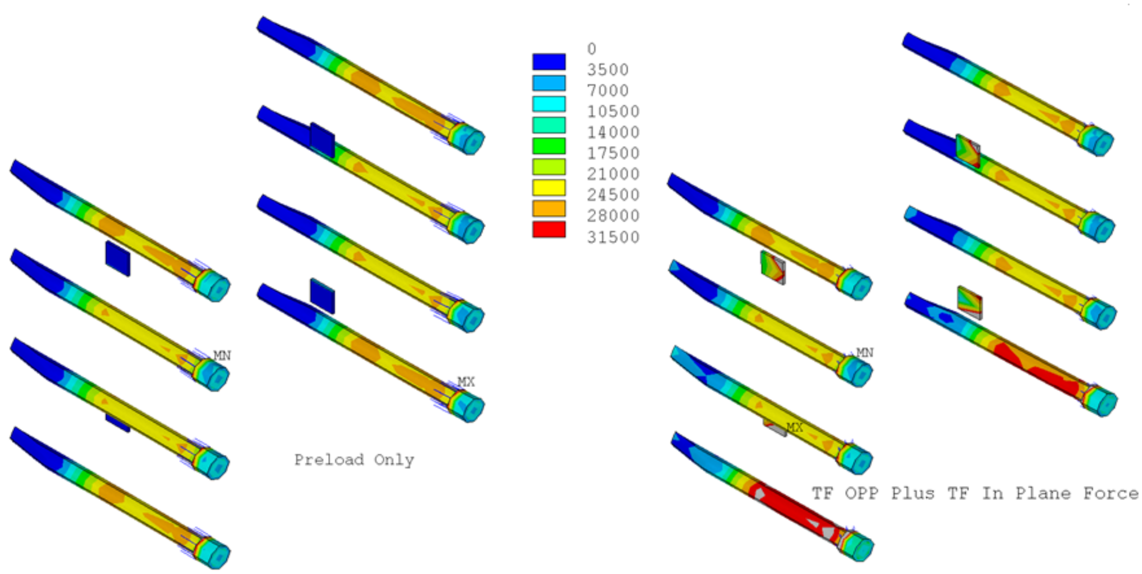


Figure 9.4-2 3/4 in bolt stress at Preload and Full Operating Load, 25 ksi Initial Bolt Preload

The toroidally oriented bolts are intended to provide clamping pressure on the TF outer leg. With the new "wing" reinforcements, the toroidally oriented bolts will also load in shear to help support the outer leg tension and moments. In the upgrade, the brackets on the inside of the umbrella structure on either side of the block, now are two larger brackets which will load all the toroidally oriented bolts in shear - instead of the current brackets that only load half the bolts in shear. This provides a total of 8 shear planes to augment the capacity of the bolt pattern on the outer face of the block.

The eight 3/4 bolts should be preloaded to a minimum of 104 ft-lbs or 8375 lbs each to avoid cyclic loading. This produces a frictional restraint of 8*8375*.3 = 20100 lbs or 89412 N frictional restraint. This is nearly enough to support the 111,829N theta load from [1] and the 90,927N theta load from [1]. With the earlier loads the theta loading was 184.8kN and, as a consequence, shimming the gap between the block and the umbrella structure opening was recommended. The [2] loads also include a large vertical load which would also have to be supported by friction. It is considered the best approach not to increase the bolt preload for fear of damaging the block flange, and retain the shims in the gap between the blocks and opening.

9.5 TF Insulation Stress

A critical design requirement of the aluminum block assembly is to hold the outer legs against the in-plane and the out-of plane loads. The in-plane loads have the potential of pulling the conductors out of the blocks. The blocks "grab" the outer leg by the clamping force provided by the four toroidally oriented bolts and by bond shear.

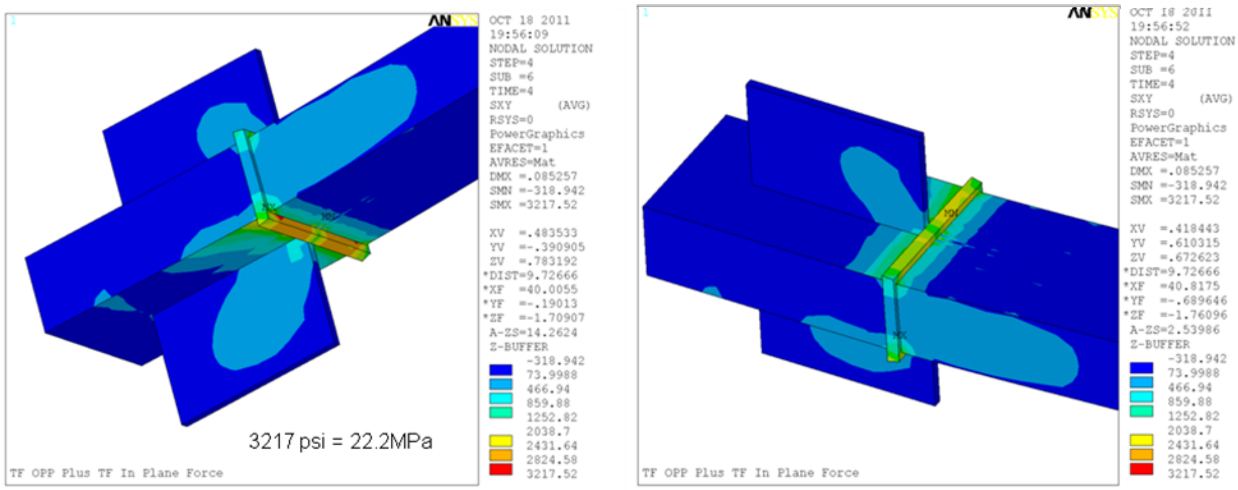


Figure 9.5.1 Radial-Vertical shear stress in the Insulation between the Block and TF Outer Leg, Run ablk11

The 22.2 MPa shear stress is beyond the qualified interlaminar shear stress for the existing insulation system but the peak shear is in the ridge of epoxy that protrudes out of the block not in the actual interlaminar shear plane. The shear stress is low over the bulk of the surface that would be bonded to the block.

TF insulation stresses were extracted from the second evolution of the reinforcements in section 10.3. The insulation stress between the aluminum block and the TF outer leg is an important load path in that the TF tension is reacted by primarily shear in the epoxy. The rings added to the outer legs take some portion of the TF bursting load. The truss elements at the knuckle take a small portion, and the remainder of the outer leg bursting load is supported by aluminum blocks via a "glued" and clamped joint formed by the two halves of the aluminum blocks.

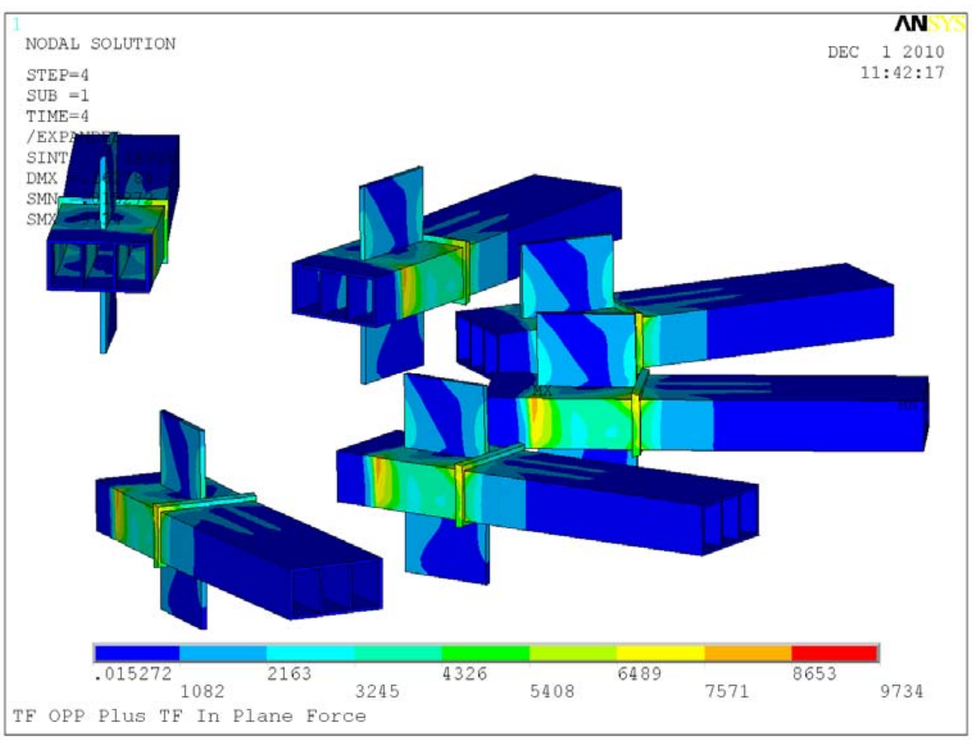


Figure 9.5-2

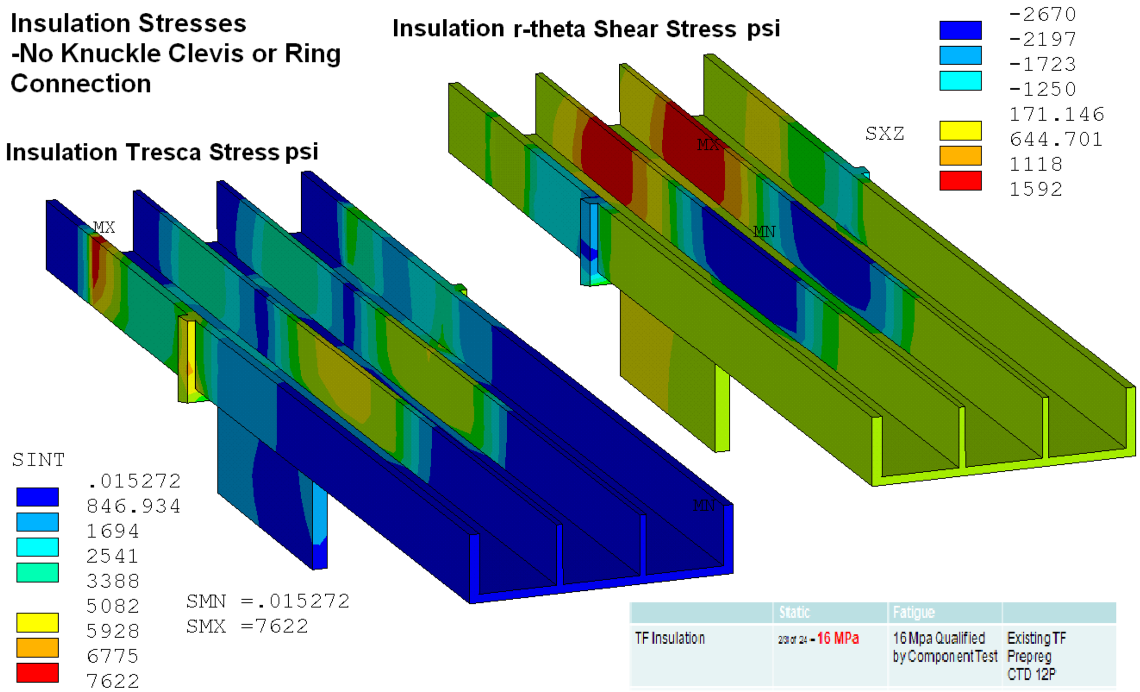


Figure 9.5-3 The TF insulation shear allowable is 16 MPa or 2320 psi.

9.6 TF Outer Leg Conductor Stress

The primary qualification of the conductor stress in the outer leg is the global model calculations. Both global model and local model results are shown in Figure 9.6-1.

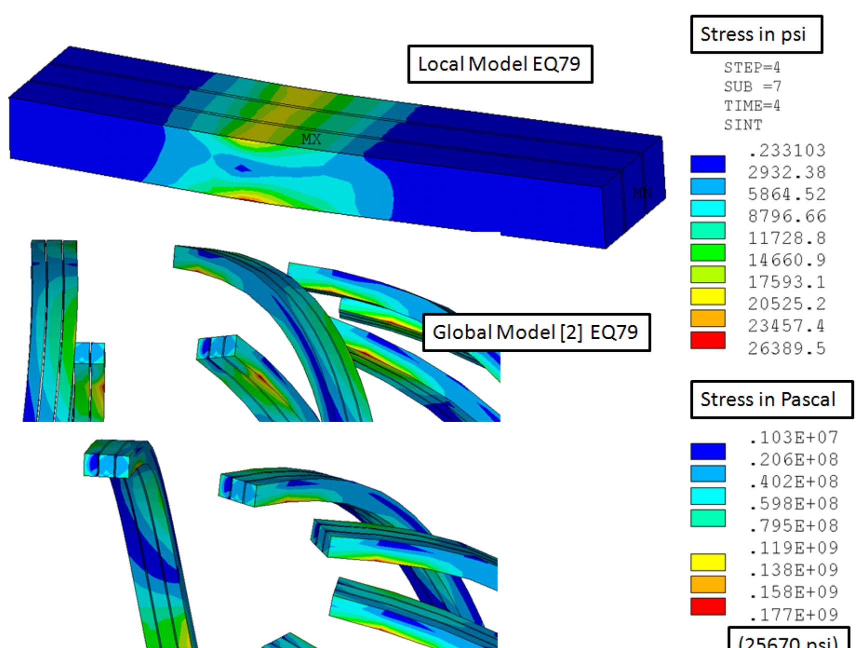


Figure 9.6-1 Outer Leg Copper Conductor Tresca Stress -Local and Global Models

The TF copper ultimate is 39,000 psi or 270 MPa[16]. The yield is 38ksi (262 MPa)[16]. Sm is 2/3 yield or 25.3 ksi or 173 MPa with adequate ductility, which is the case with this copper, which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor per [3] (it is for other structural materials). These stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10% so, the Sm value is 156 MPa or 23 ksi and the bending allowable is 34.6 ksi. The local stress in the conductor is 27 ksi, so the outer leg satisfies the static criteria at the intersection with the aluminum block. The average stress is between 3000 and 6000 psi from the contours and 242,000*.2248/6/3 = 3022 psi from P/A. This is from the in-plane bursting load on the TF.

10 Evolution of the Reinforcement Analyses

10.1 Fourth Reinforcement Concept

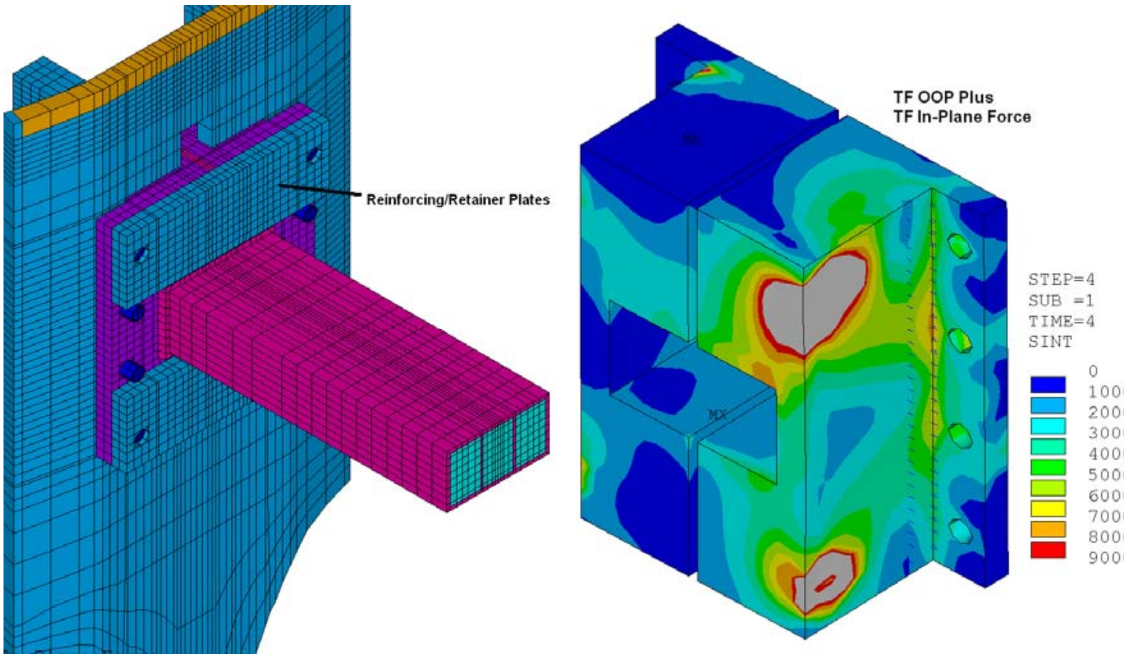
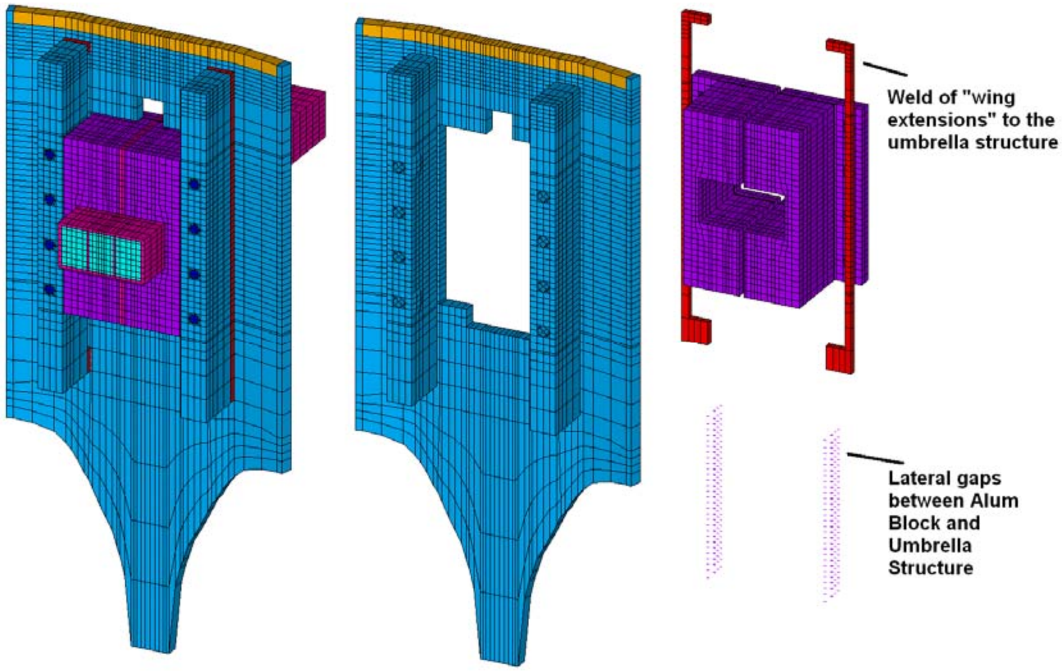


Figure 10.1-1

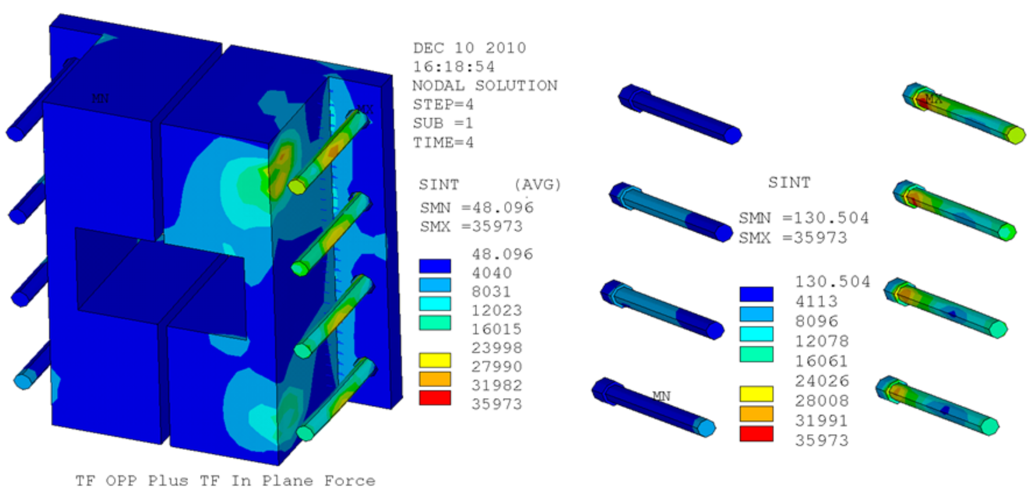
The aluminum block stress at the flange corner root went down 1 or two ksi with the addition of the outer plates. The plates also provide a retainer feature in case the flanges actually crack.

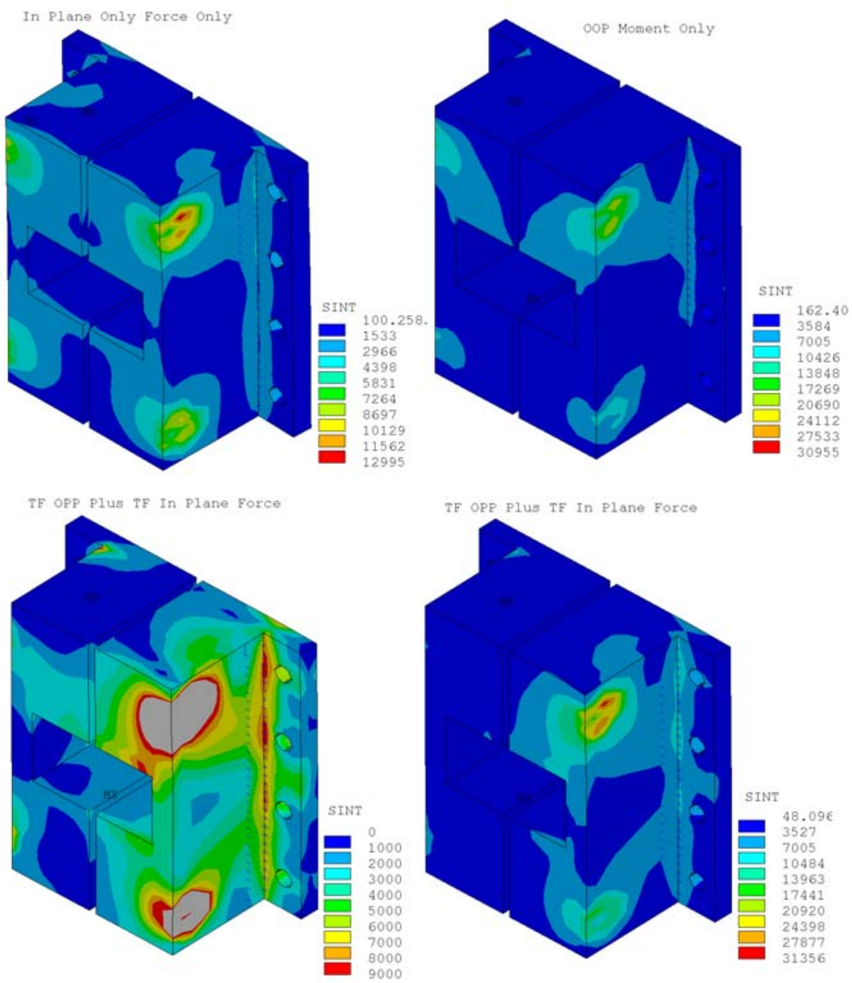
13.2 Third Proposed Reinforcement

In this proposal, the "wings" are extended upward and downward to stiffen the corners of the opening for the aluminum block.



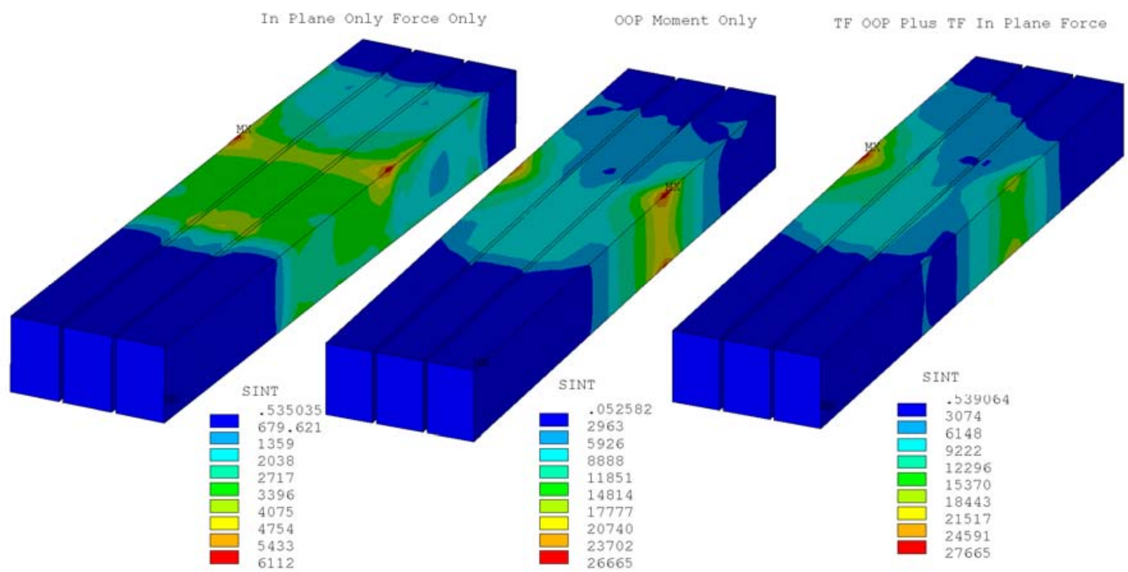
Gap elements have been added laterally between the aluminum block and the umbrella structure opening to transfer loads directly through bearing contact. This implies a tight fitting or shimmed interface. The bolt bending is much reduced in this concept.



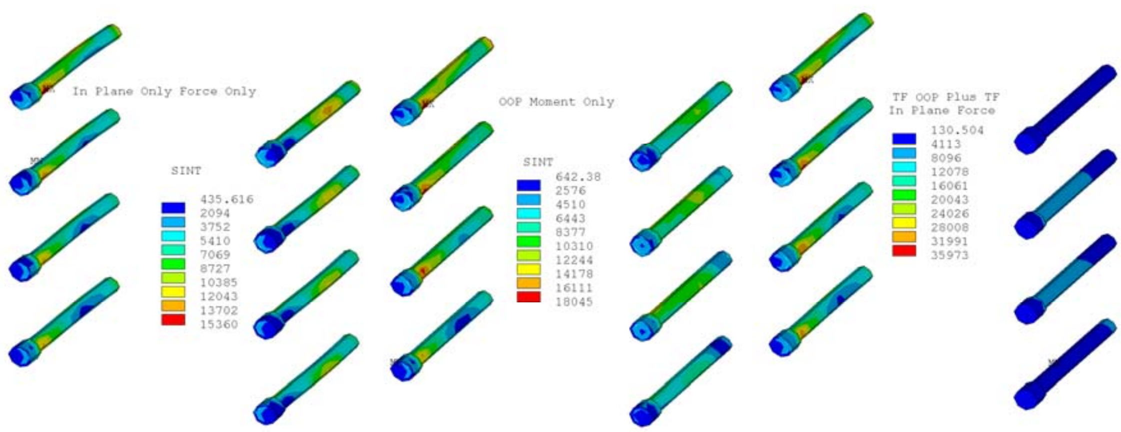


The Aluminum Block Stresses, 9000psi in the flange corner, could be a problem for cast aluminum. The actual grade of aluminum used for the blocks is uncertain at this writing, but it does not appear to be wrought material as called out in the drawings - see figure 6.5-1.

The stresses at the stainless steel "wing" attachments are only an approximate indication of the aluminum and/or bolt stresses. The cross bolt that clamps the blocks around the TF coil was modeled with 4 merged nodes, the stress at the flange corner is a concern. 9000 psi is not much, but Jim Chrzanowski indicated that while the spec says "wrot", or correctly spelled "wrought", he knows they are cast material. Many cast aluminums have yields above 20 ksi, but as of this writing, there is uncertainty regarding the material that the blocks are made of.



TF Stress Components used in the DCPS Input



Bolt Stress Components used in the DCPS Input

From the NSTX Criteria Document, Reference 3:

- (d) For bolting materials, the design Tresca stress values shall be:
    - 2/3 of the ***minimum*** specified yield strength at every point in time;

    Ref. 3(Section III, Appendix III, Article III-2120) specifies 1/3

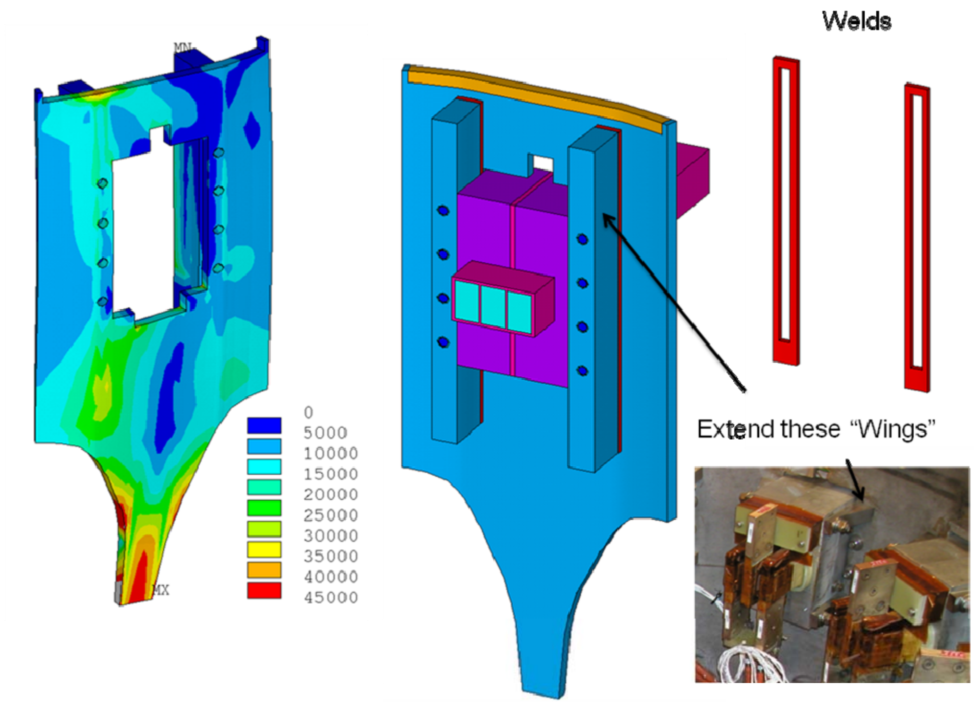
    - Also, the component must meet ductility requirements which are to be established for each material not specified by Reference [3].

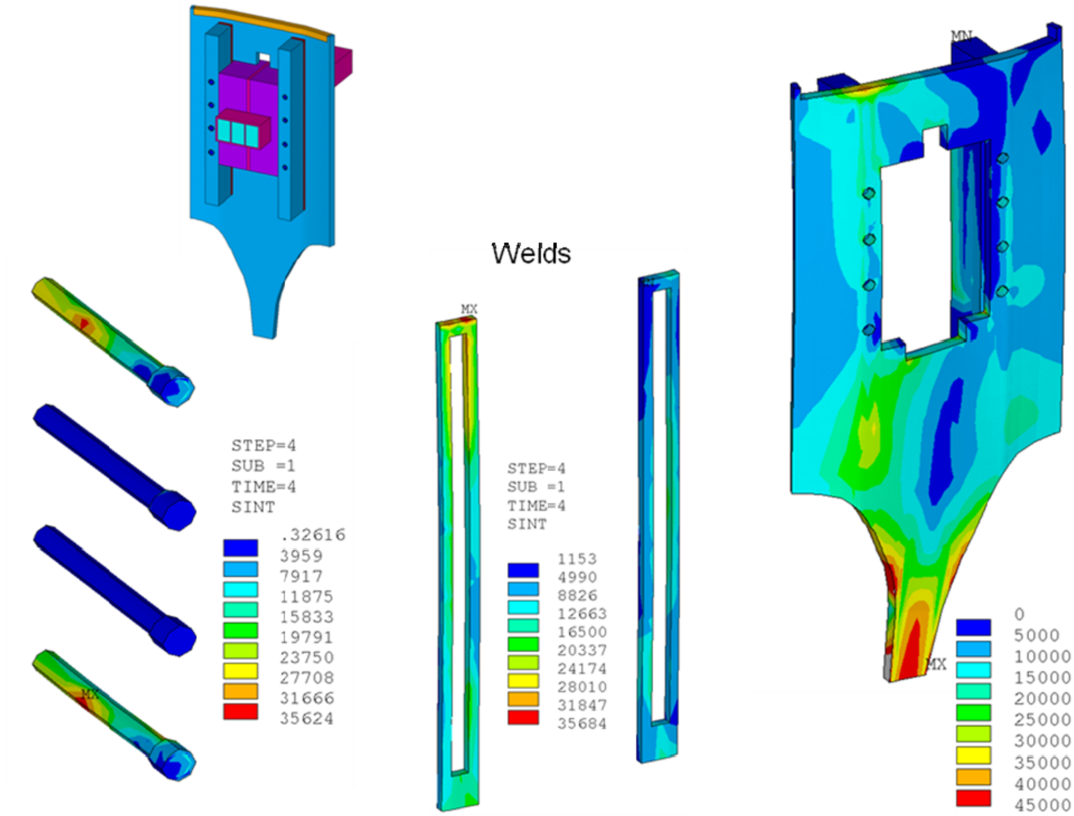
Bolt Stresses including bending are 15,360 psi due to in-plane loads, and 18,045 psi due to OOP loads. Average axial stresses are judged to be half the bending values from the contours, but these are for the full ¾-inch diameter and should be adjusted for the stress area of .335 in^2 vs. (3/4)^2*pi/4 = .44in^2 or 1.318 larger than the contours show. In MPa, the axial stresses are 69.8 due to in-plane loads and 82 MPa due to OOP loads.

The bolting criteria is for axial stress on a net section. For the local bending the bending allowable of 1.5*Sm applies.

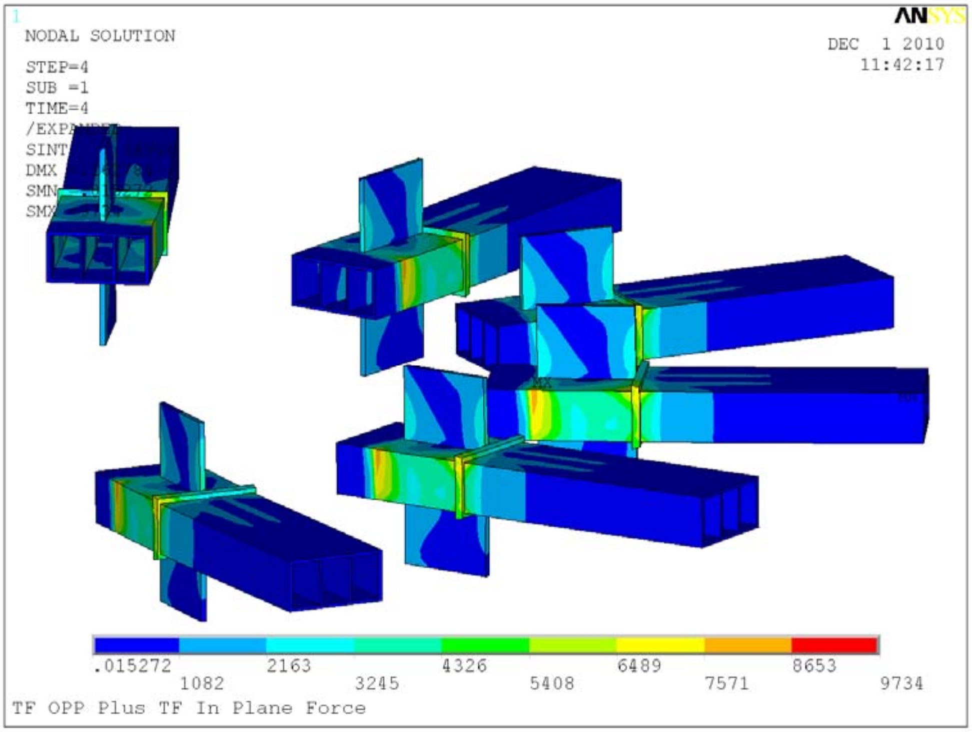
It is intended that the bolts be preloaded to avoid cyclic loading at the threads. The pre-tension should be (69.8+82)*1e6/6895 *.335 in^2 or 7375 lbs. The torque needed for this is .2*F*D = .2*7375*.75/12= 92 ft-lbs.

10.3 Second Proposed Reinforcement





With recommended reinforcements, stress levels in the 3/4 inch bolting are less than 35 ksi including bending, and are around 20 ksi average axial tension. This is based on an "eyeball integral of the contours in the upper and lower bolts in the figure above. The bolts are expected to be preloaded, and while only investigated in one of the runs, with the recommended reinforcements, the bolts are expected to be preloaded beyond the design stress and will be isolated from the cyclic loading. From the criteria document [3], section I-4.1.1, Design Tresca Stress Values (S_m) bolting materials have the same design limits as shells and other structures. The 20 ksi average tensile stress meets the 2/3 yield criteria and the 36 ksi stress satisfies the bending criteria.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7571
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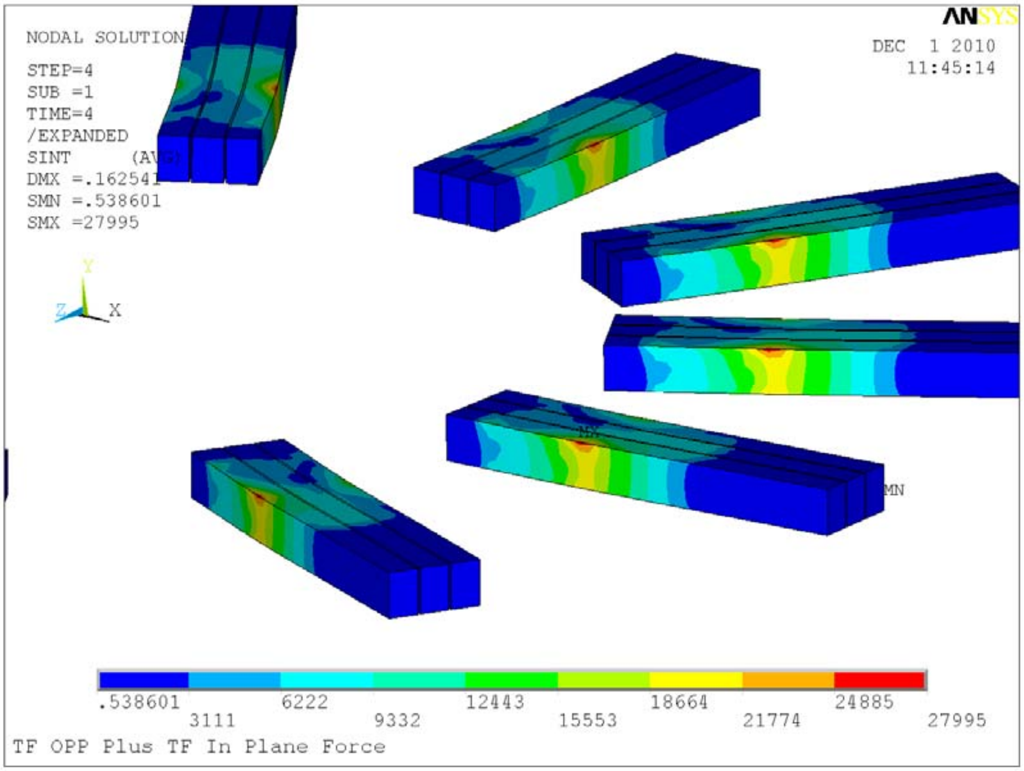
9734
TF OPP Plus TF In Plane Force



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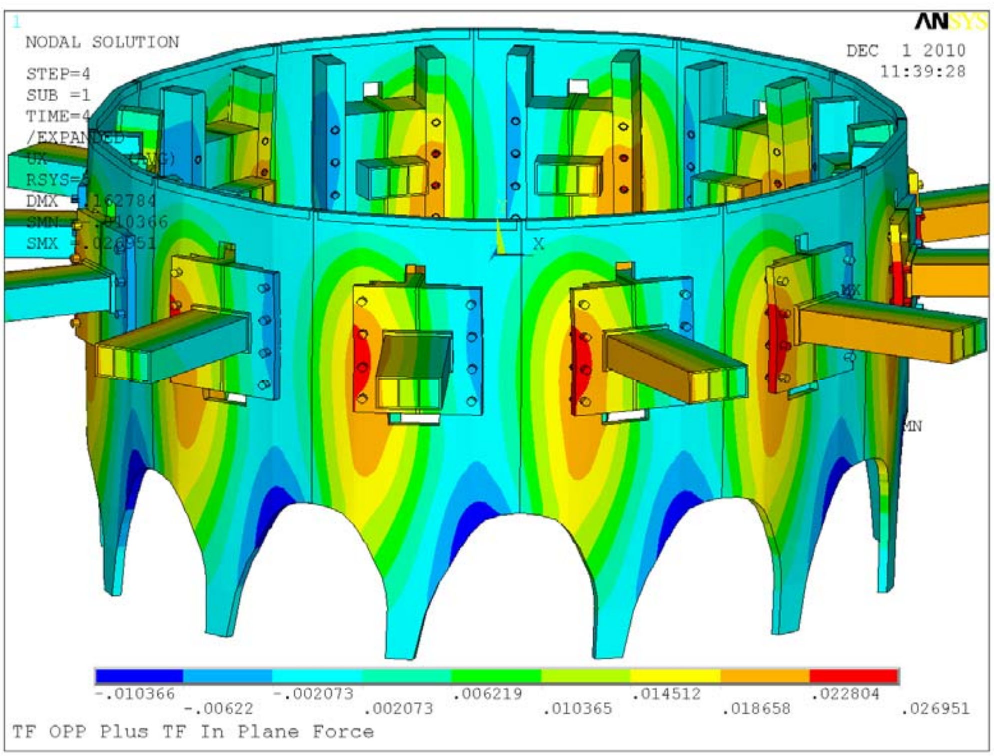
TF OPP Plus TF In Plane Force



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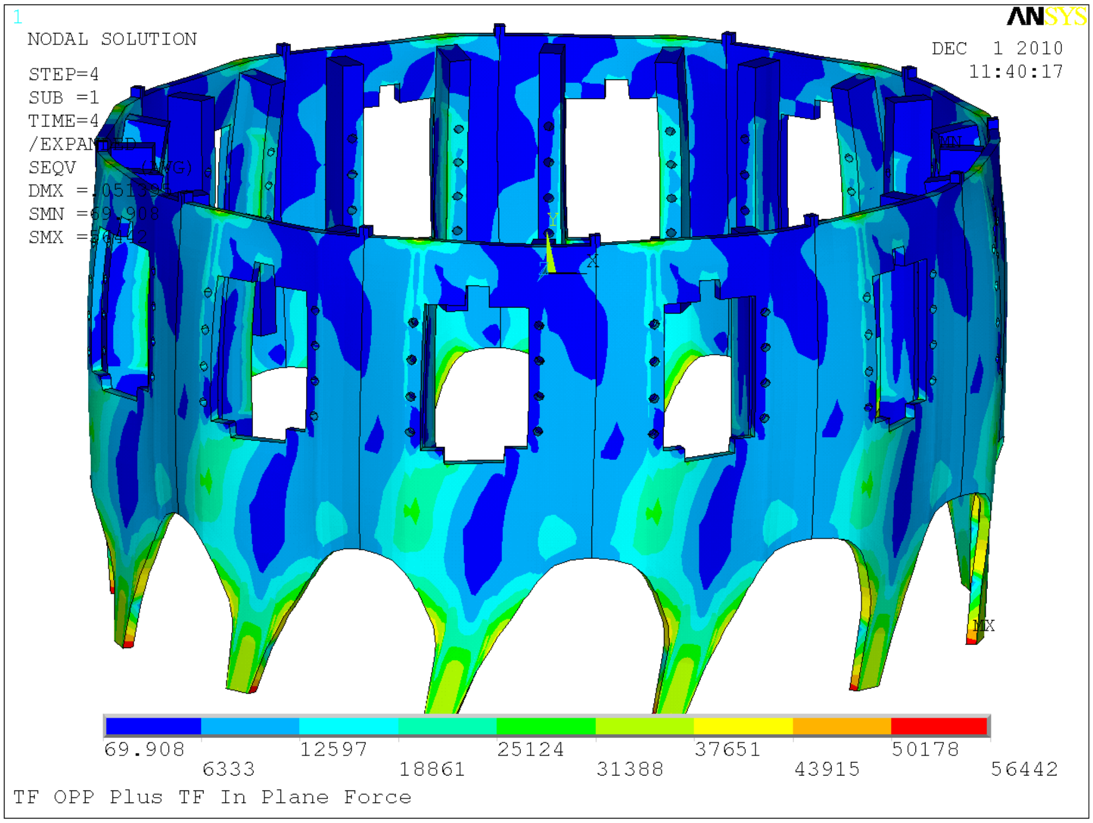
TF OPP Plus TF In Plane Force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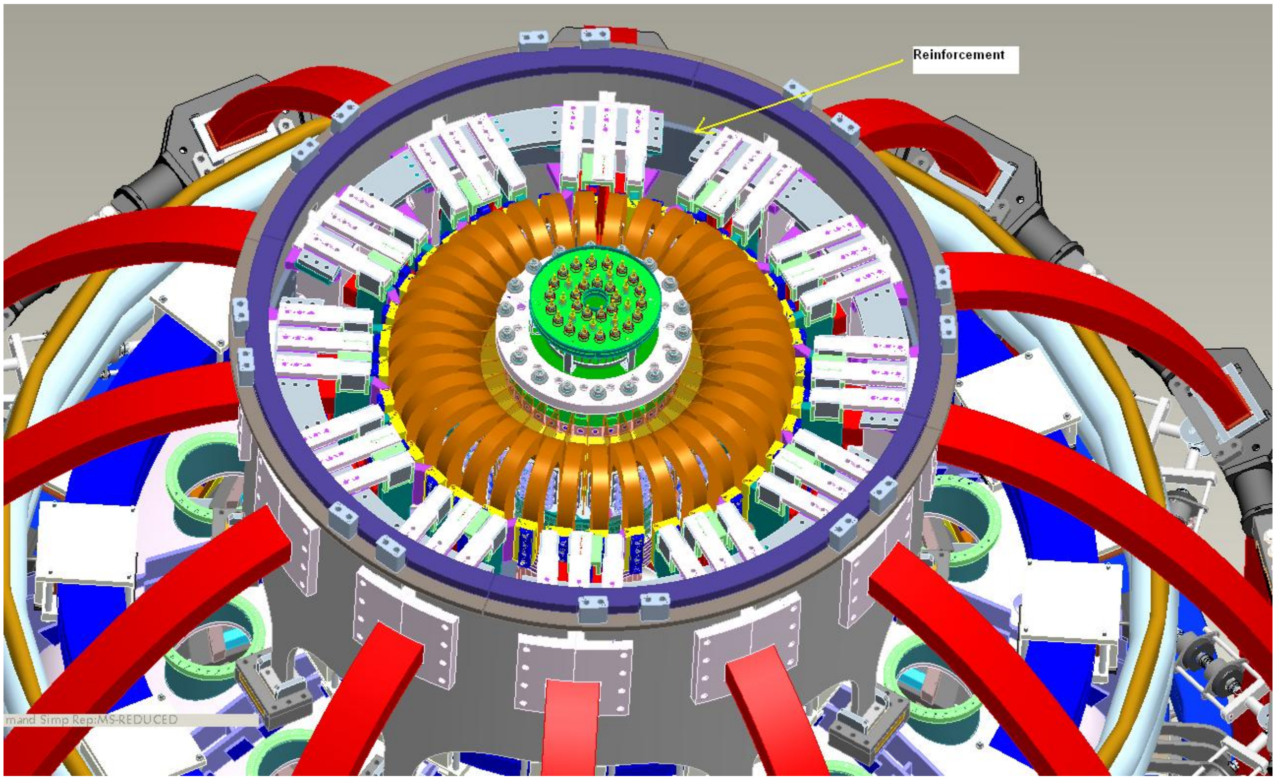
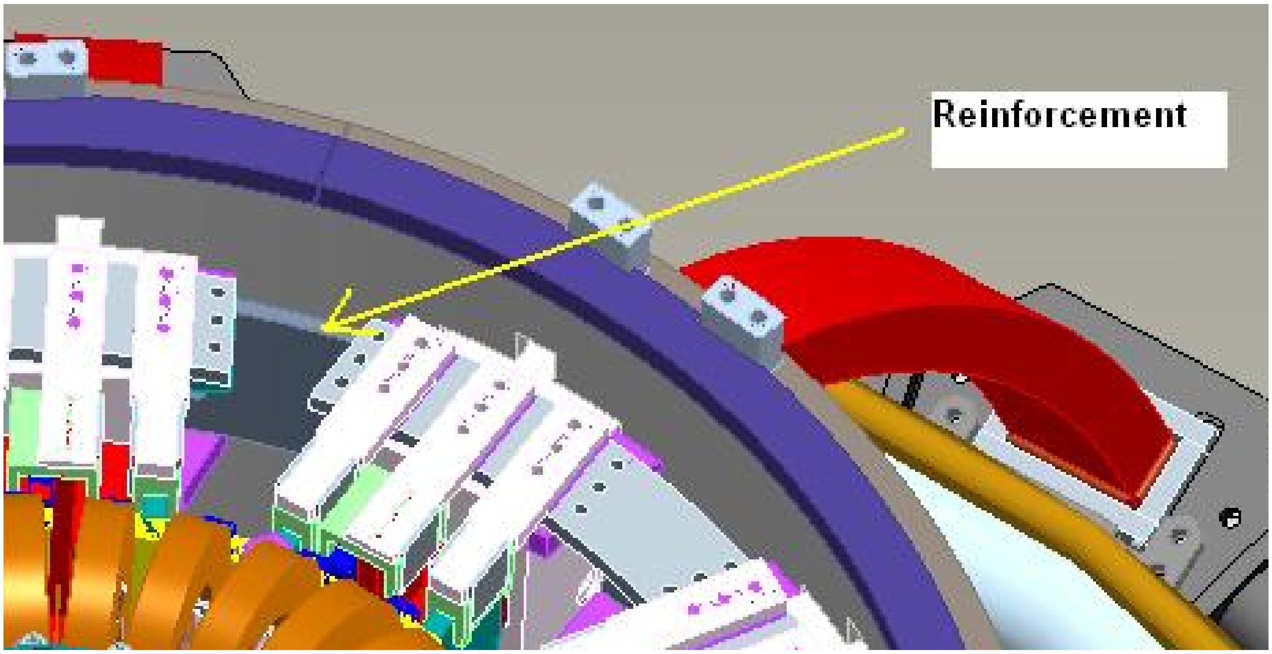
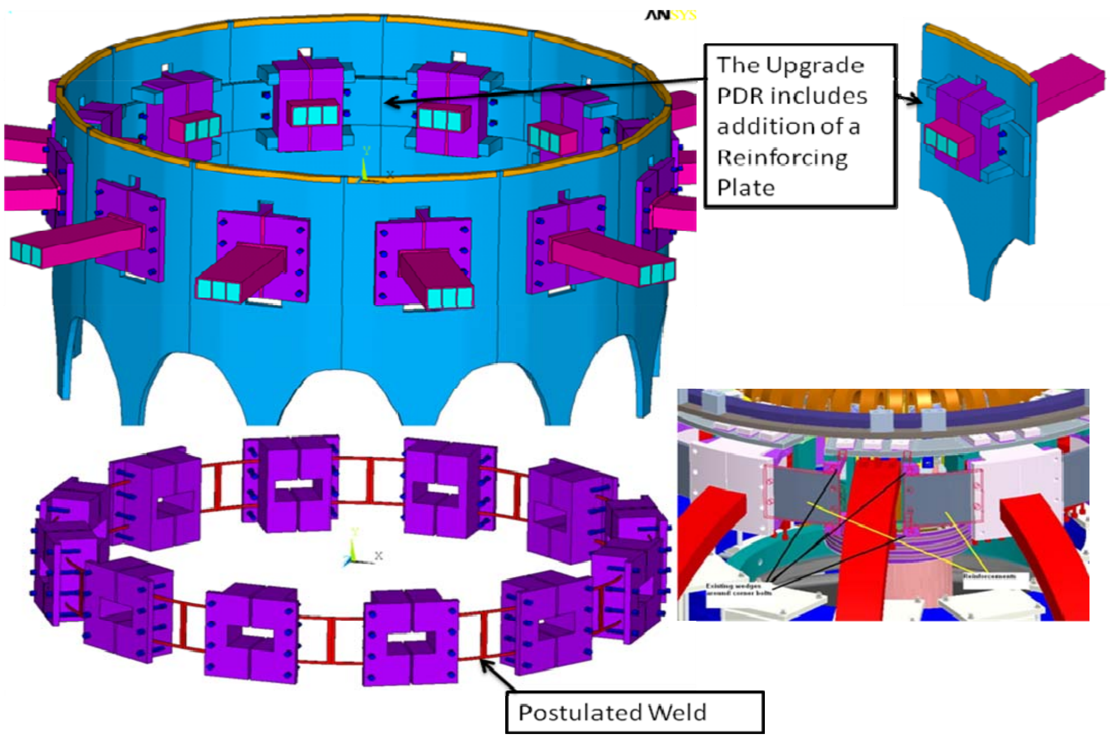
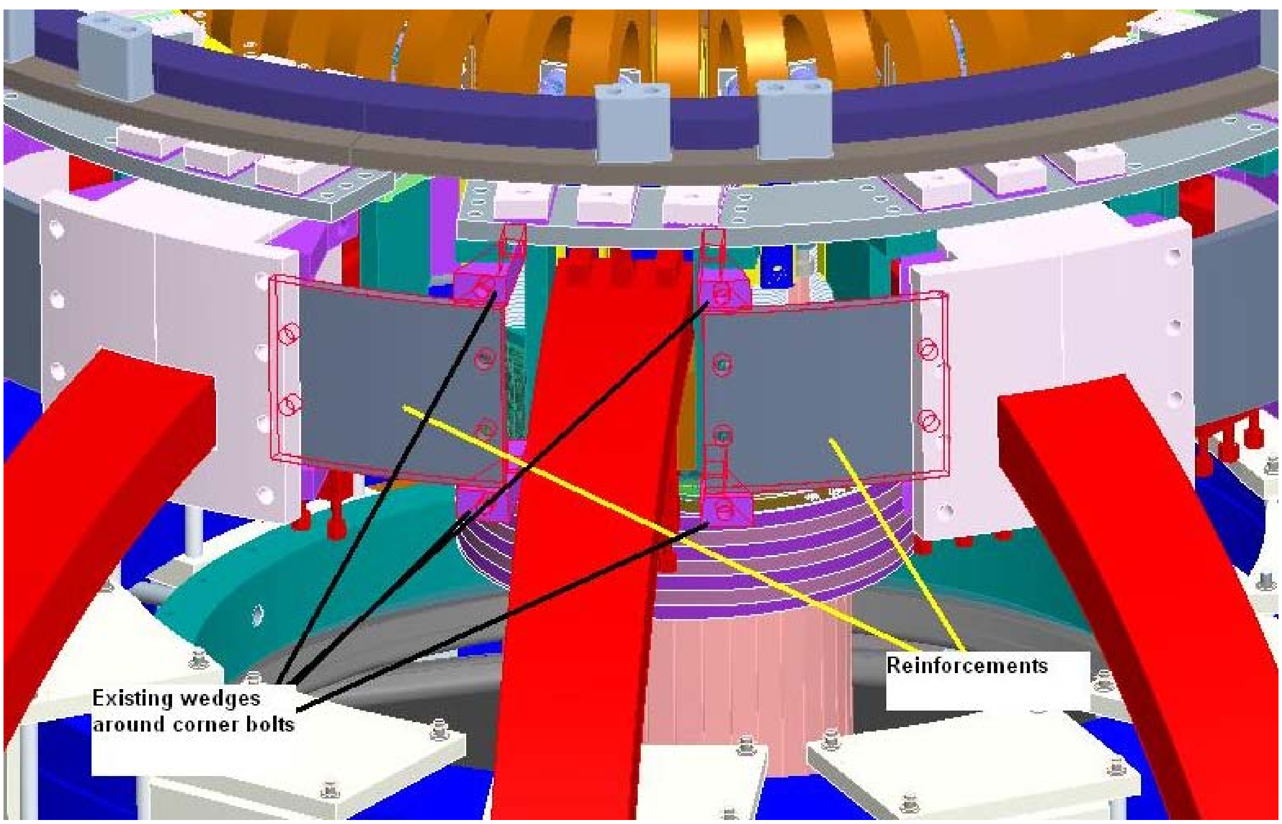
TF OPP Plus TF In Plane Force

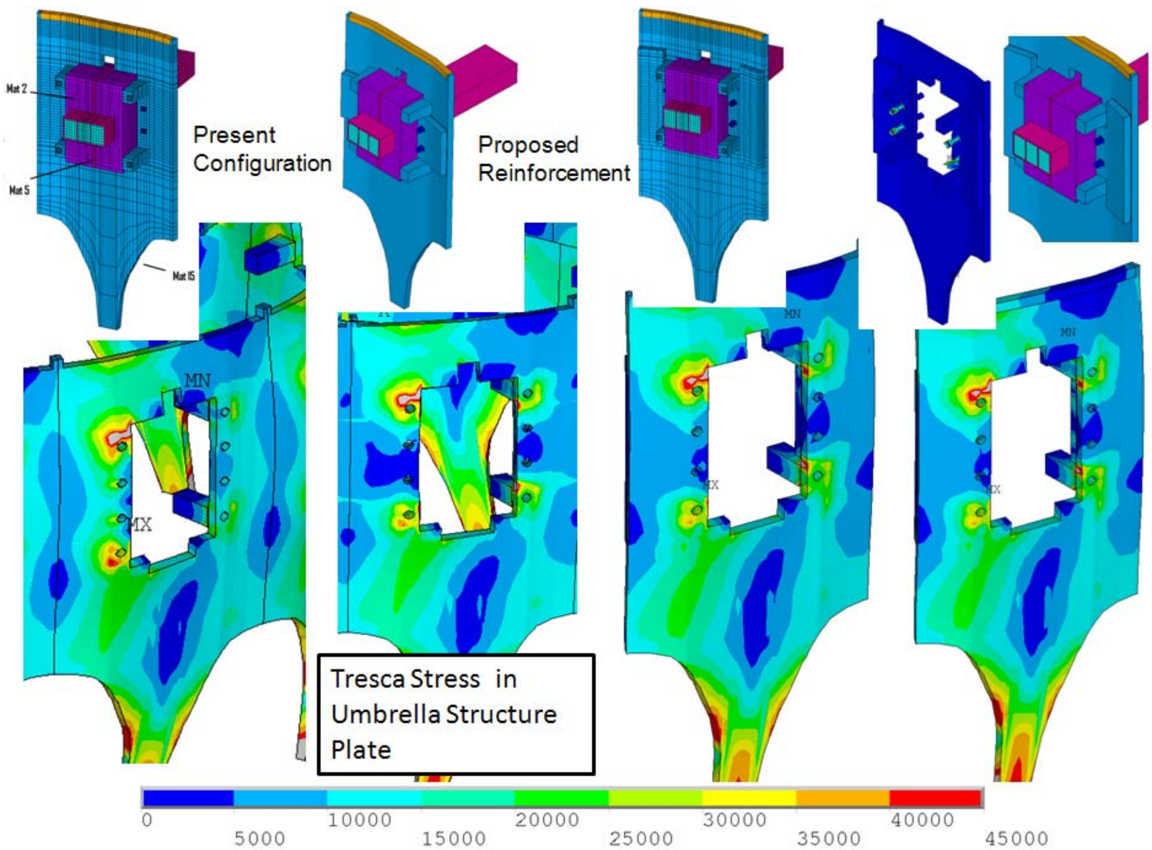
13.4 First Proposed Reinforcement (PDR)






The Upgrade PDR includes addition of a Reinforcing Plate
Postulated Weld


Existing wedges around corner bolts
Reinforcements


Present Configuration
Proposed Reinforcement
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10000
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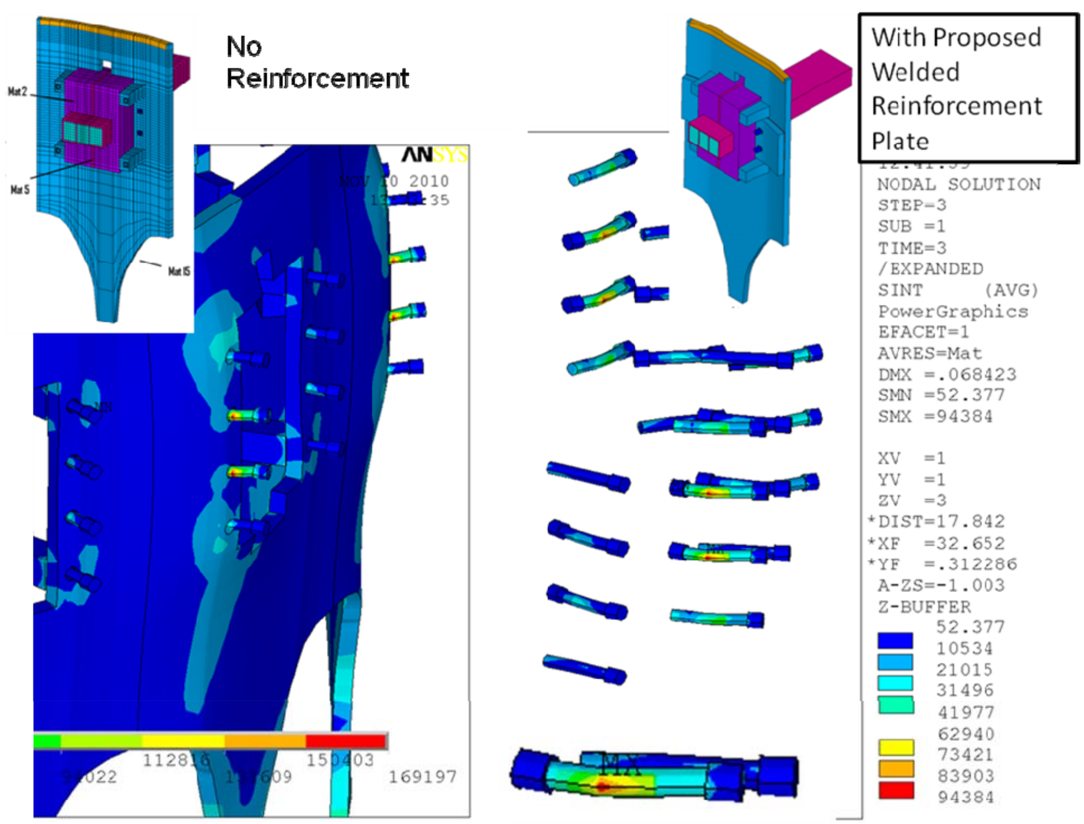
20000
25000
30000
35000
40000
45000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With Proposed Welded Reinforcement Plate
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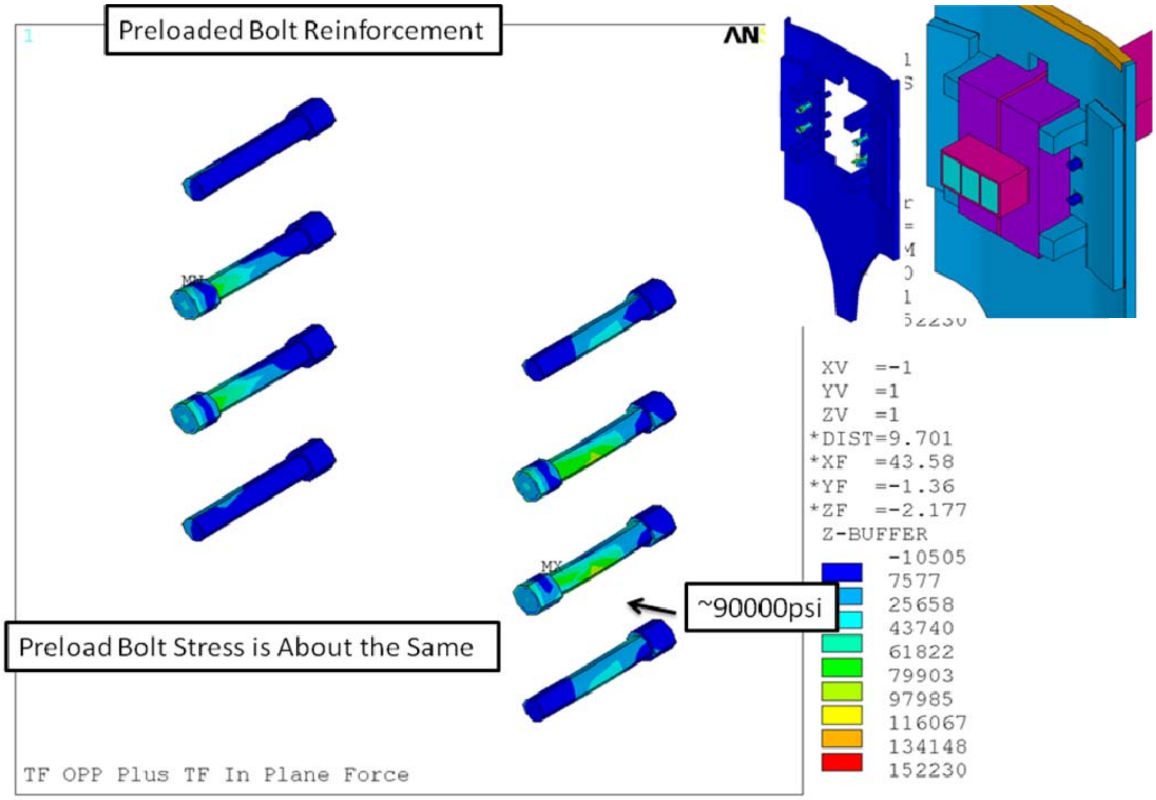
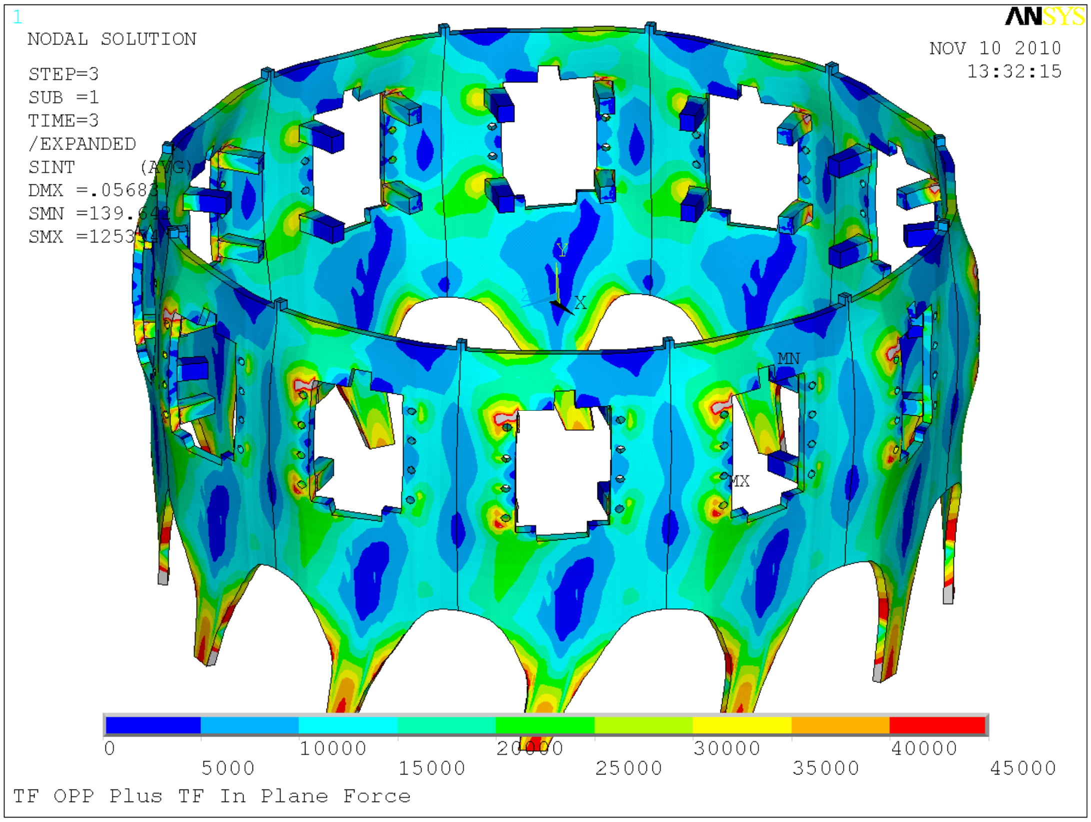
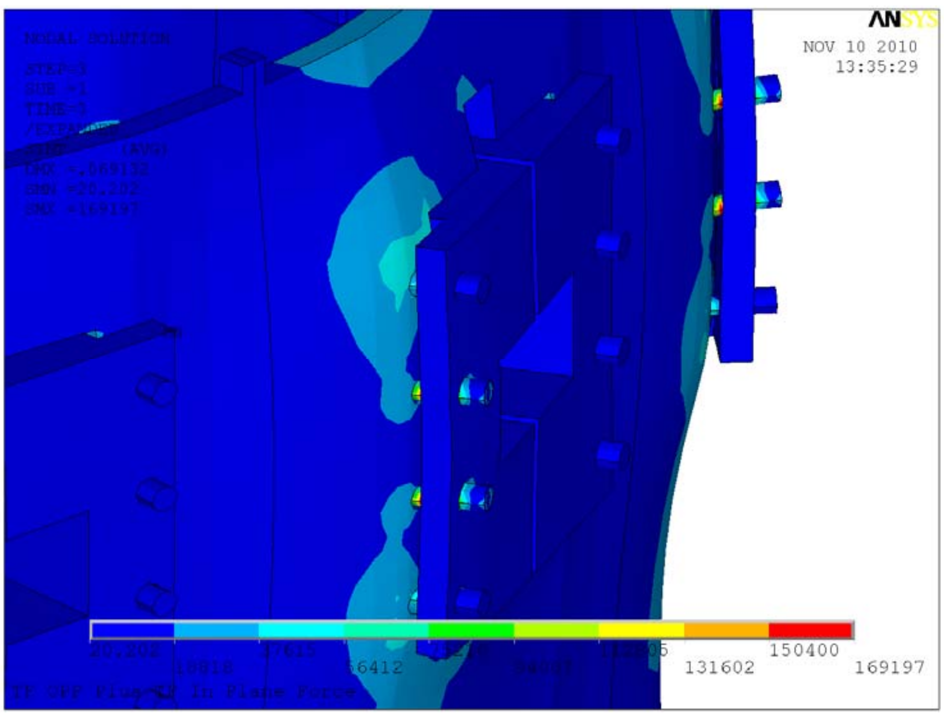


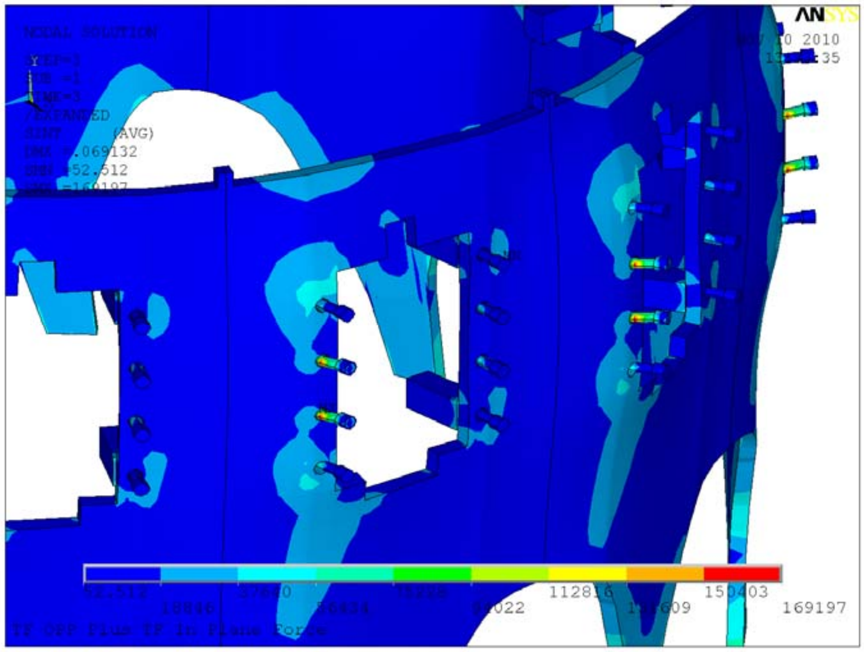
11.0 Stresses Based on Existing Hardware - No Reinforcement



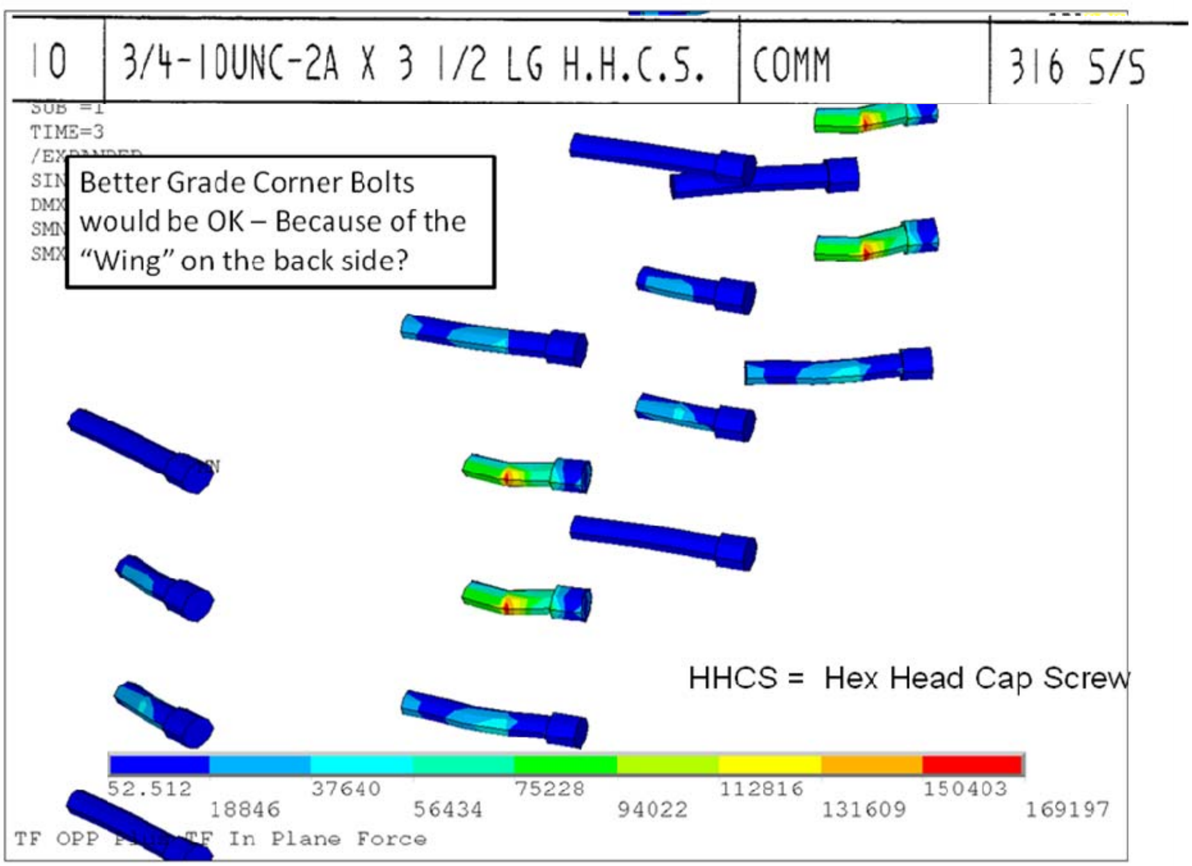
Umbrella Structure Stresses - No reinforcements NSTX-U loads



Aluminum Bolting Stress. Middle two bolts see bending from the rotation of the umbrella structure plate



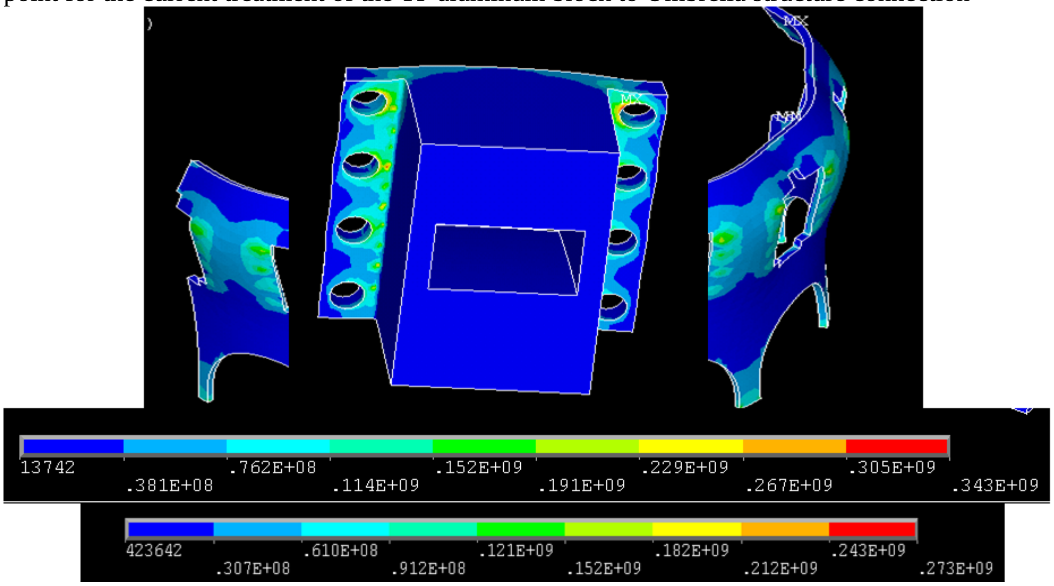
Another view of the aluminum block bolt stress showing higher stress in the middle two bolts.



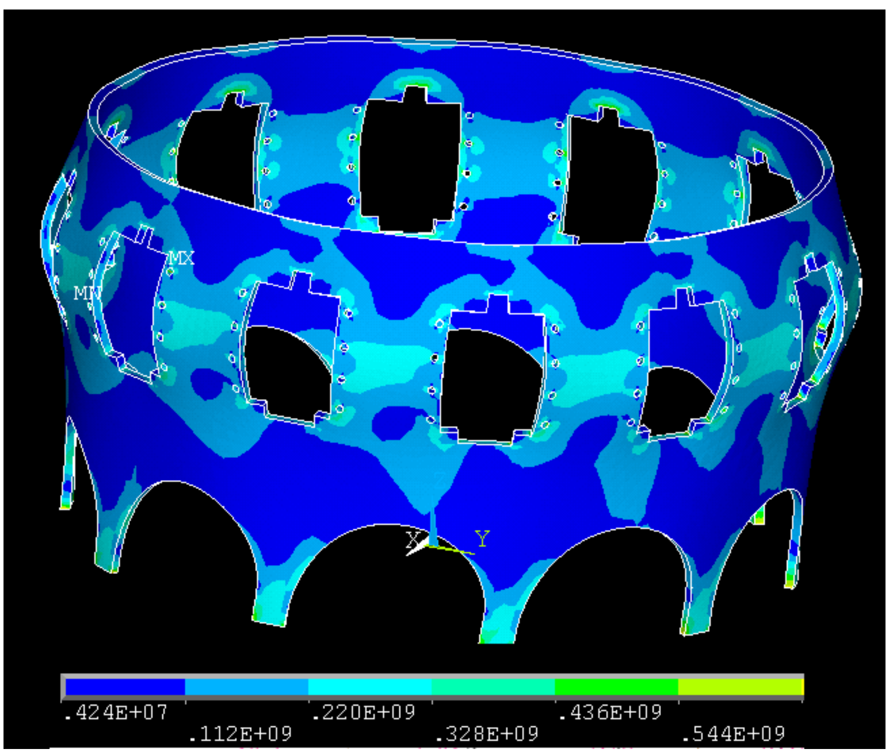
Another view of the aluminum block bolt stress showing higher stress in the middle two bolts.

Appendix A
Early 2009 Analysis Results

These results are included for historical purposes. They were presented in the CDR and were the starting point for the current treatment of the TF aluminum block to Umbrella structure connection



In this model the "wings" on the back side (ID of the umbrella structure) are not modeled and flange bending is larger than it would be had these been included.



Umbrella Structure stress as reported in the Conceptual Design Report, This work was done by S. Avasarala.

Appendix B
Cast Aluminum Properties from Wikapedia

Minimum tensile requirements for cast aluminum alloys[8]

Alloy type		Temper	Tensile strength (min) [ksi] ([MPa])	Yield strength (min) [ksi] ([MPa])	Elongation in 2 in [%]
ANSI	UNS				
201.0	A02010	T7	60.0 (414)	50.0 (345)	3.0
204.0	A02040	T4	45.0 (310)	28.0 (193)	6.0
242.0	A02420	O	23.0 (159)	N/A	N/A
		T61	32.0 (221)	20.0 (138)	N/A
A242.0	A12420	T75	29.0 (200)	N/A	1.0
295.0	A02950	T4	29.0 (200)	13.0 (90)	6.0
		T6	32.0 (221)	20.0 (138)	3.0
		T62	36.0 (248)	28.0 (193)	N/A
		T7	29.0 (200)	16.0 (110)	3.0
319.0	A03190	F	23.0 (159)	13.0 (90)	1.5
		T5	25.0 (172)	N/A	N/A
		T6	31.0 (214)	20.0 (138)	1.5
328.0	A03280	F	25.0 (172)	14.0 (97)	1.0
		T6	34.0 (234)	21.0 (145)	1.0
355.0	A03550	T6	32.0 (221)	20.0 (138)	2.0
		T51	25.0 (172)	18.0 (124)	N/A
		T71	30.0 (207)	22.0 (152)	N/A
C355.0	A33550	T6	36.0 (248)	25.0 (172)	2.5
356.0	A03560	F	19.0 (131)	9.5 (66)	2.0
		T6	30.0 (207)	20.0 (138)	3.0
		T7	31.0 (214)	N/A	N/A
		T51	23.0 (159)	16.0 (110)	N/A
		T71	25.0 (172)	18.0 (124)	3.0
A356.0	A13560	T6	34.0 (234)	24.0 (165)	3.5
		T61	35.0 (241)	26.0 (179)	1.0
443.0	A04430	F	17.0 (117)	7.0 (48)	3.0
B443.0	A24430	F	17.0 (117)	6.0 (41)	3.0
512.0	A05120	F	17.0 (117)	10.0 (69)	N/A
514.0	A05140	F	22.0 (152)	9.0 (62)	6.0
520.0	A05200	T4	42.0 (290)	22.0 (152)	12.0

535.0	A05350	F	35.0 (241)	18.0 (124)	9.0
705.0	A07050	T5	30.0 (207)	17.0 (117)†	5.0
707.0	A07070	T7	37.0 (255)	30.0 (207)†	1.0
710.0	A07100	T5	32.0 (221)	20.0 (138)	2.0
712.0	A07120	T5	34.0 (234)	25.0 (172)†	4.0
713.0	A07130	T5	32.0 (221)	22.0 (152)	3.0
771.0	A07710	T5	42.0 (290)	38.0 (262)	1.5
		T51	32.0 (221)	27.0 (186)	3.0
		T52	36.0 (248)	30.0 (207)	1.5
		T6	42.0 (290)	35.0 (241)	5.0
		T71	48.0 (331)	45.0 (310)	5.0
850.0	A08500	T5	16.0 (110)	N/A	5.0
851.0	A08510	T5	17.0 (117)	N/A	3.0
852.0	A08520	T5	24.0 (165)	18.0 (124)	N/A
†Only when requested by the customer					