NSTX Upgrade

Umbrella Arch and Foot Reinforcements, Local Dome Details

NSTXU-CALC-12-07-00

Rev 0

October 2011

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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.)**

The purpose of this calculation is to qualify the umbrella structure for increased loads and needed modifications for the NSTX CS Upgrade

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

-See the reference list in the body of the calculation

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

The in-plane and out-of-plane (OOP) loads on the umbrella structure were derived from the global model [1] and the outer leg support calculation [5]. Earlier loading did not include the knuckle clevis restraint/support, but this has been updated with later loads that include the stiffer clevis and struts. Even with the update, there is some variation in loads depending on the line of action of the TF tension. The range of loading, particularly the variation in vertical loading chosen, is assumed to adequately address the uncertainties in the TF loading at the aluminum block.

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.)**

The new solid umbrella leg is 3-inches thick and this is adequate to obtain acceptable stresses. The new leg design positions the welds in low stressed regions, and the welds are readily accessed, allowing large welds and plenty of margin. The dome is a 5/8 inch thick annealed 304 stainless steel head with a yield stress conservatively estimated to be 34 ksi (234 MPa) (if possible, testing should be performed on the head material to ascertain more accurate properties). Given that, the bending allowable is then 234 MPa and a local stress (3*Sm) allowable is 468MPa. The rib stresses and the stresses in the tabs that connect the ribs to the dome are highly stressed. In order to qualify these, more elaborate analyses needed to be used. A limit analysis was performed on the rib and umbrella foot segment of the machine. The results of this analysis show a factor of 2 on the strength of the existing weldments. The rib and tab weldments are all different and may vary from the geometry analyzed. During construction all the welds and tab positions should be inspected, and those with less weld length than analyzed, poor tab fit-up, or poor weld starts and stops should be upgraded. Tabs should be tight fitting against the rib. The global model was used to address the variety of equilibria and superposition of all loads, but does not have the detail of the sub models used in the limit analysis. The dome has a local peak stress under one of the tab welds of 270MPa (Figure 8.4-4). The 30-degree cyclic symmetry model evolved into the limit analysis model with better modeling of the tabs and welds. As details were added, linear stresses went higher, and ultimately, in order to assess the individual stress components, the limit analysis was used. Qualification of the rib, tabs and dome is based primarily on the limit analysis (section 9.4). Tab welds are partial penetration welds at the base that connect to the dome. A fracture mechanics analysis was performed to qualify this detail with the effective initial crack formed at the root of the partial penetration weld. The sliding foot hardware needs to be replaced with higher strength bolts and plate hardware - especially the "U" shaped retainer. The sliding block that attaches to the plate welded to the ribs must have lips that off load the shear from the retaining bolts. Some of the rib weld details have geometries that will have significant stress concentrations. These will be added to the inspection list.

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

Irv Zatz Irving Zatz Digitally signed by Irving Zatz
DN: cn=Irving Zatz, o=PPPL, ou, email=zatz@pppl.gov, c=US
Date: 2011.10.12 10:15:27 -04'00'

2.0 Table of Contents
Umbrella Arch and Foot Reinforcements, Local Dome Details

3.0 Executive Summary:

The umbrella structure is a part of the global TF in-plane and out-of-plane (OOP) torque structure. The umbrella structure is a continuous circular structure that support the TF radial in plane loads in hoop stress. The upper and lower ends of the TF outboard legs are connected to the umbrella structure by aluminum block clamps/split blocks. The aluminum blocks and the local details of the umbrella structure that support these loads are discussed and qualified in reference [4]. The umbrella structure also is attached to the spoked lids at their OD. Some of the machine torque is transferred to the central column through these attachments. The spoked lid is considered in reference [9]. Included in this calculation are the umbrella reinforcements, the feet or sliding pads at the vessel head ends of the umbrella legs, the ribs connected to the vessel that support the umbrella feet, and the vessel dished heads in the vicinity of the ribs. The new solid umbrella leg is 3-inches thick and this is adequate to obtain acceptable stresses. The new leg positions the welds in low stressed regions, and the welds are readily accessed, allowing large welds and plenty of margin. The dome is a 5/8 inch thick annealed 304 stainless steel head. Its yield is expected to be approximately 34 ksi. In Section 7, the bending allowable is then 234 MPa. and a local stress (3*Sm) allowable is 468MPa. This potentially is pessimistic. The mill certs (Appendix C) indicate yields prior to forming of approximately 41 ksi. The dished head was subsequently annealed, but it may not have been a full anneal and it is likely that the yield is above 34 ksi.

With the increase in loading resulting from doubling the toroidal field and doubling the plasma current, the OOP loads increase by a factor of four for the upgrade. This was addressed early in the project and the necessity to increase the load capacity of the umbrella legs was recognized. A number of concepts for improving the strength of the umbrella legs were investigated. The two main concepts that were considered were first to add flanges or ribs to the legs to turn them into cantilevered I-beams. This was judged to present a difficult in-situ fit-up and welding operation. Cover plates were also investigated. These would have been added to the legs on the inside and outside, but the field work required for these additions was also significant and the perimeter welds were at the high stress areas of the legs.

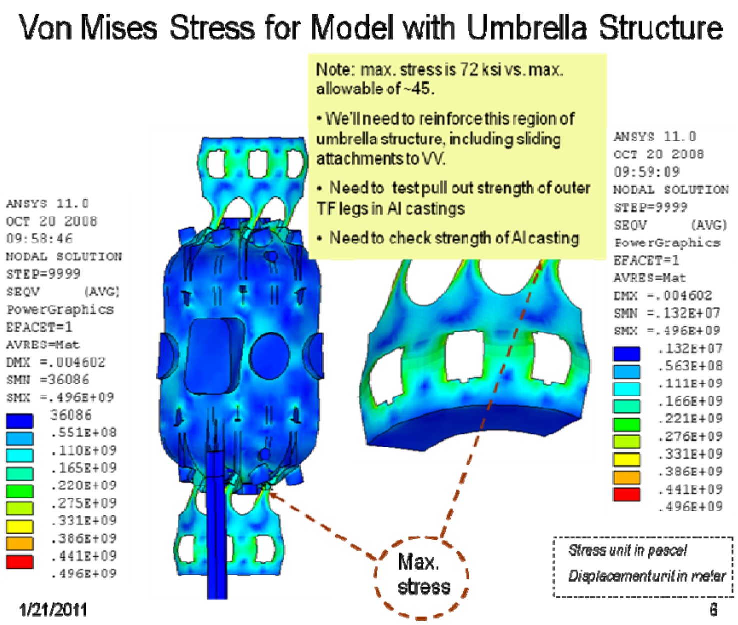


Figure 3.0-1 CDR Vintage Discussion of Required Reinforcement of the Umbrella Structure Legs [6]

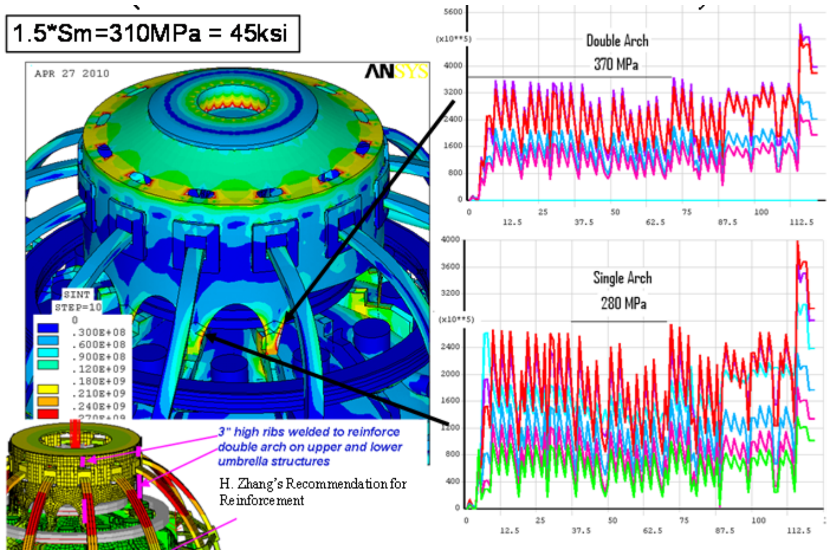


Figure 3.0-2 Need for Umbrella Structure Reinforcement - Showing the Optimistic Allowable Based on 45 ksi Yield which Subsequently was Shown to be 30 ksi

Figure 3.0-3 Solid Replacement Leg

The favored approach is to cut off the legs one by one and add a thicker leg. The weld used to re-connect the new leg is a horizontal weld on the inside and out. It is readily accessed, and can be a very robust weld. The new, much thicker legs would be fabricated in the shop. The lower foot detail of the umbrella leg also needs upgrading. The portion attached to the leg can be an integral part of the leg and done in the shop as well.

For the FDR, the rib models included some simplifications that underestimated some of the stresses - particularly in the bridging tabs. Subsequent to the FDR, further review of the as-builts, brought into question the capacity of the rib structures as they are actually welded to the dome, and to their cross reinforcing ribs, The main ribs required bridging tabs to make up a poor fit between the ribs and dome. The connection to the ribs was idealized in the earlier finite element models as fully merged. These are actually only welded on their top edges, to the ribs, and to the dome along the bottom edges.

Two evolving models of the support ribs that are welded on the vessel are used. The local 30 degree cyclic symmetry model was meshed from a ProE solid model developed by Bruce Paul from the Non-Conformance Reports for the rib welds. The ribs were cut to the expected profile of the dished head, but the profile was not perfect, and there were gaps between the ribs and vessel that needed to be bridged with tabs. The welds used were substantial and were dispositioned by H. M. Fan. The tabs between the welds stiffen the pair of ribs, and this feature was not initially included in the global model.

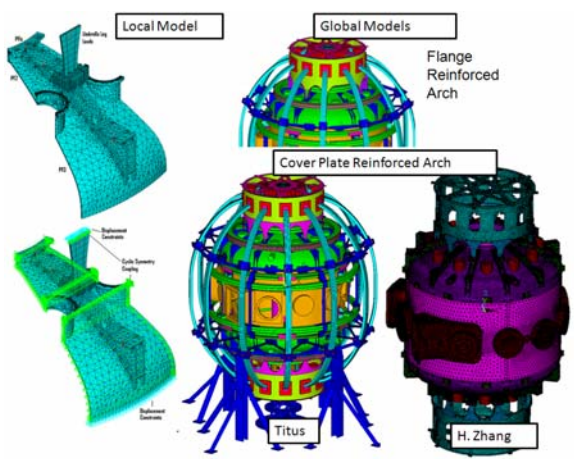


Figure 3.0-4 Local 30 Degree Cyclic Symmetry Model and Global Models

The rib stresses and the stresses in the tabs that connect the ribs to the dome are highly stressed. In order to qualify these, more elaborate analyses needed to be used. A non-linear limit analysis was performed on the rib and umbrella foot segment of the machine. The results of this analysis shows a factor of 2 on the strength of the existing weldments. The

rib and tab weldments are all different and may vary from the geometry analyzed. During construction, all the welds and tab positions should be inspected, and those with less weld length than analyzed, poor tab fit-up, or poor weld starts and stops should be upgraded. Tabs should be tight fitting against the rib. The global model was used to address the variety of equilibria and superposition of all loads, but does not have the detail of the sub models used in the limit analysis. In the earlier global model FDR results (sections 8.1 and 8.2), the dome stress was found to be less than 160 MPa. Modeling was improved with the rib-to-dome fit-up gaps and bridging tabs included. With the better modeling, the dome stress has a local peak stress under one of the tab welds of 270MPa (Figure 8.4-4).
Global modeling of rib tab reinforcements is discussed in sections 8.1 8.2 and 8.3.

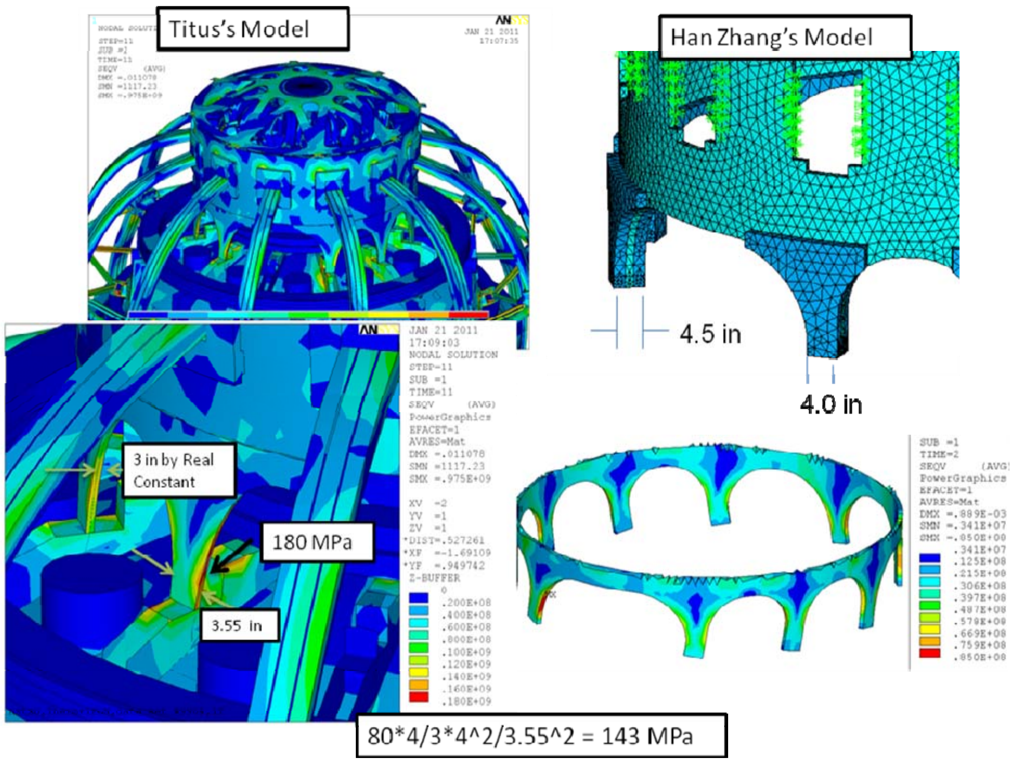


Figure 3.0-5 Comparisons of the Umbrella Structure Leg Reinforcements, References [1] and [5].

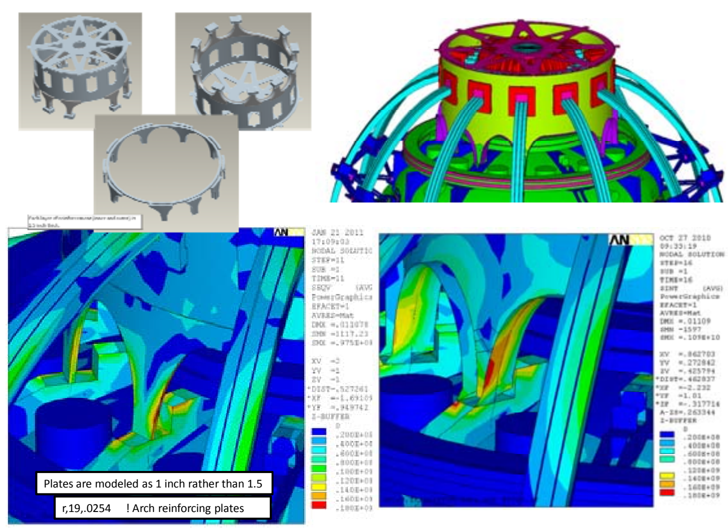


Figure 3.0-6 Results of two Reinforcement Concepts.

The 30 degree cyclic symmetry model does include the gap between the ribs and the dished head, and the tab details that bridge from the ribs to the dished head. These appear to be amply distributed and in the merged models (Section 9.3), and did not produce a stress locally in the tab, or tab weld beyond around 90 MPa. The 30 degree cyclic symmetry model evolved into the limit analysis model with better modeling of the tabs and welds. As details were added, linear stresses went higher, and ultimately, in order to assess the individual stress components, the limit analysis was used. Qualification of the rib, tabs and dome is based primarily on the limit analysis (section 9.4).

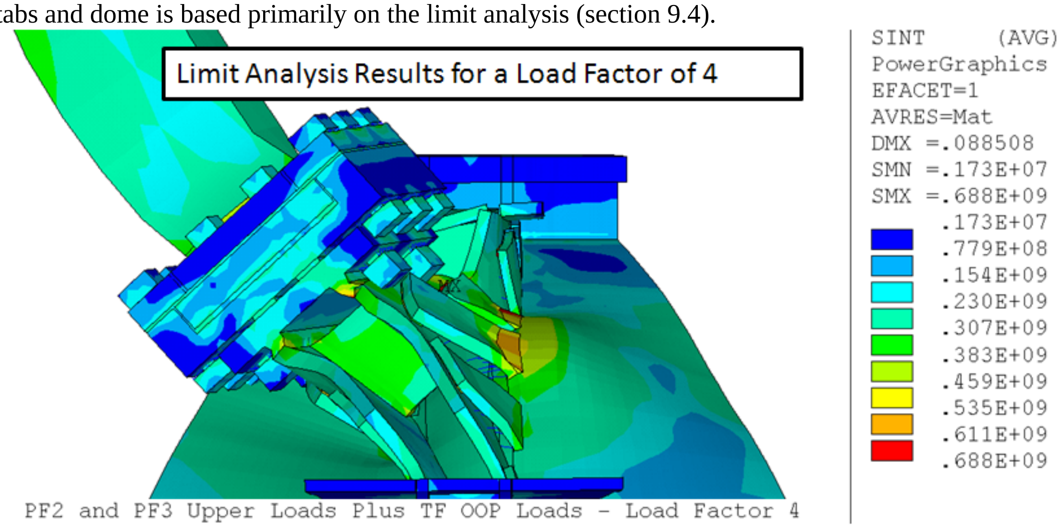


Figure 3.0-7 Results from the Limit Analysis of the Ribs and Tabs Details

Tab welds are partial penetration welds at the base that connect to the dome. A fracture mechanics analysis was performed to qualify this detail with the effective initial crack formed at the root of the partial penetration weld. This is included in section 9.6.

There is a higher stress at the ends of the welds that connect the umbrella foot sliding block mounting plate to the ribs These areas are shown in figures 9.8-1, and 2. Even with the more extensive analyses discussed below, these areas are candidates for periodic inspection.

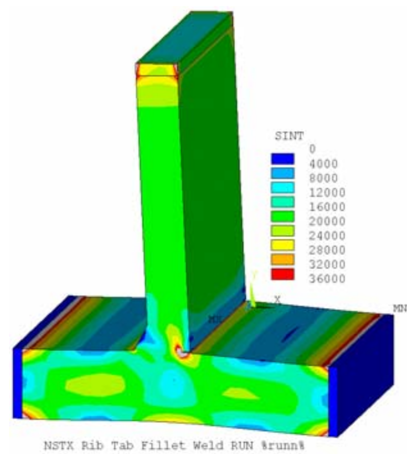


Figure 3.0-8 FEA Fracture Model Showing Stress Concentration at Weld Root

Analysis of the existing umbrella legs indicated a possibility of reinforcing only the double arch region. The bending allowable for the umbrella material had to be comparable to the cold worked value for the vessel shell of 45 ksi. The mill Cert for the Umbrella plate shows a yield of 220 MPa (32 ksi)so the design effort to reinforce the umbrella legs was continued. For 304 stainless, a 180 MPa stress range translates to a 90/(1-90/500) = 109 MPa equivalent R = -1 alternating stress. This is a strain amplitude of 109/200,000 = .05%. Entering the SN curve (Figure 7.2.1 for 304 Stainless) and applying either 2 on stress or 20 on life yields an acceptable fatigue life meeting the GRD requirement of 60,000 pulses. Figure 9.3.4 shows an area where stress concentrations are expected and which is a candidate for periodic inspection.

The umbrella support feet are mounted on sliding blocks that attach to the vessel head rib weldment. These must transfer the OOP loading from the TF outer legs as well as vertical loads. The sliding feature is intended to allow the unrestrained growth of the vessel during bake-out.

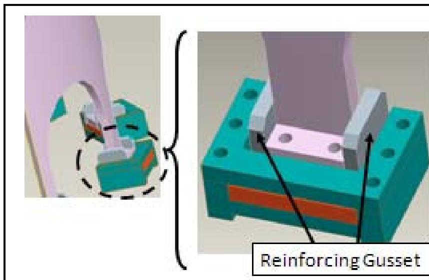


Figure 3.0-9 Foot Reinforcements

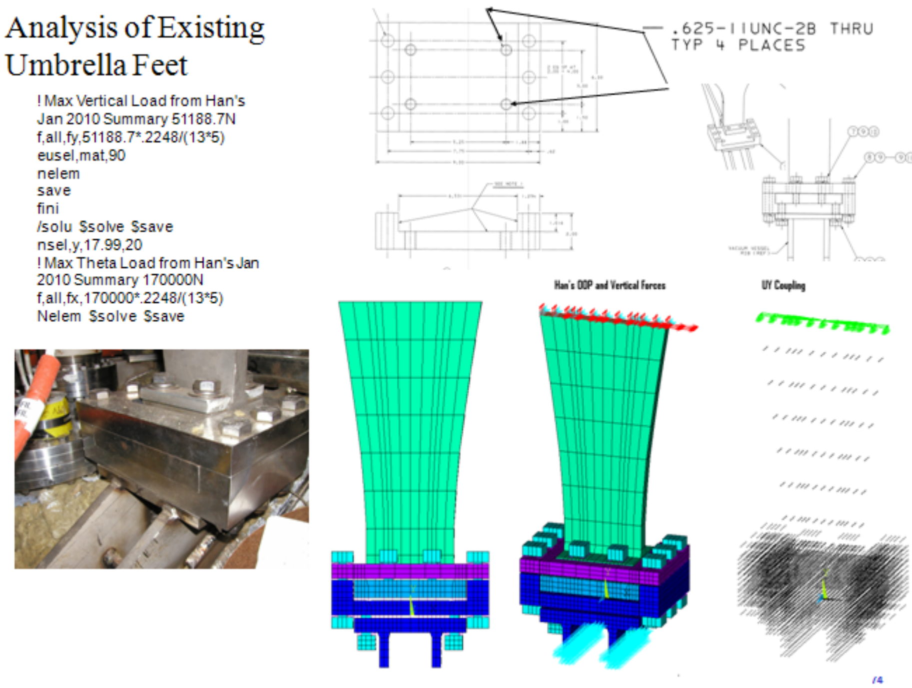


Figure 3.0-10 Local Model - Only the Umbrella Leg and Foot

In the present design, the foot is held to the weldment with four bolts that connect through the welded plate and are loaded in shear by the OOP loading. The sliding feet assembly will be replaced with stronger components. The base of the slider will have lips to capture the welded plate to takes the shear off the bolts.

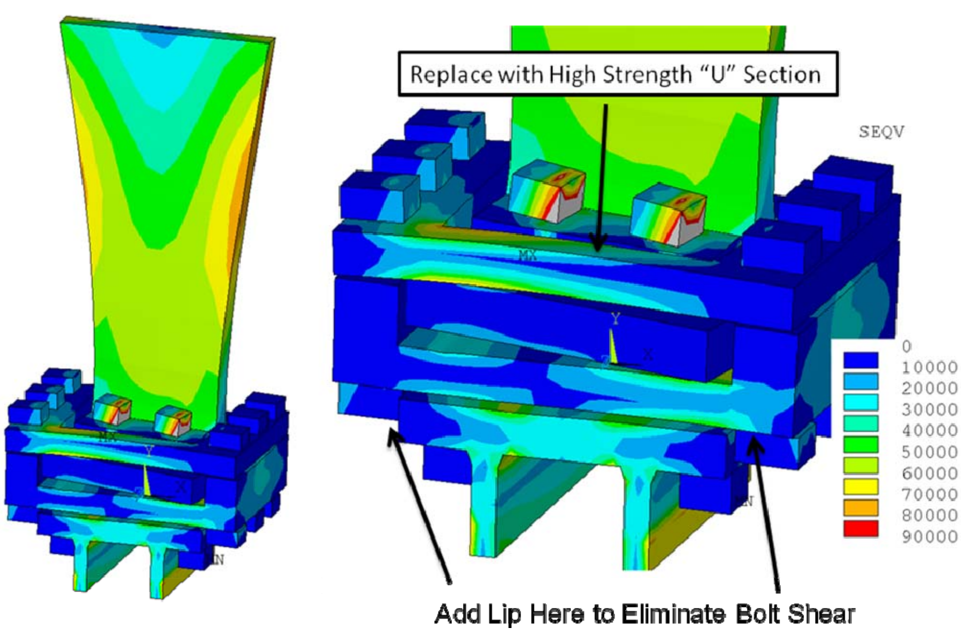


Figure 3.0-11 Local Model Stress Results

4.0 Digital Coil Protection System Input

The components covered by this calculation, the umbrella arch and foot reinforcements, and the local dome details are loaded predominantly by the global torque. This is available in the digital coil protection system from torque summaries by R. Woolley [12]. The global torque on the outboard TF leg is split between the truss at the vessel knuckle, and the umbrella structure. The series of calculations that address the umbrella structure, truss and knuckle clevis, and aluminum block use conservative load distributions. The calculations are converging on about an equal split of the OOP load between the knuckle region and the umbrella structure. If based on the earlier linear models, results in this calculation indicate 180 MPa (26 ksi) in Titus's analysis and 140 MPa (20 ksi) in H. Zhang's analyses for the max OOP torque for the 96 scenarios. The umbrella leg will have a yield and a bending allowable of at least 200 MPa (30 ksi). These results can be scaled in the DCPS. Final qualification of the ribs and bridging tabs is based on the limit analysis,

The rib weldments are also loaded predominantly by the OOP loads and can be scaled from the OOP torque, but the PF1c, PF2 and PF3 also loads the ribs and an assessment of their contributions will be added to the DCPS. Note that the analysis shown in Figure 6.2-2, (the local model of umbrella leg foot and dome/rib from as-builts) shows the full PF coil umbrella leg load inventory.

5.0 Design Input

5.1 Criteria

Coil and structural criteria are outlined in "NSTX Structural Design Criteria Document", Zatz[2]. Fatigue requirements are based on the Rev 4 GRD, recently revised in September 2011 [13]. The pertinent section is excerpted below.

b. Number of Pulses

For engineering purposes, the number of NSTX pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of 20,000 pulses based on the pulse spectrum given in Table 2-4 which allows for pulsing at various duty cycles coordinated per section 2.4 a.

Table 2-4 - NSTX CSU Pulse Spectrum

Performance	60%	75%	90%	100%	
B_t	0.6	0.75	0.9	1	T
I_p	1.2	1.5	1.8	2	MA
$T_{pulse}=T_{flat-Ip}$ (sec)					Total pulses
3	200	1800	1200	1000	4200
3.5	200	1800	1200	1000	4200
4	200	1800	1200	1000	4200
4.5	200	1800	1200	500	3700
5	200	1800	1200	500	3700
				Total	20000

Figure 5.1-1 Snapshot of the Rev 4 General Requirements Document

With a factor of 20 on life, this would require a life of 4e5 (400,000) in a SN evaluation.

5.2 Design Point Spreadsheet Loads

Table 5.2-1 Loads from the Design Point Spreadsheet.[3]

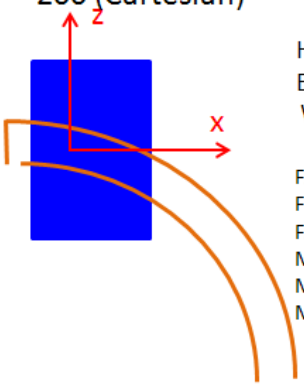
Fz(lbf)	PF1cU	PF2U	PF3U	PF3L	PF2L	PF1cL
Min	-30125	-67757	-148839	-31442	-42996	-68673
Worst Case Min	-168089	-194414	-303940	-246951	-192144	-143125
Max	68673	42996	100954	148839	54525	30125
Worst Case Max	143125	192144	246951	303940	194414	168089

5.3 Loads from Global Models

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

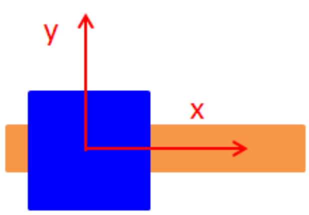
```
**** SUMMATION OF TOTAL FORCES
AND MOMENTS IN COORDINATE
SYSTEM 5
  NOTE: THE SUM IS DONE IN
COORDINATE SYSTEM 5
 FX = 149916.6
 FY = 104641.9
 FZ = 130590.1
 MX = -269111.9
 MY = 263555.7
 MZ = 114042.6

SUMMATION POINT= 0.0000    0.0000
0.0000
```

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	197,700N	243,340N
Mz at Alum Block	12044.77 N-m	-17 N-m	254831 N-m
My at Alum Block	5506.38N-m	121212 N-m	0



Top view

	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 5.3-1 Loads from Han Zhang's Outer Leg Support Model [5] and P. Titus's global model [1]

There is some variation in loads. One source of uncertainty is the line of action of the TF outer leg as it enters the aluminum block. A constant tension D would have only a tensile load in line with the coil centerline. But the NSTX TF system has the additional support of the ring for its bursting loads. This coupled with the thermal expansion of the coils, alters the direction of the TF bursting load as it is supported at the aluminum blocks. The vector sum of the outward loads is similar between [1] and [5] but there is a significant consequence to the umbrella leg. The limit analysis was run with two sets of loads. One based on Hans Zhang's (and Titus's early) loads with a modest downward load, and one with the large upward load from [1].

Table 5.3-1: Calculated Force on Aluminum block, From Ref [5]

		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

5.4 References

[1] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus June 2011

[2] NSTX Structural Design Criteria Document, I. Zatz

[3] NSTX Design Point June 2010 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[4] TF to Umbrella Structure Aluminum Block Connection NSTXU-CALC-12-04-00Rev 0 December 15 2010

[5] NSTXU-CALC-132-04-00 ANALYSIS OF TF OUTER LEG, Han Zhang, August 31, 2009

[6] Webmeeting of 10/20 2008 attended by L. Dudek, R. Parsells, J. Chrzanowski, M. Williams, M. Ono, R. Woolley, P. Titus, P. Heitzenroeder included in this presentation: NSTX Center Stack Upgrade Preliminary V.V. Analysis H.M. Fan, 10/20/2008

[7] Center Stack Casing Bellows, NSTXU-CALC-133-10-0 Prepared by Peter Rogoff.

[8] Email from Art Brooks Thu 3/11/2010 8:21 AM, providing Upper and Lower design loads for the centerstack casing halo loads, copy of the email is included in the appendices

[9] WBS 1.1.2 Lid/Spoke Assembly, Upper & Lower NSTX-CALC-12-08-00 Rev 0 May 2011 Prepared by P. Titus

[10] Dome Material Certifications Included in Appendix B "

[11] Umbrella Structure Mill Certs , Email from Larry Dudek October 8 2010

```
Pete,
Mark found the certs for the umbrellas.  Yield stress: 32ksi
Larry
```

[12] OOP PF/TF Torques on TF , R. Woolley, NSTXU CALC 132-03-00

[13] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE GENERAL REQUIREMENTS DOCUMENT NSTX_CSU-RQMTS-GRD Revision 4 September 15, 2011

[14] An Experimental Investigation of Fatigue Crack Growth of Stainless Steel 304L S. Kalnaus, F.Fan, Y Jiang, A.K. Vasudevan University of Nevada and Office of Naval Research , International Journal of Fatigue, Volume 31, Issue 5, May 2009

[15] Fatigue Life Prediction for Stainless Steel Welded Plate CTT Geometry Based on Lawrences Local Stress Approach, P. Johan Singh Materials Technology Division, Indira Gandhi Center for Atomic Research, Kalpakkam 603102, India Engineering Failure Analysis, Volume 10 Issue 6 December 2003

5.5 Drawings and Photos of Existing Components

Figure 5.4-1 Photos of the Umbrella Foot Details


Figure 5.4-2 Photo of the One of the Tabs that Connect Rib Pairs

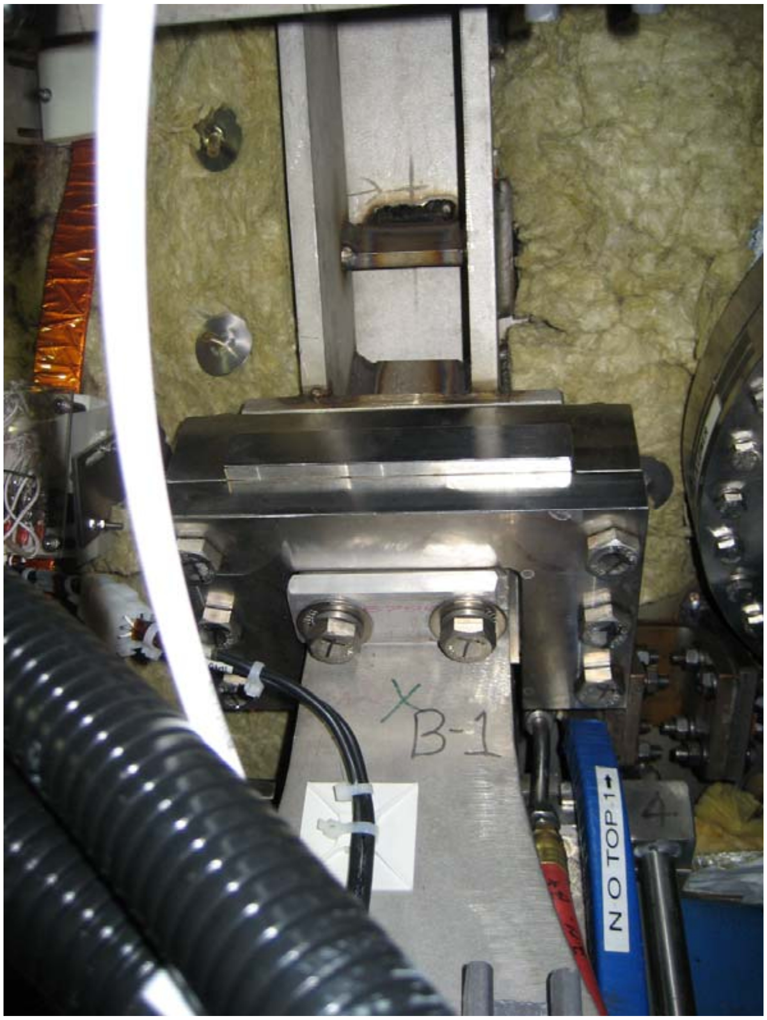


Figure 5.4-3 Photo of the One of the Lower Umbrella Sliding Feet.

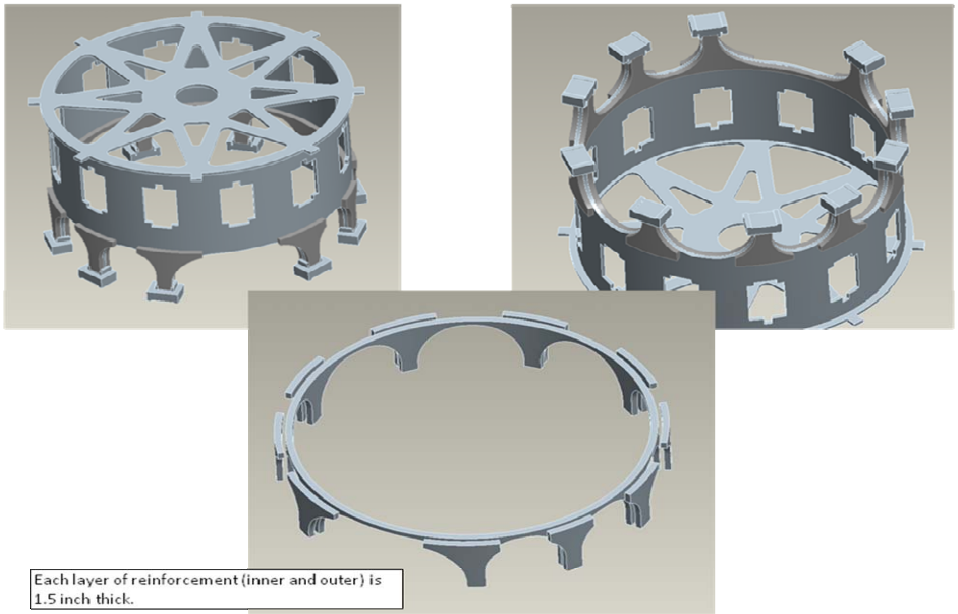


Figure 5.4-4 Cover Plate Reinforcement - For the FDR these were changed to a Solid Leg.

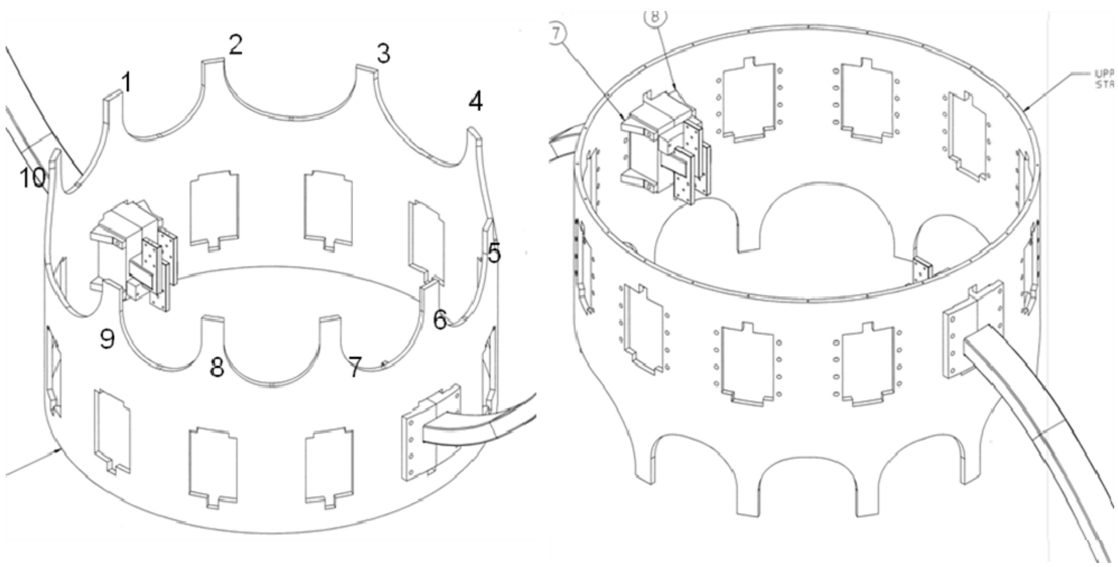


Figure 5.4-5 Existing Umbrella Structures Lower (Left) and Upper (Right)

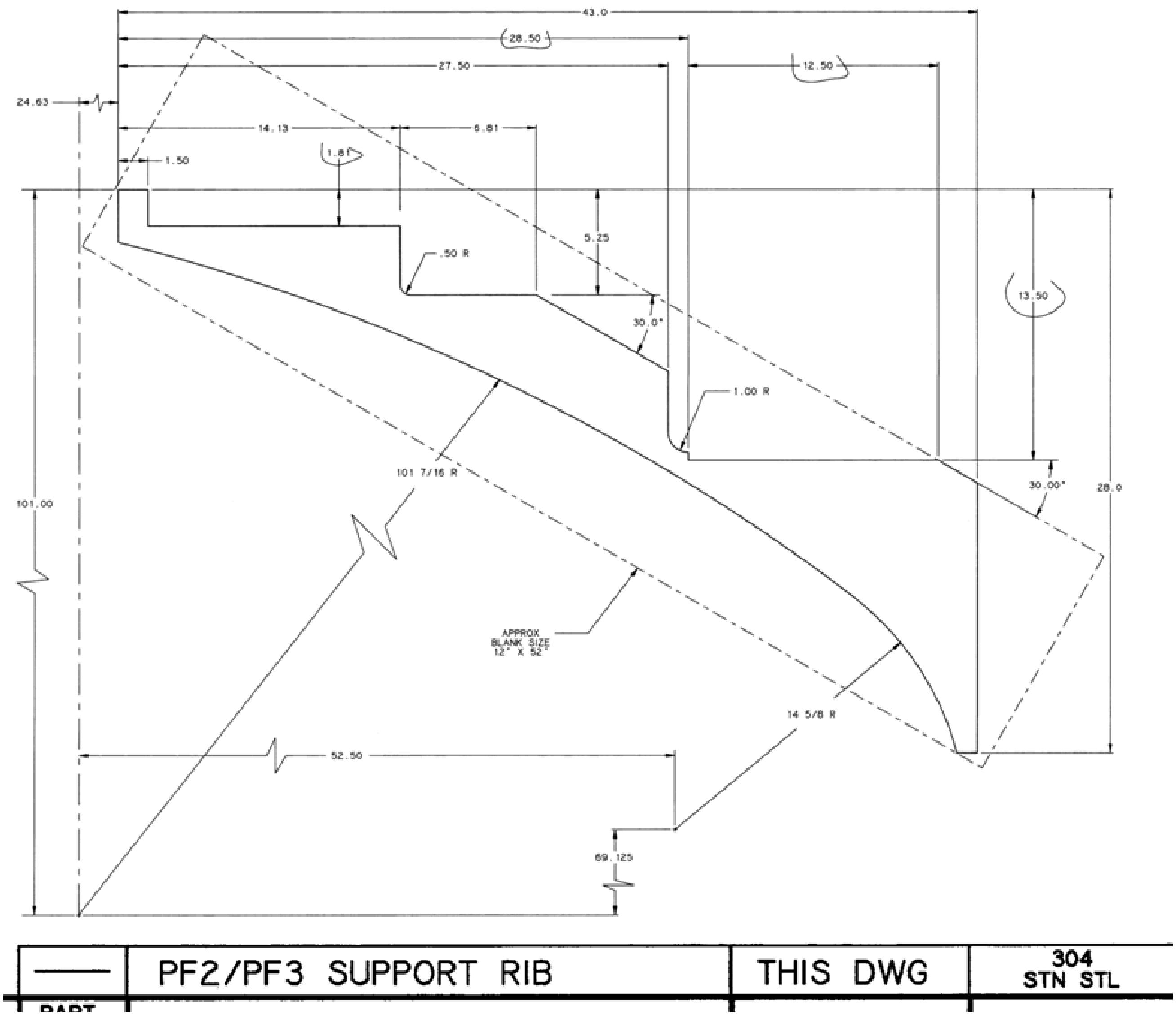


Figure 5.4-6 Support Rib Dimensions and Material

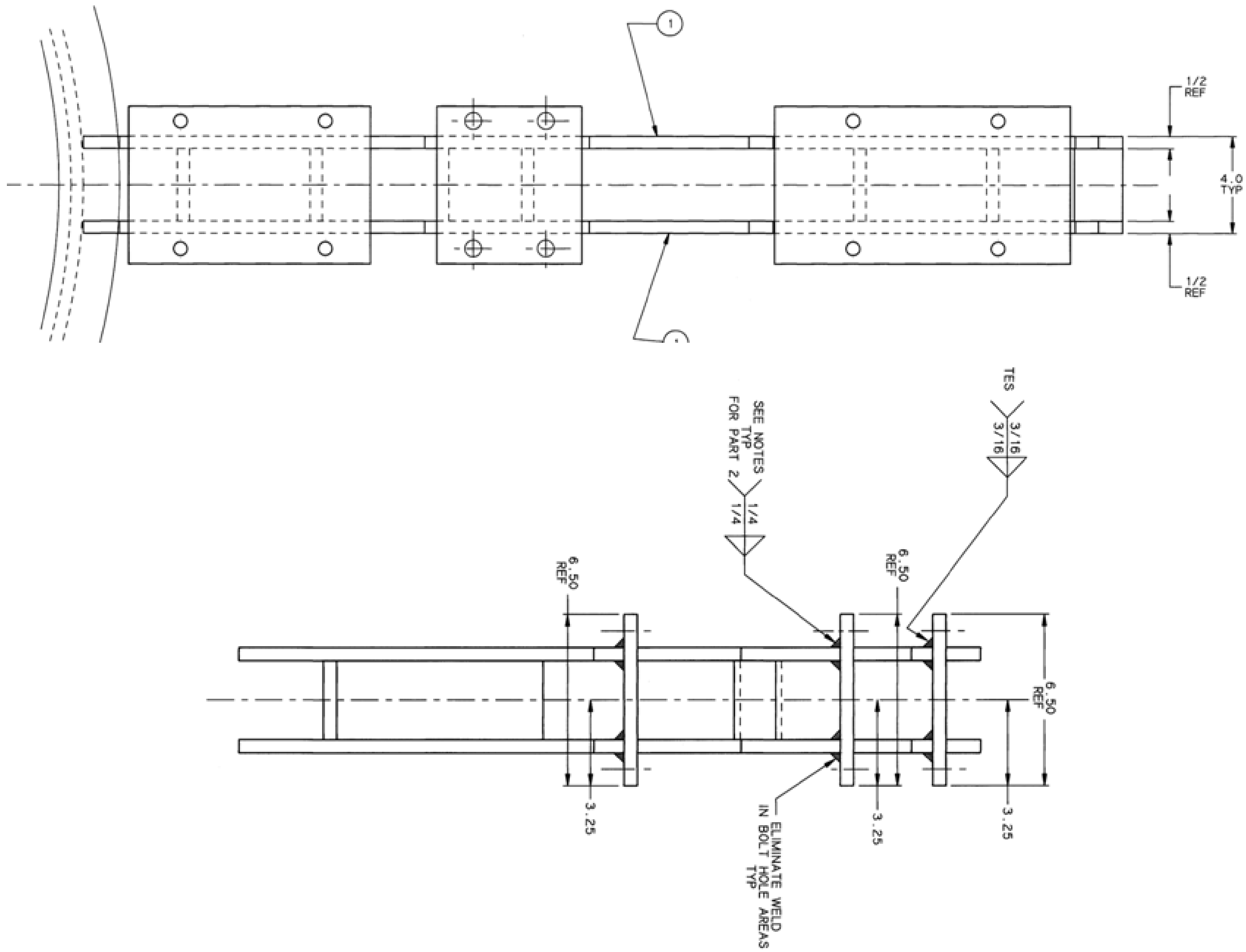


Figure 5.4-7 Support Rib Layout Showing Positions of Cross Tabs.

6.0 Analysis Models
6.1 Global Model

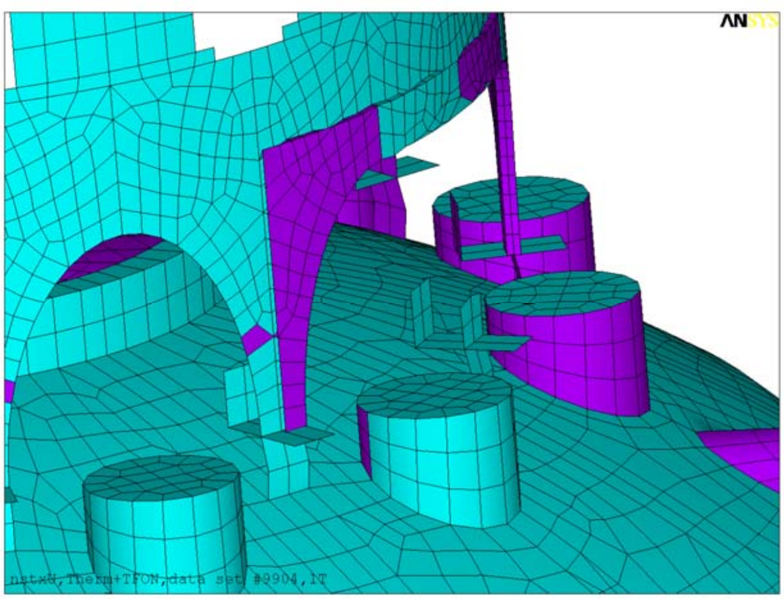


Figure 6.1-1 Global Model Umbrella Arch Region - Overlay Plates

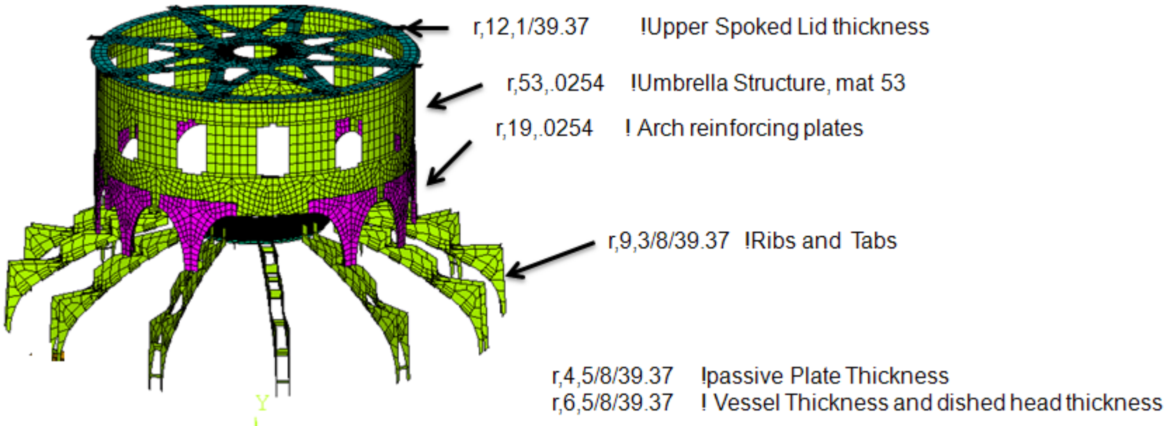


Figure 6.1-2 Global Model Umbrella Arch Region

The arch cover plates are modeled with a layer of plate elements on the outside and the inside. It was meshed by repeating the umbrella leg plate elements and bridging the gaps with a thin line of plate elements. This model is used to assess the stresses in the solid leg configuration as well.

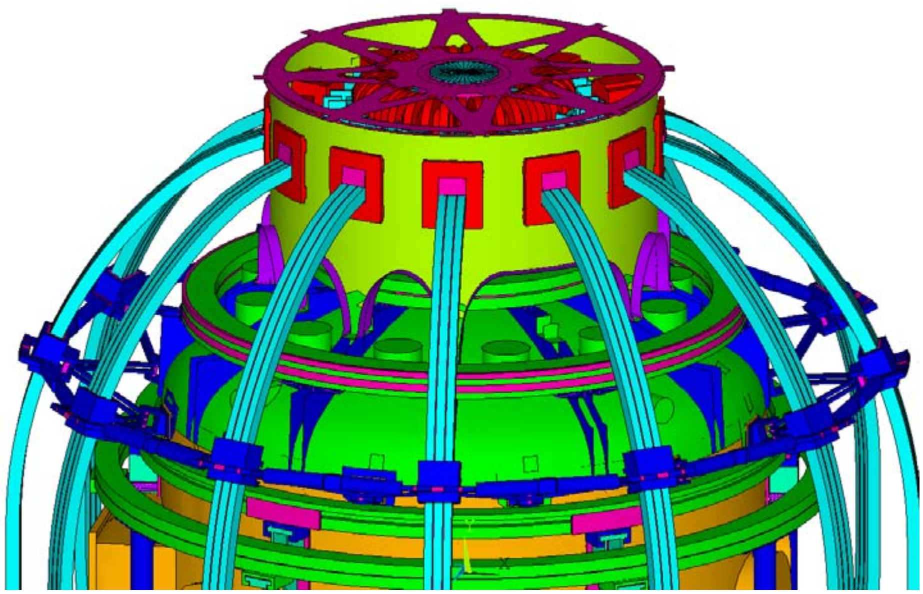


Figure 6.1-3 Global Model Umbrella Arch Region. - Flange Addition

In this model, flanges have been added to the arches, forming I-Beams as legs.

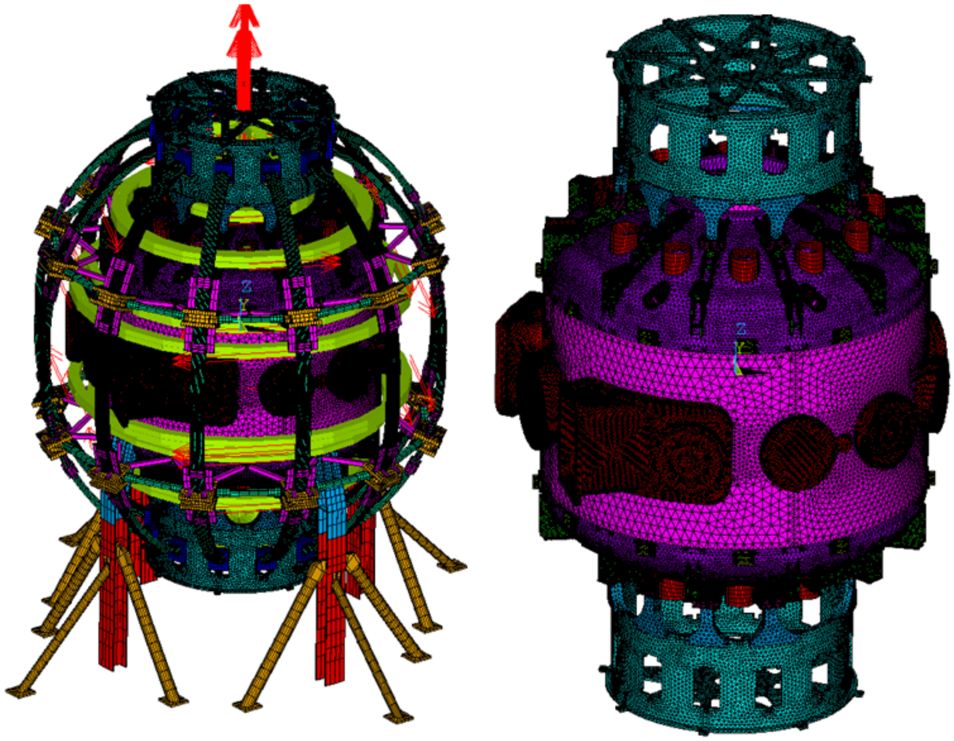


Figure 6.1-4 Han Zhang's Global Model, Reference [5]

6.2 Arch and Feet Local Models

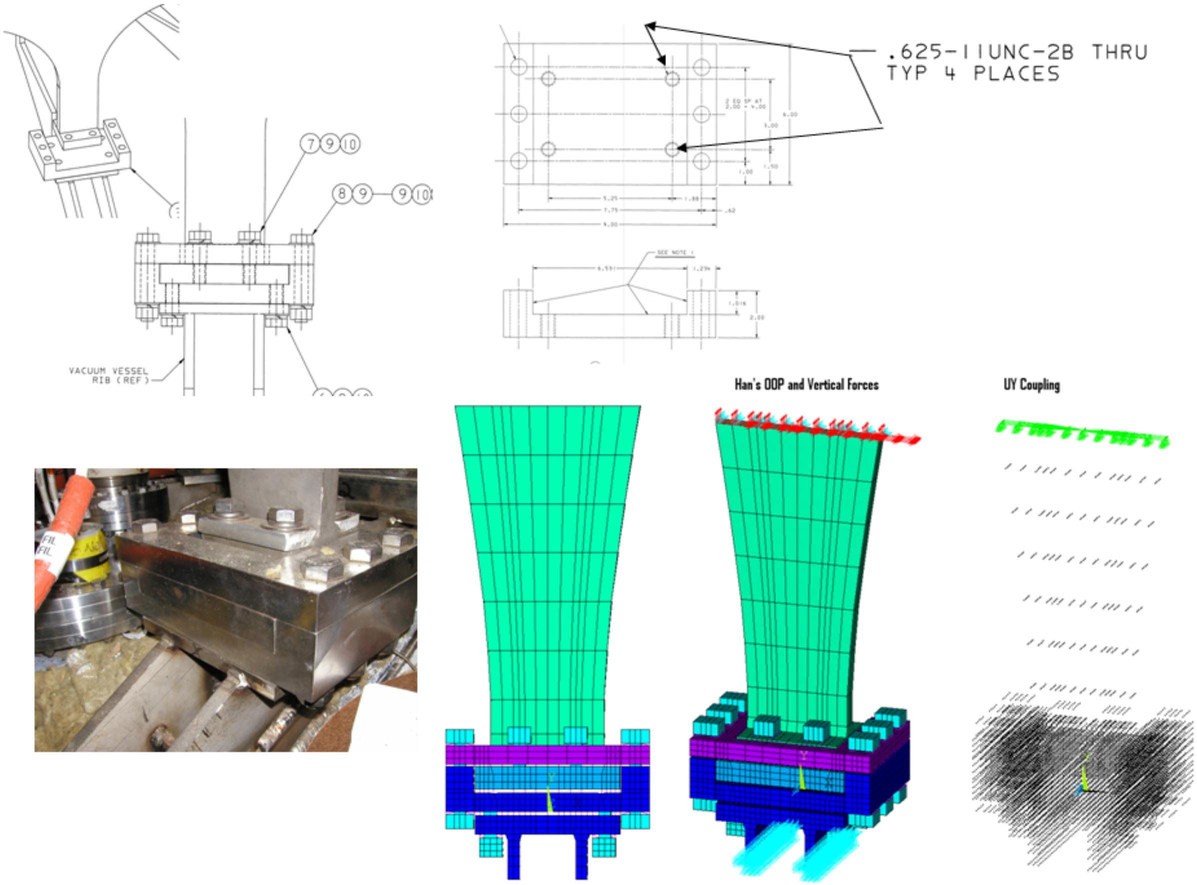


Figure 6.2-1 Local Model of only the Umbrella Leg Foot

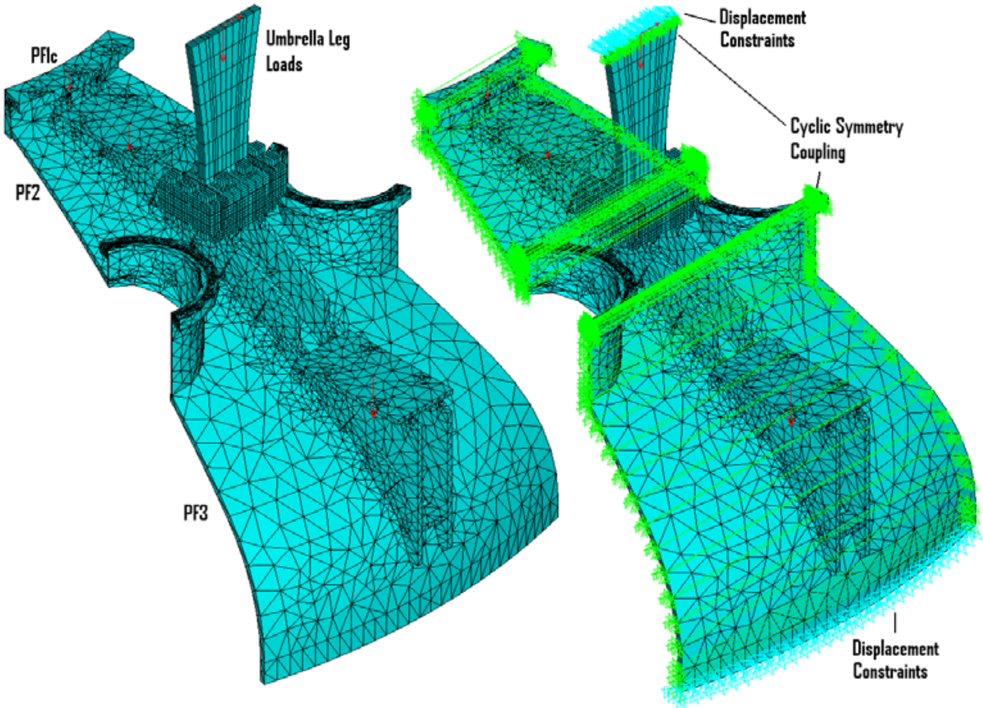


Figure 6.2-2 Local Model of Umbrella Leg Foot and Dome/Rib from As-Builts

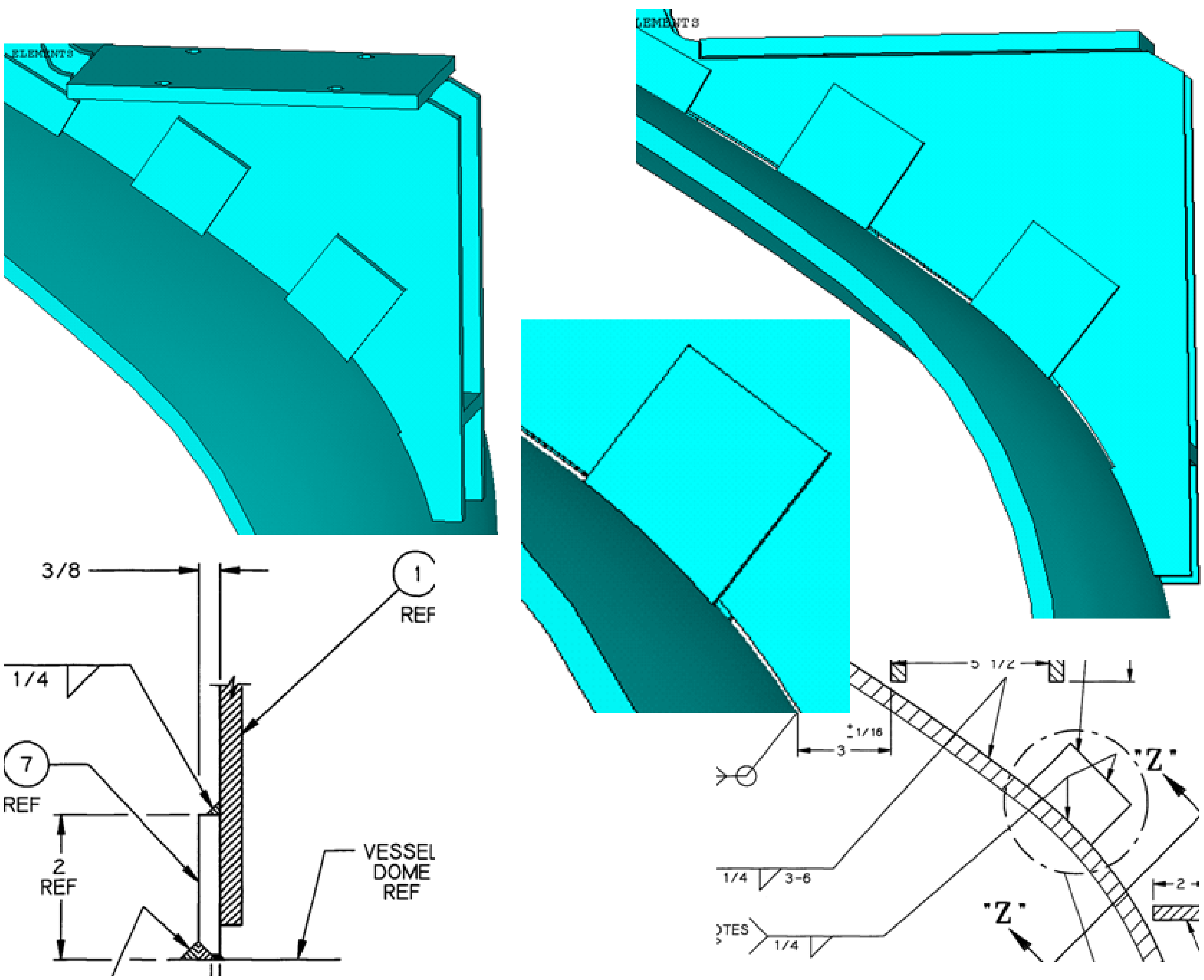


Figure 6.2-3 Local Model of Rib Showing Gaps and Modeling of the Non-Conformance Disposition

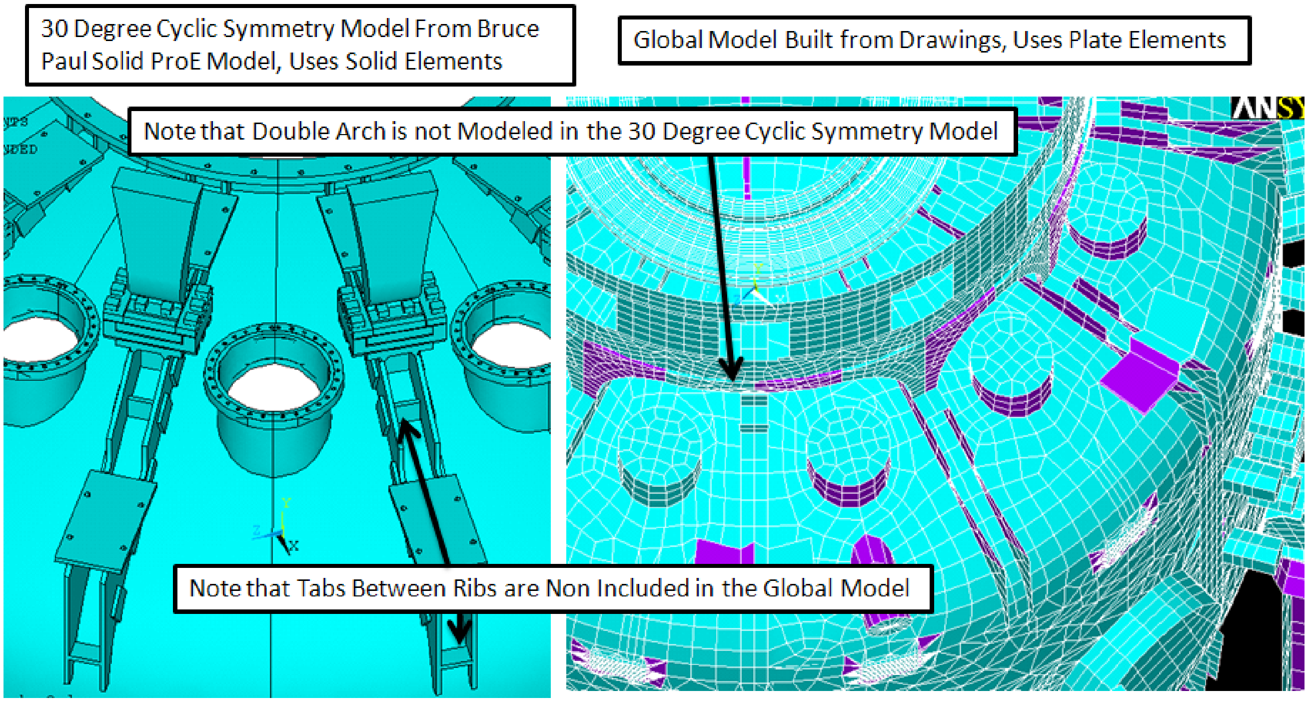


Figure 6.2-4 Comparison of 30 degree Cyclic Symmetry Model and the Global Model

Two models of the support ribs that are welded on the vessel are used. The local 30 degree cyclic symmetry model was meshed from a ProE solid model developed by Bruce Paul from the Non-Conformance Reports for the rib welds. The ribs were cut to the expected profile of the dished head, but the profile was not perfect, and there were gaps between the ribs and vessel that needed to be bridged with tabs. The welds used were substantial and were dispositioned by H. M. Fan. The tabs between the welds stiffen the pair of ribs, and this feature was not included in the global model. The global model stresses are above the 30 degree cyclic symmetry model. The lack of tabs may be the reason. The higher stresses in the global model at the double arch are real.

ANSYS ADPL Loading Commands for the 30 Degree Cyclic Symmetry Model

```
/title,PF2 and PF3 Upper 96 Scenario Vert Loads
bf,all,temp,20
f,985,fz,-30125/12/.2248      !PF1c
f,402,fz,-67757/11/.2248      !PF2
f,4588,fz,-100000     !Umb Foot
f,1237,fz,-148839/11/.2248     !PF3
solve
f,4588,fy,60000
/title,PF4 and PF5 Upper Loads Plus TF OOP Loads
solve
save
/title,OOP Loads Only
bf,all,temp,20
f,985,fz,-.001
f,402,fz,.001
f,4588,fz,.001
f,1237,fz,.001     !PF3
solve
save
/title,PF2 and PF3 Upper Worst Power Supply Loads
bf,all,temp,20
f,985,fz,-168089/12/.2248      !PF1c
f,402,fz,-194414/11/.2248      !PF2
f,4588,fz,-100000     !Umb Foot   (From the table in the input section based on [5] this should be 106000N)
f,4588,fy,.001
f,1237,fz,-303940/11/.2248     !PF3
solve
f,4588,fy,60000
/title,PF4 and PF5 Upper Worst Power Supply Loads Plus TF OOP Loads
solve
save
/title,OOP Loads Only
bf,all,temp,20
f,123,fz,-.001     !PF1c
f,409,fz,-.001
f,4588,,fz,.001
f,1277,fz,.001     !PF3
```

6.2.2 Arch and Feet Local Model Run Log and Run Files

Foot01.txt 30 degree cyclic Symmetry Model in \nstx\csu\dome, 3/4 inch thick Umbrella Leg
Foot02.txt 30 degree cyclic Symmetry Model in \nstx\csu\dome, 3 inch thick Umbrella Leg
foot04.txt   30 degree cyclic Symmetry Model, by Limit Analysis Max Downward TF Load , All TF Scaled 12/10
foot05.txt   30 degree cyclic Symmetry Model, by Limit Analysis Max Upward TF Load, All TF Scaled 12/10
Global Model Run #28 and beyond model the overlay plates or solid leg umbrella reinforcement

7.0 Materials and Allowables

7.1 Stainless Steel Static Stress Data

Table 7.1-1Tensile Properties for Stainless Steels

Material	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	275.8[7]	613[7]
316 LN SST Weld	324[7]	482[7] 553[7]
316 SST Sheet Annealed	275[8]	596[8]
316 SST Plate Annealed		579
304 Stainless Steel (Bar,annealed)	234 33.6ksi	640 93ksi
304 SST 50% CW	1089	1241 180ksi

Table 7.1-2 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)

Note that the Material Certifications for the dome indicate that the dome is annealed 304 stainless steel. The material Certs are included in Ref [10], Appendix B.

7.2 Stainless Steel Fatigue Data

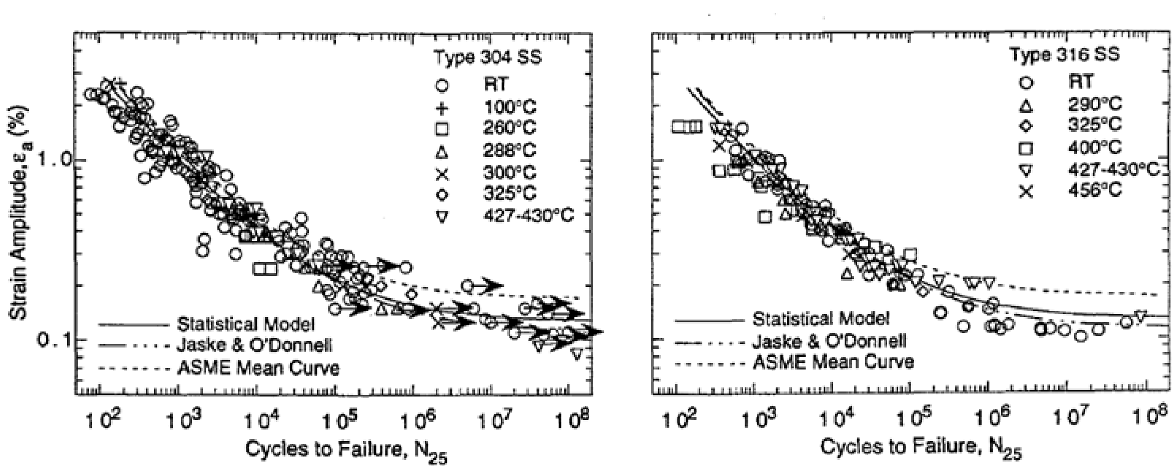


Figure 7.2-1 Fatigue Data for 304 and 316 Stainless Steels
From Tom Willard’s Collection of SST Fatigue Data
“Estimation of Fatigue Strain-Life Curves for Austenitic in Light Water Reactor Environments Stainless Steels”, Argonne Nat. Lab, 1998

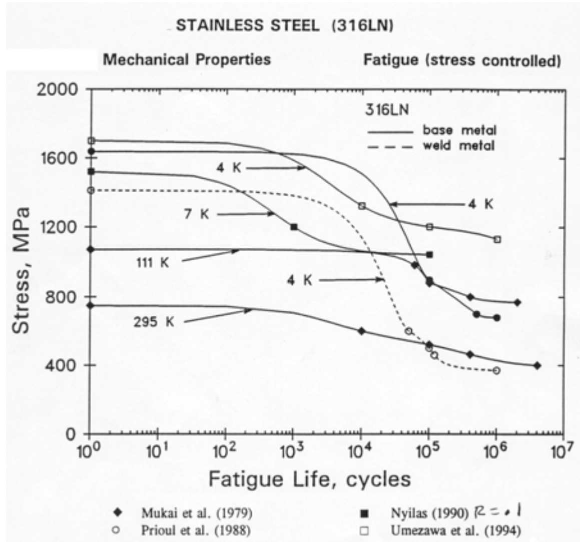
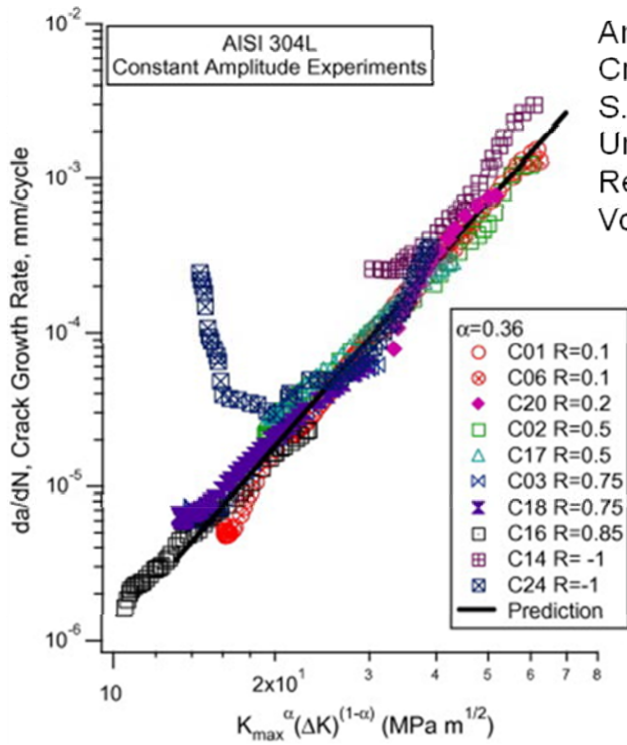


Figure 7.2-2 Fatigue S-N Curve for 316 Stainless Steel



An Experimental Investigation of Fatigue Crack Growth of Stainless Steel 304L
S. Kalnaus, F.Fan, Y Jiang, A.K. Vasudevan
University of Nevada and Office of Naval Research , International Journal of Fatigue, Volume 31, Issue 5, May 2009

Fig. 10 shows the results by using Eq. (3) for all the constant-amplitude loading experiments with different *R*-ratios conducted in the current study. For the AISI 304L stainless steel, α was found to be 0.36. Except for the early part of crack growth from the notch, Eq. (3) with $\alpha = 0.36$ can bring all the crack growth curves together into one master curve. This master curve (thick line in Fig. 10) can be described by using the Paris type power law,

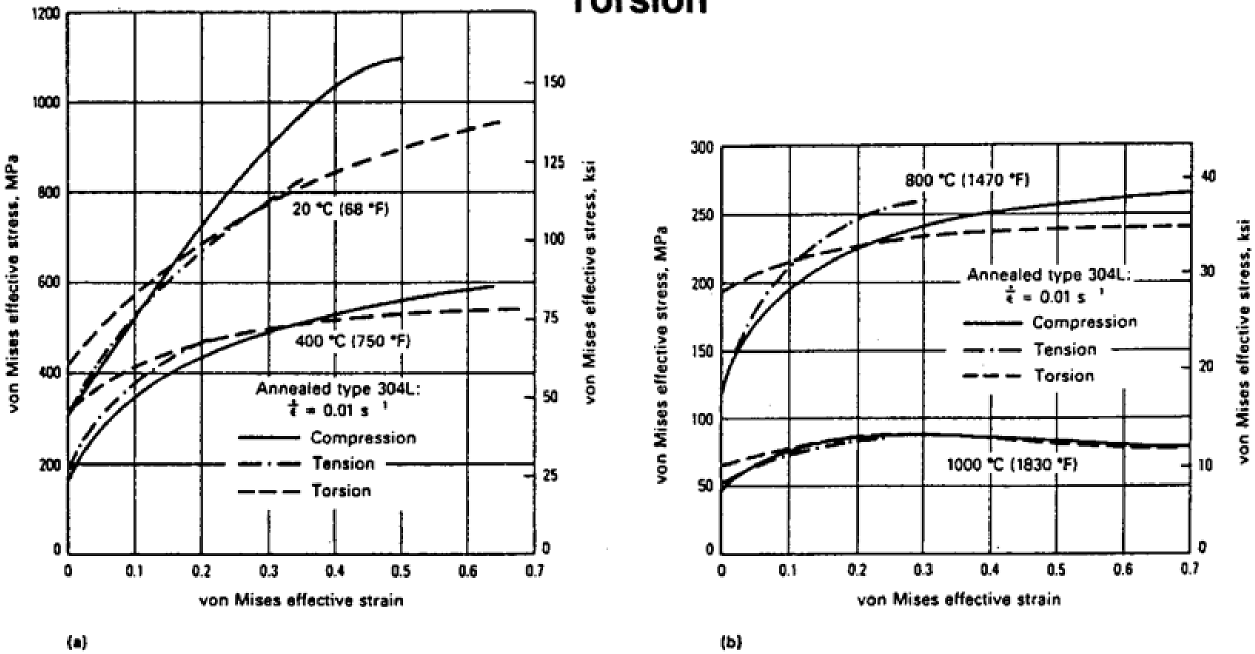
$$da/dN = C_1 k^{n_1} \quad (4)$$

where C_1 and n_1 are material constants. For the 304L alloy, $C_1 = 1.25 \cdot 10^{-10}$ and $n_1 = 3.97$, with da/dN in mm/cycle and k in $MPa\sqrt{m}$.

Figure 7.2-3 Paris Constants for 304L Stainless Steel

7.3 Stress Strain Data

11-16. Type 304L Stainless Steel: Compression, Tension, and Torsion



From: Howard E. Boyer, Atlas of Stress-Strain Curves, ASM International, .

Comparison of effective stress-strain curves determined for type 304L stainless steel in compression, tension, and torsion. (a) Cold and warm working temperatures. (b) Hot working temperatures.

Figure 7.3-1 Stress Strain Data

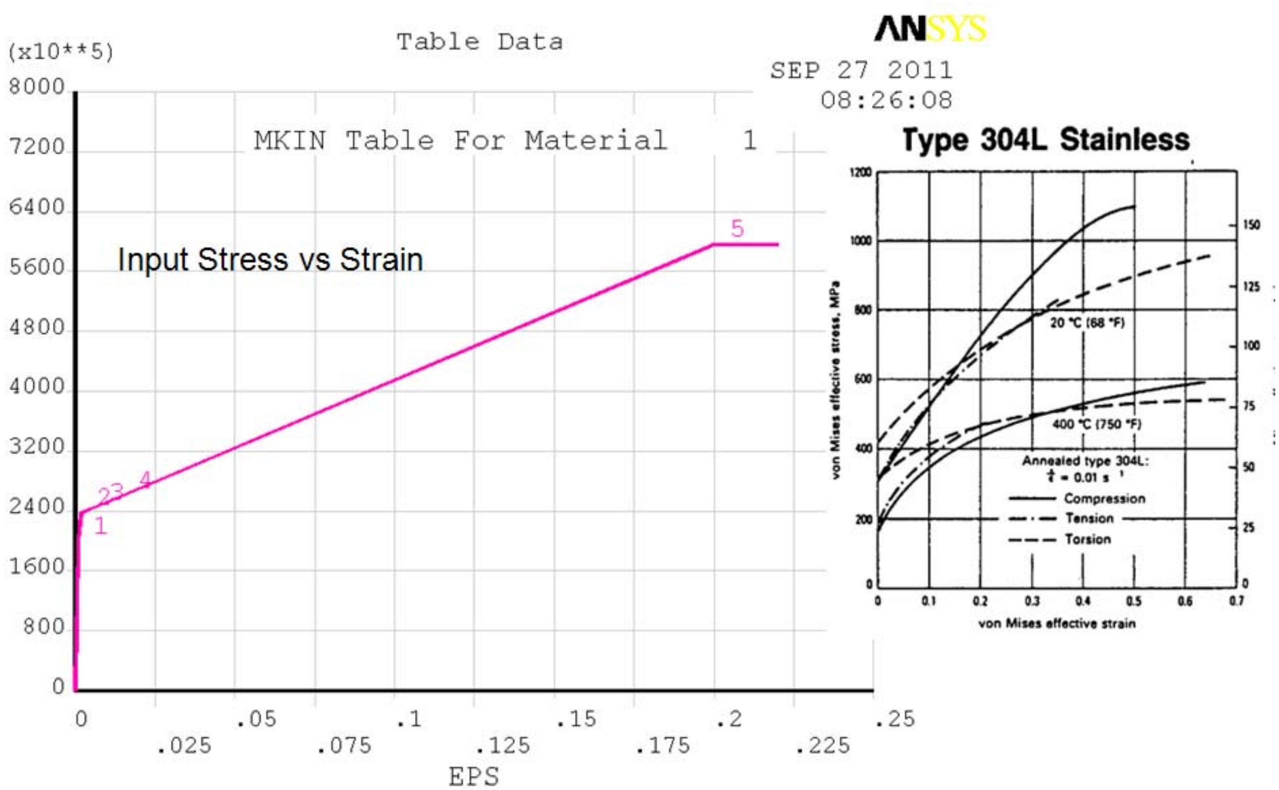


Figure 7.3-2 Stress Strain Curve Used in the Limit Analysis (Section 9.4)

7.4 Bolt Strength Data

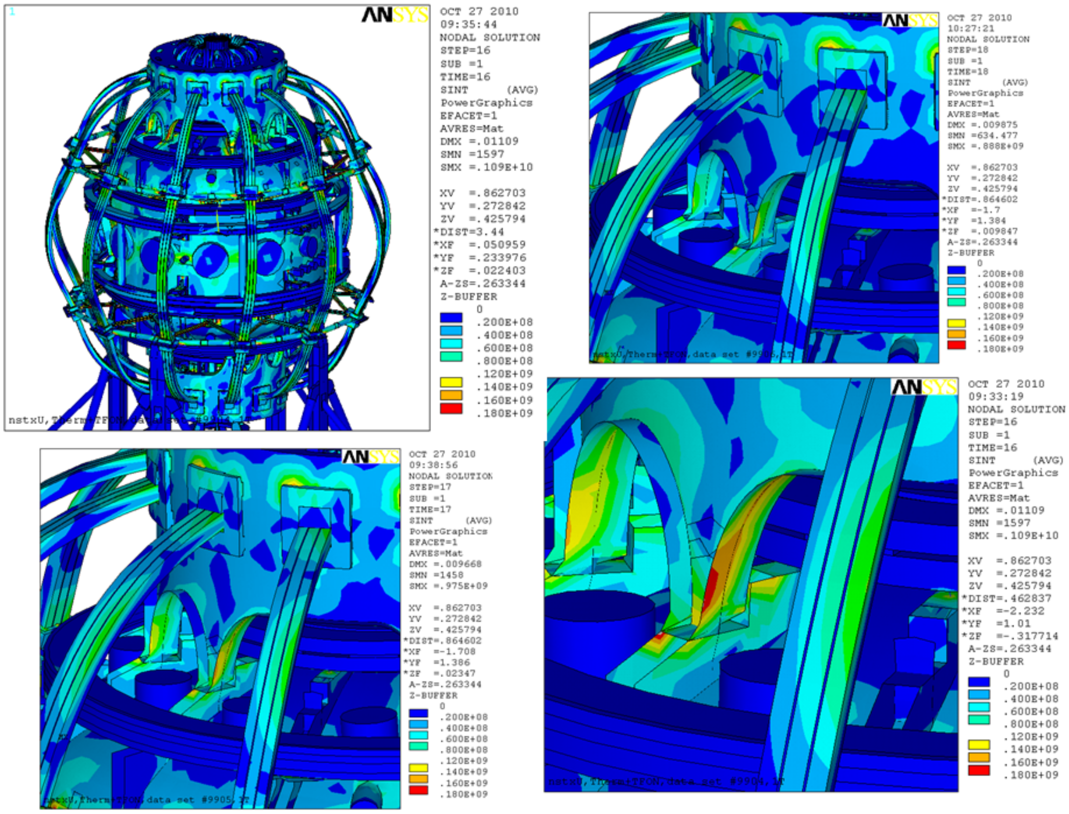
ASTM A193 Bolt Specs from PortlandBolt.com

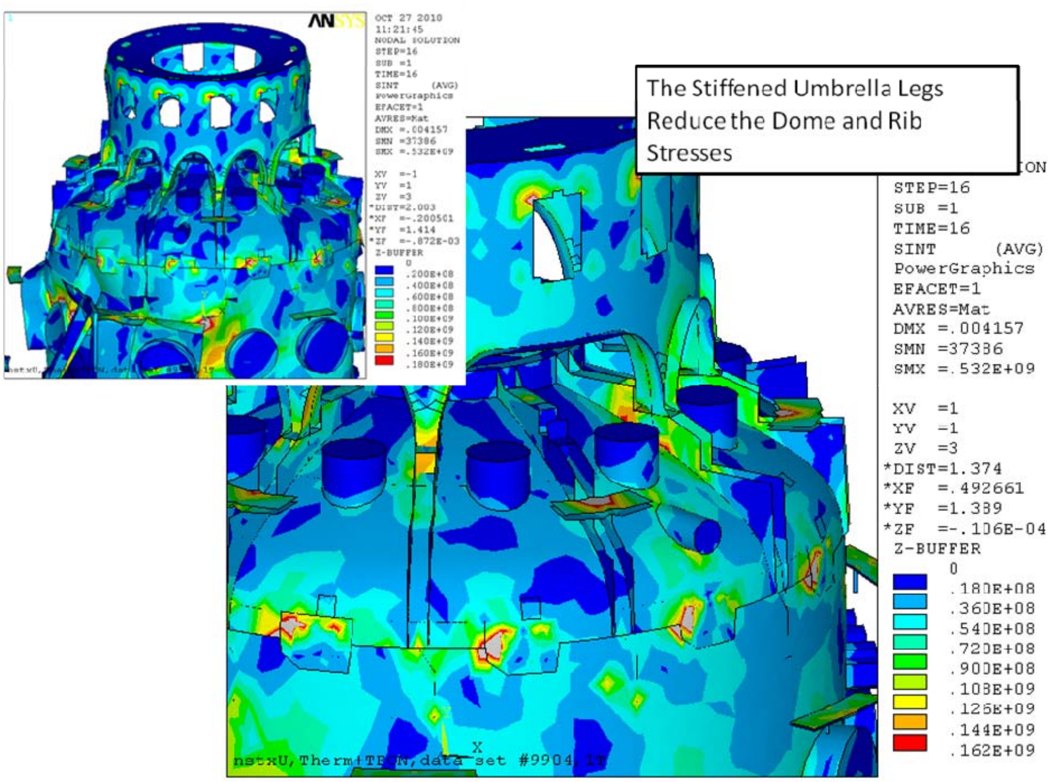
B8M	Class 1 Stainless steel, AISI 316, carbide solution treated.
B8	Class 2 Stainless steel, AISI 304, carbide solution treated, strain hardened
B8M	Class 2 Stainless steel, AISI 316, carbide solution treated, strain hardened

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

8.0 Global Model Results
8.1 Arch Reinforcements
8.1.1 Addition of Flanges





8.1.2 Cover Plates inside and out

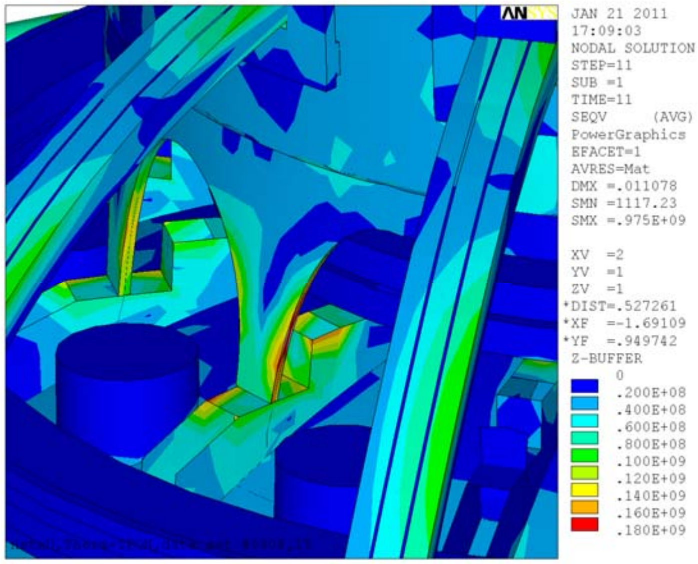


Figure 8.1.2-1 Typical Cover Plate Stress

Use of cover plates in this concept puts the welds at the high stress edge of the umbrella legs. If this model is interpreted as modeling 3 inch thick solid legs, replacing the existing 1 inch thick legs, then the high stress is not in a region of the weld. The horizontal weld, represented by the upper edge of the cover plate in this model, is in a low stress region.

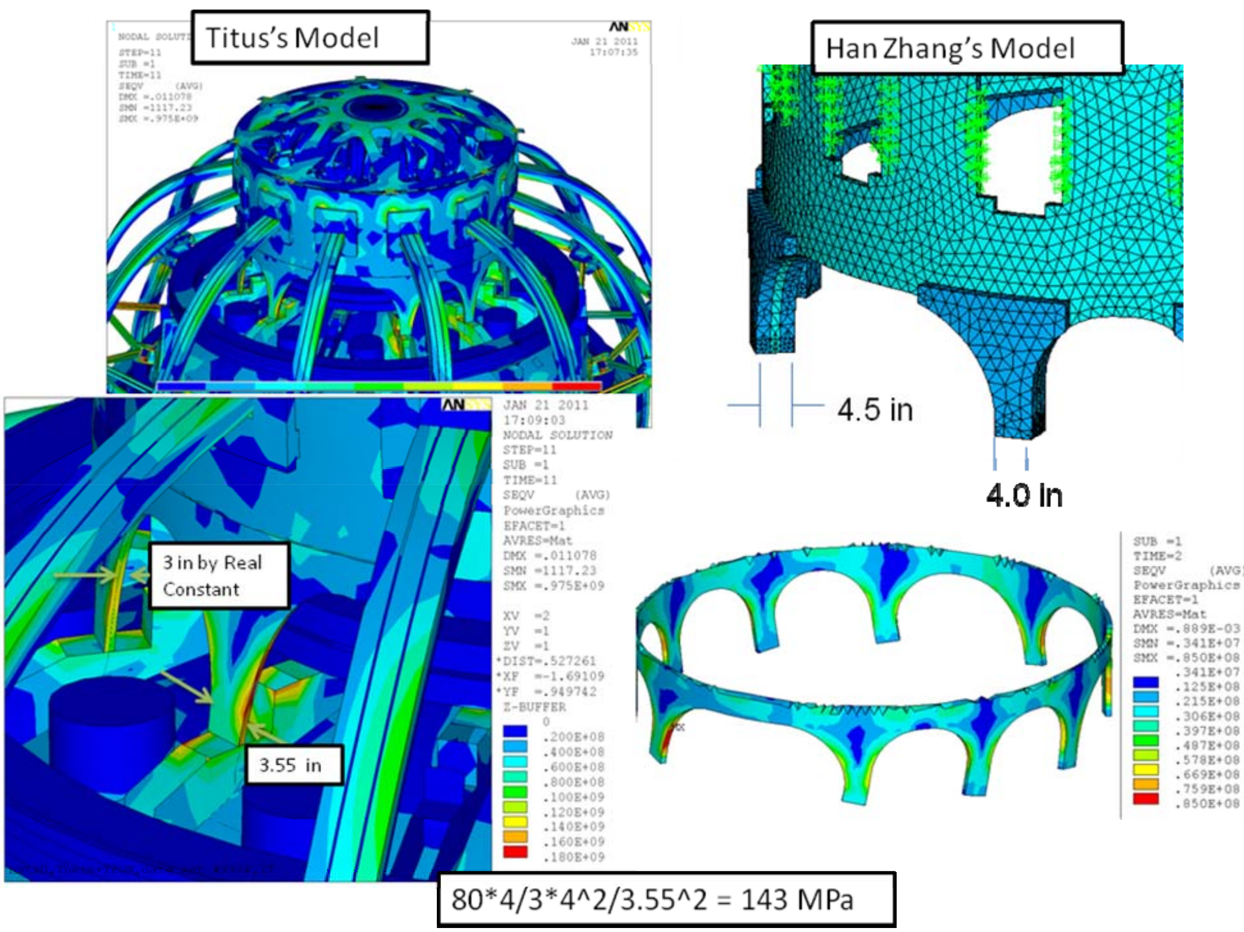


Figure 8.1.2-2 Comparison of Results

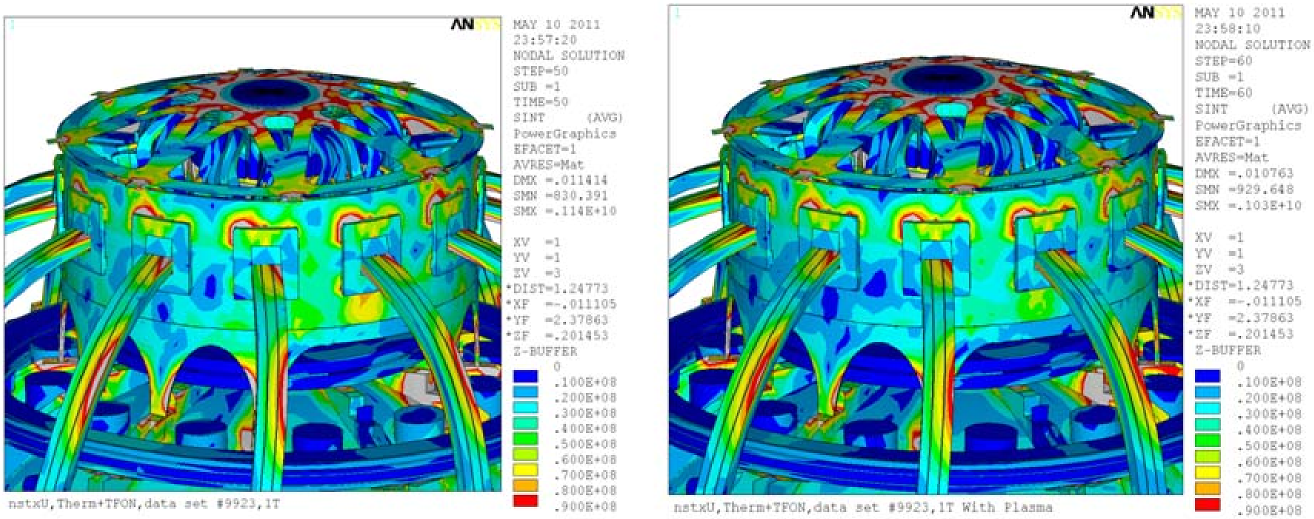


Figure 8.1.2-3 Cover Plate Stress Results

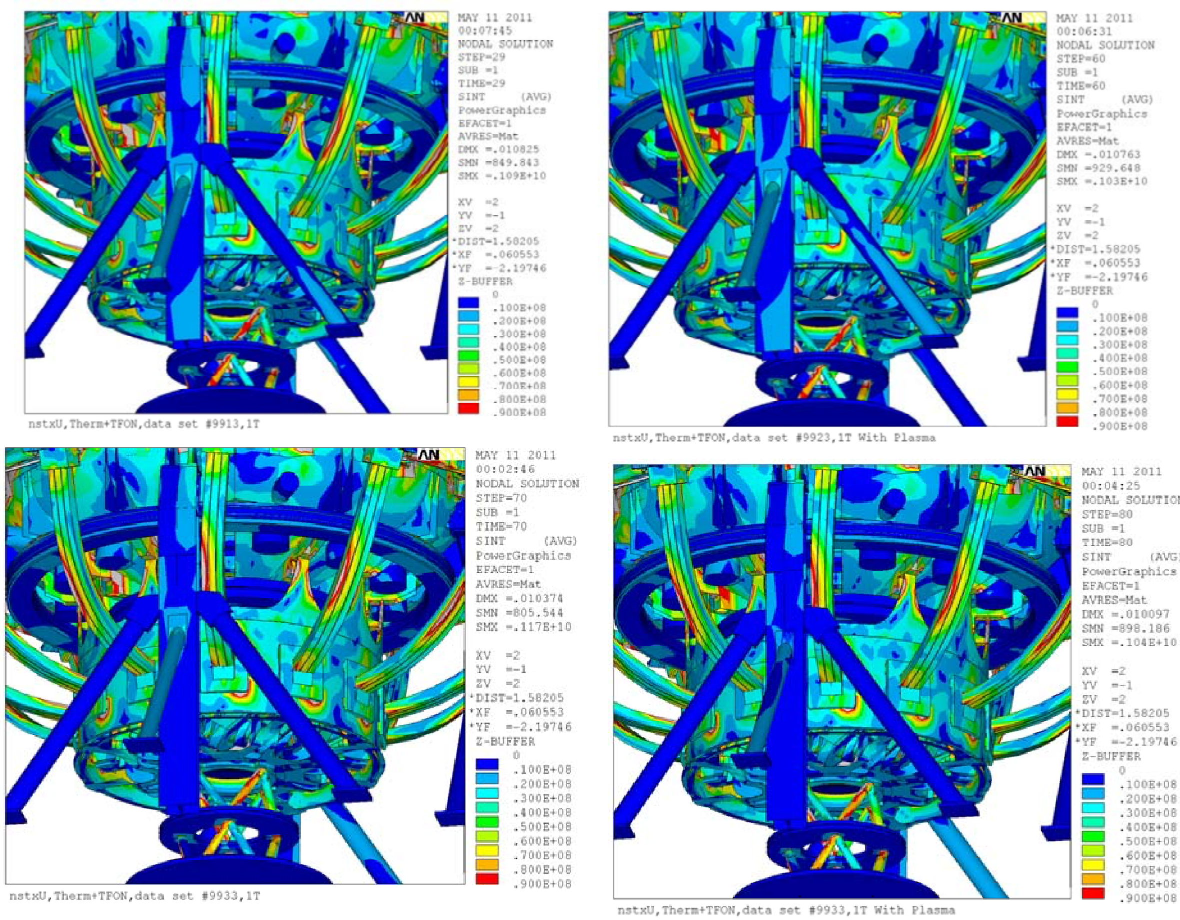
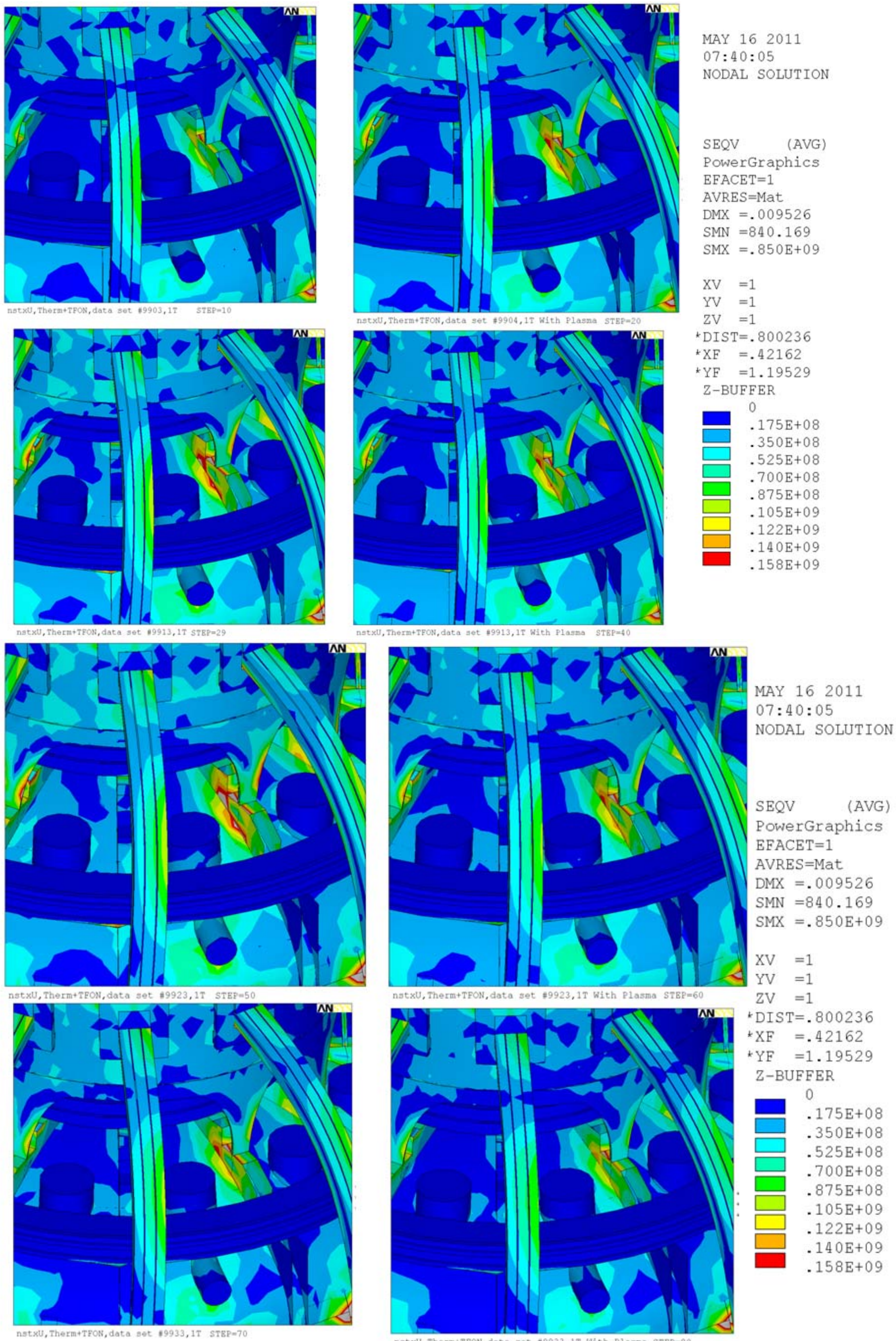
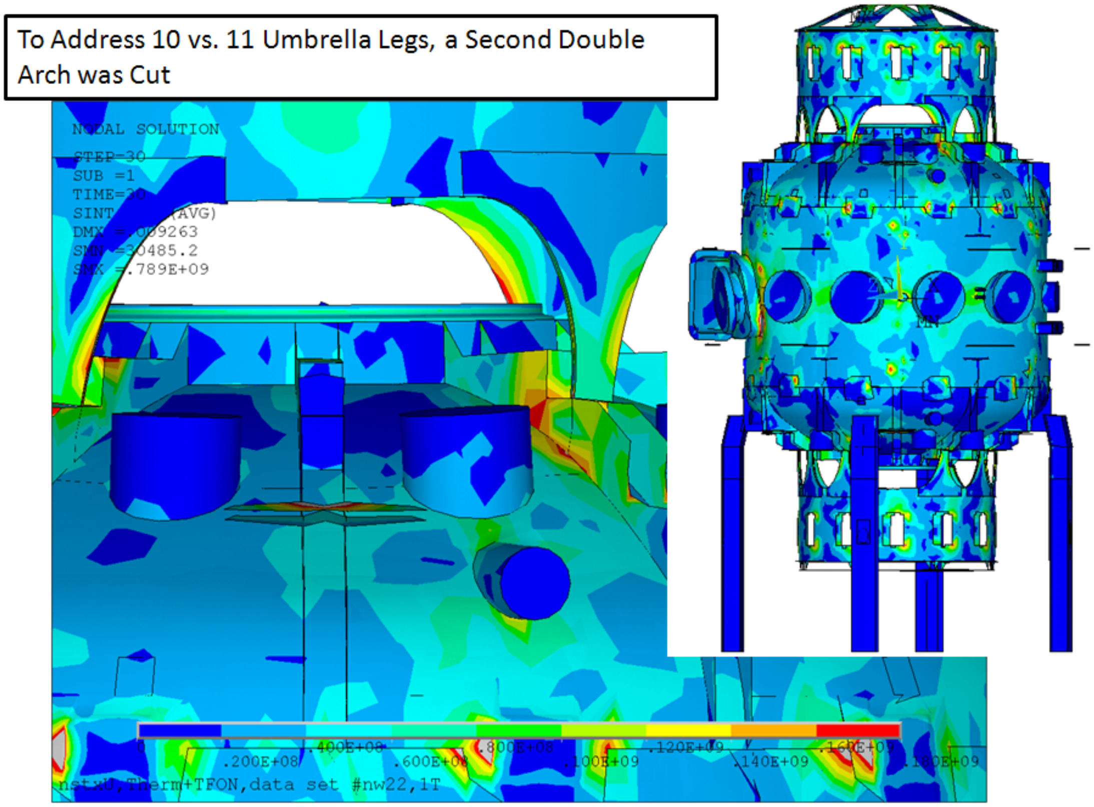


Figure 8.1.2-4 Lower Umbrella Structure Cover Plate Stress Results

8.2 Dome/Rib Details



8.3 Ten vs. 11 or 12 arches



The global model was initially built from quarter symmetry model parts supplied by H.M.Fan and has evolved into a 10 legged umbrella structure by deleting two of the umbrella legs. This is not precisely consistent with the layout of the arches but it captures the worst loading concentration when the 30 degree cyclic symmetry is disrupted by the large arch that bridges over an unused pair of ribs.

8.4 Global Model with Updated Rib Tabs Connected Only on Top and Bottom

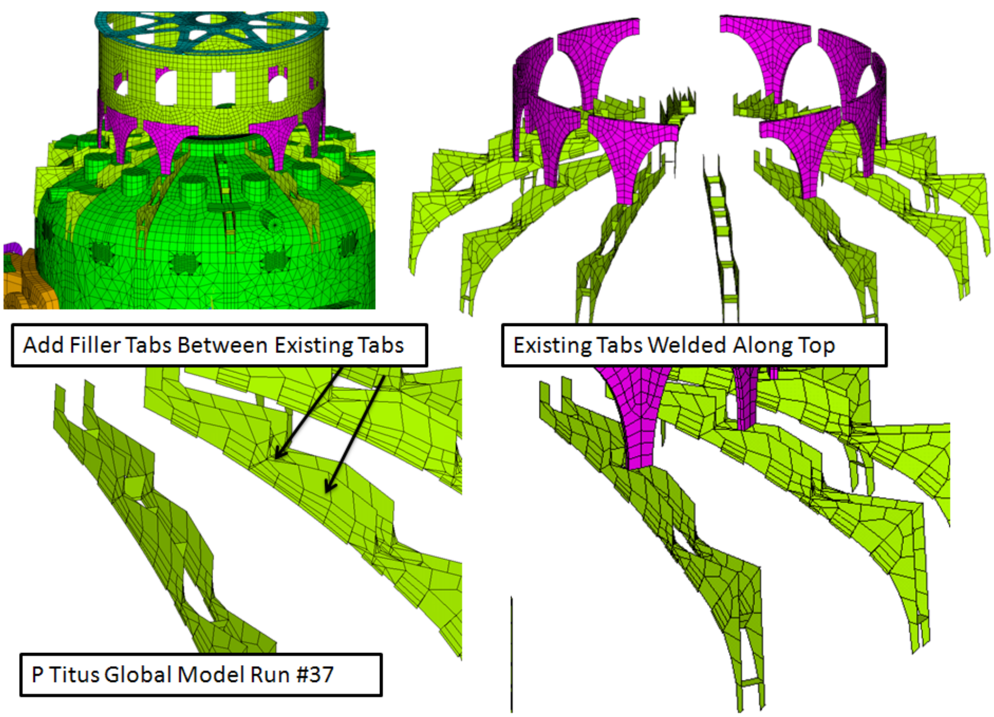


Figure 8.4-1 Global Model including Welded Tabs, Ribs and Dome

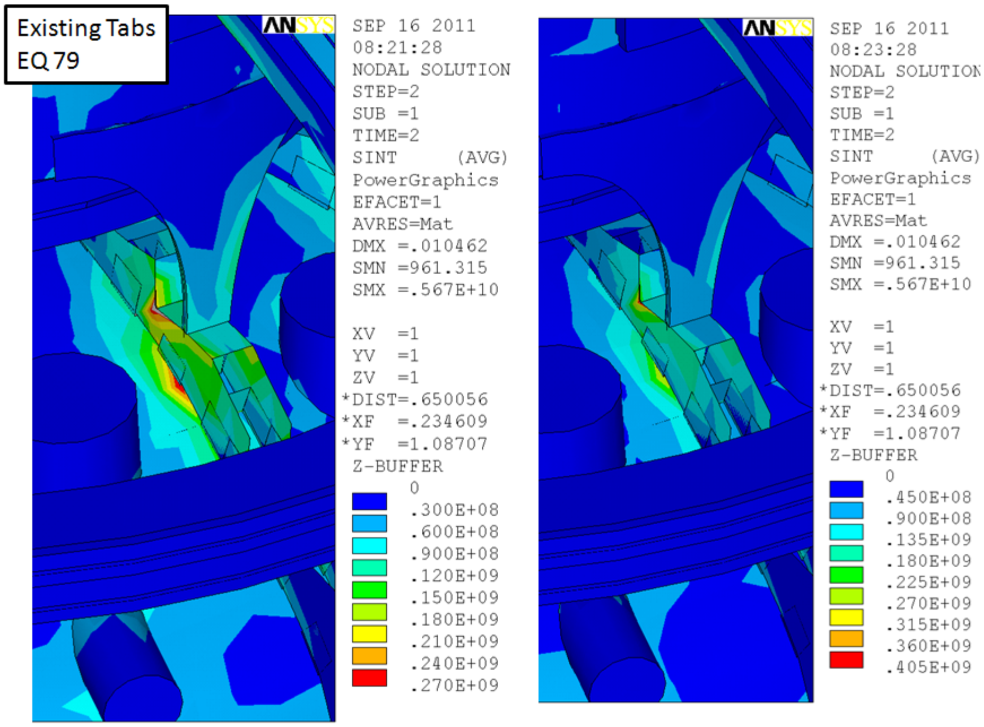


Figure 8.4-2 Stress near Umbrella Feet

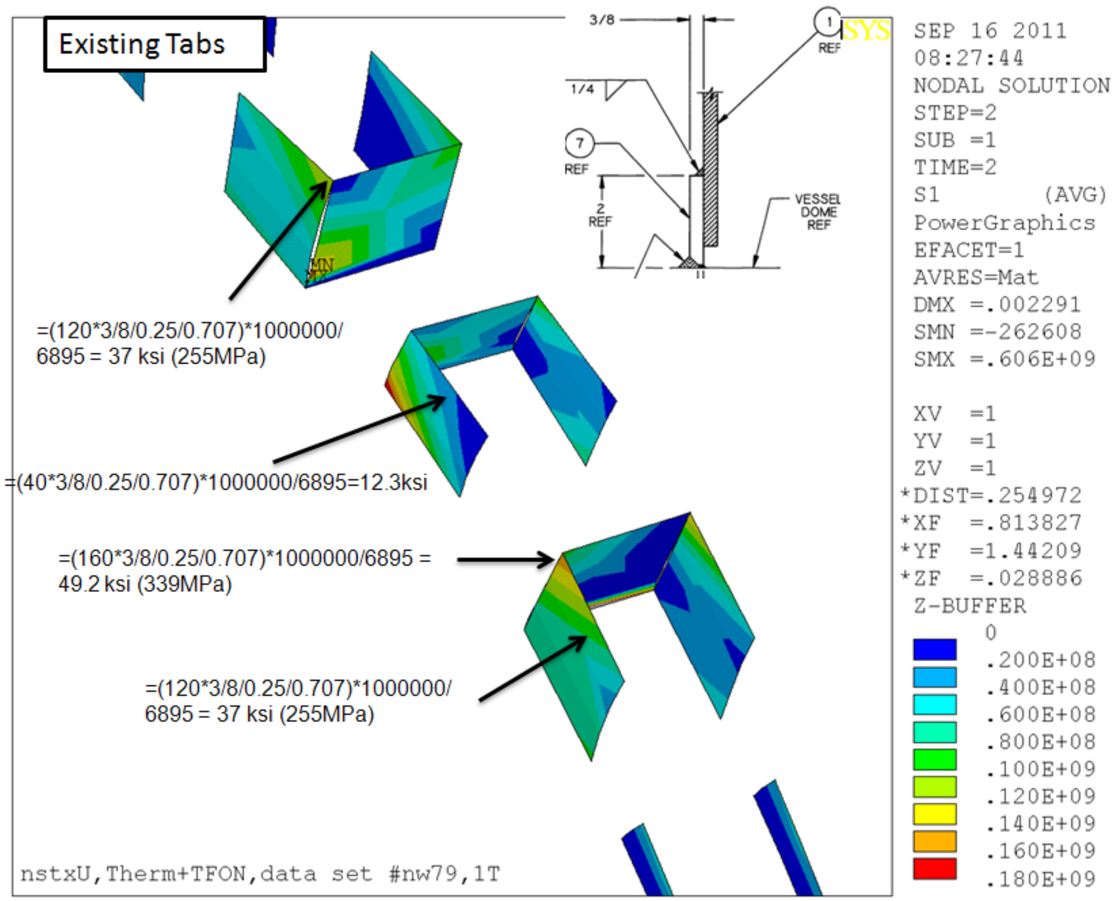


Figure 8.4-3 Stress in Tabs

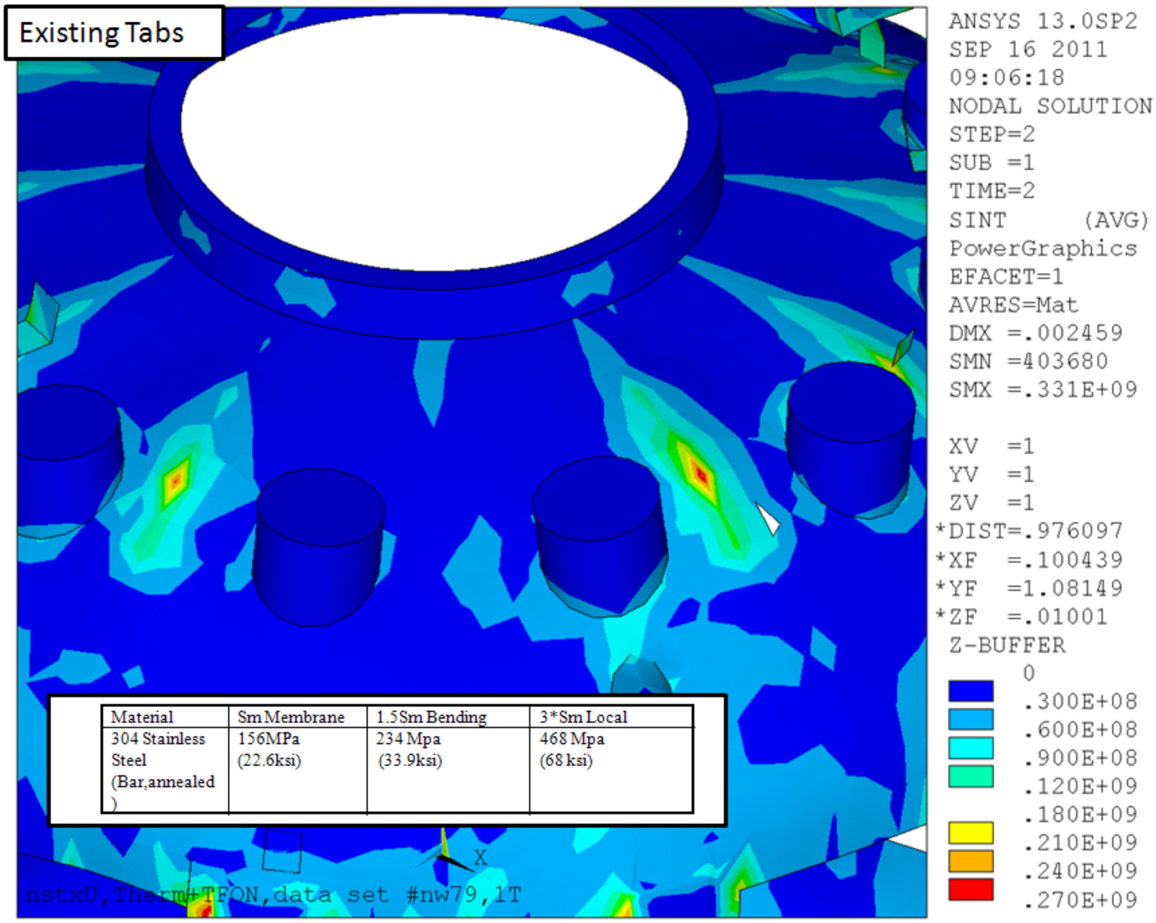


Figure 8.4-4 Dome Shell Stress - With Ribs shown Removed

8.5 Global Model with Filler Tab Reinforcements

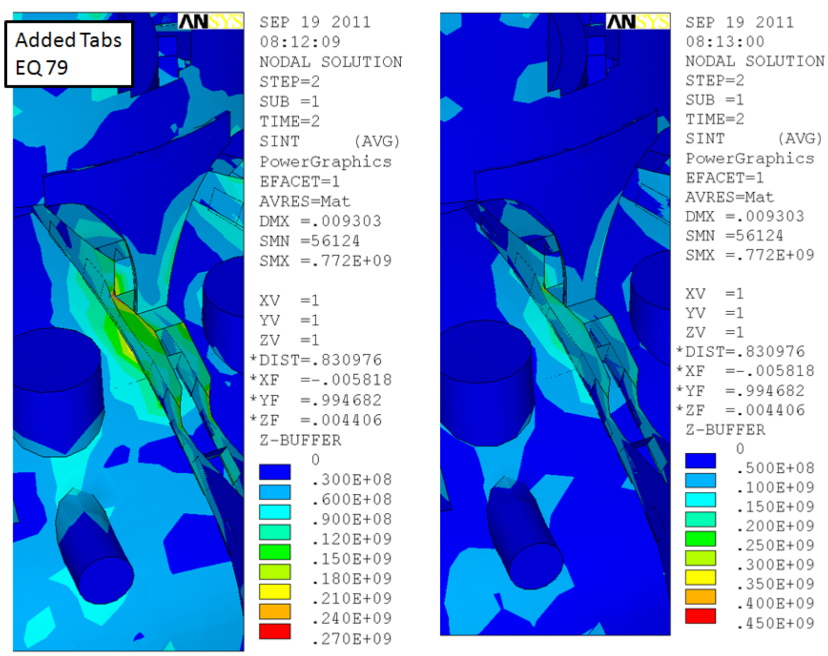


Figure 8.5-1 Stress in Ribs and Tabs with fillers

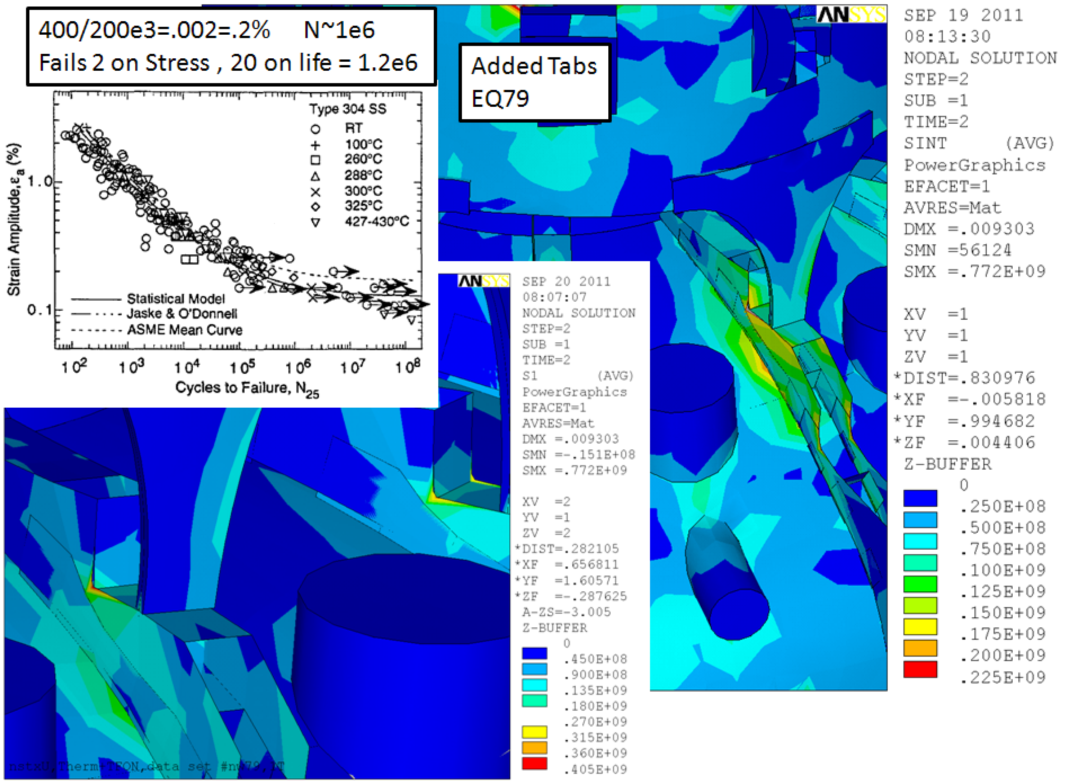


Figure 8.5-2 Stress in Ribs and Tabs with fillers Fatigue Life Estimate

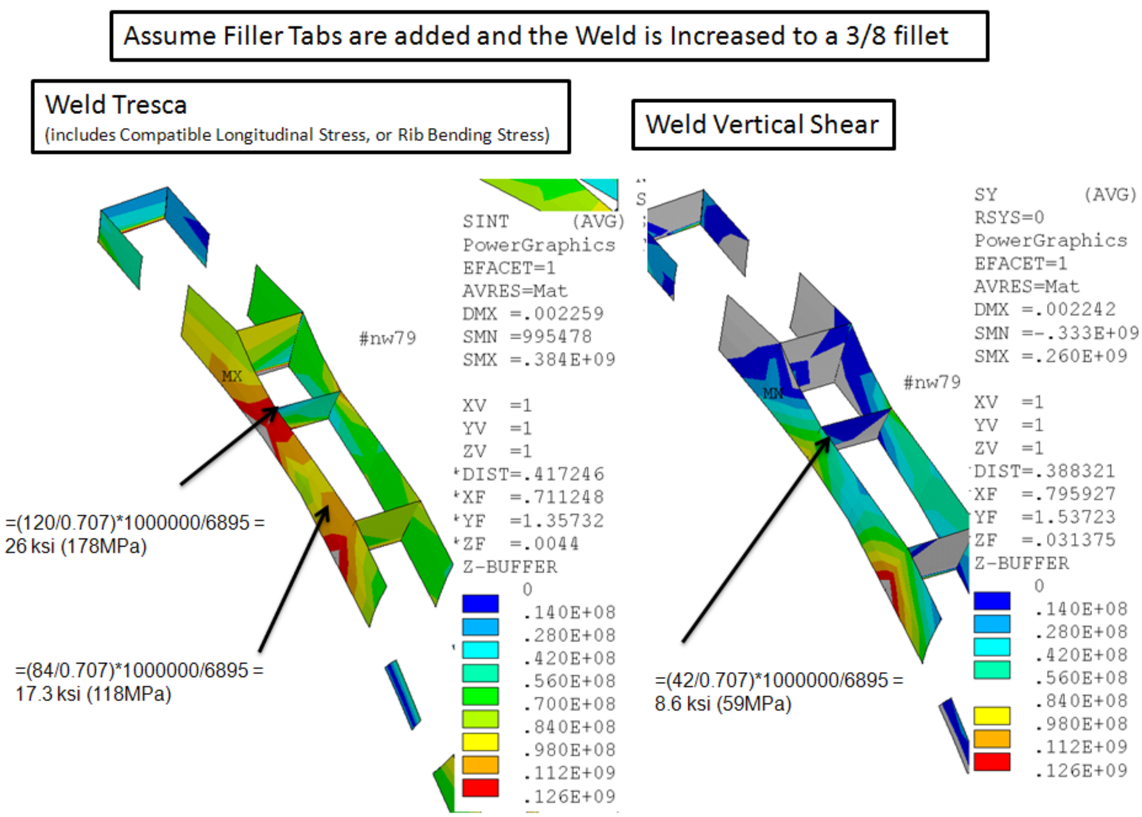
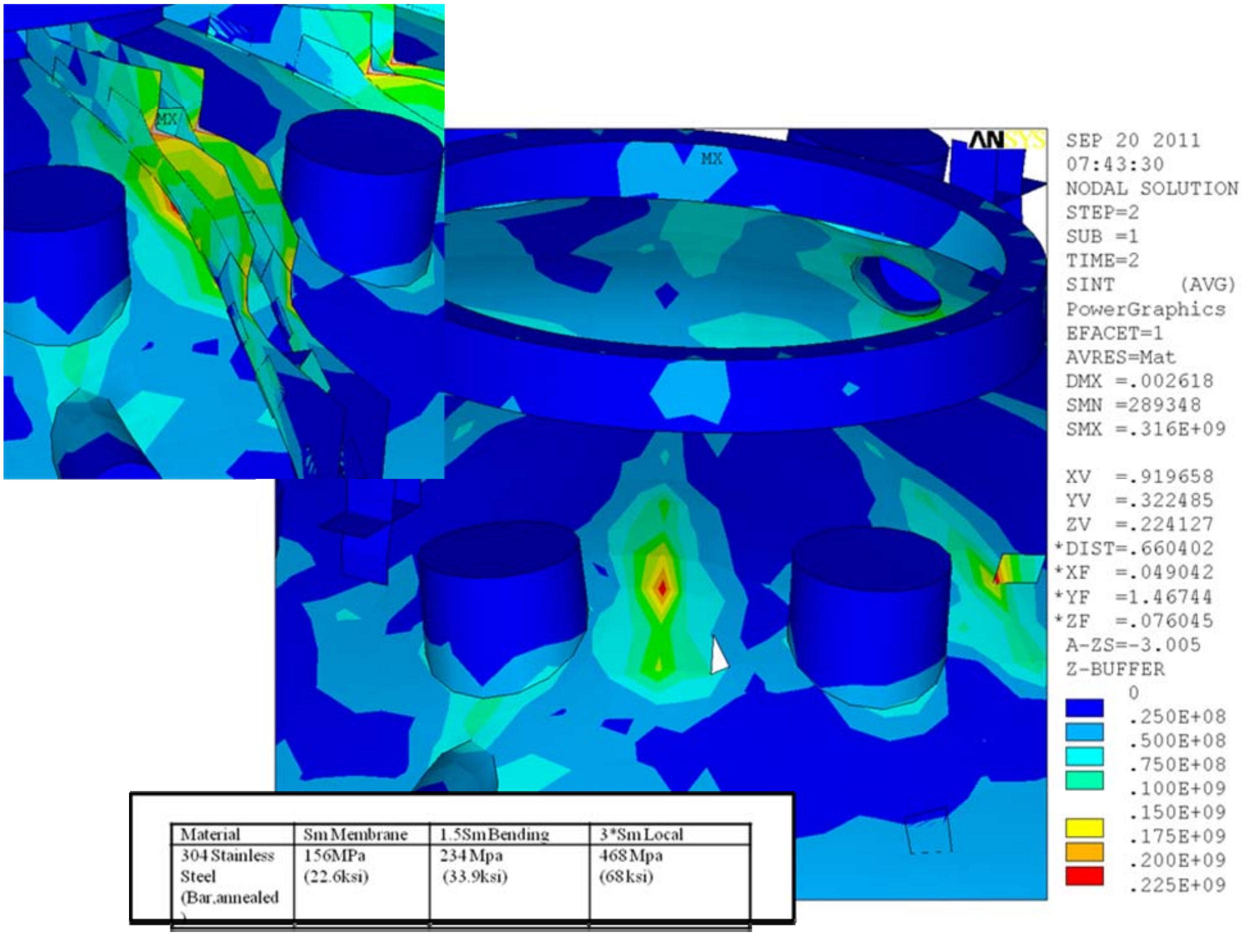


Figure 8.5-3 Stress in Tabs with Fillers Between Tabs



Material	Sm Membrane	1.5Sm Bending	3*Sm Local
304 Stainless Steel (Bar,annealed)	156MPa (22.6ksi)	234 Mpa (33.9ksi)	468 Mpa (68 ksi)

Figure 8.5-4 Stress in Dome Shell with Ribs and Tabs and Fillers Removed

8.6 Global Model with Angled Plate Rib Tab Reinforcements

Angled plates "leaning" against the ribs would be a relatively simple addition if they can clear the top of the existing tabs. These were analyzed by adding plate elements in the global model by connecting the plate elements to the existing mesh. This is the explanation for the non-rectangular shape. The plates did not make a significant difference. But depending on the as-builts of the tabs these may still be a viable option to improve the load carrying capacity of the rib details. These form a pair of triangular box beam sections to support the umbrella feet loading, and should improve the stresses more than this analysis would indicate.

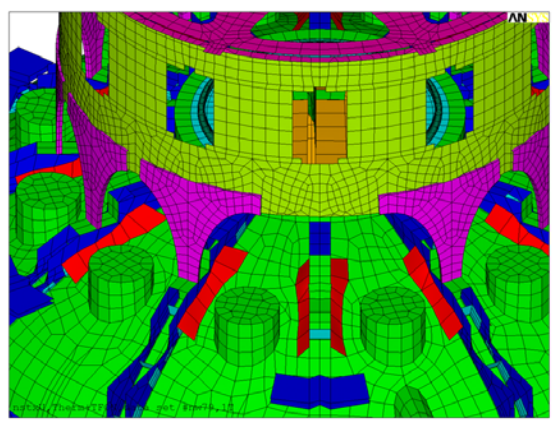


Figure 8.6-1 Model with Angled Plates

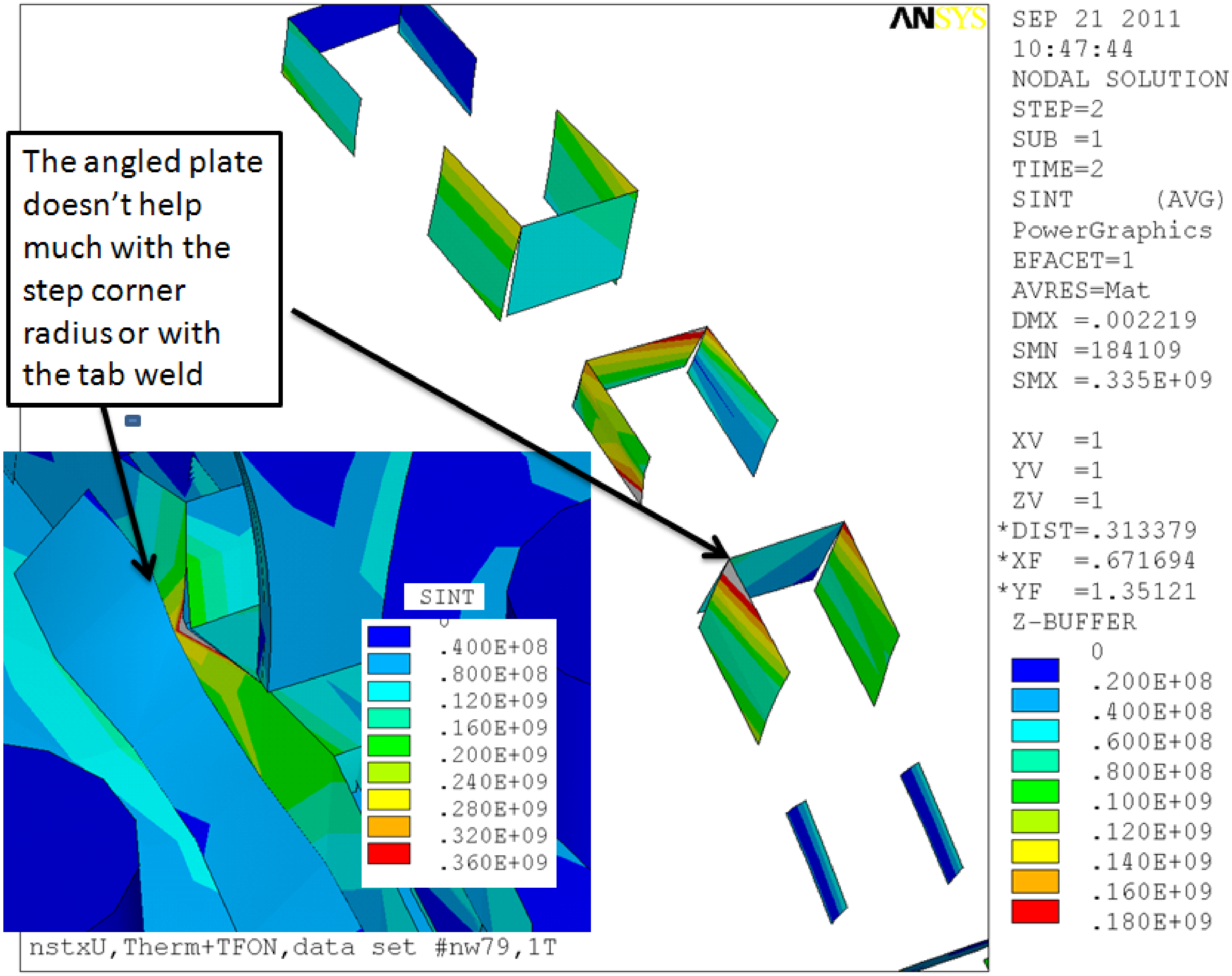


Figure 8.6-2 Tab Stress with Angled Plates

9.0 Local -Model Results

9.1 Existing Umbrella Feet Sliding Block Analyses

The umbrella support feet are mounted on sliding blocks that attach to the vessel head rib weldment. These must transfer the OOP loading from the TF outer legs as well as vertical loads. The sliding feature is intended to allow the unrestrained growth of the vessel during bake-out. In the present design, the foot is held to the weldment with four bolts that connect through the welded plate and are loaded in shear by the OOP loading. The sliding feet assembly will be replaced with stronger components. The base of the slider will have lips to capture the welded plate to take the shear off the bolts.

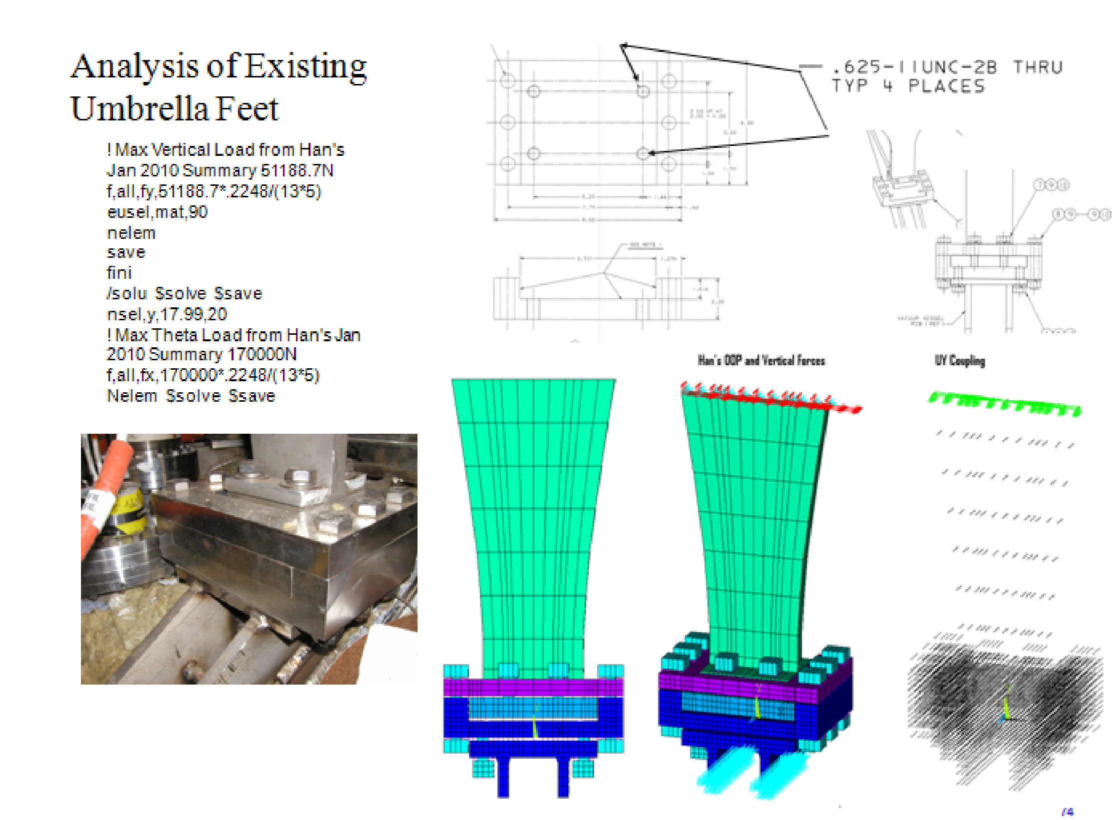


Figure 9.1-1 Analysis of Existing Umbrella Feet

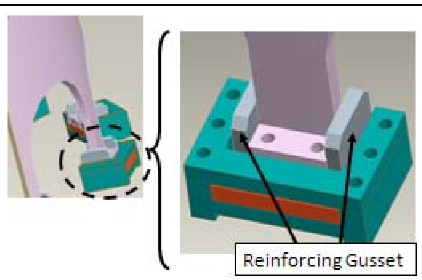


Figure 9.1-2

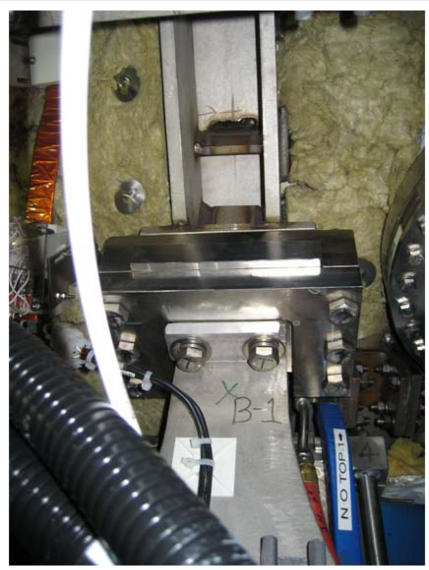


Figure 9.1-3

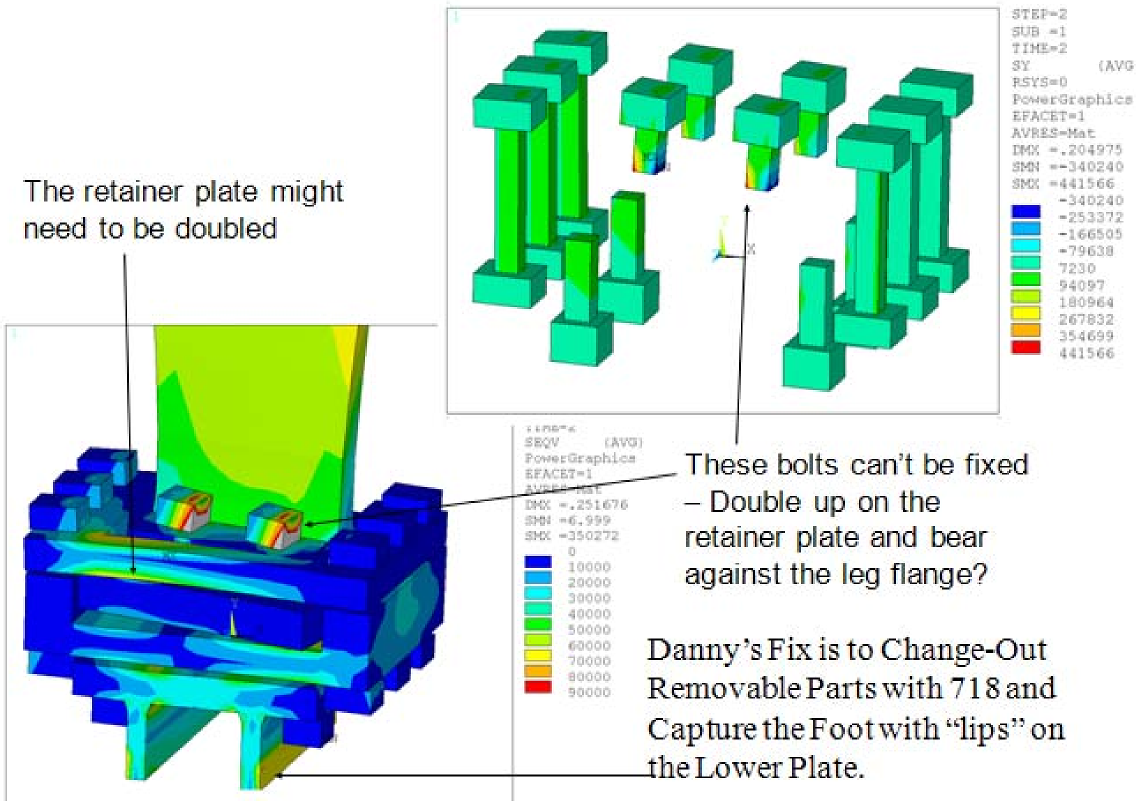


Figure 9.1-4 Bolt and Retainer Over-Stress. "Danny's fix" refers to the upgrades proposed by D. Mangra during the PDR and which has been retained for the Final Design.

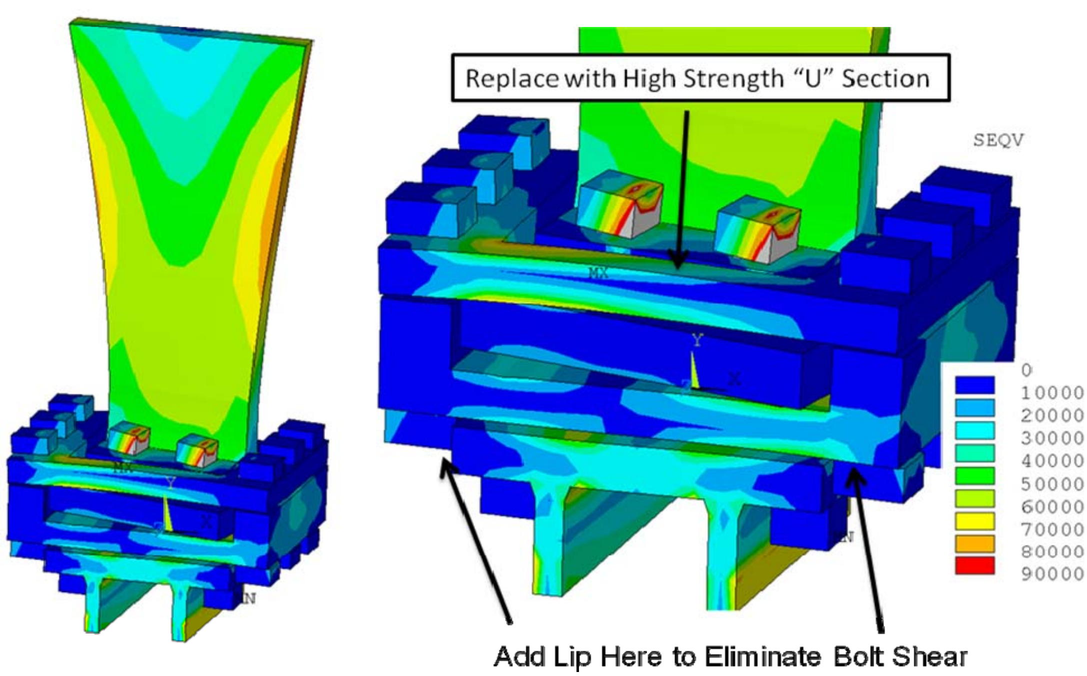


Figure 9.1-5 Location of "lip" in the proposed Upgrade

9.2 Umbrella Feet - With Dome Segment

This model integrates the umbrella leg/foot and the dome segment corresponding to a 1/12 sector of the machine. This is a non conservative assumption given that there are eleven umbrella feet, and the stresses peak at the double arch. The 3D model, described in section 8 captures this effect.

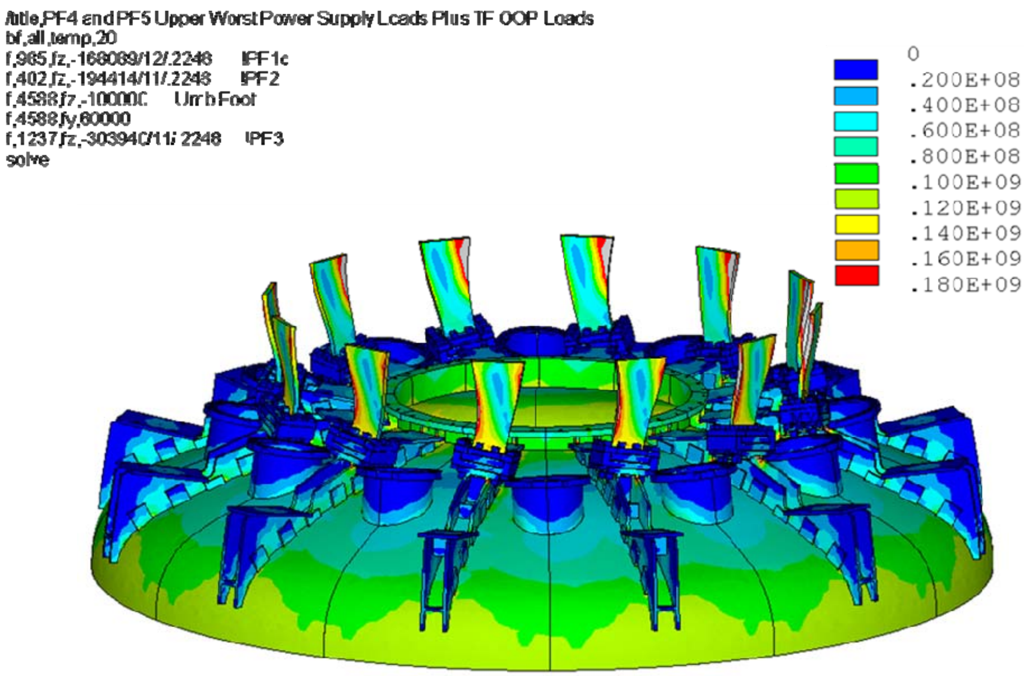


Figure 9.2-1 Model with 12 fold symmetry expansion

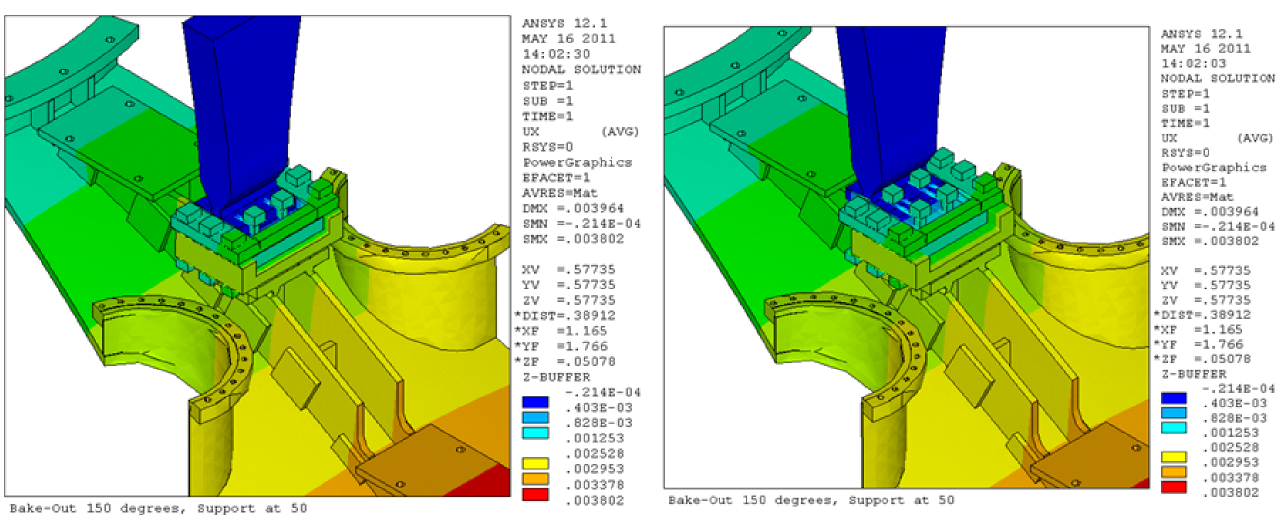


Figure 9.2-2 Bake-Out Radial Displacements

9.3 Dome/Rib Details

There are rib weldments on top and bottom of the vessel, welded to the domes or dished heads to form mounting "shelves" for the PF 2, and 3 supports and the umbrella structure legs. Upgrade loads go up by a factor of 4 for twice the TF field and twice the plasma current. Early analyses for NSTX used a quarter symmetry model and evenly spaced ribs. Actually, there are 10 umbrella legs and 11 pairs of ribs supporting PF3. About half of these were used to support PF2.

PF 2 and 3 coils and support pads are addressed in a separate calculation. The nominal machine symmetry is still used for a number of the vessel and rib analyses, with loads adjusted by factor of 12/10.

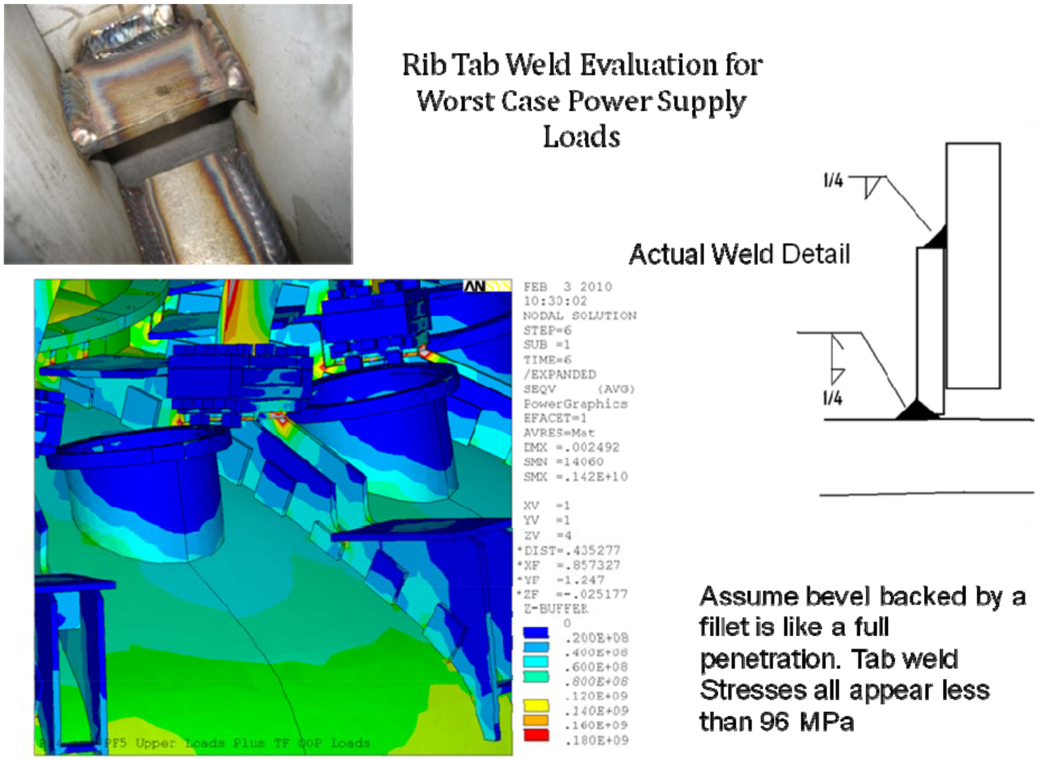
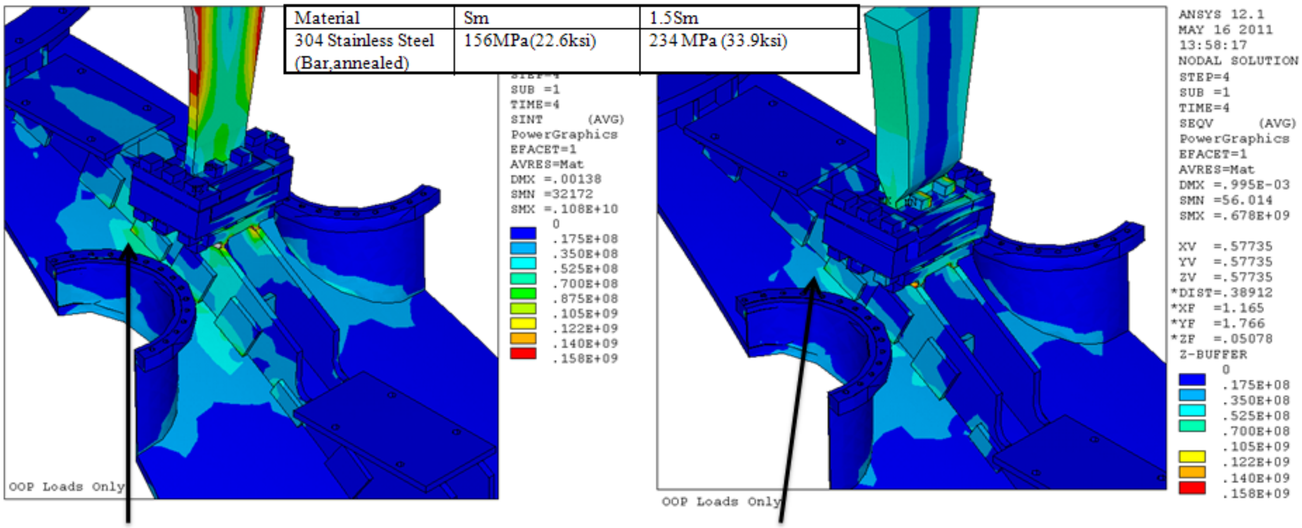


Figure 9.3-1 Rib Tab Detail and Stress - Note the High Stress Point at the End of the Weld – Also see Figure 9.3.4

When NSTX was first built, the vessel head or domes were purchased with a specified profile which was not matched in the spun head. The ribs were cut from the specified profile, not the as-built one. Tabs were welded on the sided of the ribs to bridge the gap left between the rib and dome. The bridging tabs were placed as the fit-up required and have some variation in position and size. A complete solid model of all the tab geometries was never built - only a representative one. The analysis focused on the gaps between the ribs and the dome, and tab stresses at the base of the tabs and not the fillets at the top, which were assumed to cover 3 sides of the tabs. Only the top surface was welded. The cross plates between the ribs were at first assumed to be welded to the dome from photos of the visible plates - but they are not all welded to the dome or head. In the model shown in figure 9.3.1, the tabs are fully merged to the rib. Had the tabs been welded to the rib along three sides this would have been a fair modeling of the attachment, but this is not the case.



The Thicker Umbrella Structure Slightly Reduces the Dome Stress

Figure 9.3-2 Effect of Umbrella Leg Stiffness on Dome Stress

The rib/dome stresses are related to the stiffness of the umbrella foot. The stresses are a result of the TFR OOP shear load transferred through the umbrella legs and the bending rotation of the umbrella leg.

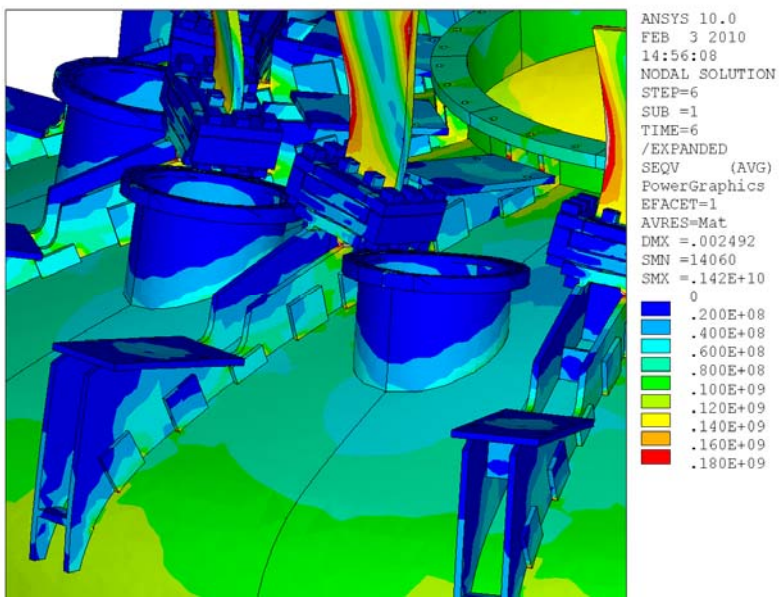


Figure 9.3-3 Stress Results with a 3/4 inch Umbrella Leg

Subsequent to this analysis the Umbrella Structure was found to be made from 1 inch plate, and the Upgrade reinforcement is to replace the legs with 3 to 4.5 inch thick legs.

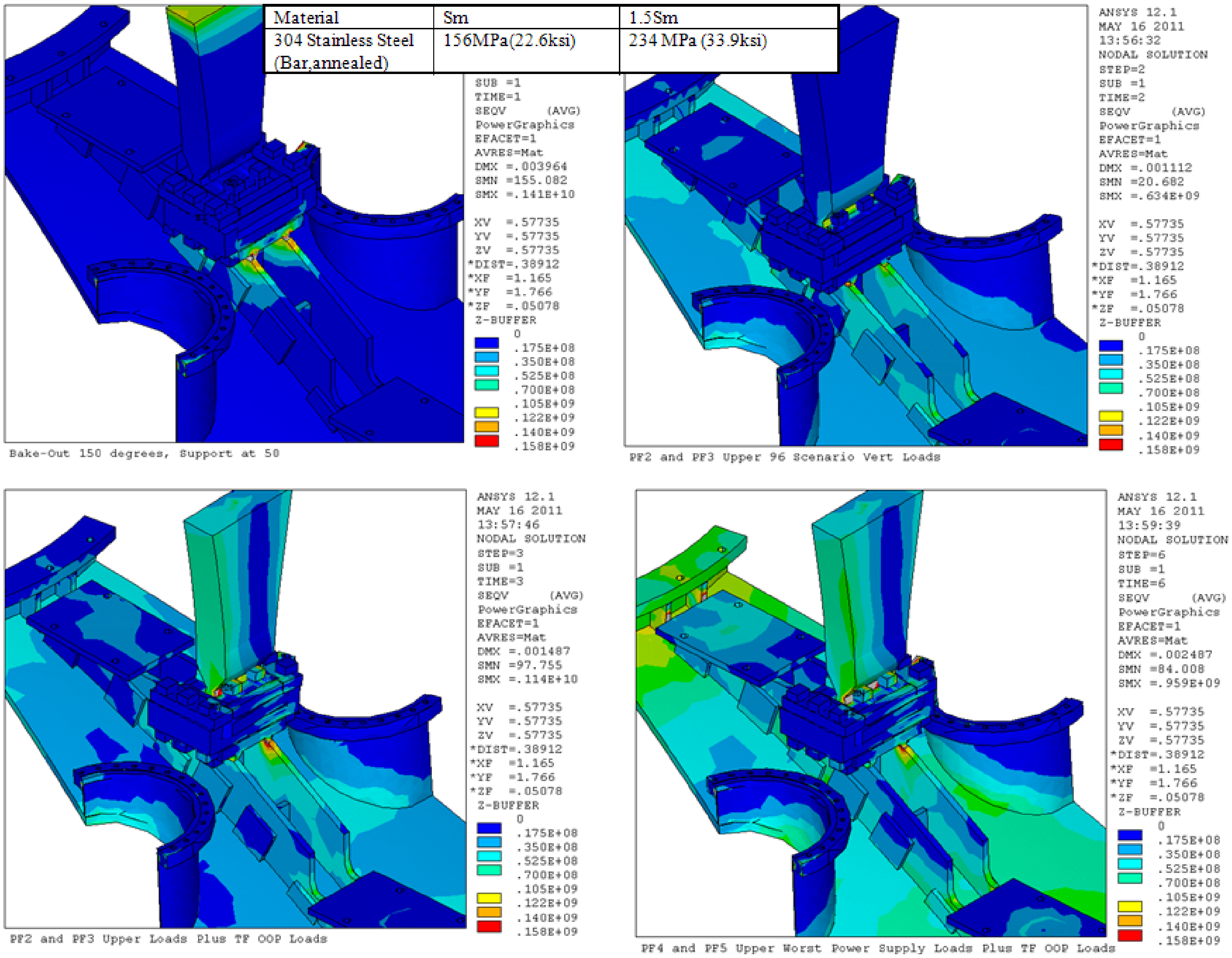


Figure 9.3-4 Dome Stresses in the 30 Degree Cyclic Symmetry Model

9.4 Limit Analysis of the Ribs and Dome

9.4.1 Limit Analysis of the Ribs and Dome With a Downward Force from the TF

Figure 5.3-1 tabulates loads from Han Zhang's outer leg support model [5] and P. Titus's global model [1]. The loads are different, especially regarding the umbrella leg. In this section, the loading with a modest downward load is considered. The PF1c, PF2, and PF3 loads are applied downward and the loading from the TF was intended to aggravate the loading from the PF coils.

This section also initiates another qualification approach, which is to assess the stresses according to the limit analysis section of the NSTX Design Criteria Document [2].

From the NSTX Design Criteria:

An exception to this elastic analysis approach can be when the nature of the structure and its loading make it difficult to decompose the stresses into the above mentioned categories. In such an instance, a detailed, non-linear analysis that accounts for elastic-plastic behavior, frictional sliding and large displacement shall be used to determine the limit load on the structure. The limit load is that load which represents the onset of a failure to satisfy the Normal operating condition as described in Section I-2.6. The safety factor of limit load divided by the normal load shall be greater than 2.0.

The rib/tab local model had to be re-meshed to remove the merged connection between the tabs and ribs. A 30 degree cyclic symmetry model was retained but with the TF loads scaled by 12/10 to reflect the lower number of umbrella legs than TF coils. Non-linear material properties are input for the 304 stainless steel. The stress strain curve used is shown in Figure 7.3-2. Gap elements are used between the tabs and the ribs, with zero initial gap, assuming that the tabs were well clamped to the ribs when they were welded. Large displacement solution is used - this is more appropriate for a buckling simulation, because large displacements would be an indication of the failure of this structural detail to perform its required function which is to limit strains elsewhere in the machine.

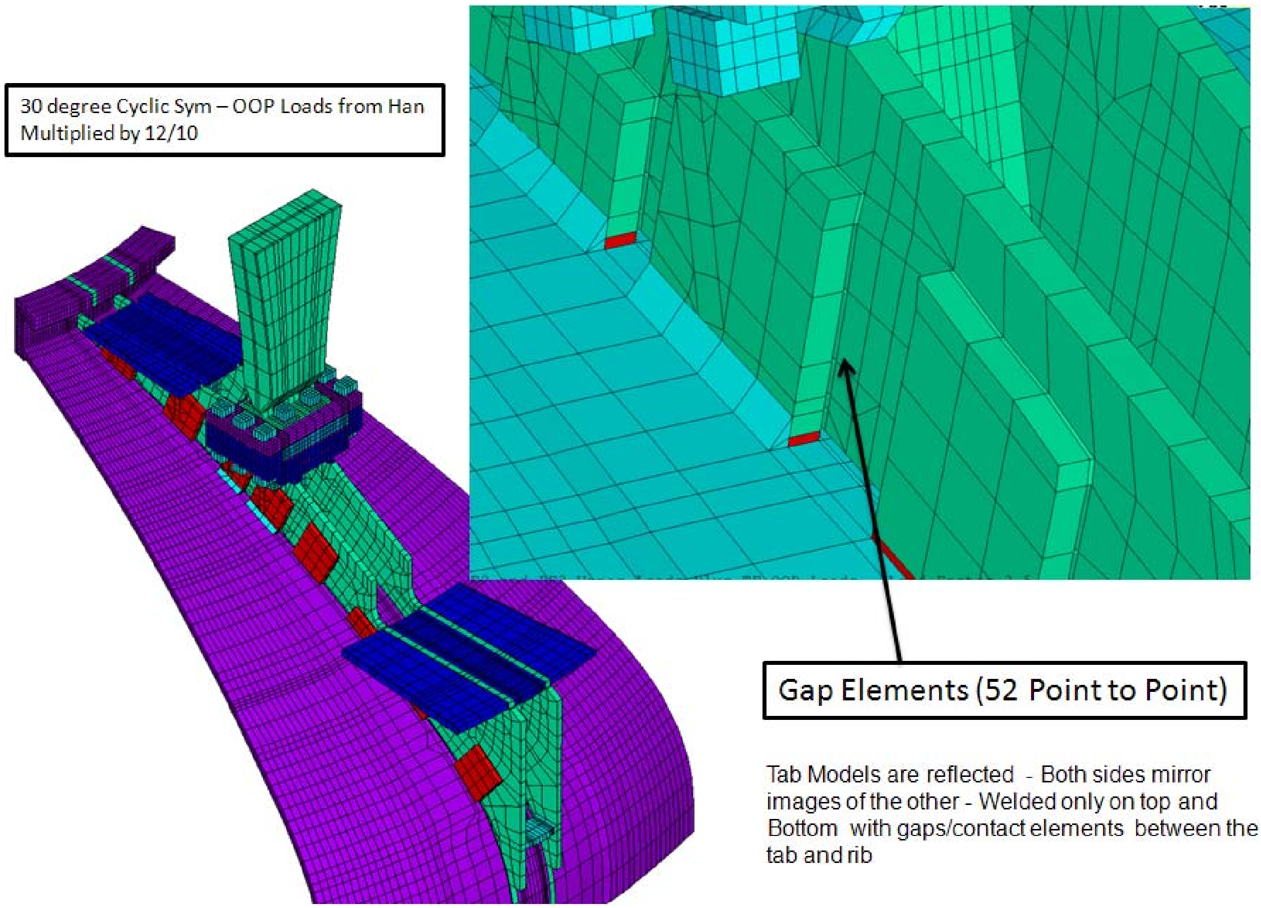


Figure 9.4.1-1 Non-Linear model used for the limit analysis

The model used for the limit analysis replaces the fully merged tabs with tabs welded at the top and at the dome and bearing against the rib through gap or interface elements.

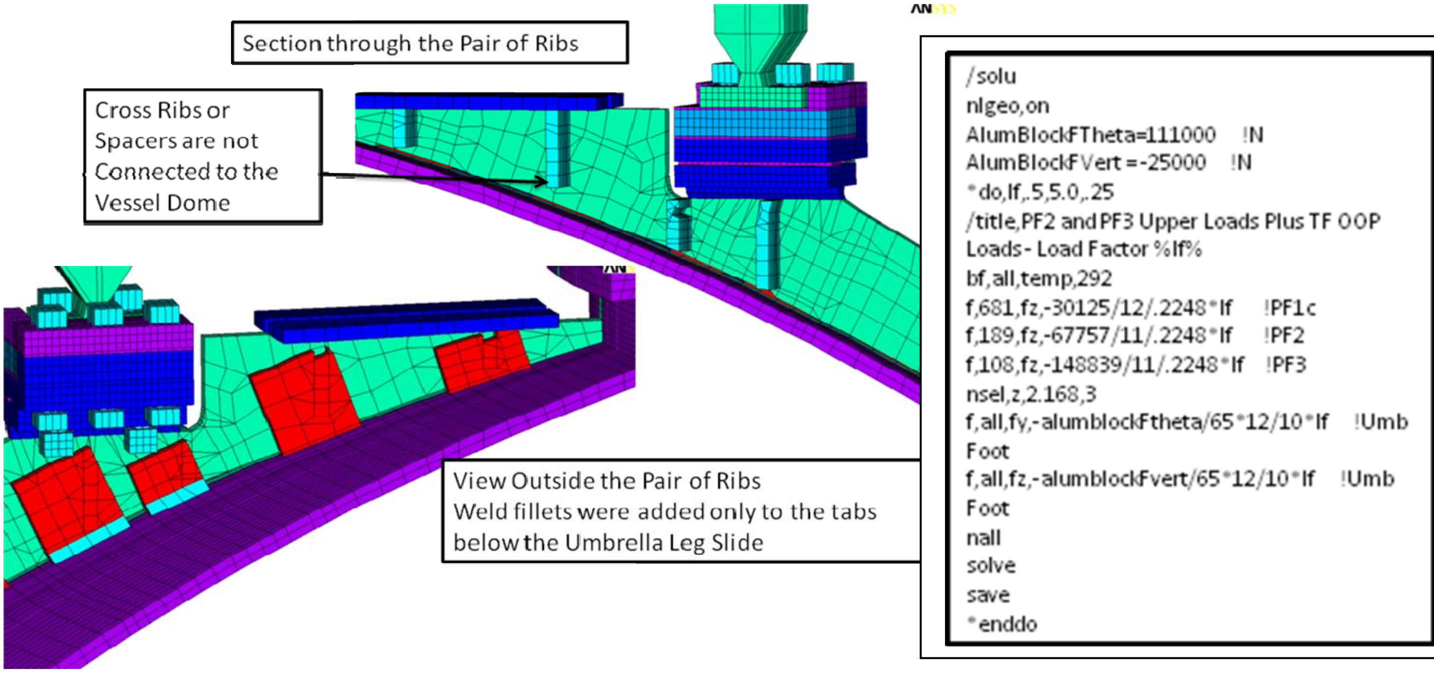


Figure 9.4.1-2 Non-Linear model used for the limit analysis

The analysis was carried out for multiple load steps and ended when the solution failed to converge. The displacement plot below shows stable elastic response up to a load factor of 2.75 and sharply increasing displacements beyond that. Non convergence occurred at a load factor of 5.

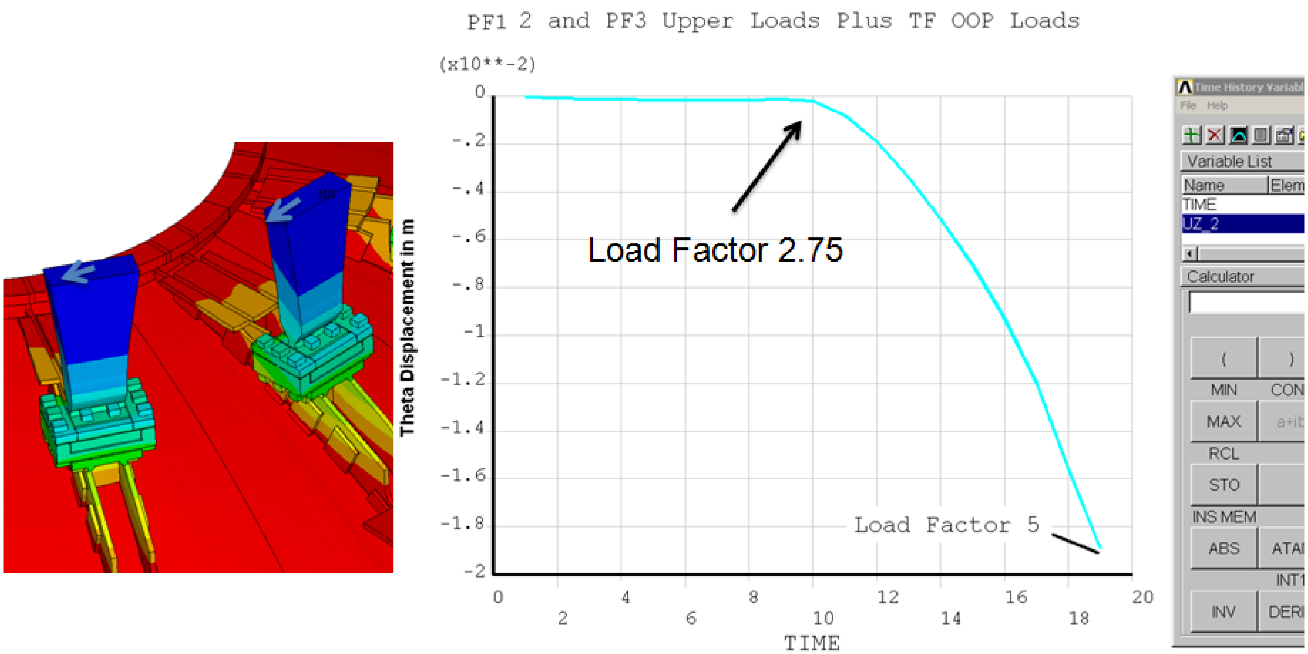


Figure 9.4.1-3 Out-of-Plane (OOP) Displacement as a Function of Load Factor

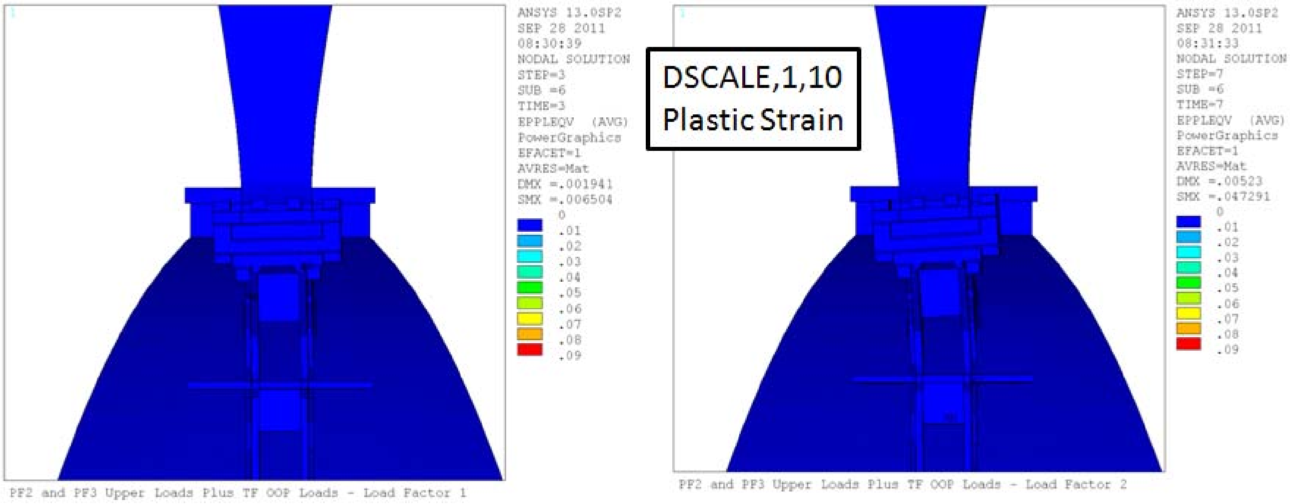


Figure 9.4.1-4 Plastic Strain for Load Factors of 1.0 and 2.0

Plastic strain is not visible in either of the plots for load factors of 1.0 and 2.0. There is some plastic strain

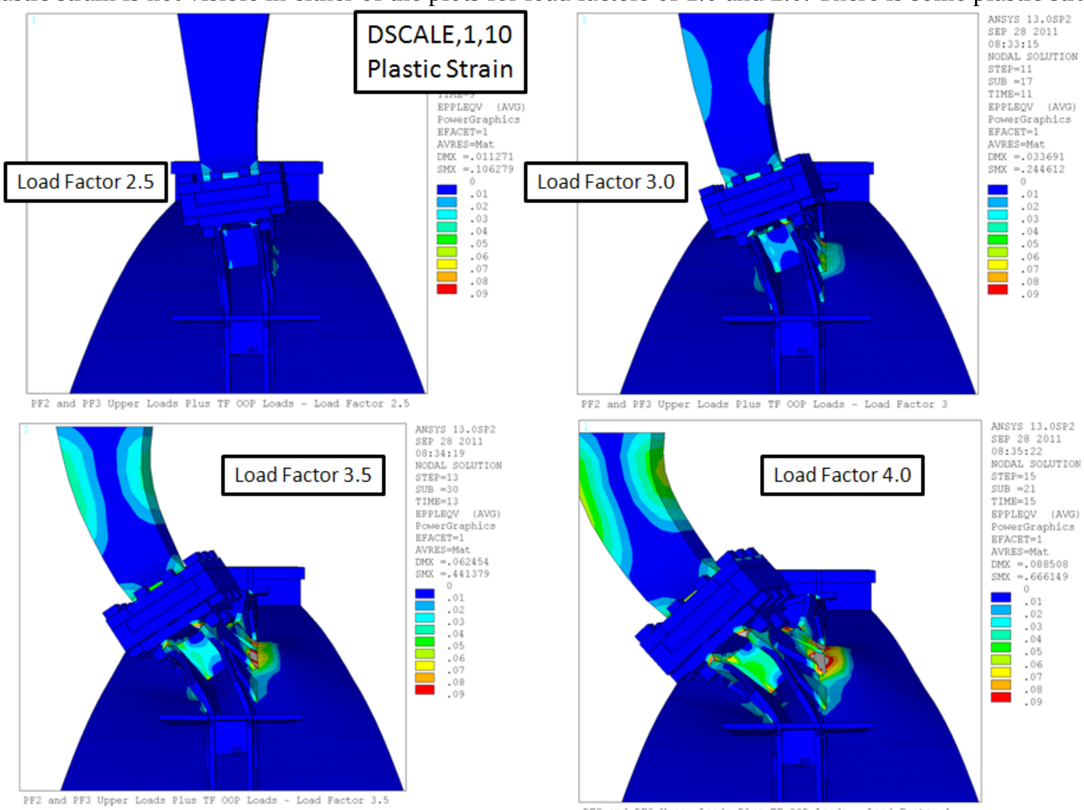


Figure 9.4.1-5 Plastic Strain as a Function of Load Factor (Continued)

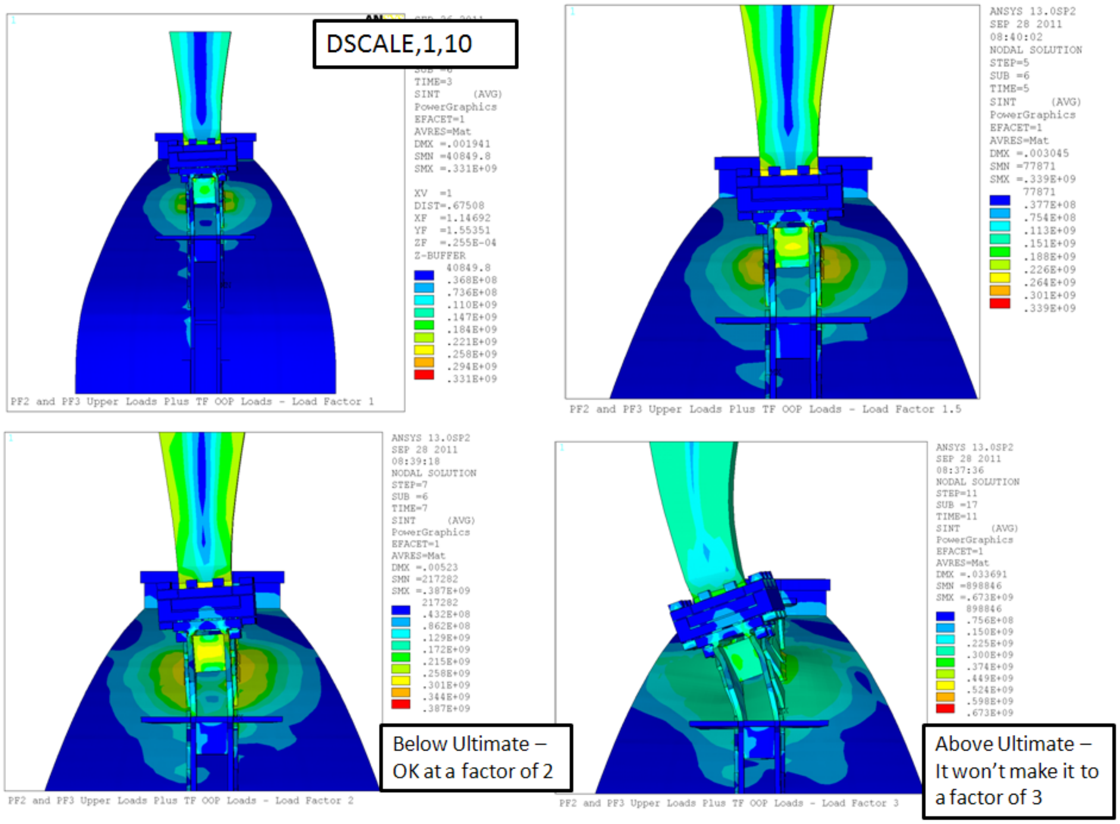


Figure 9.4.1-6 Tresca Stress as a Function of Load Factor

The limit analysis does not model the consequences of stresses and strains above the ultimate. The strain values are extrapolated from the input stress strain curve, even though the stress is above the ultimate. For the load factor of 2 on stress is well below ultimate, but local areas go above ultimate at the load factor of 3. This may still not indicate collapse but the analysis model is not predictive with local stresses above ultimate.

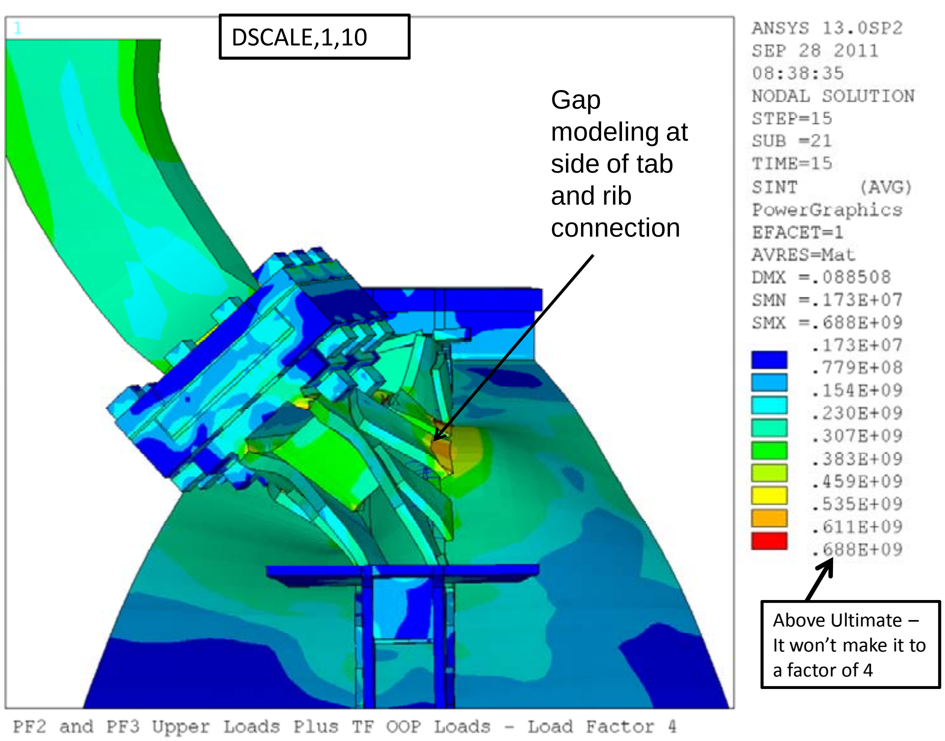


Figure 9.4.1-7 Tresca Stress at a Load Factor of 4

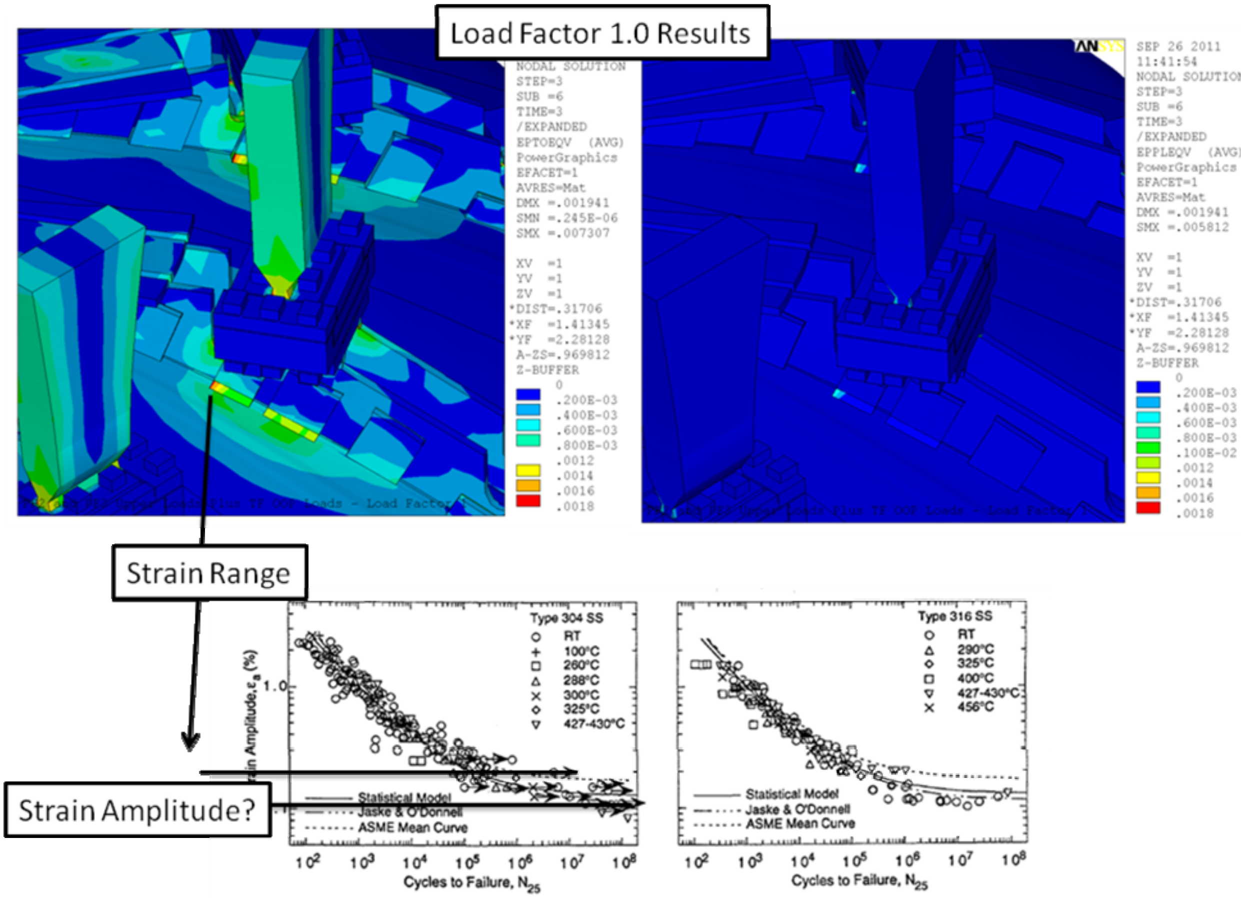


Figure 9.4.1-8 Strain Range at a Load Factor of 1.0

The strain range shown in figure 9.5.7 is .2 % . The strain amplitude would be half this - assuming that the global moment does not reverse. Even though the OH reverses the total machine moments do not. In the Design Point Spreadsheet, the total half plane TF moment is always negative for both the max and min loading. This means there is no reversal of the OOP loading and the appropriate R value is 0, which means that the strain amplitude is half the strain range. At a strain amplitude of .1, the life is 10e8 cycles. The new GRD (see section 5.1) [13] has a complex mix of shots at various loads, but this is summarized as 20,000 pulses or 4e5 with the factor of 20 on life. It doesn't quite make the factor of 2 on stress.

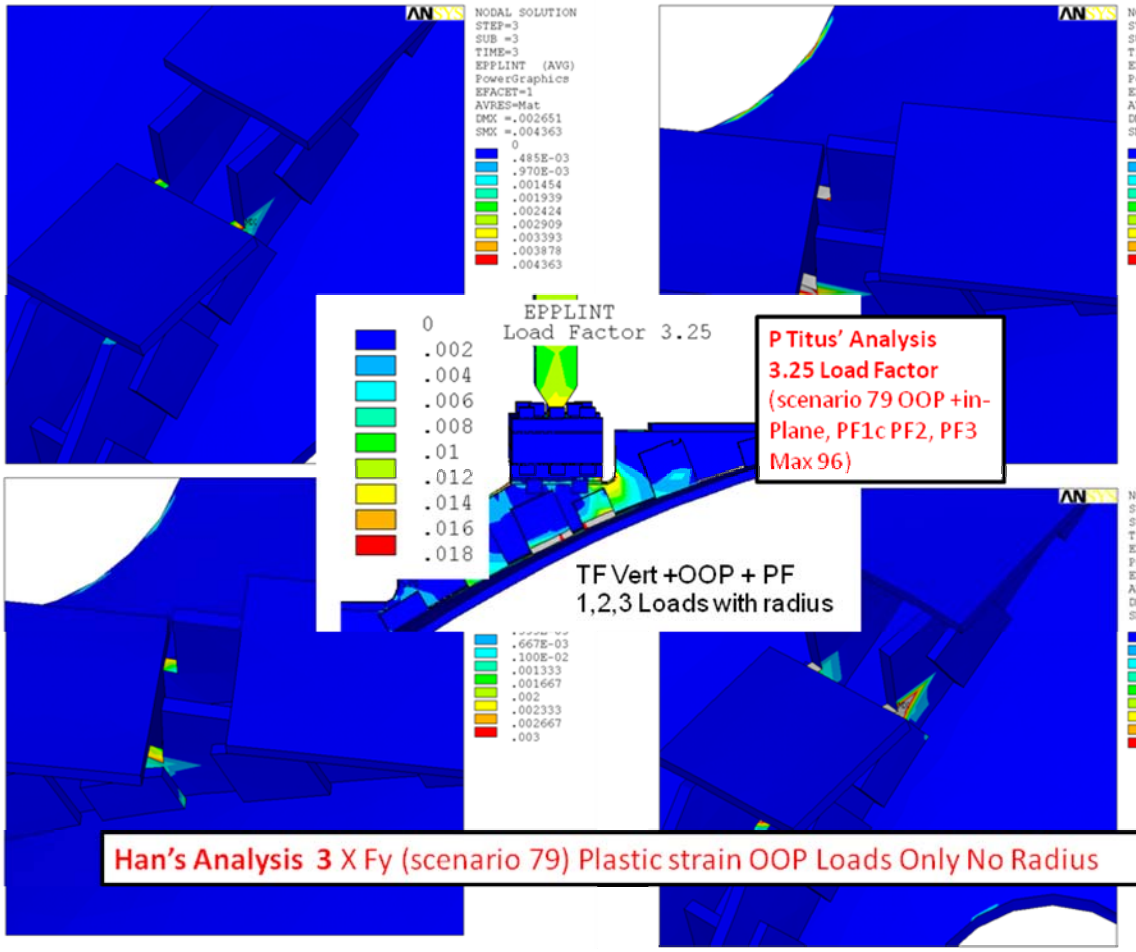


Figure 9.4.1-.8 Comparison of Plastic Strain with [5] at a Load Factor of 3.0

Figure 9.4.1-8 is a comparison of the buckling analysis by H. Zhang [5] and the limit analysis done for this calculation. Qualitatively they are similar. Ref [5] uses a slightly higher yield and has the merged tab FEA modeling vs. the gapped tabs used in this calculation. Ref [5] also does not have the radius at the corner of the step cut-out. This region is the subject of section 9.5.

9.4.2 Limit Analysis with large Upward Loads from the TF Coils.

Figure 5.3-1 tabulates loads from Han Zhang's outer leg support model [5] and P. Titus's global model [1]. The loads are different, especially as regards the umbrella leg. The line of action of the TF outer leg would be in line with the coil centerline if the coil behaved like a constant tension D. In NSTX some of the radial bursting load is taken by the ring and the ring imposes radial displacement constraints as the Lorentz load is applied, and as the coil heats up. Lorentz forces in the TF coils are perpendicular to the coil current which is essentially vertical as the coil enters the aluminum block, and are only resolved into membrane like tension if the shape of the coil is contoured to produce only tension. The global model [1] produces a large vertical load at the aluminum block. In this section, the limit analysis is re-done with this large upward load.

```
! Input Loading foot05.txt
AlumBlockFTheta=111000     !N
AlumBlockFVert = 130590    !N
*do,lf,.5,5.0,.25
/title,PF2 and PF3 Upper Loads Plus TF
OOP Loads - Load Factor %lf%
bf,all,temp,292
f,681,fz,-30125/12/.2248*lf       !PF1c
f,189,fz,-67757/11/.2248*lf       !PF2
f,108,fz,-148839/11/.2248*lf     !PF3
nsel,z,2.168,3
f,all,fy,-alumblockFtheta/65*12/10*lf
!Umb Foot
f,all,fz,-alumblockFvert/65*12/10*lf
!Umb Foot
nall
solve
save
```

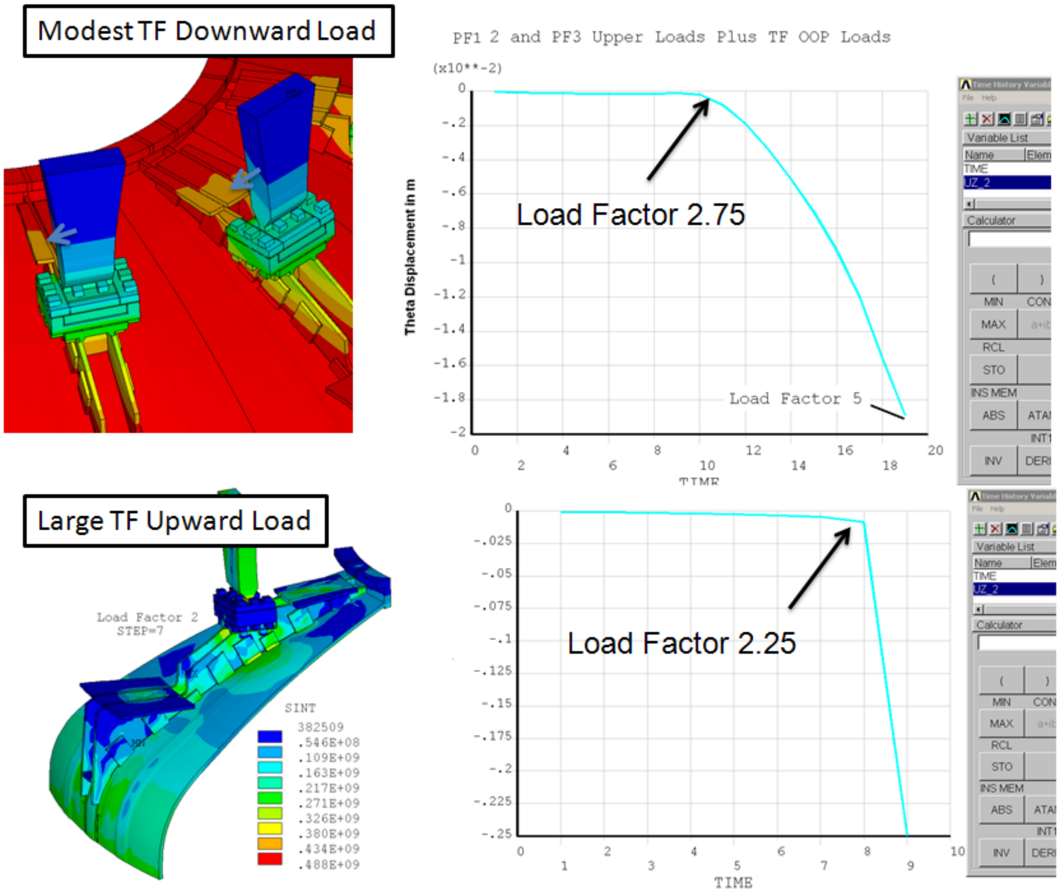


Figure 9.4.2-1 Comparison of Limit Load Factors for the Two Loading cases

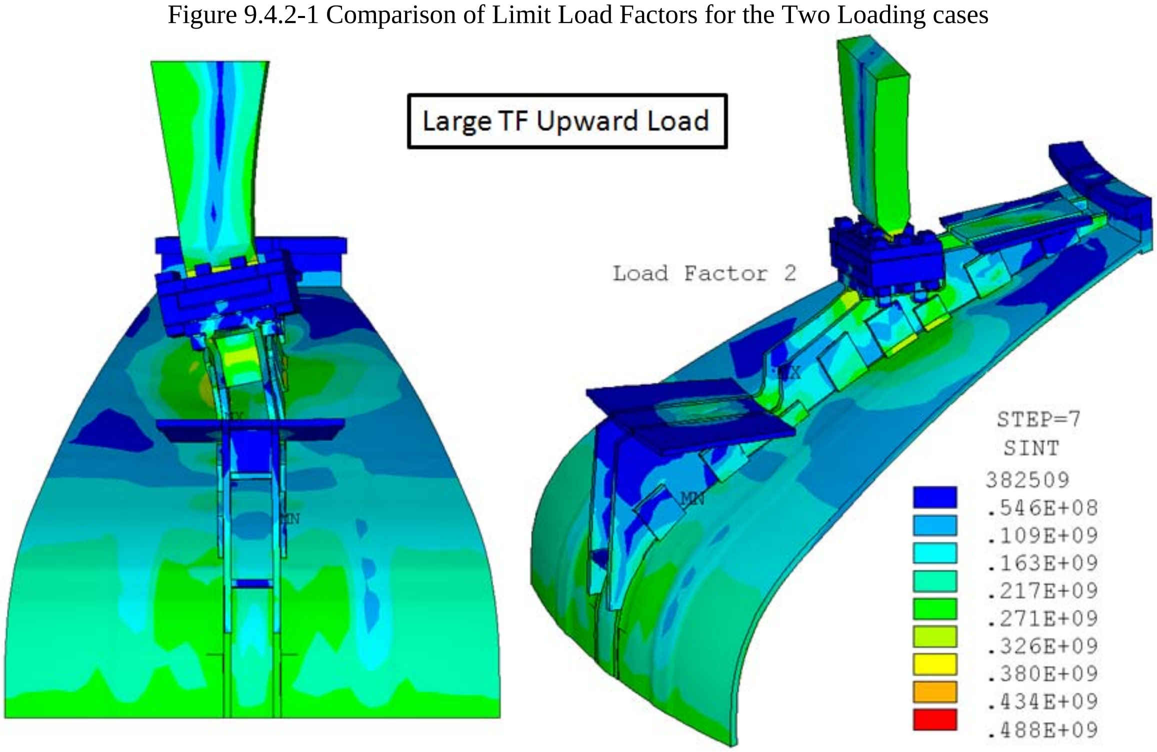


Figure 9.4.2-2 Comparison of Limit Load Factors for the Two Loading cases

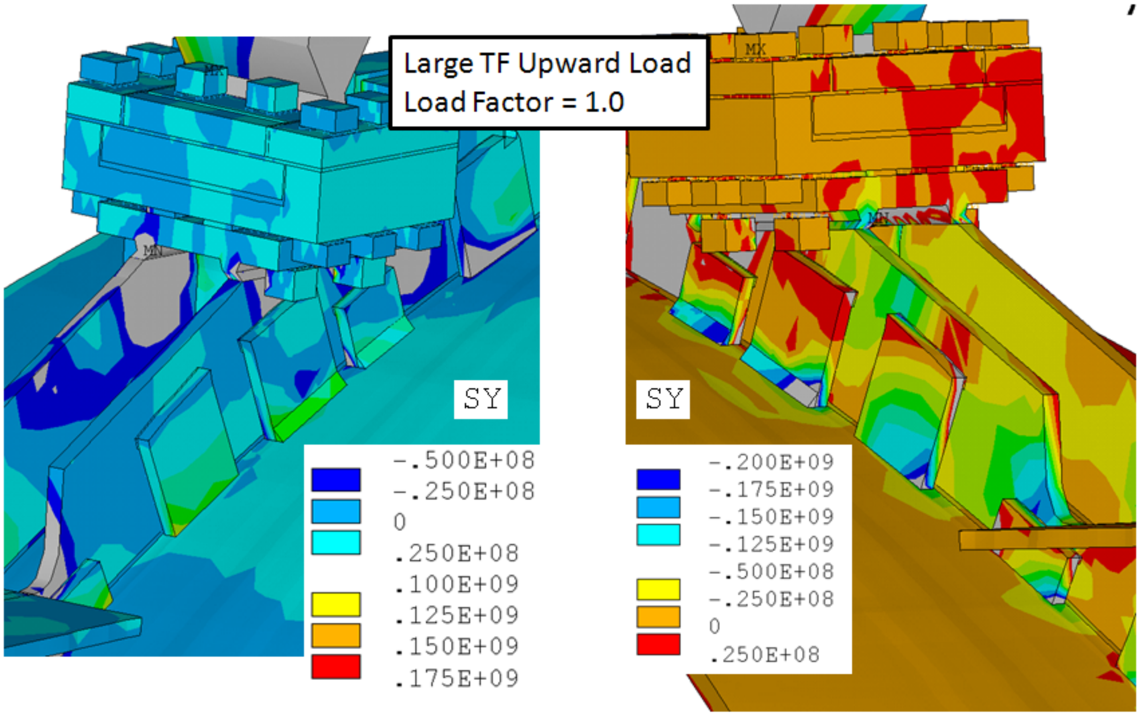


Figure 9.4.2-3 Tab Vertical Stress at a Load Factor of 1.0

In Figure 9.4.2-3, the tab vertical stress contours are shown. The vertical stress (SY) away from the weld in the tab is used in the fracture mechanics calculation (Section 9.6) to check the partial penetration tab weld. The fracture mechanics model uses 13ksi or 90 MPa away from the details of the weld in the central region of the tab. On the tensile side (left in the figure), the stress is between the 25 and 100 MPa contours. On the side with the crack it is compressive.

9.5 Rib Umbrella Foot Step Radius

There is a high stress area of the ribs directly under the Umbrella feet. The radius at the reduced section at the umbrella foot "shelf" is highly stressed mainly because it is a reduced section. There was also a rib to dome fit-up problem that resulted from the spun dome not matching the curvature defined for the ribs. Bridging tabs were added.

A manageable set of hardware solutions could be implemented with modest cost and schedule alterations. If timed to occur as each umbrella leg is removed and PF2 lifted (to insert the added slide bracket), the amount of labor would be a small percentage increase. Irv Zatz suggested a preferred fix which is a 9 inch by 3 inch, 3/8 plate welded at an angle to form a triangular box beam on either side of the ribs. There would be two per pair of ribs, or 40 total.

In the discussions of the as-built conditions of the ribs and tabs it was evident that they are all different. The FEA models in this calculation are all based on a survey of a single rib.

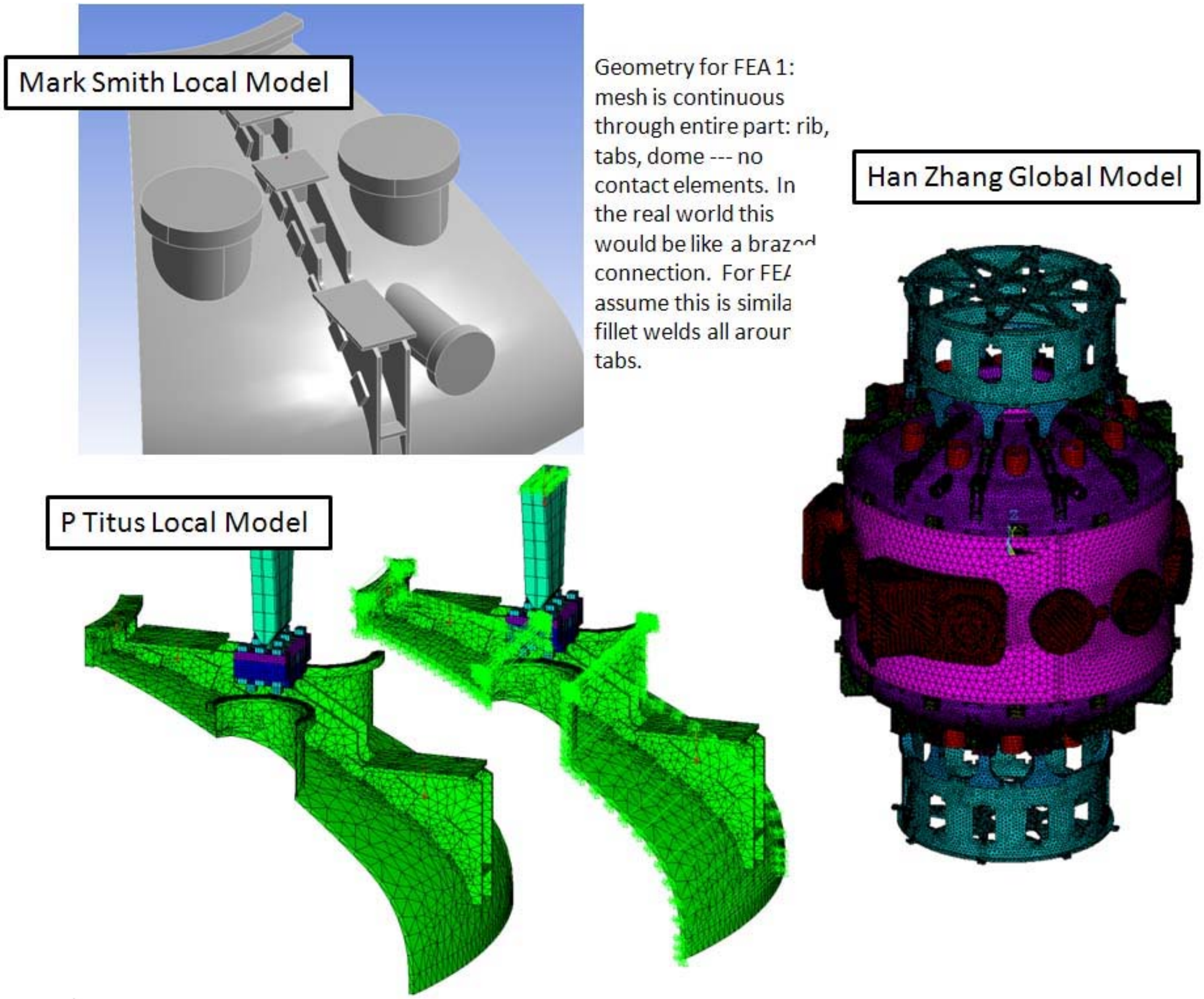


Figure 9.5-1 Available Models of the Ribs and Dome

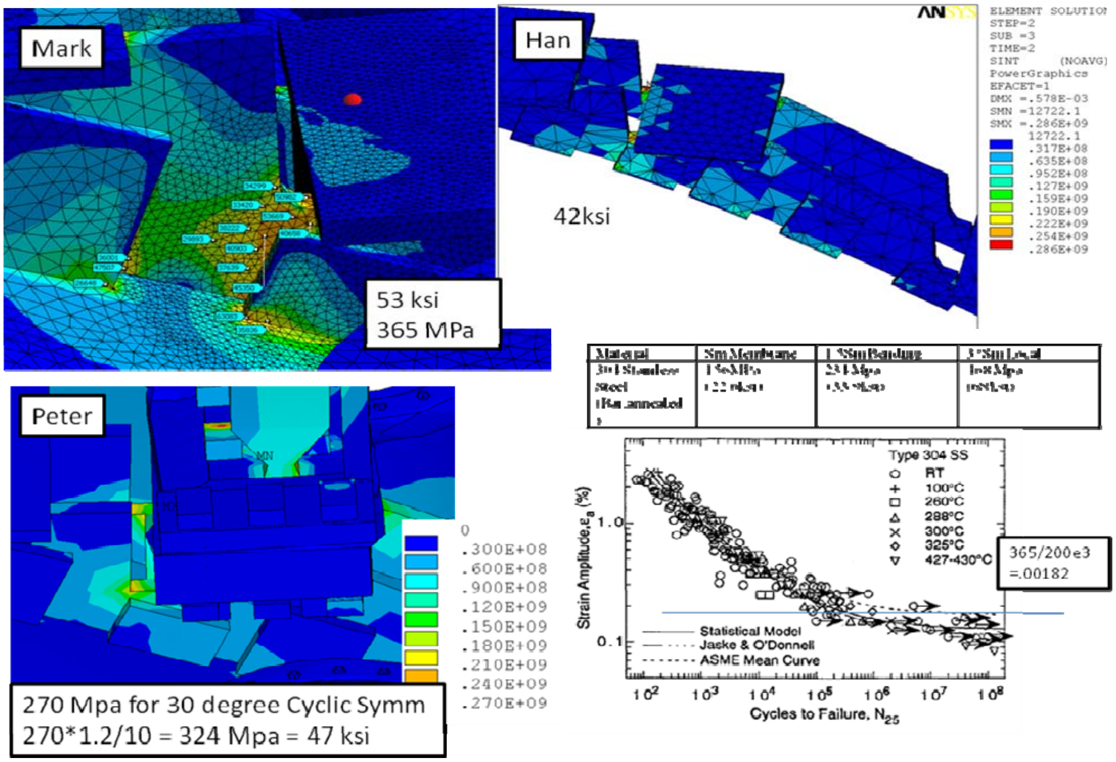


Figure 9.5-2 Comparison of Rib Stresses at the Umbrella Foot Support Step Radius

In figure 9.5-2, the results of three models are compared. All have stresses in the radius of the umbrella foot step of around 50 ksi. This stress level would indicate significant life but not enough to pass the criteria of 2 on stress or 20 on life. This radius can be added to the fatigue inspection list.

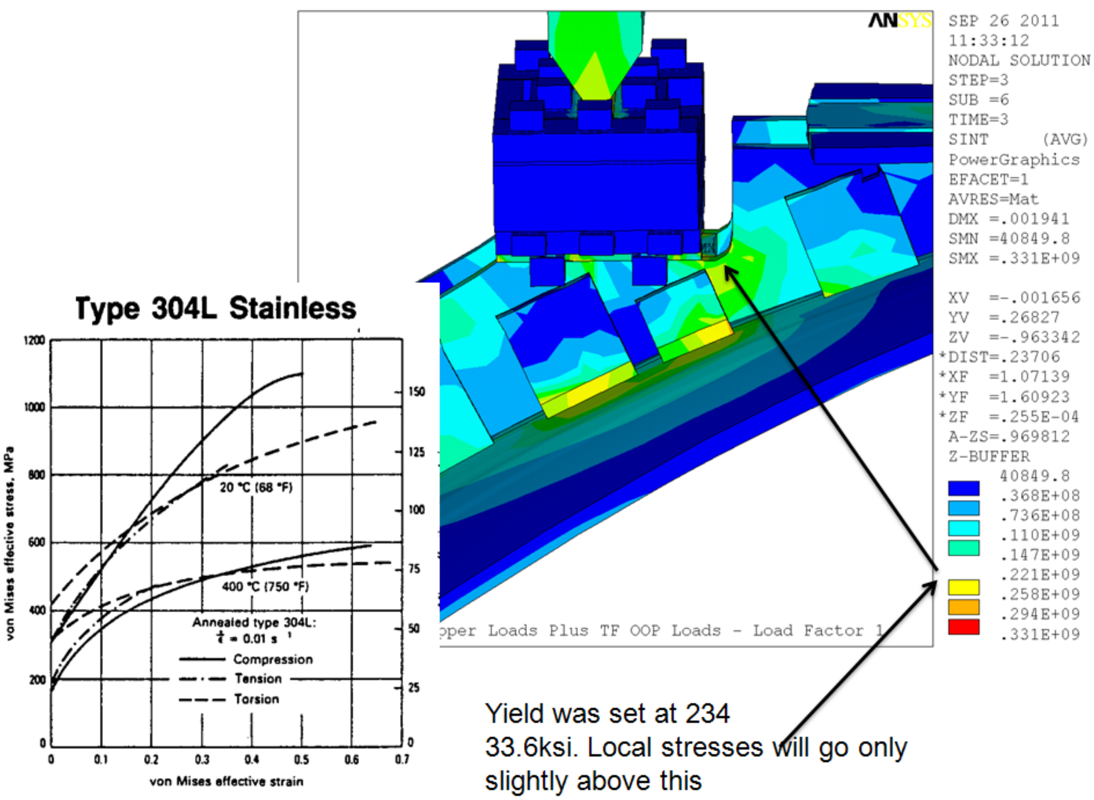


Figure 9.5.3 Tresca Stress at the Step Radius based on the Limit Analysis Described in Section 9.5

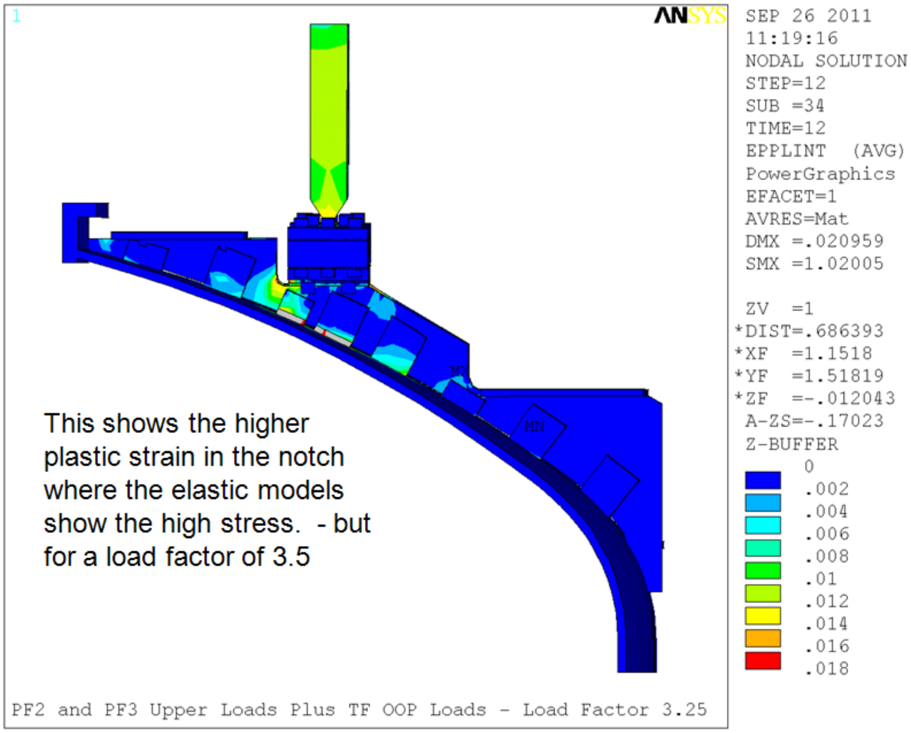


Figure 9.5-4 Plastic Strain at the Step Radius based on the Limit Analysis Described in Section 9.5

9.6 Rib Tab Welds

The tab weld is a 1/4 inch, one sided partial penetration weld with a 1/4 inch fillet. This butts against the dome and leaves a 1/8 inch root crack. A fracture mechanics analysis of the tab weld was performed to provide an assessment of the potential for fast fracture of the weld and the weld's fatigue life.

For a one sided partial penetration weld, the root of the weld forms an initial crack geometry that is not readily compared with handbook treatments of stress intensity factor (SIF). To calculate the SIF, the ANSYS crack tip element is used. Solid 95 elements with mid side nodes are used for the model. Wedge elements are arrayed around the crack tip. The midside nodes of the crack tip elements are positioned 1/4 of the length of the side. This causes a singularity that can be used by the KCALC ANSYS command to calculate the stress intensity factor (SIF). A 2 inch section of the tab weld is modeled in 3D. The root of the weld is assumed to be a crack geometry and the SIF is computed in ANSYS. The PATH command is used to define a path with the crack face nodes (NODE1 at the crack tip, NODE2 and NODE3 on one face, NODE4 and NODE5 on the other (optional) face). A crack-tip coordinate system, having x parallel to the crack face (and perpendicular to the crack front) and y perpendicular to the crack face, must be the active RSYS and CSYS before KCALC is issued.

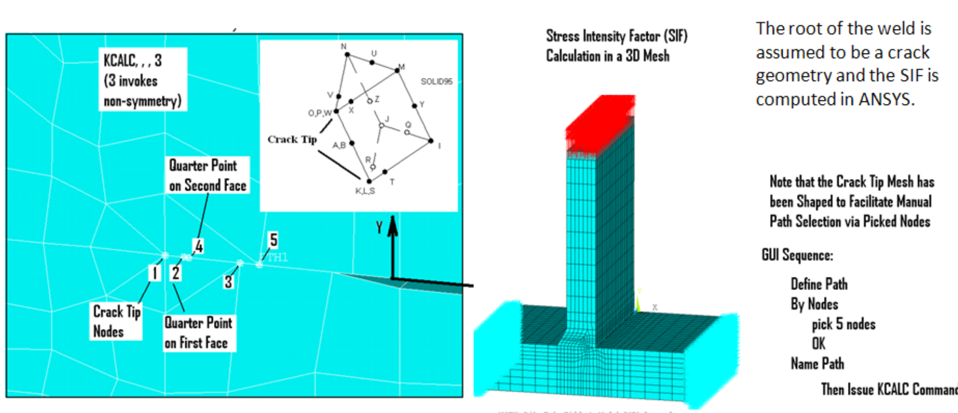


Figure 9.6-1 Fracture Mechanics ANSYS Model

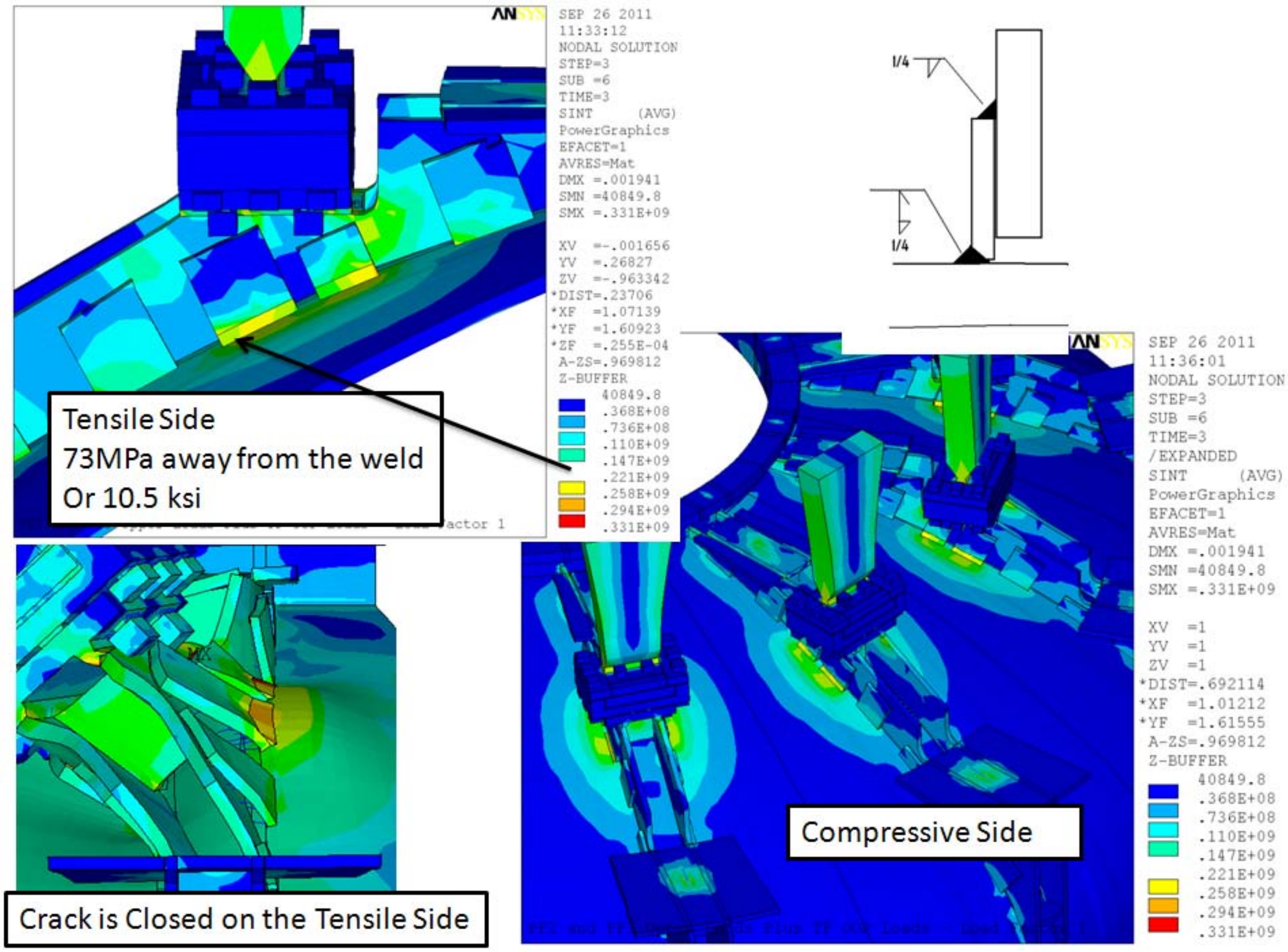


Figure 9.6-2 Applied Loads and Displacements for the Fracture Mechanics ANSYS Model

When the umbrella leg load is bent by the OOP loading it tends to close the crack on the tension side of the pair of ribs. This is evident in the extremely exaggerated displacement and stress plot of the load factor of 4 plotted results in the lower left hand corner of figure 9.6-2. The appropriate modeling would impose the bending displacement that would tend to close the crack. Conservatively, the tab is held horizontally. For comparison sake, one with no displacement constraints at the top of the tab is also shown. The loading is applied at the top of the tab model, and the stress in the limit analysis model away from the weld stress concentration is used to estimate the tensile loading in the tab.

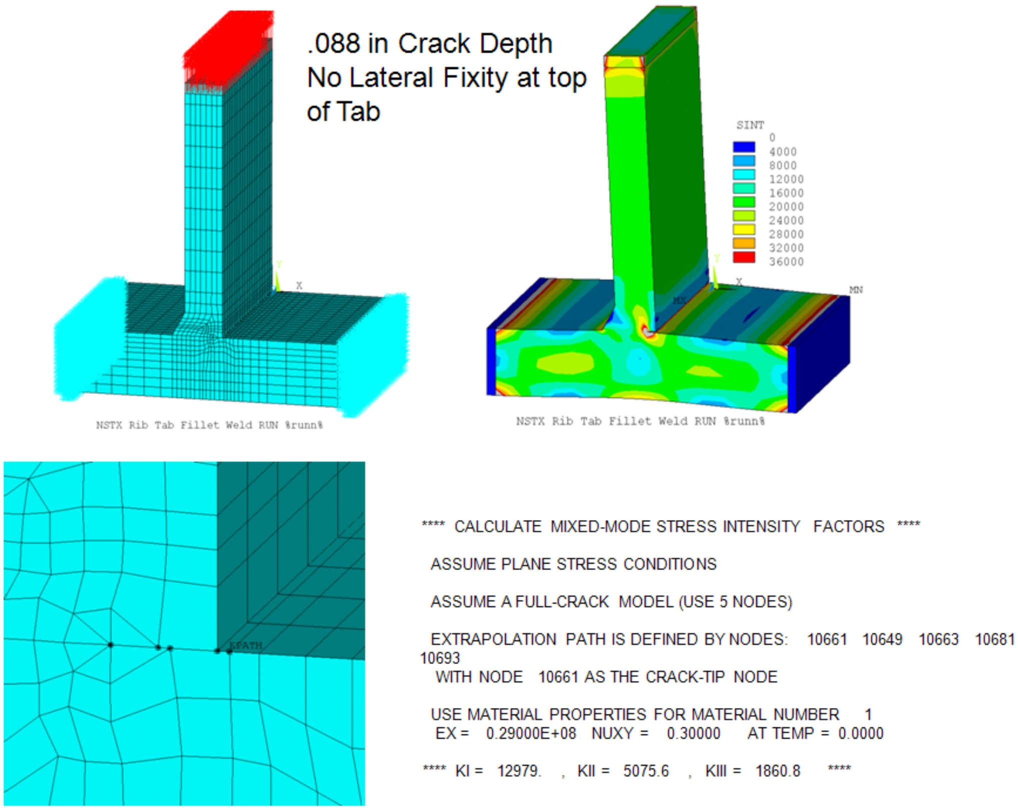


Figure 9.6-3 Stress Intensity Results with No Lateral Restraints

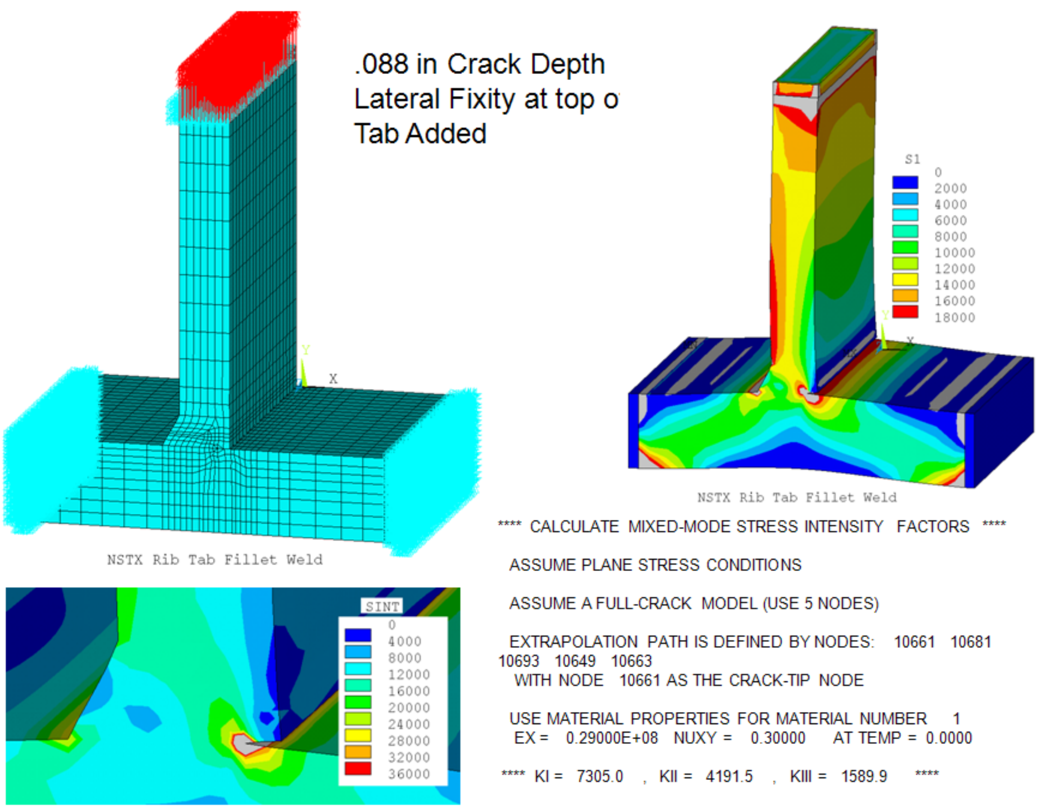


Figure 9.6-4 Stress Intensity Results with Lateral Restraints

The SIF goes down with added restraint, and would presumably be reduced further with displacements that tend to close the crack as in the actual rib tab attachment. It is expected that the 1/4 bevel weld will have a penetration depth in excess of 1/4 inch, but if it doesn't, two crack dimensions were analyzed, including the nominal crack length of .125 inch.

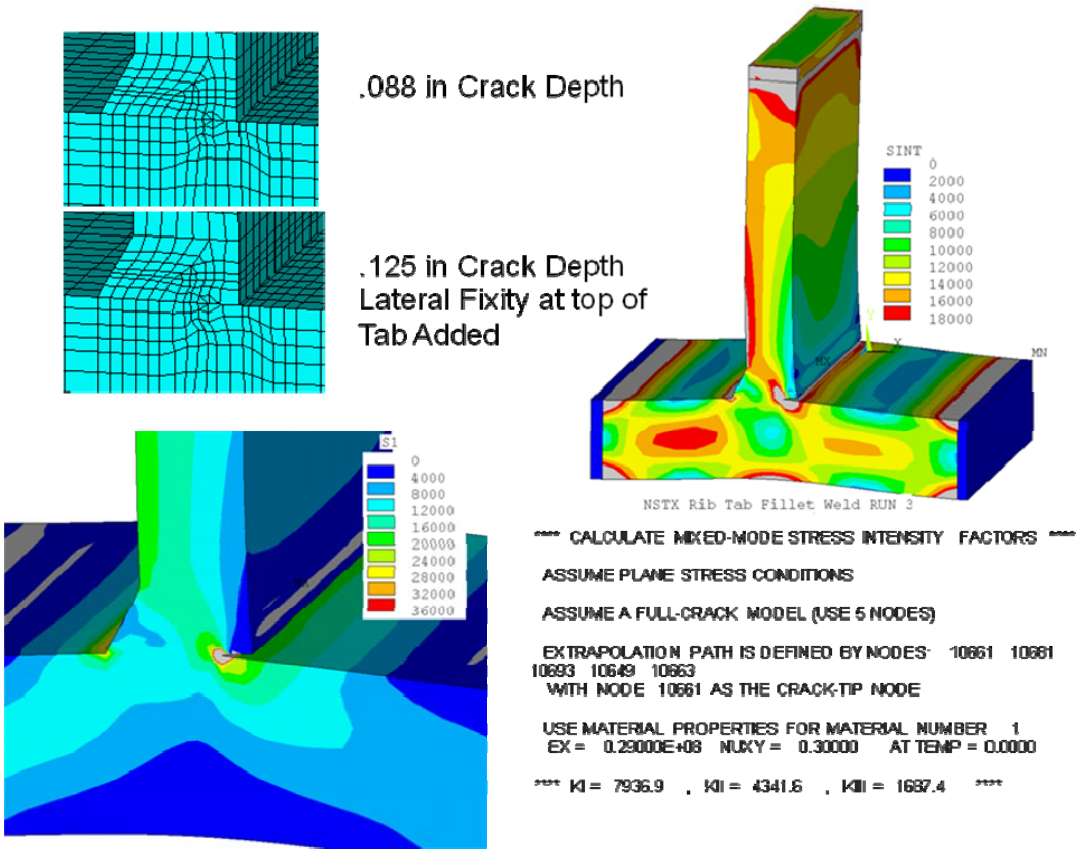


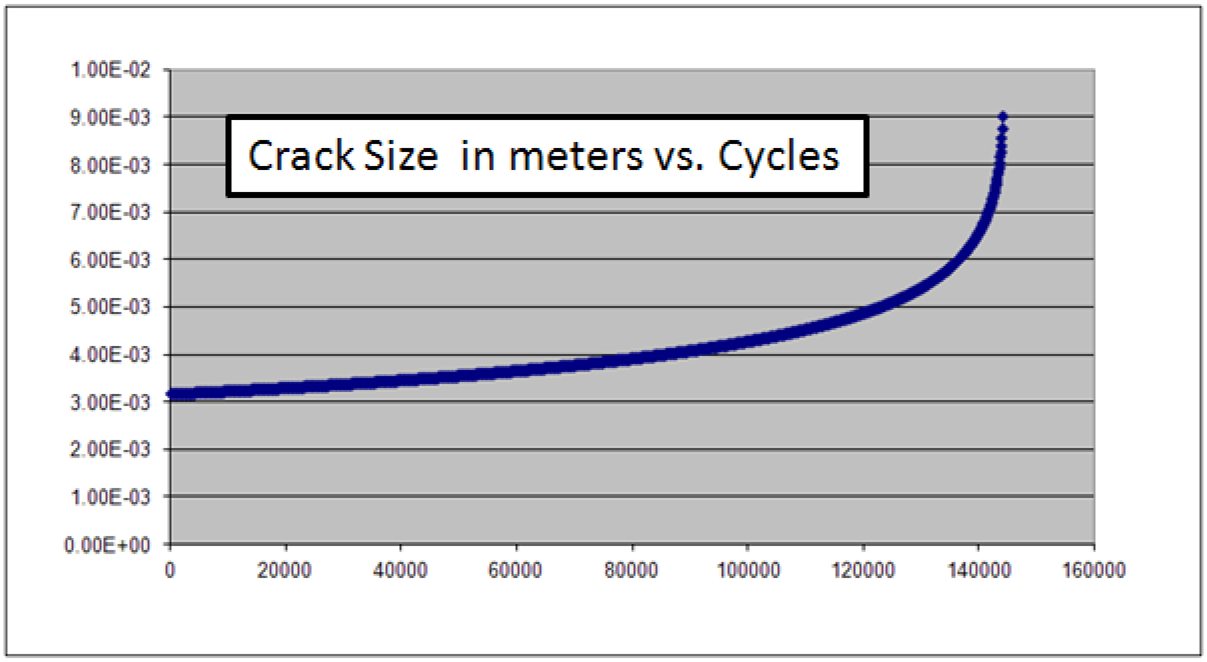
Figure 9.6-5 Stress Intensity Results with Lateral Restraints and .125 inch crack

The SIF went up from 7305 to 7937 psi root inch.

A small True Basic code (at right) was written to integrate the Paris relation. The results, plotted using 316 stainless steel Paris Constants are shown. Reference [14] and [15] constants were run as well. Ref [15] values produced a longer life and Ref [14] smaller - around 80,000 cycles.

```
! Simple da/dn integral for 304 Stainless Steel
let t=.5*.707/39.37
let ainit=.125/39.37
let m=2.95
let c=5.43e-12
let fractTough=100
let deltak= 7305*6895/1e6/39.37^.5
let a=ainit
let abreak=ainit+t
let counter = 0
!for i= 1 to 10000

do
!deltak is linear in crack length
let delk=deltak/ainit*a
!assume the delta k scales with the orig thick/remaining thickness
let delk=delk*(t+ainit)/(t+ainit-a)
let i=i+1
let counter=counter+1
let dadn=c*delK^m
let a=a+dadn
if counter = 100 then
print i;",";delk;","; a
let counter = 0
end if
if a>abreak or delk>fractTough then exit do
!next i
loop
print "Cracked Through"
end
```



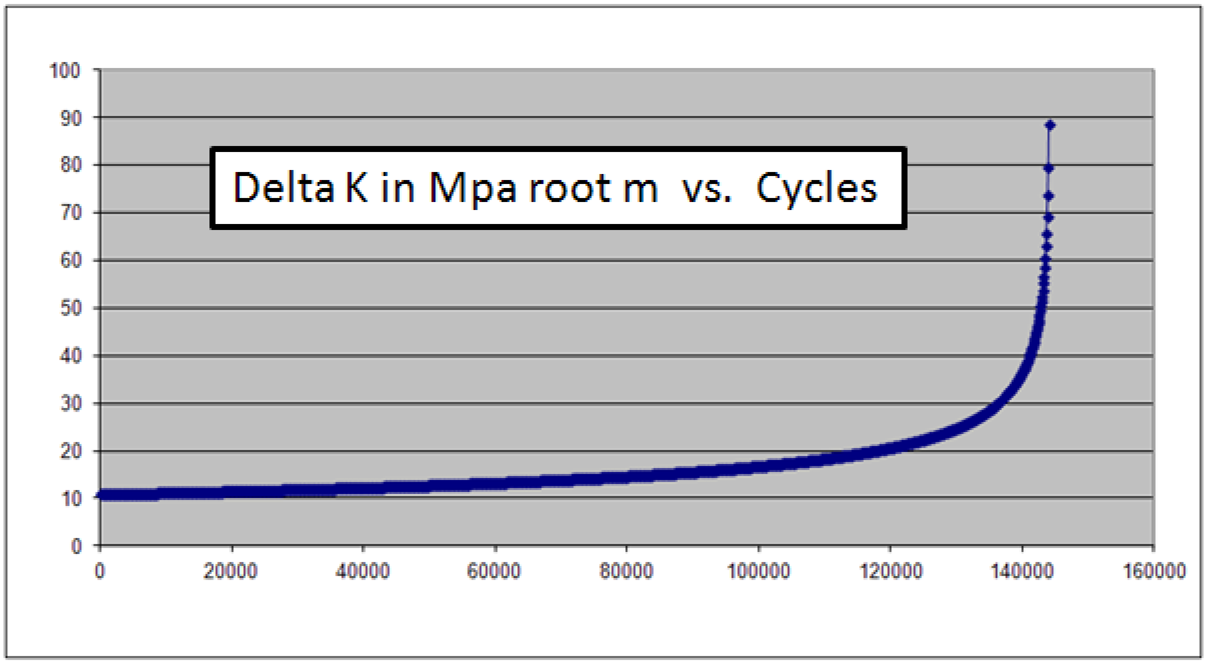


Figure 9.6-6 Crack size vs. cycles and Stress Intensity vs. cycles

Figure 9.6-6 qualifies the rib tab weld for 140,000 cycles or 35000 with the required factor of safety of 4.

9.7 Sliding Block Bolting

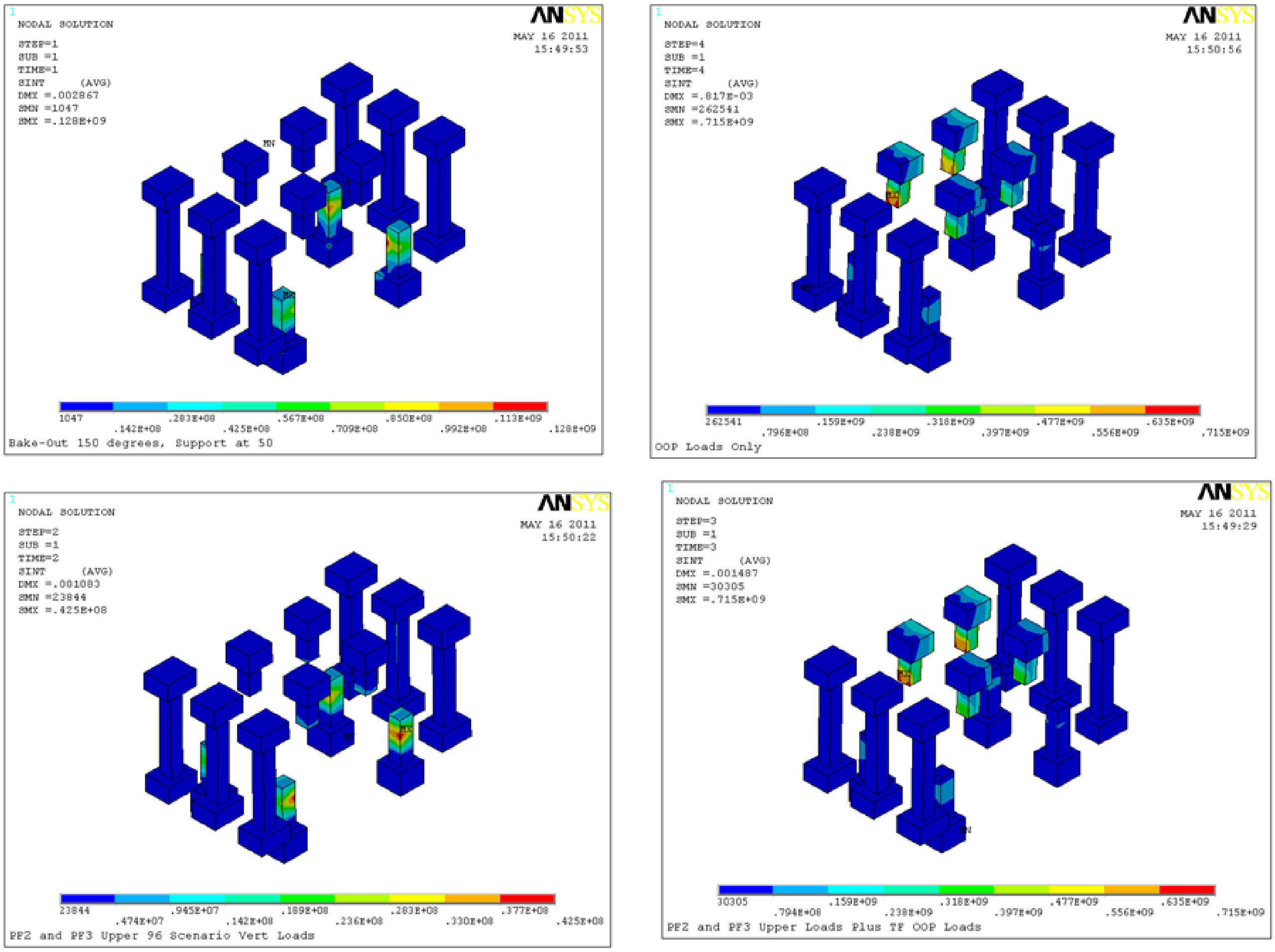


Figure 9.7-1 Bolt Stresses from the 30 degree Cyclic Symmetry Model

Significant stresses occur only in the four bolts that currently take the OOP shear load as shear across the bolt thread. The Upgraded design will employ "lips" on the sides of the sliding block assembly that will engage the plate welded to the ribs. All hardware is being replaced with Inconel 718 hardware for additional margin.

9.8 Fatigue

Specific analyses of fatigue life occur in previous sections of the calculations. The following discussion relates to areas which look problematic from both the analysis of the design and the inspected condition of the weld or feature.

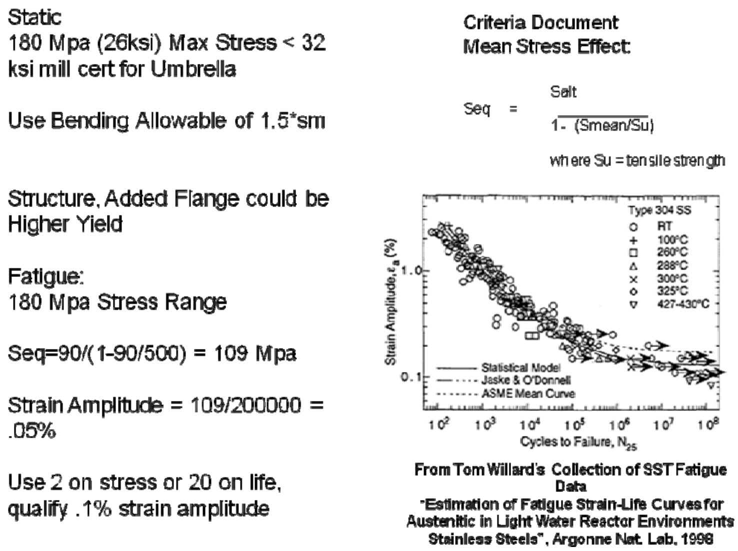


Figure 9.8-1

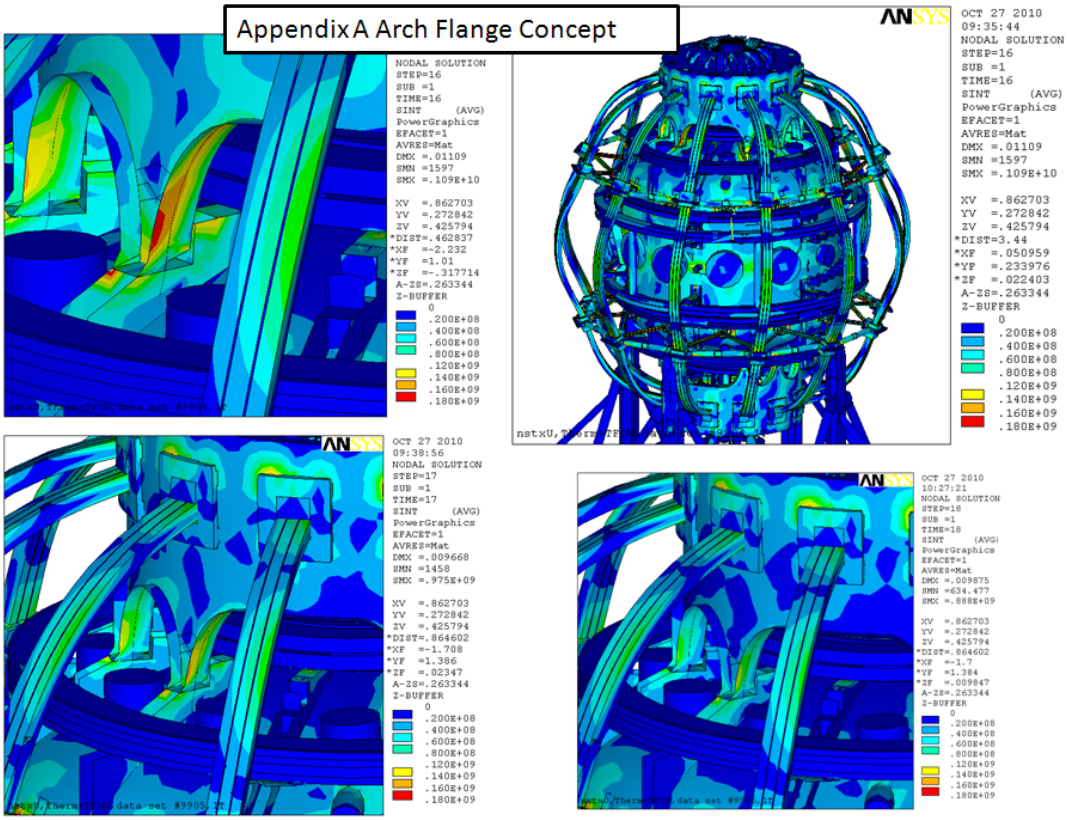
For 304 stainless, a 180 MPa stress range translates to a 90/(1-90/500) = 109 MPa equivalent R = -1 alternating stress. This is a strain amplitude of 109/200,000 = .05%. Entering the SN curve (Figure 7.2.1 for 304 Stainless) and applying either 2 on stress or 20 on life yields an acceptable fatigue life meeting the GRD requirement of 60,000 pulses.

Figure 9.8-2 Area Recommended for Inspection

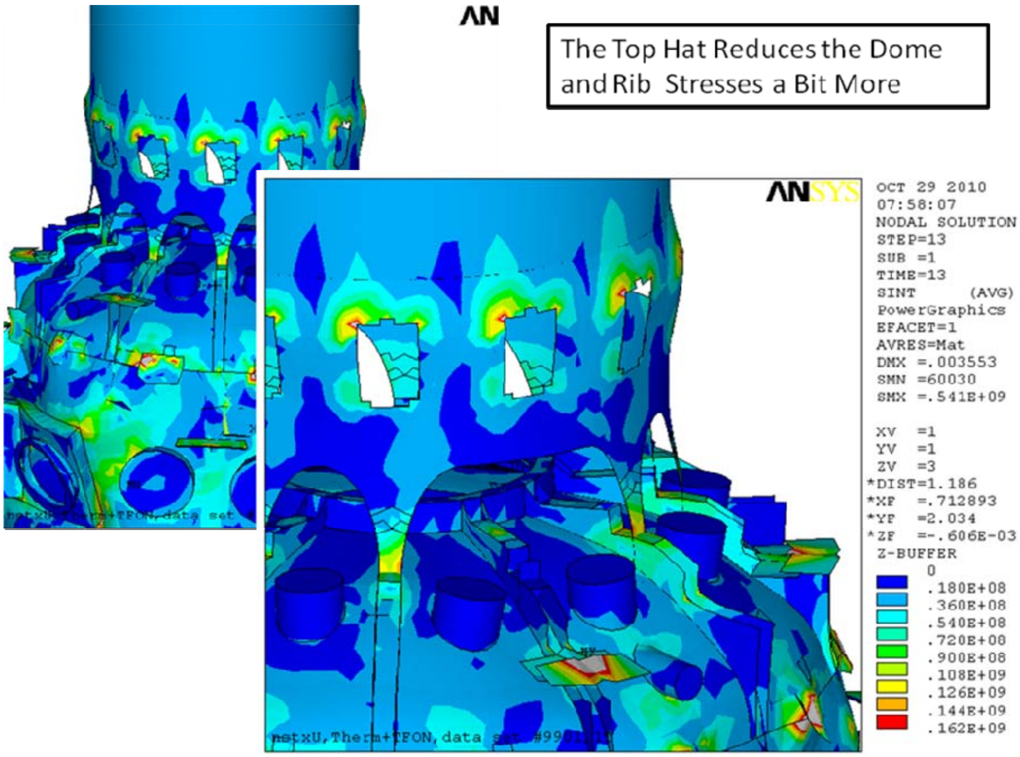
Figure 9.8-2

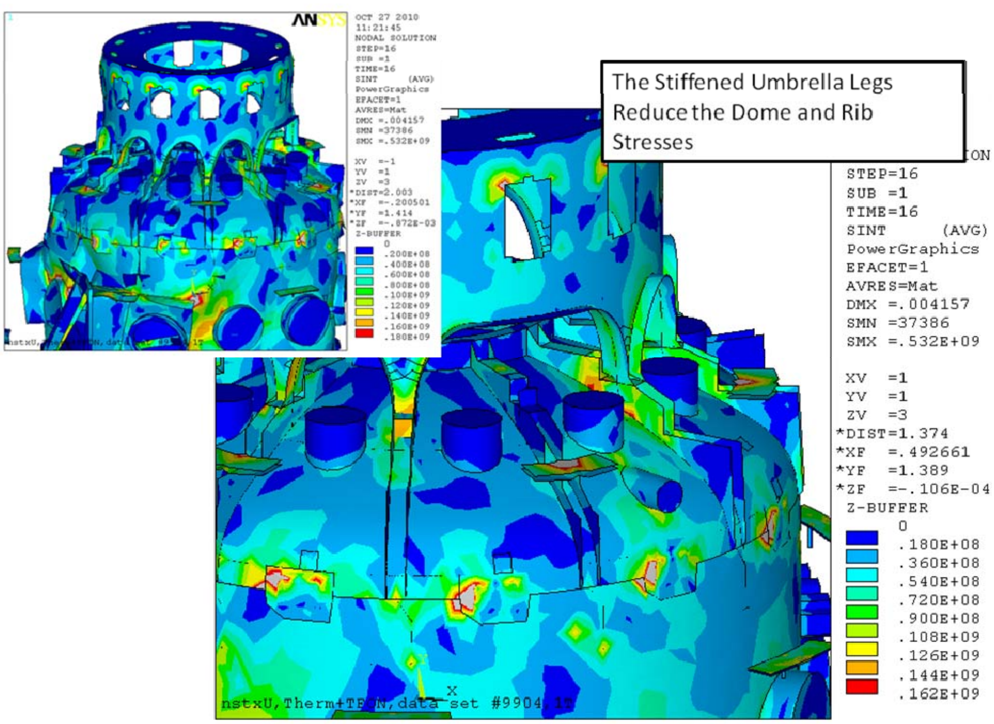
At September 28, 2011 meeting, photos of "bad" welds at the Umbrella foot plate to rib weld details were discussed. Figure 9.8-2 shows one of them. This might have passed inspection for the weld in the middle of its length, but the start and stop of the weld occurs where the FEA shows the max stress (also see figure 9.3-4). Grinding out this area and welding around the ends of the plate to rib junction will be needed.

Appendix A
Arch Flange Reinforcement



Appendix B "Top Hat" Torque Frame





Appendix C
Dome Material Certifications

#1

Process Systems Int'l **Receiving Inspection Report**

Job No: V19077- **HEADS:** #1 BOTTOM HEAD

PSI P.O. # 558628 **ITEM #** 001

PSI MIC # D019 **HEAT #** 879461 /SL52960

DISCRIPTION: 133" I/D ASME F&D SA-240-

QUANTITY: 1

REVIEW MATERIAL CERTIFICATION: OK ARB 6-9-98

REVIEW RADIOGRAPHS: OK ARB 7-27-98

VERIFY DIMENSIONS; ROUNDNESS - ON MACHINE (RESTRAINED) WITHIN .050"

THICKNESS - .680"

CIRCUMFERENCE - 134.240"⌀

VERIFY MAGNETIC PERMEABILITY - IN ACCORDANCE WITH SPECIFICATION V077-2-002, PARA. 2.4.

1.01mu – 1.05mu MEASURED BASE MATERIAL @ 0°, 90°, 180° 270° FROM WELD EDGE To Top of DOME 6 places @ 6" SPACING.

1.05mu – 1.10mu SEAM WELD IN HEAD, except: area 2" ABOVE KNUCLE RAD MEASURES 1.1-1.2 @ 90° and 1.2-1.3 @ 180° AND A 4" LONG AREA IN THE MIDDLE OF A REPAIRED AREA NEAR TOP OF DOME MEASURES OVER 3.0 mu. (THIS AREA WILL BE ORIENTED SO IT IS A NOZ-CUTOUT).

INSPECTED BY: Alan L Braddock **DATE:** 6-9-98

#2

Process Systems Int'l **Receiving Inspection Report**

Job No: V19077- **HEADS:** #2 TOP HEAD

PSI P.O. # 558628 **ITEM #** 001

PSI MIC # D019 **HEAT #** 879690/SL 01980

DISCRIPTION: 133" I/D ASME F+D SA-240

QUANTITY: 1

REVIEW MATERIAL CERTIFICATION: OK ARB 6-9-98

REVIEW RADIOGRAPHS: OK ARB 7/27/98

VERIFY DIMENSIONS: ROUNDNESS - UNRESTRAINED WITHIN 3/8"

THICKNESS - .672" – .678"

CIRCUMFERENCE - 134.263" ϕ

VERIFY MAGNETIC PERMEABILITY - IN ACCORDANCE WITH SPECIFICATION V077-2-002, PARA. 2.4.

1.01mu – 1.05mu Measured Base Material @ 0°, 90°, 180°, 270° From Weld Edge to Top of Dome 6 places @ 6" spacing.

1.2mu – 1.3mu WELD SEAM IN HEAD Above Knuckle Radius for 30"

1.05mu – 1.1mu WELD SEAM IN HEAD below Knuckle Radius to WELD BEVEL.

INSPECTED BY: ARBradbury **DATE:** 6-9-98

Jessop Plate Products Division

a-a2657

Page 1

500 Green Street CERTIFIED MATERIAL TEST REPORT
Washington, Pennsylvania 15301

PSI MIC NO. D019

Billto: Shipto:
PLATE PROD DIV / A-L PLATE PROD DIV / A-L
1201 VALLEY ROAD 1201 VALLEY ROAD
COATESVILLE PA 19320 COATESVILLE PA 19320

HELEN M. O'CONNOR
Quality Assurance Representat

PROCESS SYSTEMS INT'L., INC.
Reviewed this report and it complies with SA-~~SB~~- 240 Gr. 304
1995 Edition, 97 Addenda
By AR Bradbrook Date 6-10-98

Memo No:142331-01

Our Order no: LP7800588
Your Order No:1089
Date: 01/03/98
DUAL CERT

JESSOP T 304 STAINLESS HRAP
ASTM A240-96; ASME SA-240-A95; AMS 5513F;

Heat	Slip	Lot No	Size	Pcs	Weight
879461	52960 D	39172	.6250 x 101.0000 x 350.0000	1	6587 GV-STOCK

Heat	C	MN	P	S	SI	NI	CR	MO	CO	CU	N
879461	.025	1.74	.03	.0004	.38	8.22	18.25	.40	.12	.36	.079

Lot No	Gauge	Yield Strength	Tensile Strength	Elong	Red. of Area	Hardness	Bend	Corrosion	Grain Size
39172	.6250	41.4 KSI	87.6 KSI	57.2	77.6	BHN163	OK	OK	

MATERIAL WAS NOT WELDED

Memo No:142399-01

Our Order no: LP7800588
Your Order No:1089
Date: 01/08/98
DUAL CERT

JESSOP T 304 STAINLESS HRAP
ASTM A240-96; ASME SA-240-A95; AMS 5513F;

Heat	Slip	Lot No	Size	Pcs	Weight
879461	52960 D	39178	.6250 x 101.0000 x 350.0000	1	6587 GV-STOCK

Heat	C	MN	P	S	SI	NI	CR	MO	CO	CU	N
879461	.025	1.74	.03	.0004	.38	8.22	18.25	.40	.12	.36	.079

Lot No	Gauge	Yield Strength	Tensile Strength	Elong	Red. of Area	Hardness	Bend	Corrosion	Grain Size
39178	.6250	42.9 KSI	88.0 KSI	54.0	77.1	BHN163	OK	OK	

MATERIAL WAS NOT WELDED

Memo No:143044-01

APPROVED
MAR 25 1998
Q.C. DEPT.

Our Order no: LP7426810
Your Order No:2022
Date: 01/19/98
DUAL CERT

JESSOP T 304 STAINLESS HRAP
ASTM A240-96a; ASME SA-240-A96; AMS 5513F
UNS 30400

EXCEPT AS OTHERWISE NOTED, THIS MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH THE LISTED SPECIFICATIONS AND RESULTS CONFORM TO THE SPECIFICATION AND ORDER REQUIREMENTS. THE ABOVE INFORMATION HAS BEEN REPRODUCED FROM THE ORIGINAL CERTIFIED MATERIAL TEST REPORT.

ORIGINAL

Allegheny Ludlum CORPORATION
Jessop Plate Products Division

Page 2

500 Green Street CERTIFIED MATERIAL TEST REPORT
Washington, Pennsylvania 15301

MIC NO. D019

Billto:
PLATE PROD DIV / A-L
1201 VALLEY ROAD
COATESVILLE PA 19320

Shipto:
PLATE PROD DIV / A-L
1201 VALLEY ROAD
COATESVILLE PA 19320

HELEN M. O'CONNOR
Quality Assurance Representa

Heat	Slip	Lot No	Size	Pcs	Weight
879690	01980 C	39287	.6250 x 90.0000 x 325.0000	1	5450 GV-76863

Heat	C	MN	P	S	SI	NI	CR	MO	CO	CU	N
879690	.025	1.75	.033	.0004	.40	8.18	18.23	.39	.14	.37	.09

Lot No	Gauge	Yield Strength	Tensile Strength	Elong	Red. of Area	Hardness	Bend	Corrosion	Grai Siz
39287	.6250	41.5 KSI	89.7 KSI	55.2	76.4	BHN163	OK	OK	

MATERIAL WAS NOT WELDED

PROCESS SYSTEMS INT'L., INC.
Reviewed this report and it complies
with SA/~~SB~~- 240 Gr. 304
1995 Edition, 97 Addenda
By A L Bradbrook Date 6-10-98

MIC #

TOP HEAD HT-879690/SL 01980 D019

BOTTOM HEAD HT 879461/SL 52960 D019

APPROVED
MAR 25 1998
Q.C. DEPT.

EXCEPT AS OTHERWISE NOTED, THIS MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH THE LISTED SPECIFICATIONS AND RESULTS CONFORM TO THE SPECIFICATION AND ORDER REQUIREMENTS. THE ABOVE INFORMATION HAS BEEN REPRODUCED FROM THE ORIGINAL CERTIFIED MATERIAL TEST REPORT.

ORIGINAL

PSI MIC NO. D019

PG - 3 OF 4

TRINITY INDUSTRIES, INC.
HEAD DIVISION
11861 MOSTELLER RD * CINCINNATI OH 45241 * (513)-771-2300
MTR COVER LETTER

PROCESS SYSTEMS INTERNATIONAL INC
20 WALKUP DR
WESTBOROUGH MA 01581-1019

ATTN : PAUL CLARK

REFERENCE : CUSTOMER P/O 558628 , TAG #
TRINITY S/O 2-29237

GENTLEMEN :

ATTACHED ARE COPIES OF MILL TEST REPORTS FOR THE FOLLOWING MATERIAL PROVIDED ON YOUR REFERENCED PURCHASE ORDER.

LABOR & MATERIAL
2-SA240-304 ASME-F&D HEAD 133.0000 ID 0.6250 NOM
100.8000 RD. 14.0000 ICR. WITH 2.5000 SF.

HEAT NUMBER

879461-52980 HC*
879690-01980 HC*

ALL HEADS WERE COLD FORMED AND ARE IN COMPLIANCE WITH REGULATION UG - 81 AND UG - 79 AS STATED IN SECTION VIII DIVISION I OF THE ASME BOILER AND PRESSURE VESSEL CODE. HEADS WERE FORMED WITHOUT COMING IN CONTACT WITH MERCURY OR ANY OF IT'S COMPOUNDS

ALL HEADS WERE ANNEALED AT 1950 +/- 50 F FOR ONE HOUR PER INCH AND WATER QUENCHED.

IF YOU HAVE ANY FURTHER QUESTIONS CONCERNING MILL TEST REPORTS ONLY, PLEASE CONTACT ME IN CINCINNATI, OHIO AT 1-800-543-1644

VERY TRULY YOURS,

Larry R. Stegeman 5/5
TRINITY INDUSTRIES, INC
HEAD DIVISION

FORM U-2A MANUFACTURER'S PARTIAL DATA REPORT (ALTERNATIVE FORM)
A Part of a Pressure Vessel Fabricated by One Manufacturer for Another Manufacturer
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1. Manufactured and certified by Trinity Industries Inc. Head Division 11861 Mosteller Rd.,Cinti.OH 45241
(Name and address of Manufacturer)

2. Manufactured for Process Systems International Inc,20 Walkup Dr.,Westborough MA 01581-1019,PO#5586
(Name and address of Purchaser)

3. Location of installation Unknown (Name and address) PSI MIC NO. D019

4. Type: ASME(2PC)Heads 133"ID x .625 NOM THK 2-29237-162 PC-4 of 4
(Description of vessel part (shell, two-piece head, tube bundle)) (Mfg's. serial No.) (CRN)

(Nat'l. Bd. No.) (Drawing No.) (Drawing prepared by) 1998 (Year built)

5. ASME Code, Section VIII, Div. 1 1995 Edition 1996 ADD
(Edition and Addenda (date)) (Code Case No.) (Special Service per UG-120(d))

6. Shell (a) No. of course(s): (b) Overall length (ft & in.):

Course(s)			Material	Thickness		Long. Joint (Cat. A)			Circum. Joint (Cat. A, B, & C)			Heat Treatment	
No.	Diameter, in.	Length, ft & in.	Spec./Grade or Type	Nom.	Corr.	Type	Full, Spot, None	Eff.	Type	Full, Spot, None	Eff.	Temp.	Time

7. Heads: (a) SA240-304 S/S * (b)
(Mat'l Spec. No., Grade or Type) H.T. – Time & Temp.) (Mat'l Spec. No., Grade or Type) H.T. – Time & Temp.)

	Location (Top, Bottom, Ends)	Thickness		Radius		Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure		Category A		
		Min.	Corr.	Crown	Knuckle					Convex	Concave	Type	Full, Spot, None	Eff.
(a)		.573		100.8	14							1	Full	
(b)														

If removable, bolts used (describe other fastening)
(Mat'l Spec. No., Grade, Size, No.)

8. MAWP ______ (internal) ______ (external) psi at max. temp. ______ (internal) ______ (external) °F. Min. design metal temp. ______ °F at ______ psi.

9. Impact test
(Indicate yes or no and the component(s) impact tested)

10. Hydro., pneu., or comb. test press. Proof test

11. Nozzles, inspection, and safety valve openings:

Purpose (Inlet, Outlet, Drain, etc.)	No.	Diameter or Size	Flange Type	Material		Nozzle Thickness		Reinforcement Material	How Attached		Location (Insp. Open.)
				Nozzle	Flange	Nom.	Corr.		Nozzle	Flange	

12. Supports: Skirt ______ (Yes or no) Lugs ______ (No.) Legs ______ (No.) Others ______ (Describe) Attached ______ (Where and how)

13. Remarks: No design functions performed by Trinity Industries Inc. Head Division
Customer is responsible for specifying minimum design metal temp.
* Heads were annealed at 1900°F minimum 1 hour per inch and water quenched.

CERTIFICATE OF SHOP/FIELD COMPLIANCE

We certify that the statements made in this report are correct and that all details of material, construction, and workmanship of this pressure vessel part conform to the ASME Code for Pressure Vessels, Section VIII, Division 1.

U Certificate of Authorization No. 25,479 Expires March 25, 2000

Date 5-27-98 Name Trinity Industries Inc. Head Division (Manufacturer) Signed [signature] (Representative)

CERTIFICATE OF SHOP/FIELD INSPECTION

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and/or the State or Province of Ohio and employed by Commercial Union Insurance Companies of Boston, MA have inspected the pressure vessel part described in this Manufacturer's Data Report on 5-27, 19 98, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel part in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel part described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 5-27-98 Signed [signature] (Authorized Inspector) Commissions [signature] (Nat'l Board (incl. endorsement), State, Province and No.)

(12/91) This form (E00121) may be obtained from the ASME Order Dept., 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300 REPRINT 3/92

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Run Date: 28-JUL-1998  Time: 10:14 AM          Process Systems International, Inc.                User: ALB          Page 00001
P O   H i s t o r y   b y   O r d e r #

PO:    558628-00 Vendor:  43718 Buy-From:  43718 TRINITY INDUSTRIES INC          Ship to:01 PROCESS SYSTEMS INTERNATIONAL  Buyer: 03
Date:  3/18/98                                   11861 MOSTELLER ROAD                       20 WALKUP DRIVE                    Fob: 1
                                                 SHARONVILLE, OH 45241                      WESTBORO, MA 01581            Ship Via: 1
                                                 ATTN: DAVE SCHAEFER                                                         Terms: 1
                                                       (800)543-1644
                                                  ------- Ordered -------      Received    Inspection --Rej+Disp--  Change Voucher Amt
Lin Item Number                                   UM    Cost(   $)    Qty   By       Qty     Qty      Code    Qty    to Inv   Dollars

  1 V077M202 1         HEAD,SST304 SA240 CMTR,ASME   F&D,133.000I.D.,.625 NOM THK
   3/17/98 16:15:46 Add  Rq: 5/18/98 Pm: 5/18/98 EA   7736.0000     2
   3/18/98 08:28:45 Cncl                              7736.0000     2-
   3/18/98 09:20:35 Add  Rq: 5/18/98 Pm: 5/18/98 EA   7736.0000     2
   6/10/98 10:41:55 Rcpt Dt: 6/10/98                  7736.0000          JRW        2                                2
                    DELIVERED TO NIMCO PER LARRY
   6/10/98 10:41:55 Qty Sent Inspct:        2                                              2                         2-
   6/25/98 10:35:37 Qty Passed Insp:        2                                              2-                        2
                    REC,D AT NIMCO  PER LARRY.
   7/01/98 09:56:27 Vouch  Number:104463   Inv:5-8945                                                                         [redacted]
                          for         2 EA  Job:V19077
                                       ------------------------------------------------------------------------------------------
                                       Line totals                  2                   2       0                0       2   [redacted]
                                       ------------------------------------------------------------------------------------------

    7 RECORDS SELECTED
```

RECEIPT INSPECTED AT VENDOR WITH
MIKE VIOLA OF PPPL ON 6-9-98

[signature]