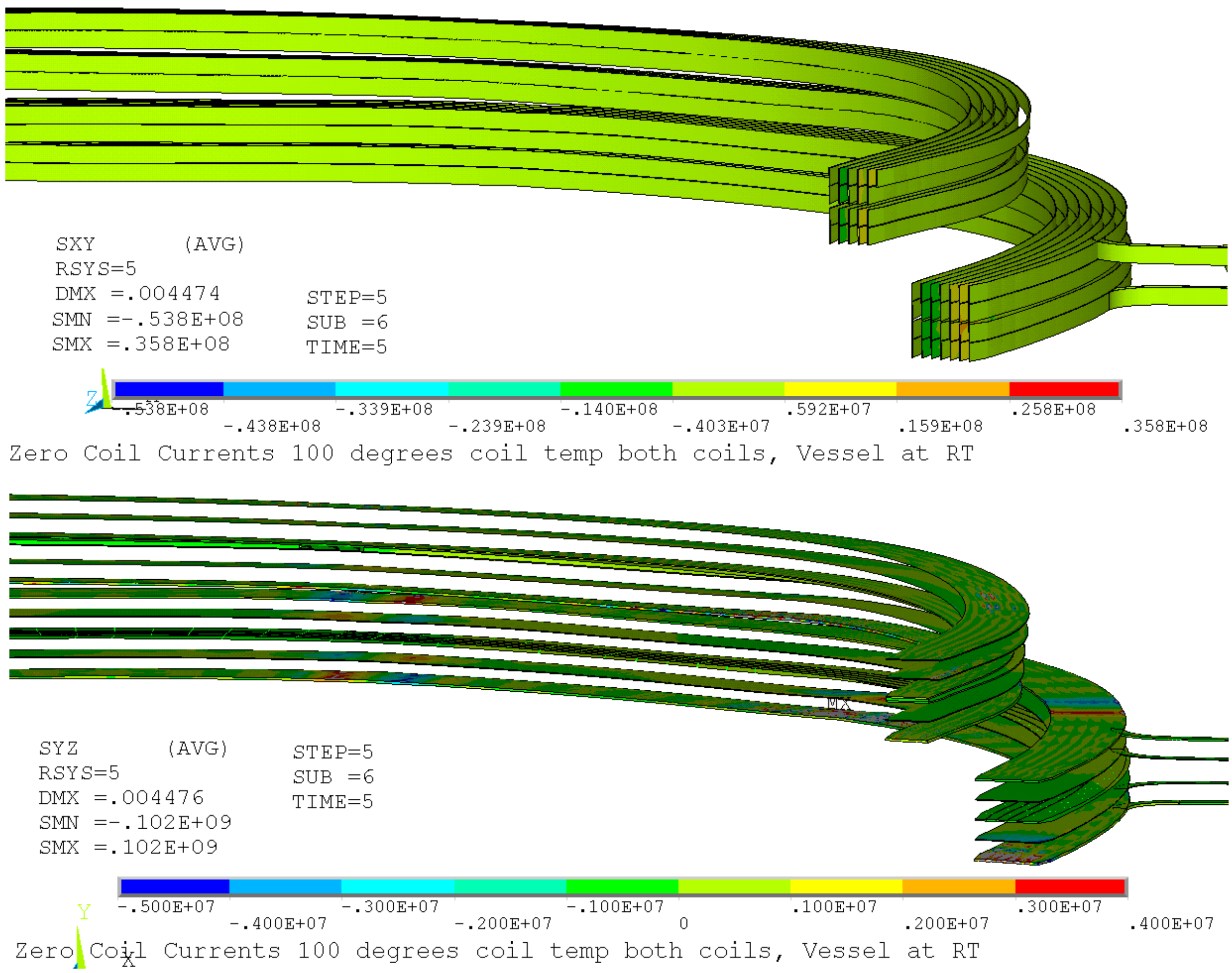


Figure 8.3-6 Radial -Vertical Shear for, No Coil Currents, Both Coils Hot

8.4 TF Ripple Loads on PF 4 and 5

PF 4 and 5 pass by the TF outer leg. The local toroidal field at the outer TF legs imposes periodic torques on the neighboring PF coils. The torques add bending stress to the existing bending stresses which result from the discrete coil support points. The ripple effect is being quantified independent of other loading. To accomplish this, the Lorentz Loads are quantified with and without the TF current and the two files are differenced to obtain loading for only the effect of the TF currents.

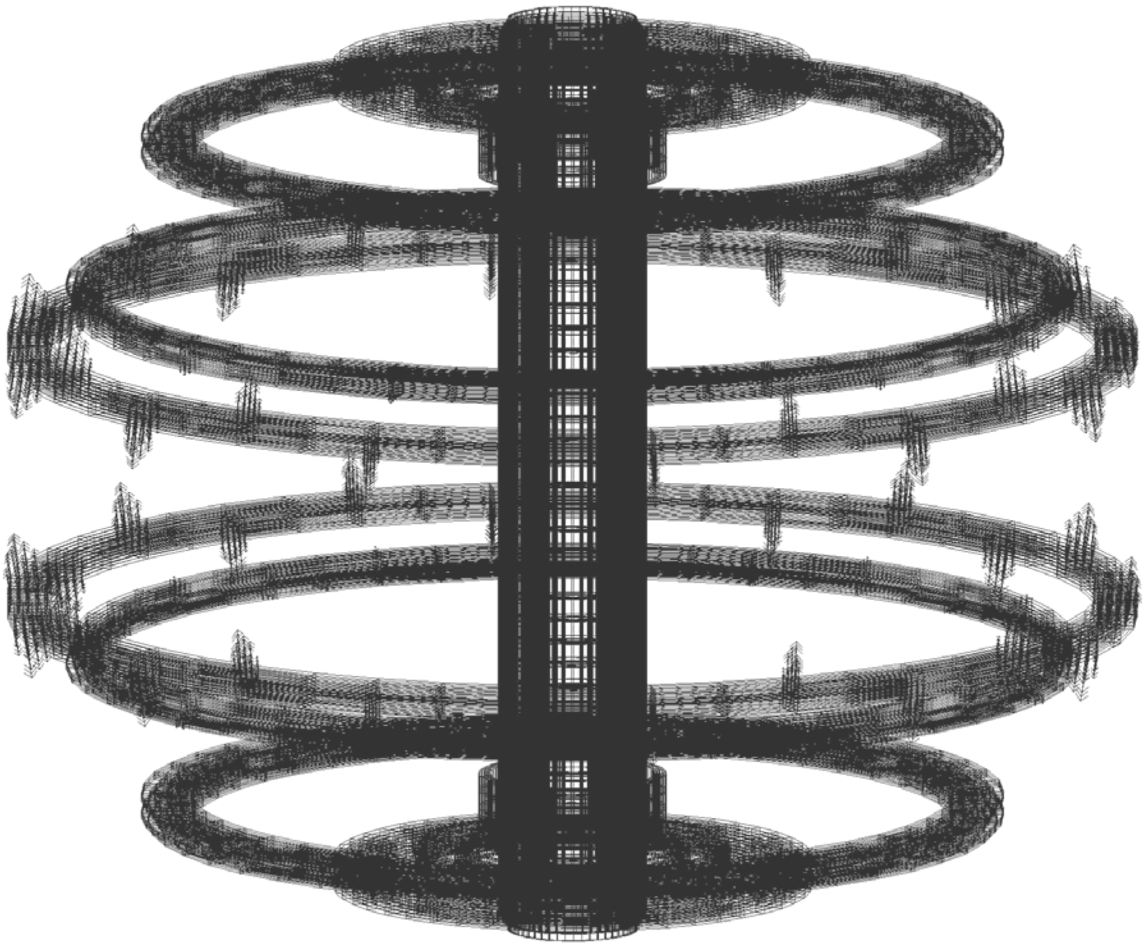


Figure 8.4-1 The Result of the Subtraction of (PF+TF) Load File and (PF Only) Load File, with only the PF coils plotted. Only the effect of the TF on the PF remains.

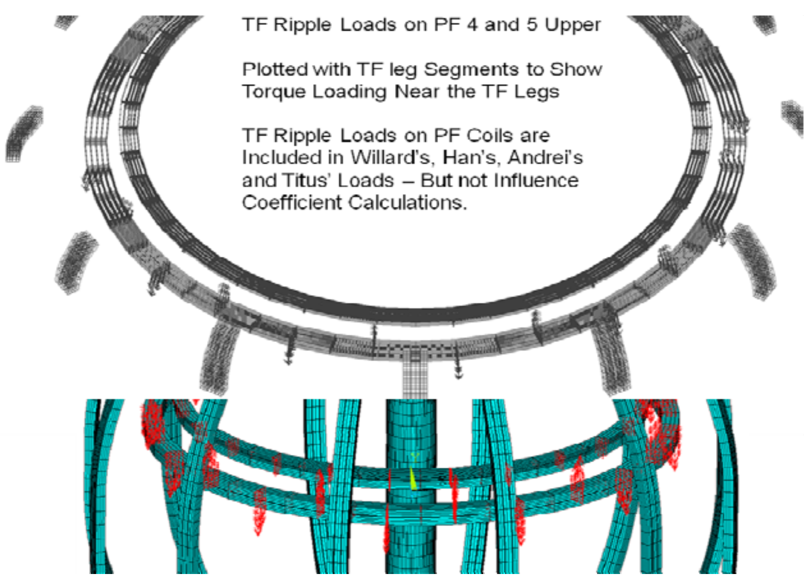
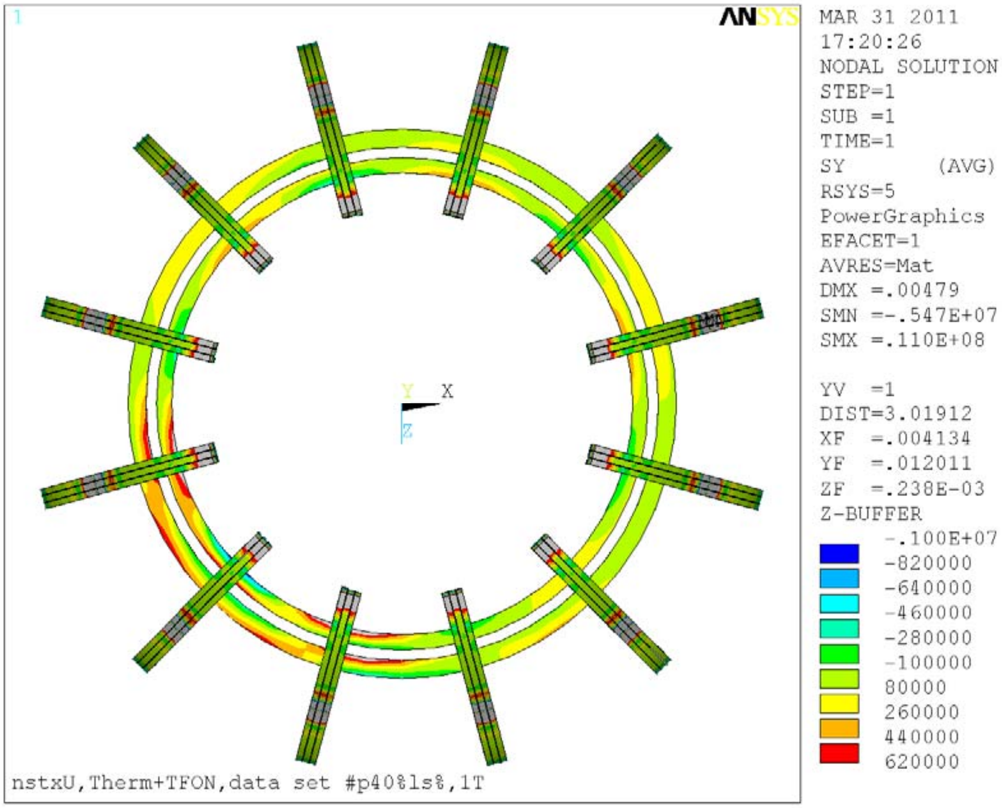


Figure 8.4-2 The Result of the Subtraction of (PF+TF) Load File and (PF Only) Load File, with only the PF coils plotted. Only the effect of the TF on the PF remains.



8.4-3 Hoop Directed Stress - Bending Stress Due to TF Ripple.

The bending stress in PF4 and 5 is less than 11 MPa at most locations. The asymmetry is due to local support bracket and port modeling.

9.0 Digital Coil Protection System Input

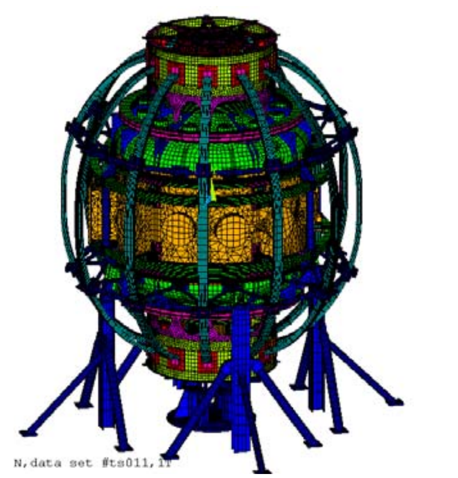


Figure 9.0-1 Linear Global Model Used in Calculating DCPS Stress Multipliers, Ref [2]

The approach used for the PF4 and 5 coils for calculating the stress multipliers/algorithms is to utilize a global model [2] that simulates the whole structure and includes an adequately refined modeling of the component in question. Unit terminal currents are applied to each coil separately, Lorentz loads are calculated, and the response of the whole tokamak and local component stress is computed. This approach is correct for stresses that are a consequence of an individual coil load which is, in turn, a result of the superposition of contributions from all other coil currents. Local component stresses may then be computed in the DCPS or in a spreadsheet for the many scenarios required by the GRD. This approach has been applied to the PF4 and 5 coil stress. Where a component stress is a consequence of multiple coil loads, the approach must derive coefficients from unit loads which, in turn, are computed from the influence coefficients. This analysis approach has been exercised for the existing PF 4 and 5 support welds and is discussed in section 9.3 (moved to the Appendix)

At this writing, thermal stresses are assumed to be a consequence of uniform heat-up of the coils. Stresses due to temperature gradients in the coils are not considered.

Two approaches are used to provide the needed multipliers/algorithms.

The first is to use the loads on PF coils computed by the DCPS software and apply these to local models of components. It is usual practice to utilize influence coefficient calculations to determine hoop and axial (vertical for tokamak's) loads from coil currents. However, the centroid of the Lorentz loads may not be at the geometric center of the coils, and a moment about a geometric center of the coil may be produced. The effect of this offset in force centroid, especially on local PF supports, is discussed.

The second approach to calculating the stress multipliers/algorithms is to utilize a global model that simulates the whole structure and includes an adequately refined modeling of the component in question. Unit terminal currents are applied to each coil separately, Lorentz loads are calculated, and the response of the whole tokamak and local component stress is computed. Local component stresses may then be computed in the DCPS or in a spreadsheet for the many scenarios required by the GRD.

9.1 PF5 Coil Stress DCPS Input

9.1.1 Influence Coefficients and Stress Multipliers

First, a candidate "worst case" location is selected. The stress state that will be checked must be an individual stress component. For PF5, the peak stress in the conductor is driven by a combination of hoop stress and bending stress, in the same direction, caused by the 12 discrete points at which the large ring coil is supported.

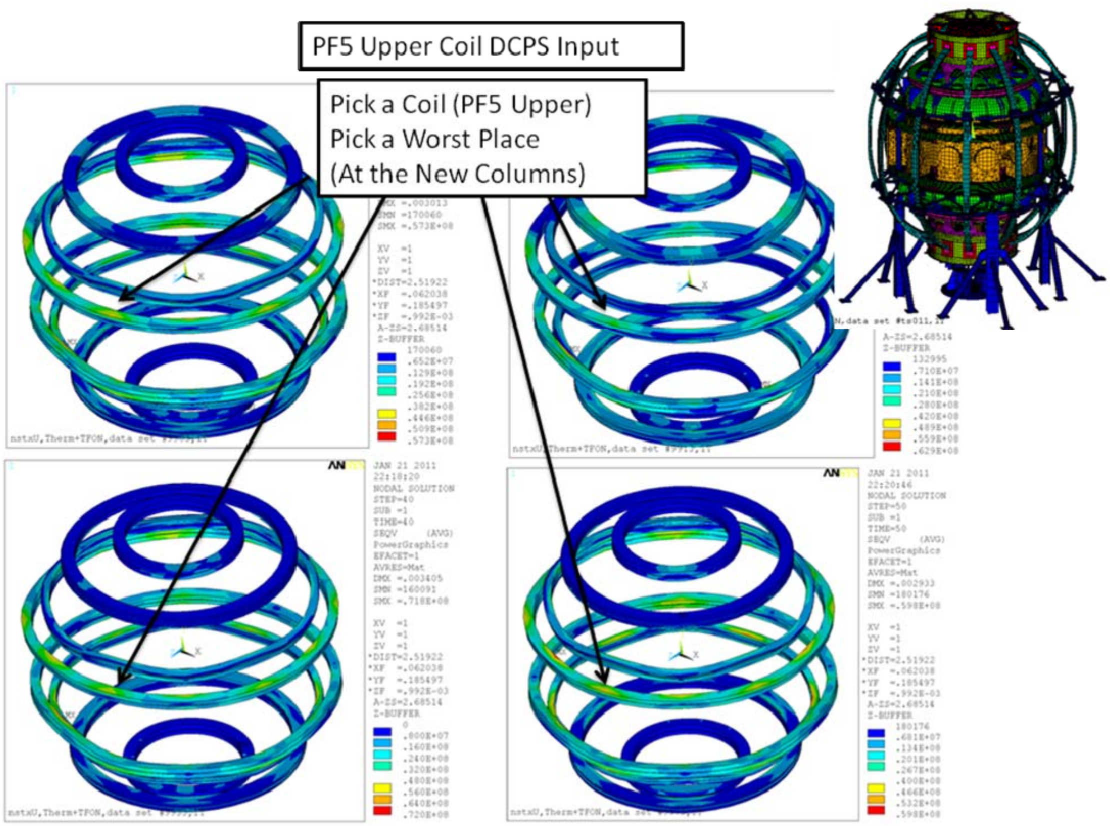


Figure 9.1.1-1 Finding a Worst Case Location to use for Calculating Coefficients

The next step is to calculate Lorentz forces. The PF 5 coil was chosen as a critical component. Lorentz Forces for each combination of PF 5 unit current and unit currents in each other coil. Stresses are determined at the critical location for each of these unit load files. In this case, the critical stress location has been chosen as the conductor on the top surface of the winding over the new column supports. The stress values form the stress influence coefficients for each PF current. These can be used in a spreadsheet to calculate the stress value for the critical location for each set of equilibrium currents or any set of coil currents.

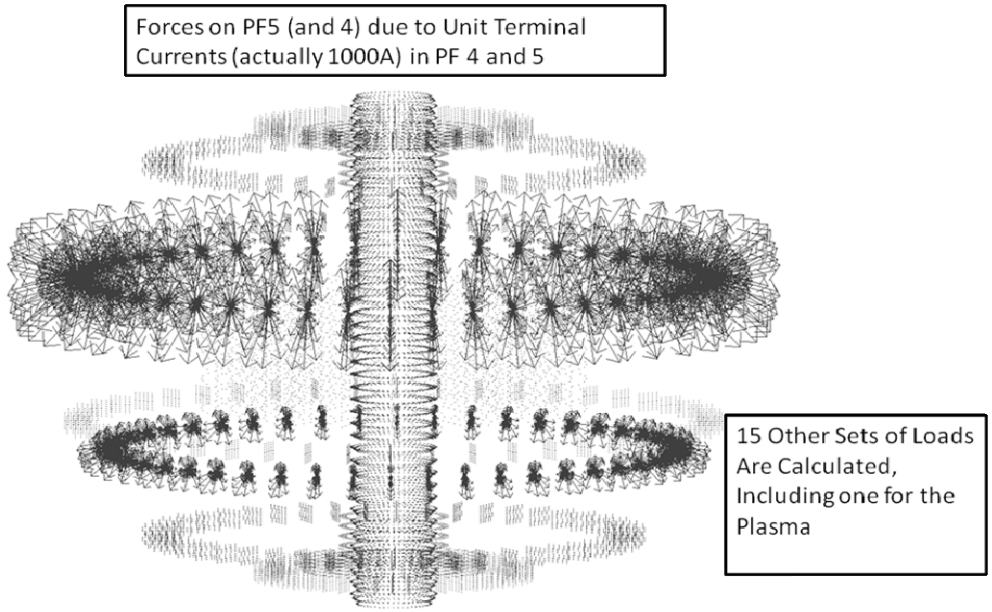


Figure 9.1.1-2 Unit Current Biot Savart Load Calculation

PF5 Stress Influence Coefficients

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
2.26E+10	2.35E+10	2.36E+10	2.51E+10	2.41E+10	2.34E+10	3.00E+10	-2.41E+10	2.40E+10	2.50E+10	2.60E+10	2.40E+10	2.58E+10	3.57E+10	4.21E+10	-1.92E+10

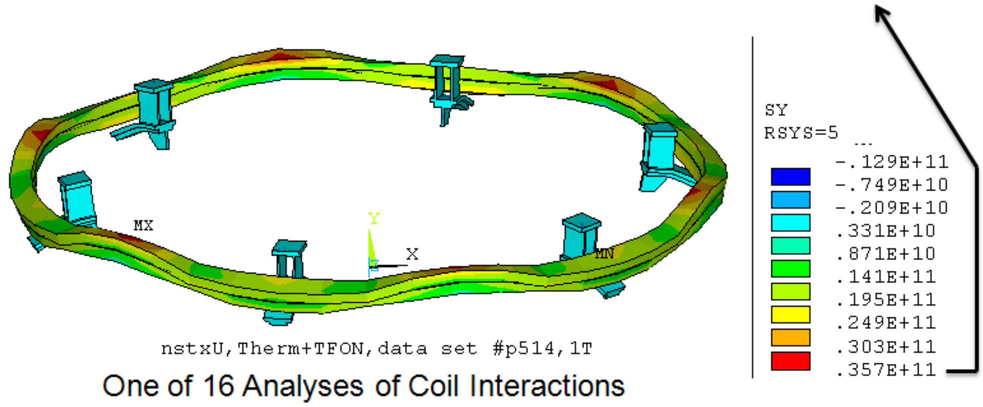


Figure 9.1.1-3 ANSYS Results for One of 16 Sets of Loads/Coefficients

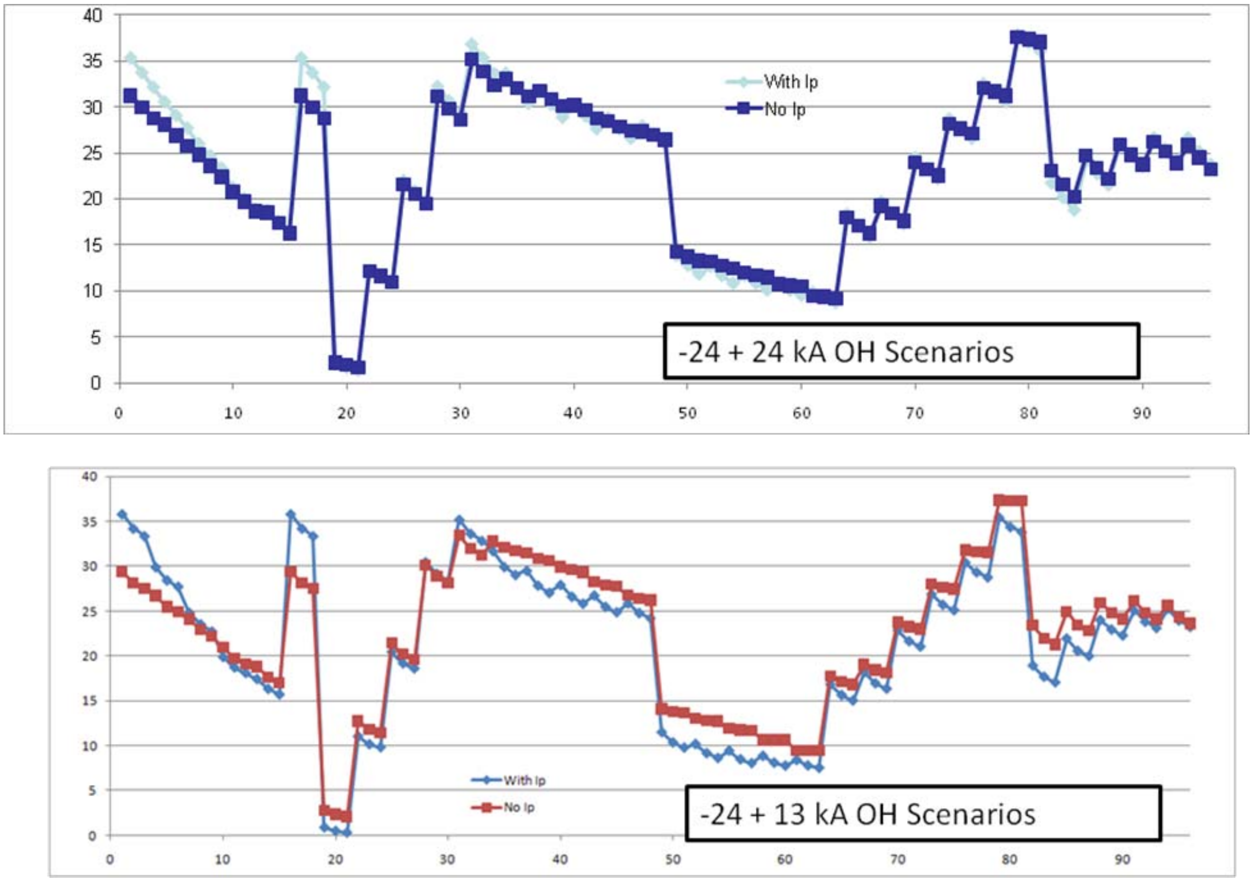
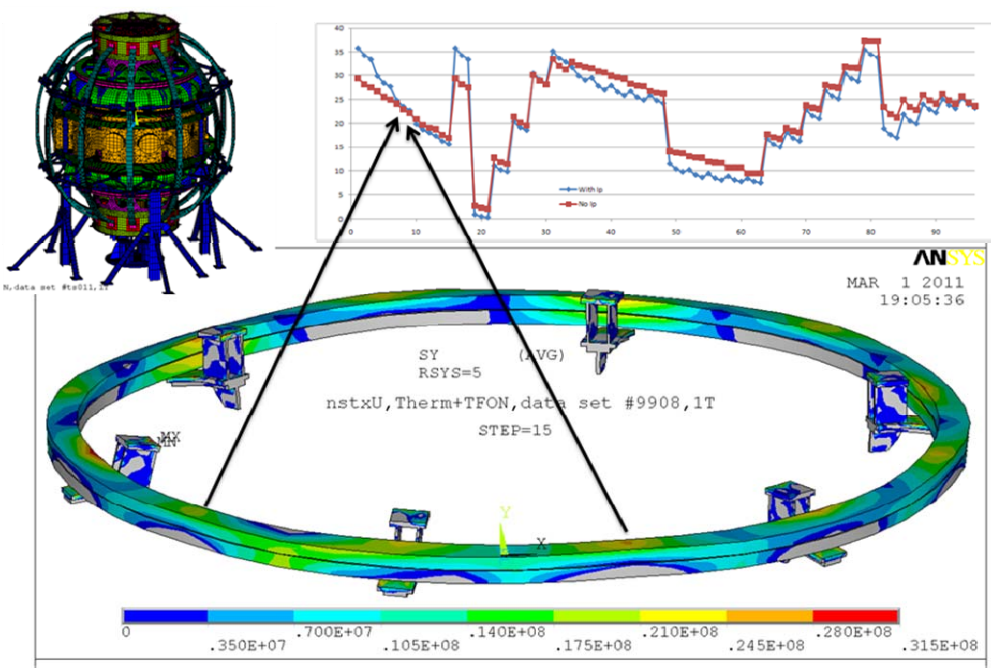
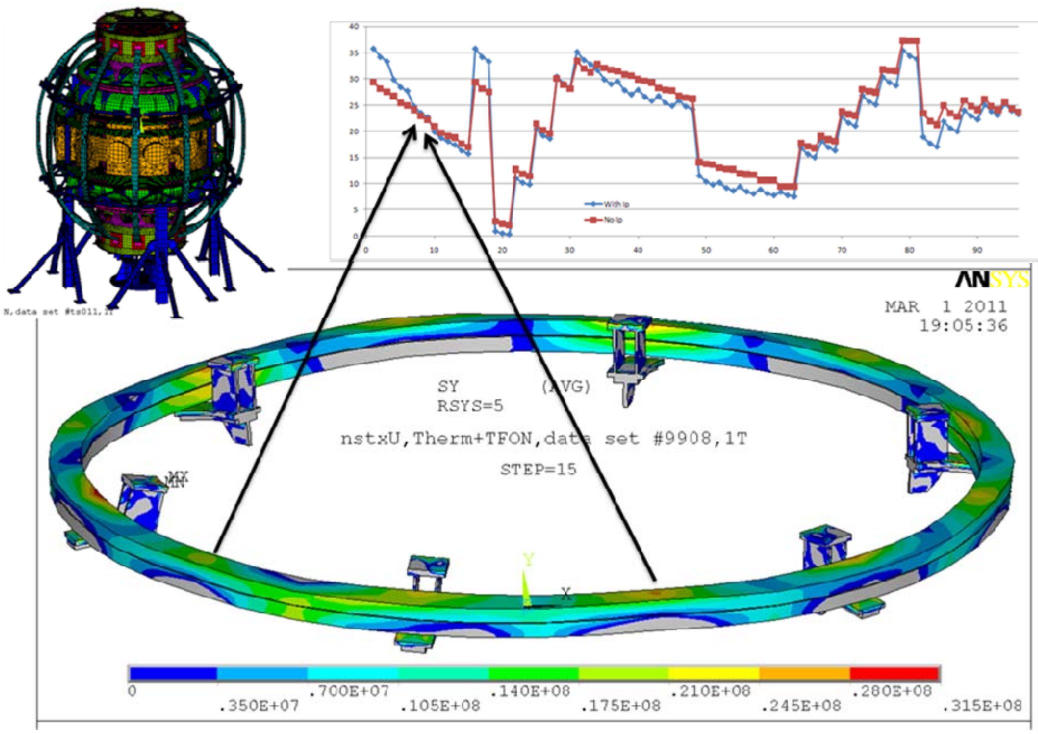


Figure 9.1.1-4 Application of Stress Coefficients to the Old Scenario



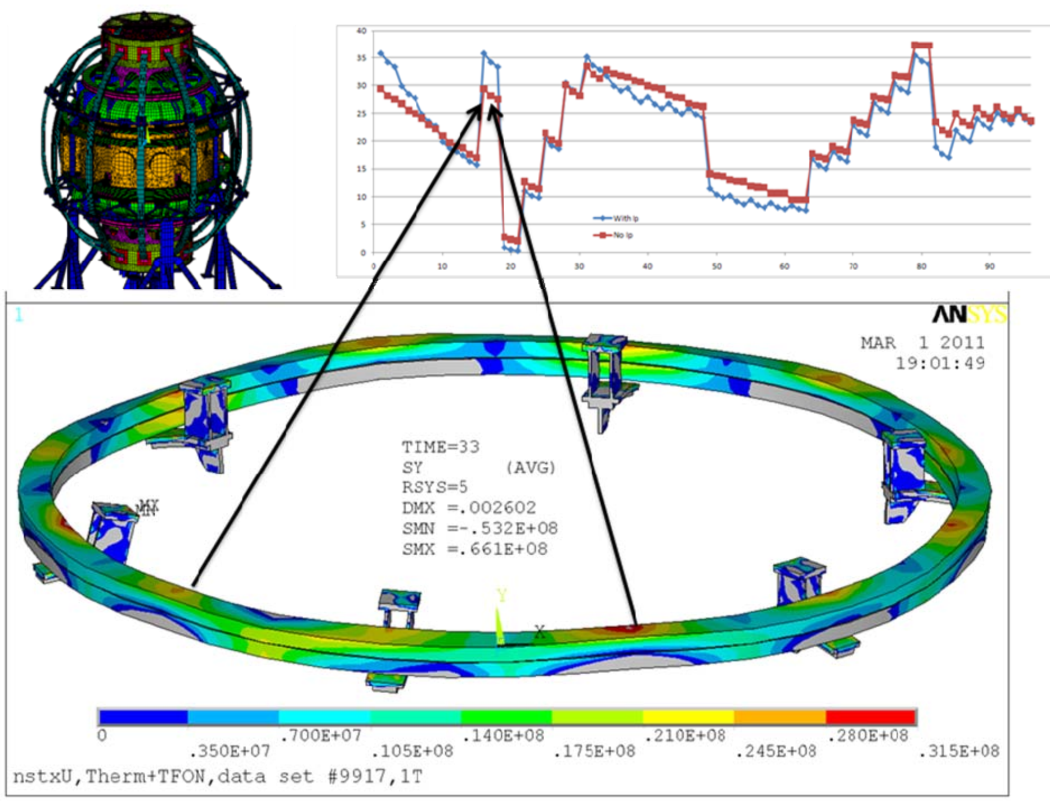
Check Influence Coefficients Against Global Model

Figure 9.1.1-5 Comparison with Global Model Results



Check Influence Coefficients Against Global Model

Figure 9.1.1-6 Another Comparison with Global Model Results



Check Influence Coefficients Against Global Model

Figure 9.1.1-7 Another Comparison with Global Model Results

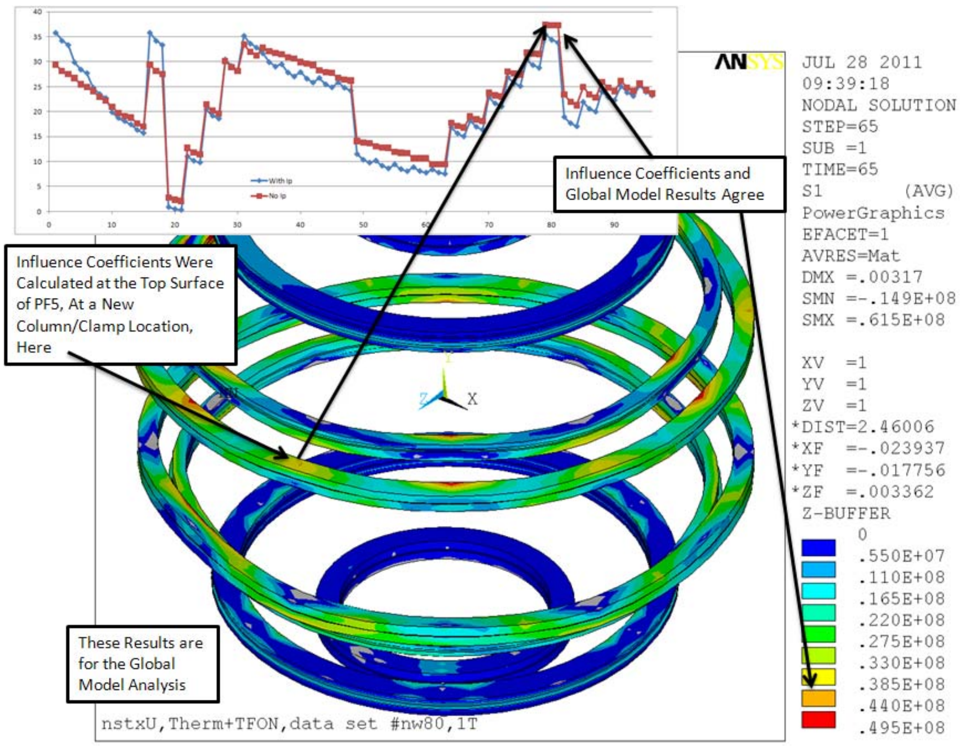


Figure 9.1.1-8 Comparison with Global Model EQ #80 Results

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
0	0	0	0	0	0	16	32	0	0	0	0	0	16	32	0
0	-6.07	9.4451	13.3051	2.9049	-8.822	3.482	-24.5839	-6.07	9.4451	13.3051	2.9049	-8.822	3.482	-24.5839	2
13.0237626	-5.8489759	10.1476777	14.3719632	5.46775943	-7.876963	3.44423109	-24.13404	-5.8489759	10.1476777	14.3719632	5.46775943	-7.876963	3.44423109	-24.13404	2
-24	-1.4573	6.2247	6.7393	-2.2799	-10.2215	2.1806	-24.6842	-1.4573	6.2247	6.7393	-2.2799	-10.2215	2.1806	-24.6842	2
0	-1.2113	7.8008	9.0773	2.1979	-8.4659	2.071	-23.82	-1.2113	7.8008	9.0773	2.1979	-8.4659	2.071	-23.82	2
13.0237626	-1.0236493	8.5927533	10.2738039	4.66796512	-7.478427	2.0253083	-23.38663	-1.0236493	8.5927533	10.2738039	4.66796512	-7.478427	2.0253083	-23.38663	2

Full Current in PF4 and 5, 16 and 32 kA, Produces 21 Mpa Smeared Stress from the influence coefficients

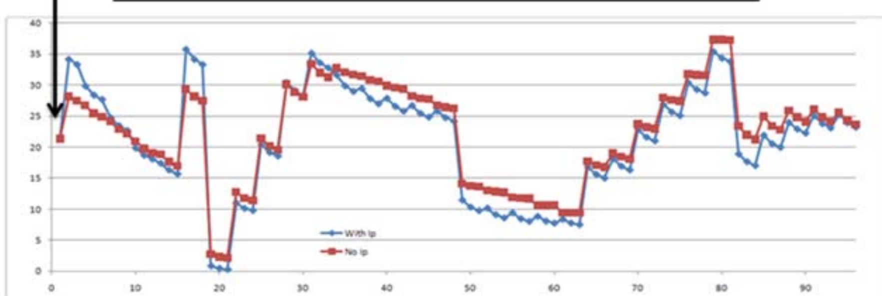


Figure 9.1.1-9 Using a Scenario/Current Set Consistent with the Local Model, Calculate a Smeared Stress for the Full Current in PF4 and 5 Model/Analysis

For computation of the stress multiplier, a consistent smeared stress must be calculated from the influence coefficients for the detailed model that had full currents in PF4 and 5 - but no other PF currents. To make the comparison with the smeared results, an "equilibrium" current set was added in the spreadsheet, that had only full currents in PF4 and 5 and the spreadsheet calculated the smeared stress that the influence coefficients would produce for this current set. This is 21 MPa.

Smeared to Local Stress Multipliers

So far, the stress computed from the influence coefficients is the "smeared" stress from the global model. The coils are more complicated than represented in the global model. There are coolant holes and a portion of the cross section is insulation and not copper. These will increase local copper stress over what is reported in the global model. Local models have better modeling of the interactions between the support pads and the coils, and include non-linearities - frictional interfaces that may increase or decrease the stress with respect to the global model results. Two detailed local models are available. The first is the upper symmetry quadrant of the PF4/5 and vessel. This is loaded with the peak currents allowed in the two coils. A second model which is a full modeling of the PF4/5 coils is loaded with the EQ#80 currents. This second model is presented in more detail in section 9.1.2. Rigorously, the stress multipliers should be consistent with the location chosen as the critical "spot".

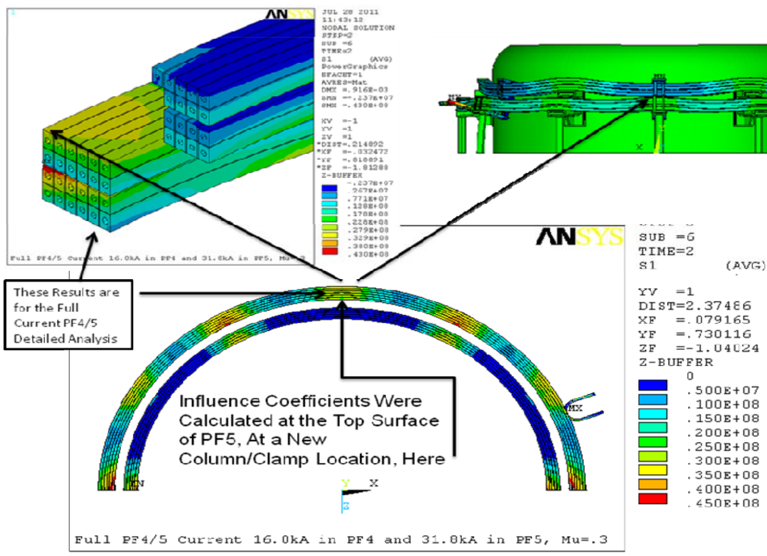


Figure 9.1.1-10 Stress Multiplier for the Full Current Loading and Model

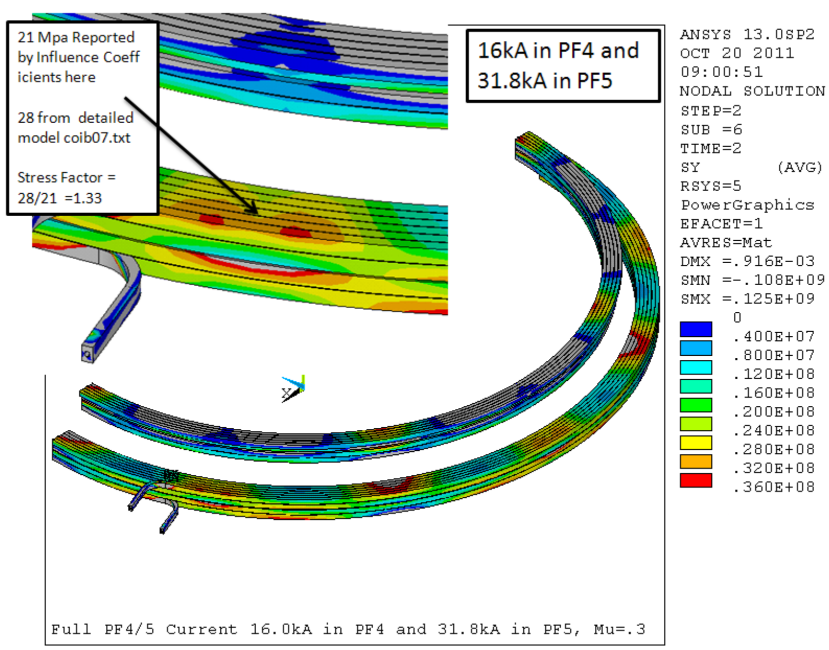


Figure 9.1.1-11 Stress Multiplier for the Full Current Loading and Model

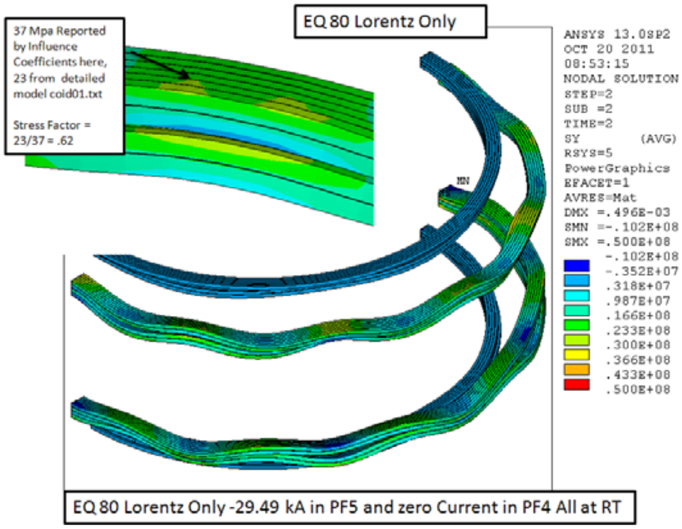


Figure 9.1.1-12 Stress Multiplier for the Full Model and EQ#80 Currents

There are two different stress multipliers for different loads but the same geometry. Unfortunately, the local models are non-linear. It was hoped that the behavior would be sufficiently linear to support the influence coefficient approach. Of the two examples chosen, the EQ#80 is more representative of the bulk of the design equilibria in which PF4 is not used near its capacity. This may change to even out thermal excursions of the coils. To obtain practical stress multipliers, some enveloping of both behaviors and positions is needed. The location above the fixed supports is also highly stressed, and in the local models the peak stress is not always on the top and bottom of the winding packs, but may be at the pancake interfaces at the mid-build of the coils.

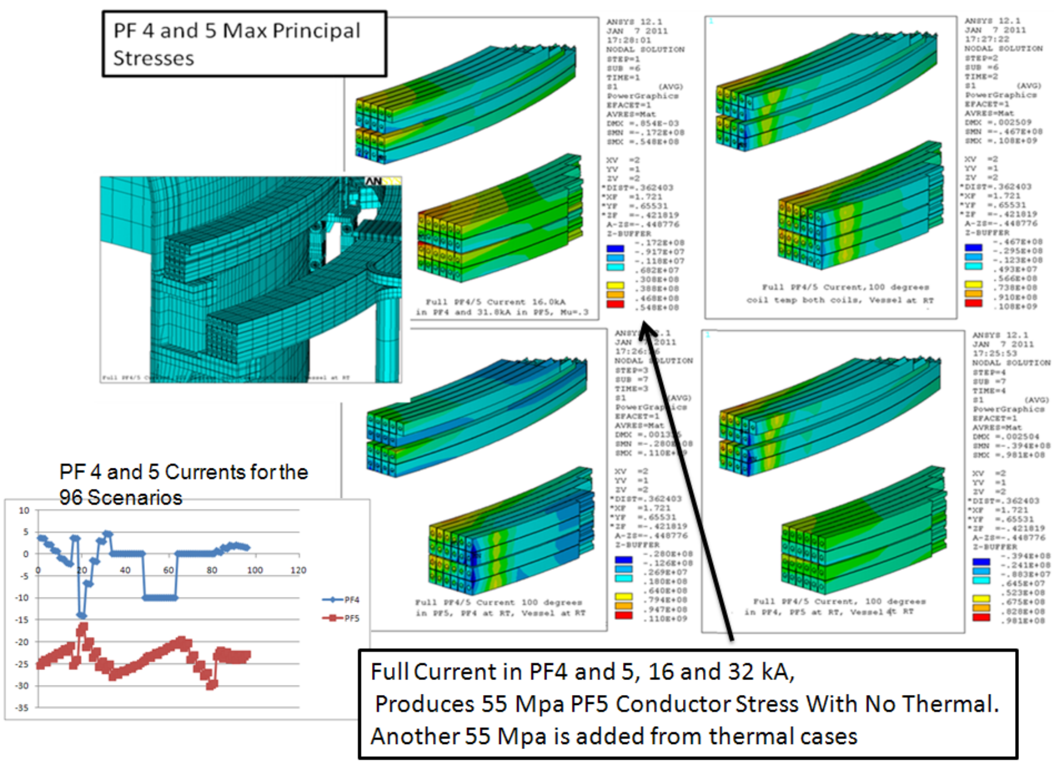


Figure 9.1.1-13 Peak Stresses at other locations within the coils

Table 9.1.1-1 Stress Multipliers with the Influence Coefficient Results as a Base

Analysis Location	Critical "Spot" Over New Column	Worst over New Column	Worst over the Fixed Support	Worst Stress With Thermal	Thermal Adder
Max PF4/5 Current Model and Loading	28/21 = 1.33	40/21 = 1.9	55/21 = 2.6	110MPa	55MPa
Section 9.1.2 Benchmark Eq#80 Model	23/37=.62	40/37 = 1.08	52/37 = 1.4	126 MPa	74MPa
	88.7	51.6	53.3	53.3	

The procedure for calculating the peak hoop directed tension stress is to use the stress multipliers multiplied by the influence coefficients multiplied by the coil currents, then add the appropriate thermal contribution. Since the peak current in PF4, for all 96 scenarios, at present is 4kA, choosing the multiplier for the EQ#80 results is probably sensible.

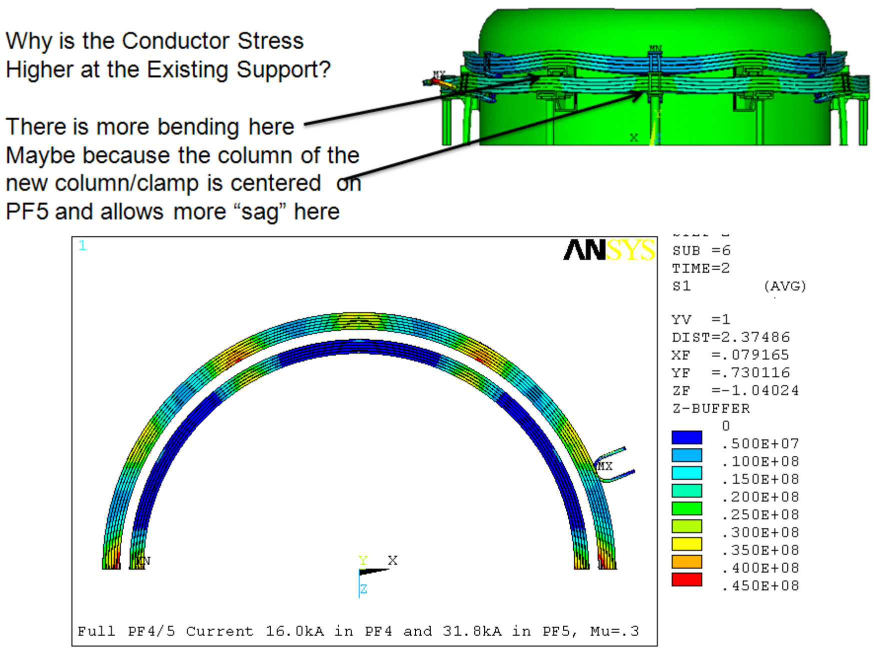


Figure 9.1.1-14 Effect of New Column Position

Also, it looks like the non-uniformity in the coils stresses at the two different supports is related to compliance in the new clamp/column because the column is centered on PF5 resulting in an offset when PF4 and 5 are on. This causes a sagging of the new support which transfers load to the existing clamp location.

9.1.2 EQ 80 Benchmark

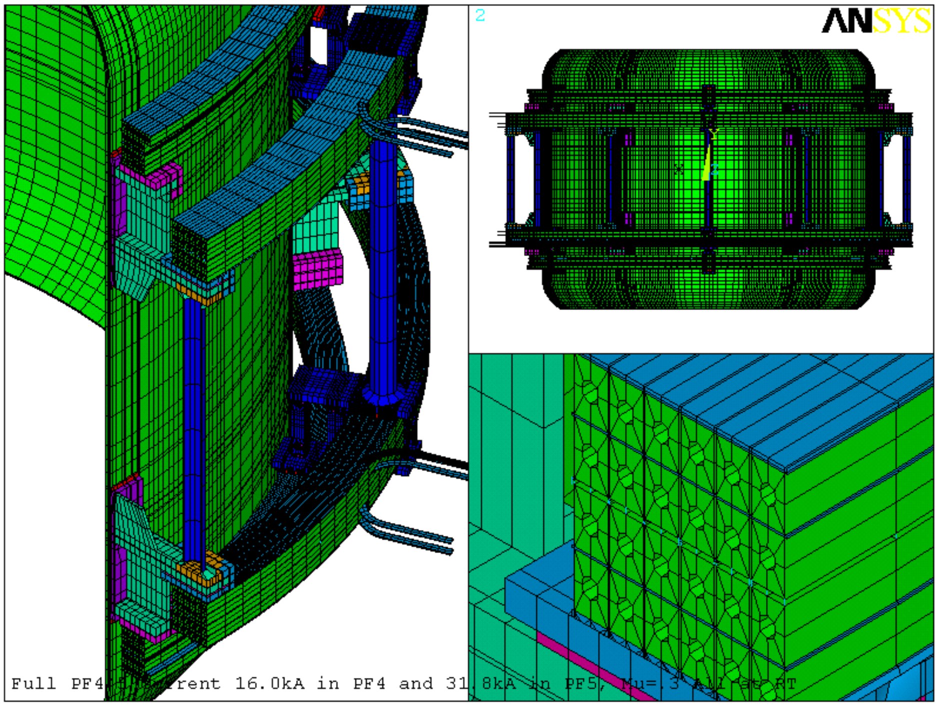


Figure 9.1.2-1 Model Without Equatorial Plane Symmetry Boundary Conditions

	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF3L	PF2L	PF1CL	PF1BL	PF1AL	OH
1	7.6648	0	0	1.7032	2.3009	0	-29.7351	2.3009	1.7032	0	0	7.6648	0

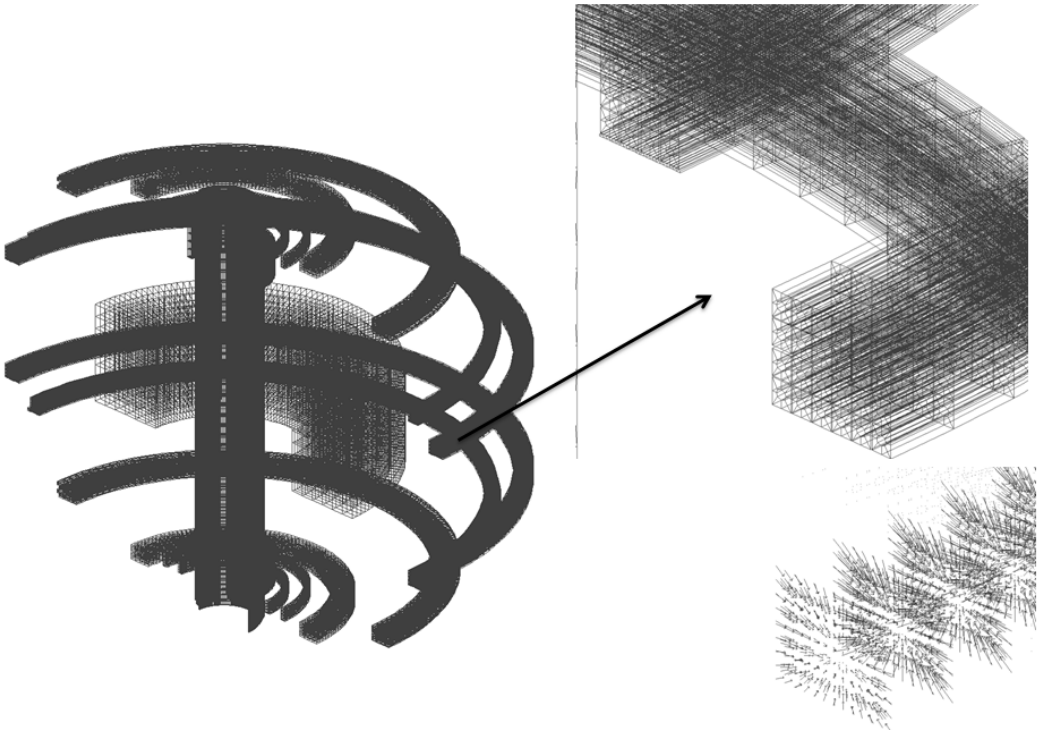


Figure 9.1.2-2 Biot Savart Model and Resulting Force Vectors

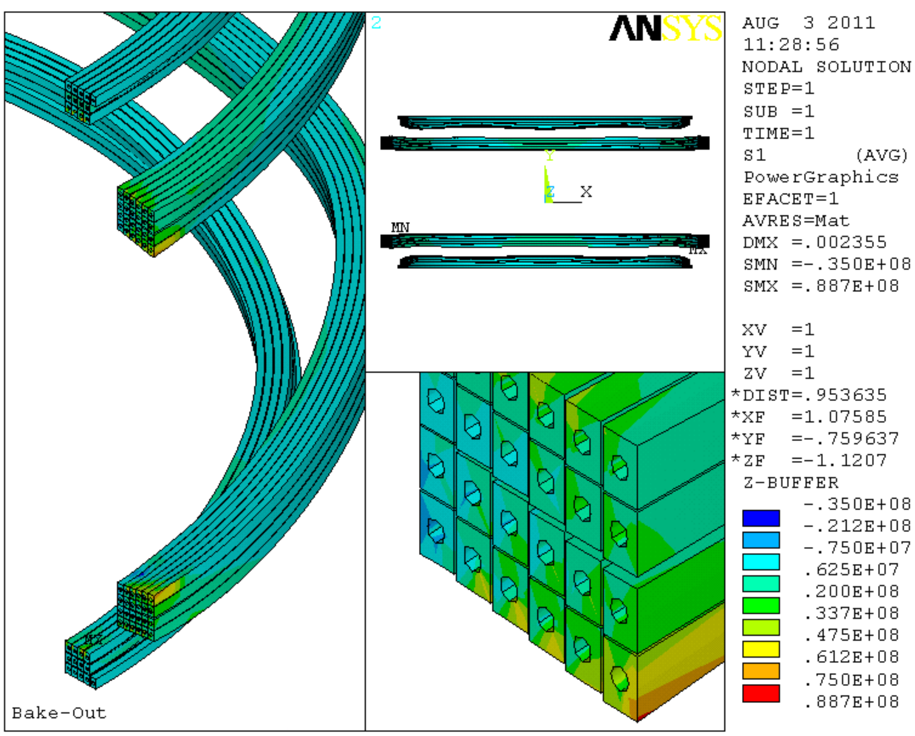


Figure 9.1.2-3 Bakeout Conductor Stress

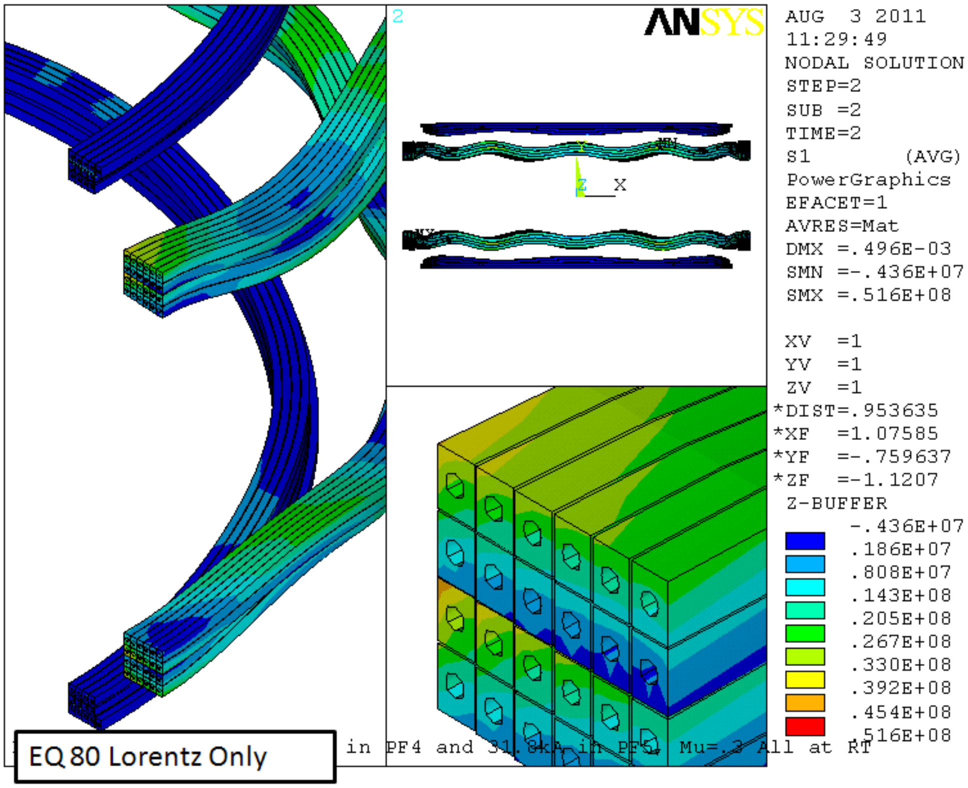


Figure 9.1.2-4 EQ80 Lorentz Only Stress

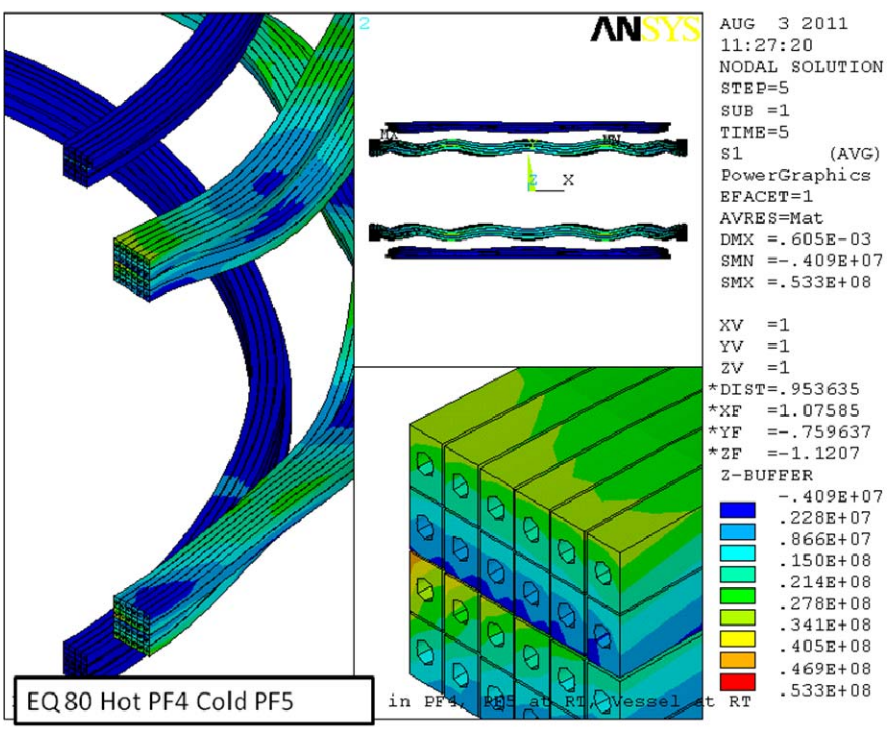


Figure 9.1.2-5 EQ80 Thermal Stress Hot PF4 Cold PF5

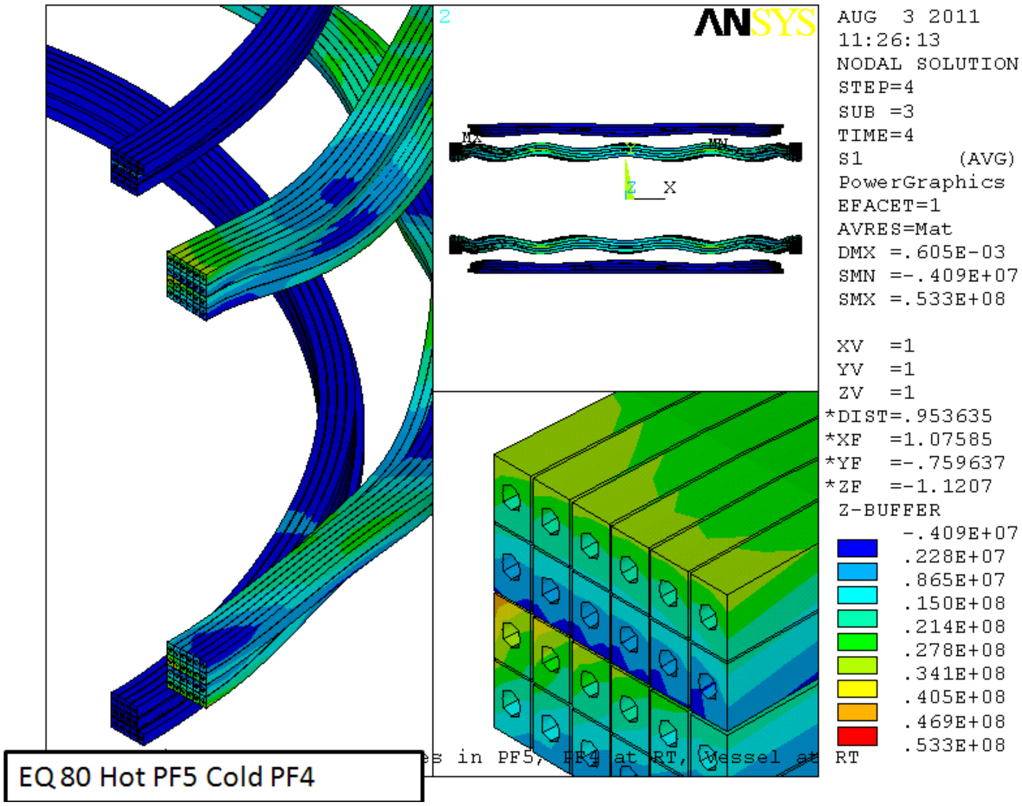


Figure 9.1.2-6 EQ 80+ Thermal Stress Hot PF5, Cold PF4

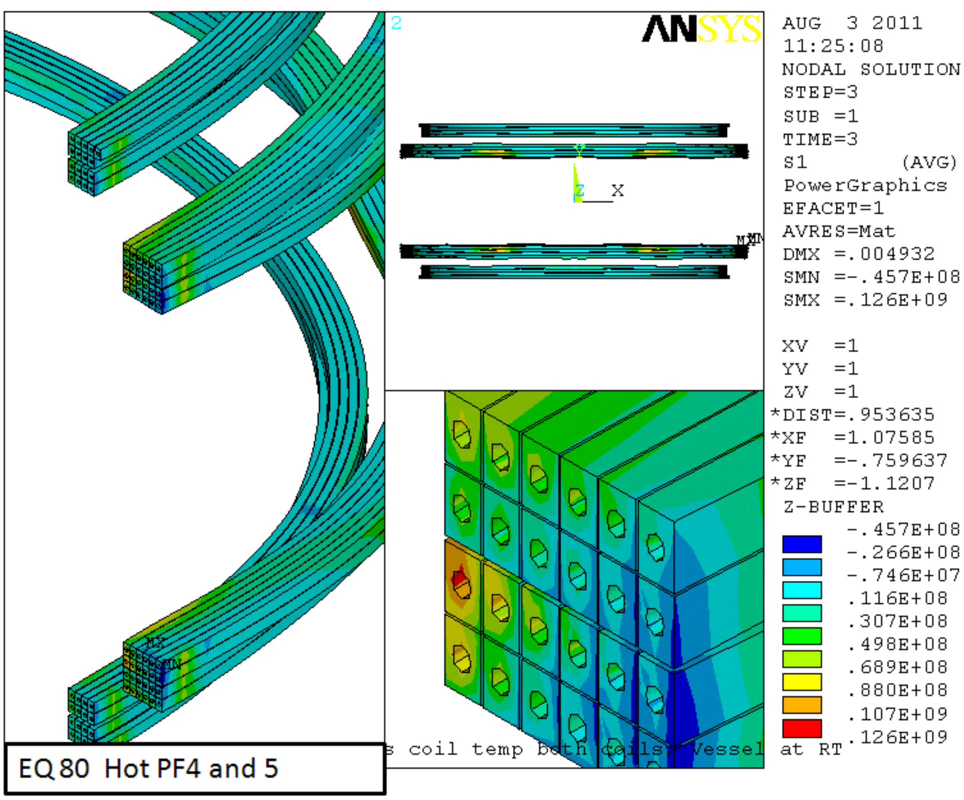


Figure 9.1.2-7 EQ 80+ Thermal Stress Hot PF4 and 5

9.2 PF4 Coil Stress DCPS Input

The procedure outlined above is applied to PF4 in this next section. The results of the ANSYS runs and multipliers are included in a spreadsheet that is available for implementation in the DCPS.

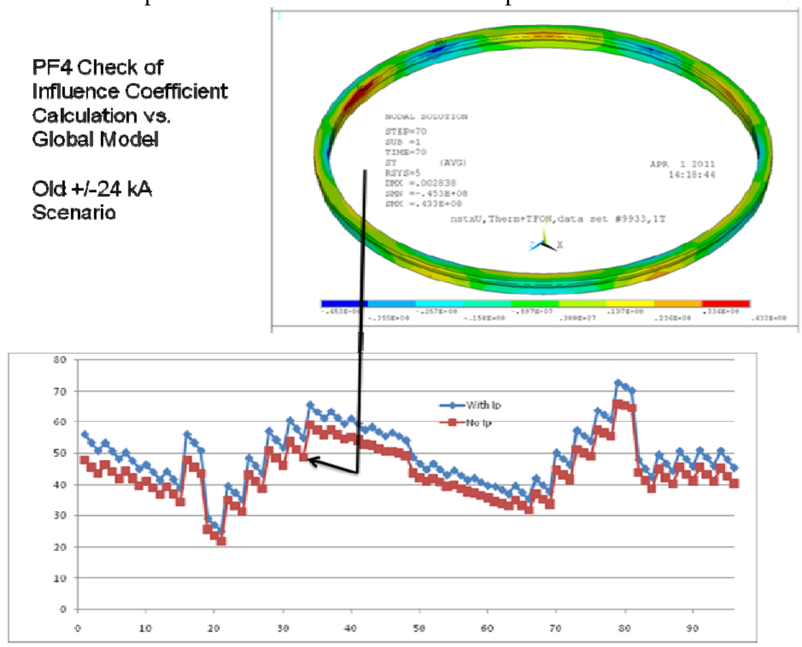


Figure 9.2-1 Comparison of Global "Smeared" Stress Results and the Results from the Influence Coefficients

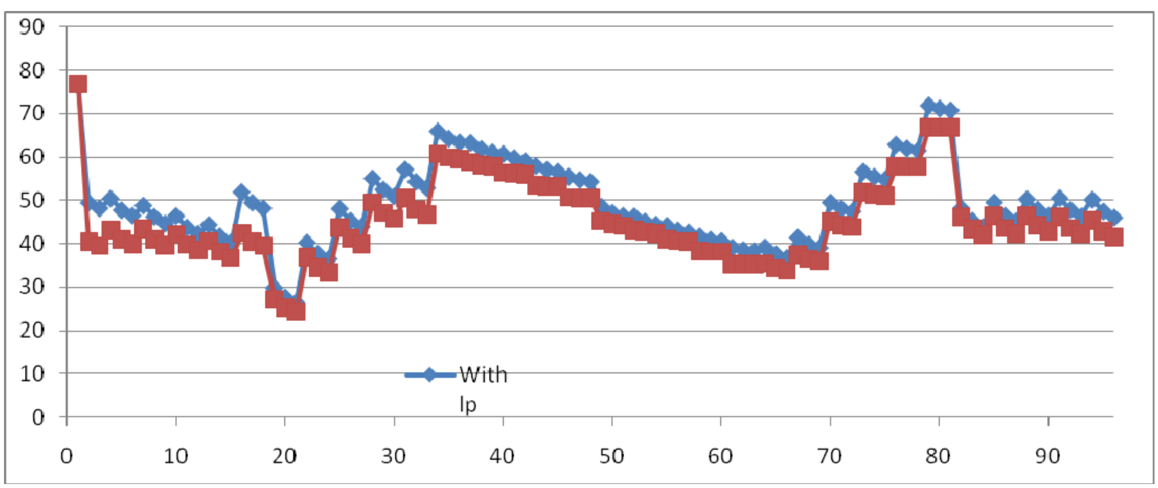


Figure 9.2-2 96 Equilibrium Results with the Full Current result replacing EQ 1

9.3 Existing Support Weld Stress Multipliers

This section derives from (Reference 9) an analysis of coefficients to relate PF4 and 5 loads to the weld stress of the bracket pad. This is pertinent to the upgrade because it was used for a protection system that was implemented in 2010 in NSTX. This same approach can be translated to the DCPS requirements. This section has been shifted to the appendices because it is not specific to the upgrade.

10.0 Leads

Analysis of the PF4 and 5 leads has been included in the analysis of the PF4/5 supports because the logic of the 180 degree "fixed" supports allows "rigid" supports of the leads if they are positioned near the fixed coil support points.

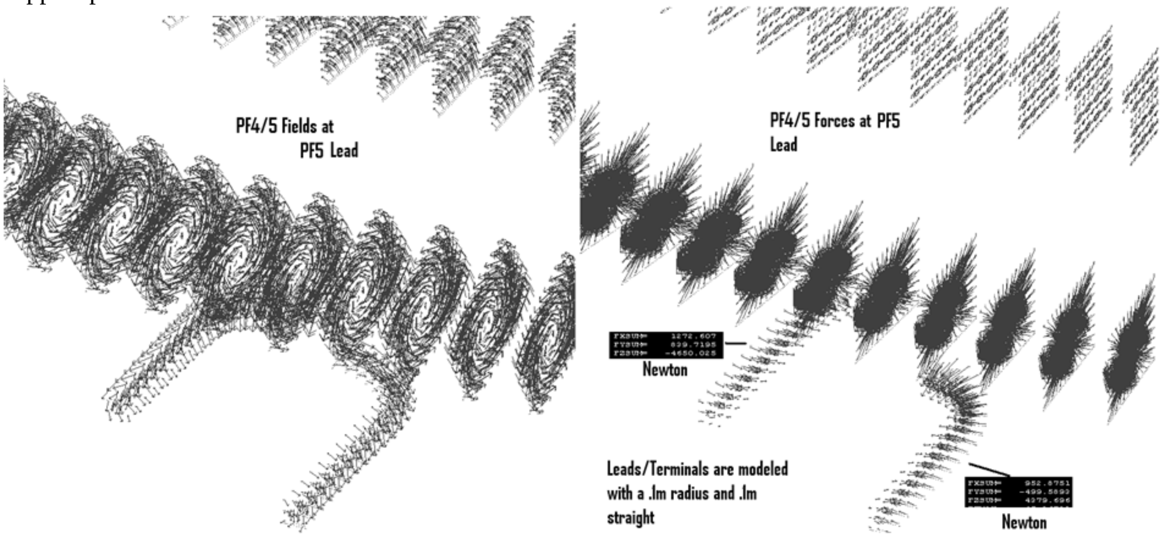


Figure 10.0-1 Fields and Forces Near the Leads

Cantilevered, un-supported leads produced excessive bending stresses due the Lorentz Loads caused by the local coil fields. The unsupported lead stresses are shown in Figure 10.0-2 (Below).

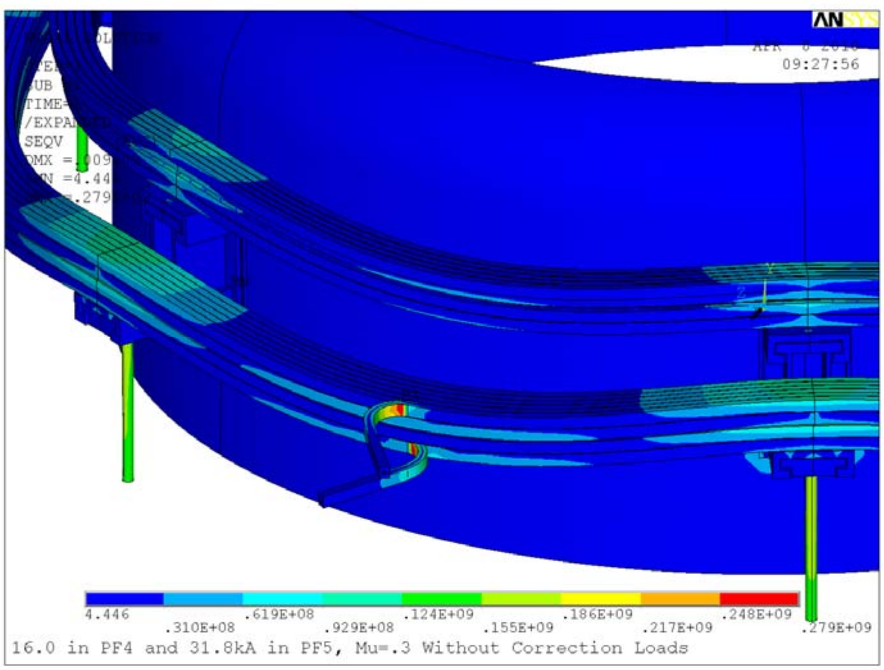


Figure 10.0-2 Local Lead Bending Stress

The bending stress would be relieved by taking credit for the connection to the bus bars on the unistrut at the support platform. This was modeled by displacement constraints. These would produce stresses if the coils move relative to the bus bar support. The PF4/5 support concept imposes fixity at two locations 180-

degrees apart. Choosing one fixed point near the lead break-out will limit the differential displacement stress in the leads.

11.0 Fatigue Analysis

Principal stresses for the PF4 and 5 coils are shown below for full currents in PF4 and 5 for various combinations of temperatures. In Section 9, the digital coil protection system stress multipliers were used to calculate the tensile stress in the hoop direction for all the available scenario currents with the 10% headroom applied with and without the plasma included.

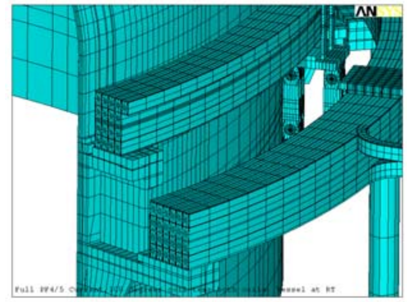


Figure 11.0-1 Link Model

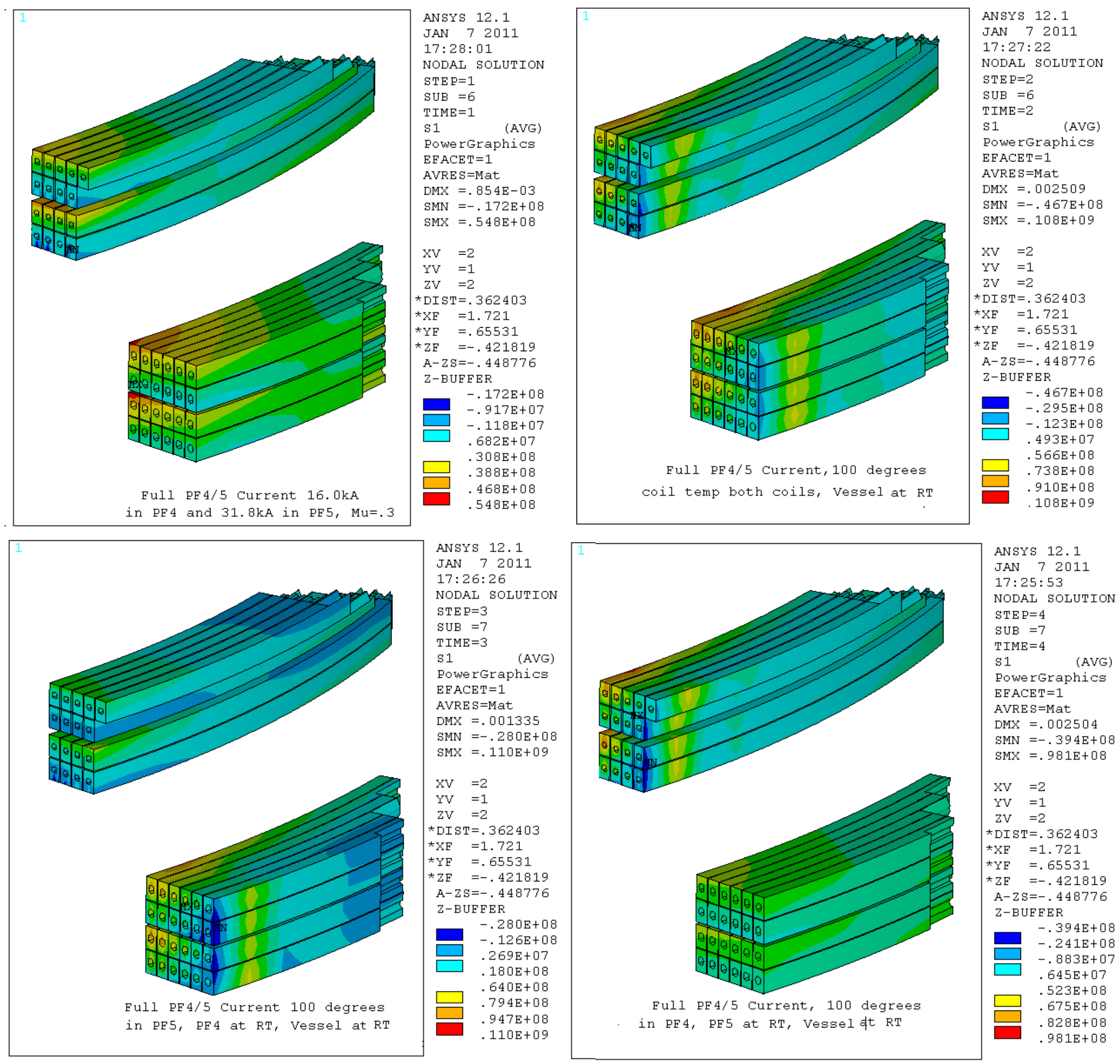


Figure 11.0-2 From Section 9, the peak Max Principal Stress in PF5 for all scenarios is=55*(37/21)+55 = 152 MPa.

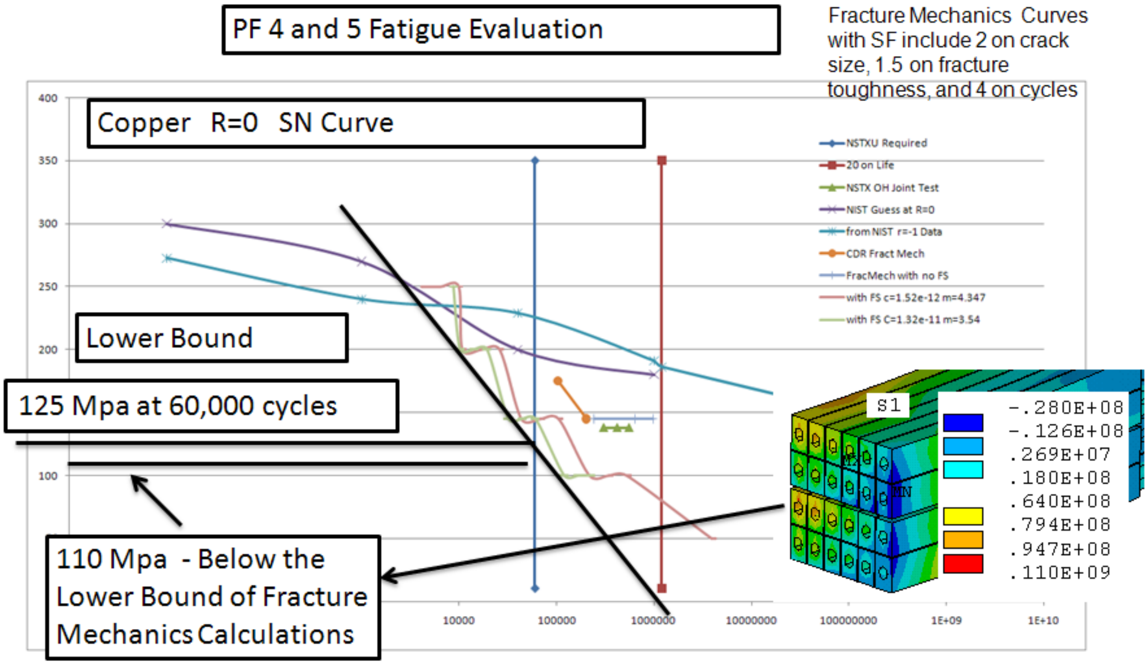


Figure 11.0-3 Fatigue Stress Evaluation for Full Currents in PF4 and 5 - No other PF currents

The PF5 Maximum Max Principal Stress for all scenarios, for all thermal conditions is 152 MPa (see Section 9). The allowable stress to meet the cyclic fatigue limit was developed for the OH coil fatigue calculation [7] and is 125 MPa.

It should be emphasized that this evaluation conservatively assumed that all 60,000 pulses utilize the scenario that produces the worst case stress, and that this stress occurred when the thermal stresses are at a peak.

12.0 Brackets, Hardware and Bracket-to-Vessel Welds

12.1 Existing Bracket to Vessel Welds

This is included in the upgrade calculations because this analysis was used in an early version of the DCPS which is currently in operation. The weld stress vs. load factors calculated here were applied during operation and the coil protection system disallowed a normal test shot. The problem is that the corners of the rectangular weld pattern have significant concentrations that would be plastically relieved, but the strain range would remain to affect the fatigue life. The corners were inspected, and no fatigue indications were noted. This region will be added to an inspection regimen during outages to ensure that fatigue sensitive welds are not developing cracks.

The weld is nominally 5/16-inch, but the QA report recommends that it be treated as an effective ¼ inch weld. To facilitate meshing the weld, an arbitrary cross section is used, then the weld stress is scaled by the ratio of the weld section in the model to the actual weld section. In this case, the weld was intended as a fillet, but material has been added to accommodate the vessel curvature, and the resulting weld was derated.

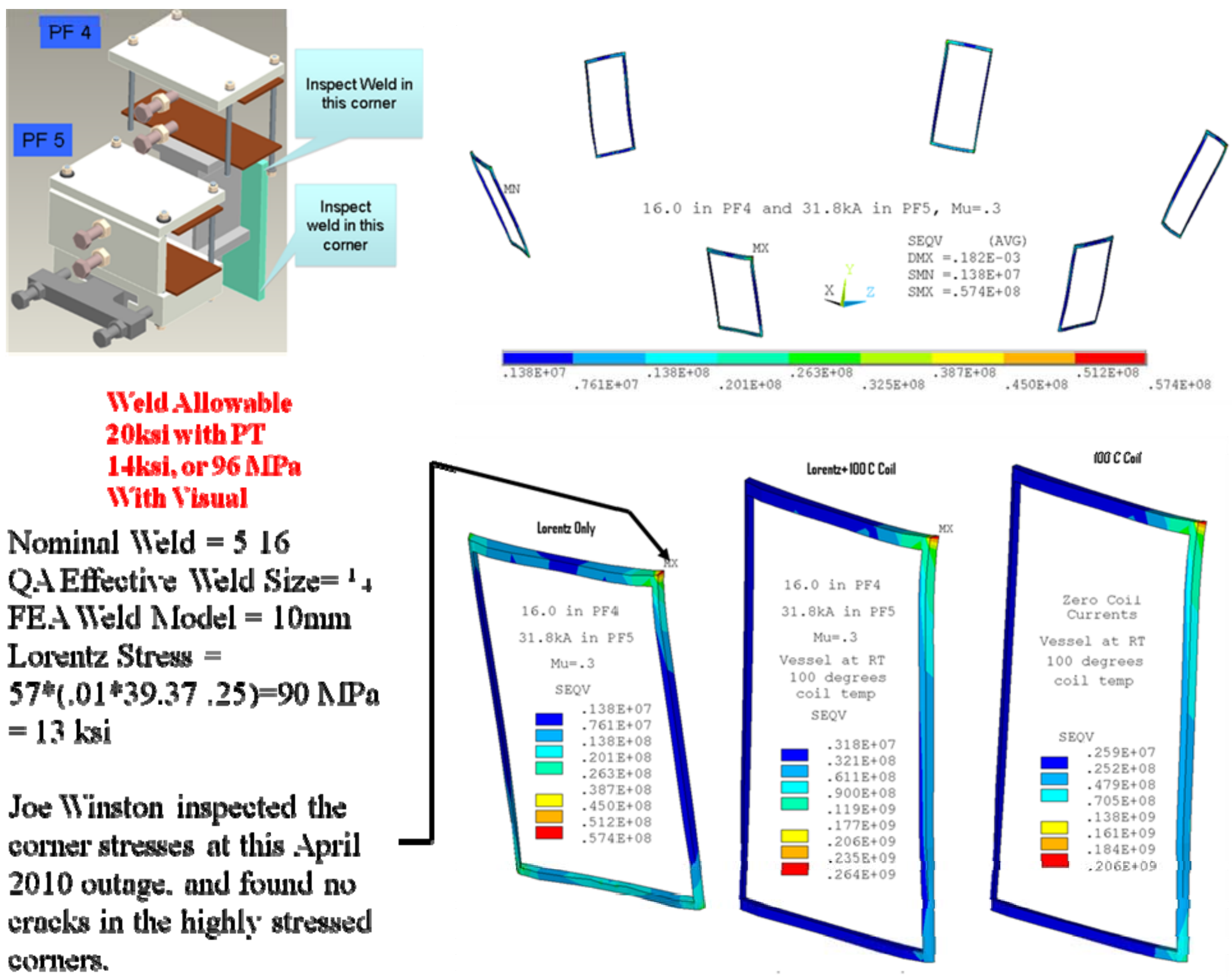


Figure 12.1-1 Weld Stresses in the Existing Bracket to Vessel Weld

The weld is assumed to have a larger cross section than a fillet, so the .707 factor was not applied. Weld allowable is a function of the level of inspection that is applied. At PPPL, only visual inspection is routine. ASME would require a weld efficiency of 0.7 or lower.

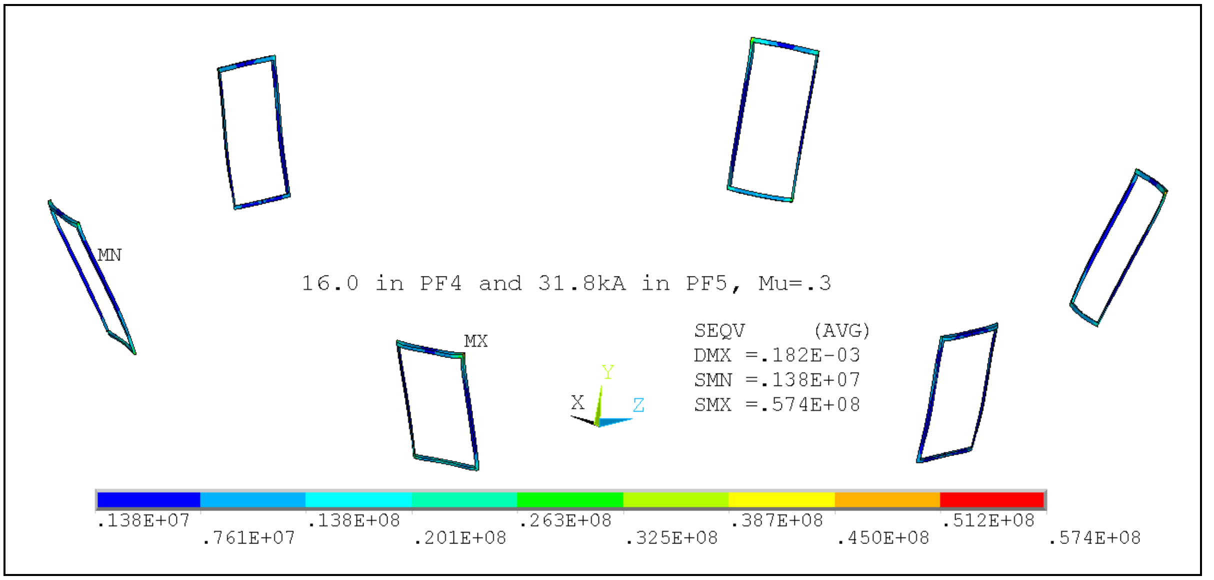


Figure 12.1-2 Weld Stresses in the Existing Bracket Weld to the Vessel - Lorentz Loads Only

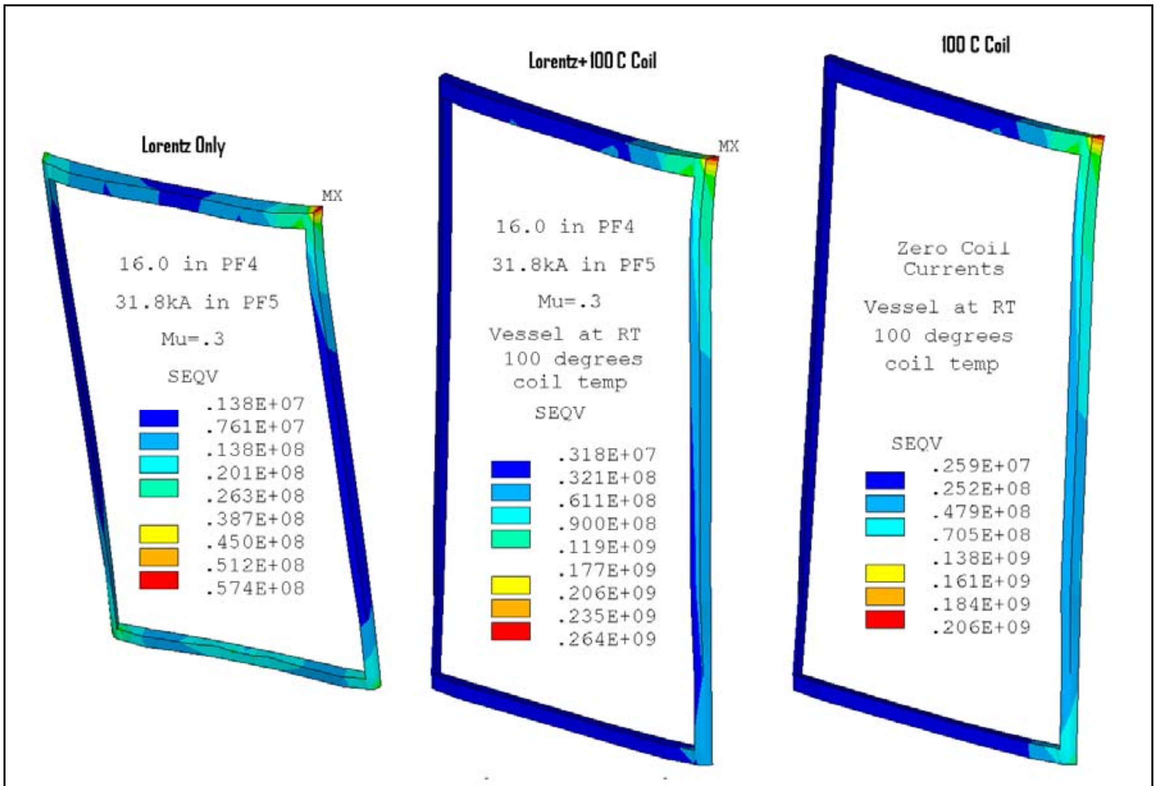


Figure 12.1-3 Weld Stresses in the Existing Bracket Weld to the Vessel

/title,PF4 and PF5 Upper Loads
!Remove OOP Loads
bf,all,temp,20
f,436,fz,-204000/12/.2248
f,1098,fz,-241000/12/.2248
Solve

PF4/5 Weldment
Nominal Weld = 5/16 in.
QA Effective Weld = 1/4
FEA Weld Model Thick =10mm
Weld Stress =90*(.01*39.37)/.25
=142 MPa = 30555 psi

Ron: Scale Weld Stress by ratio of your forces to those that I applied

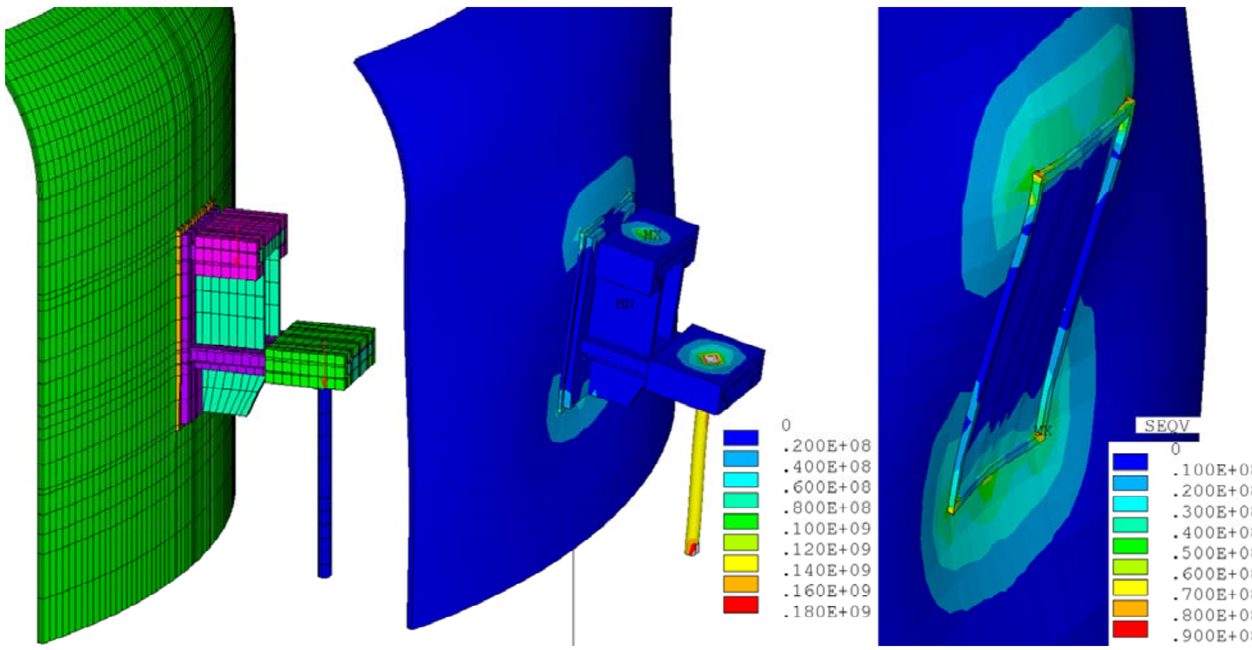


Figure 12.1-4 Weld Stresses in the Existing Bracket Weld to the Vessel
In-Plane PF4 and 5U Loads With Strut

12.2 Bracket Welds for Upgrade Loads

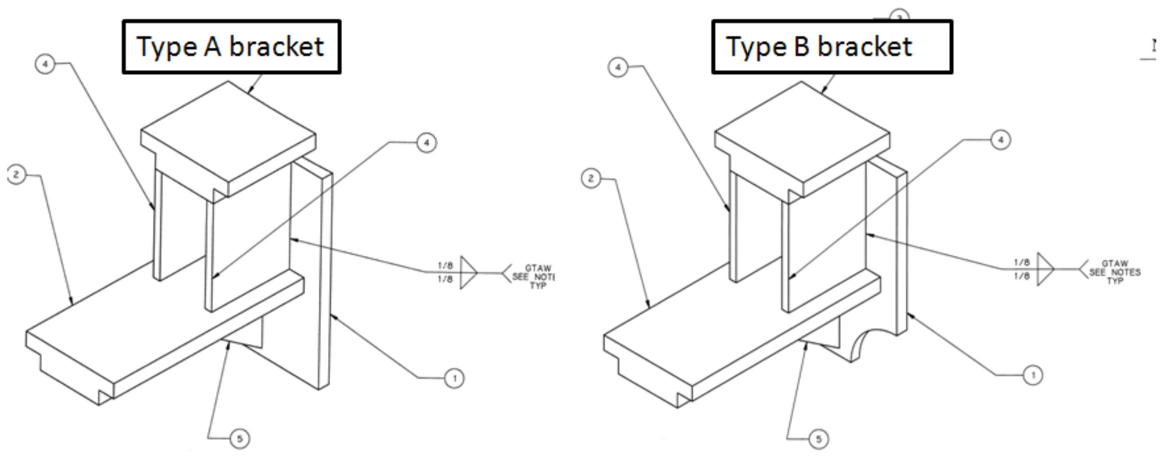


Figure 12.2-1 Bracket Types and Weld Specifications

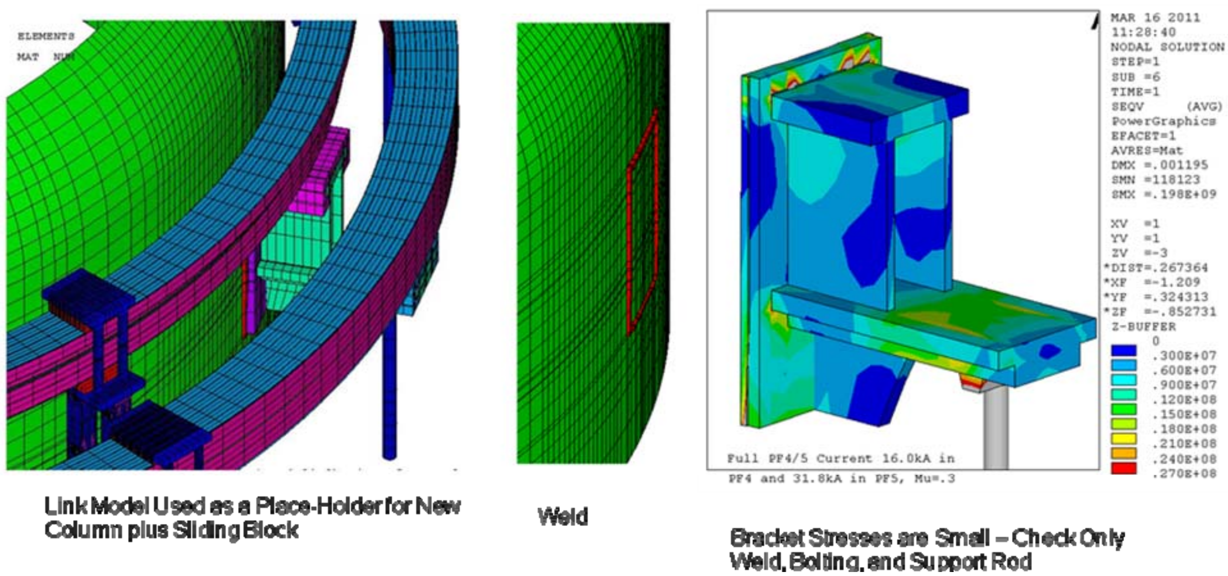


Figure 12.2-2 Analysis Model Weld Details

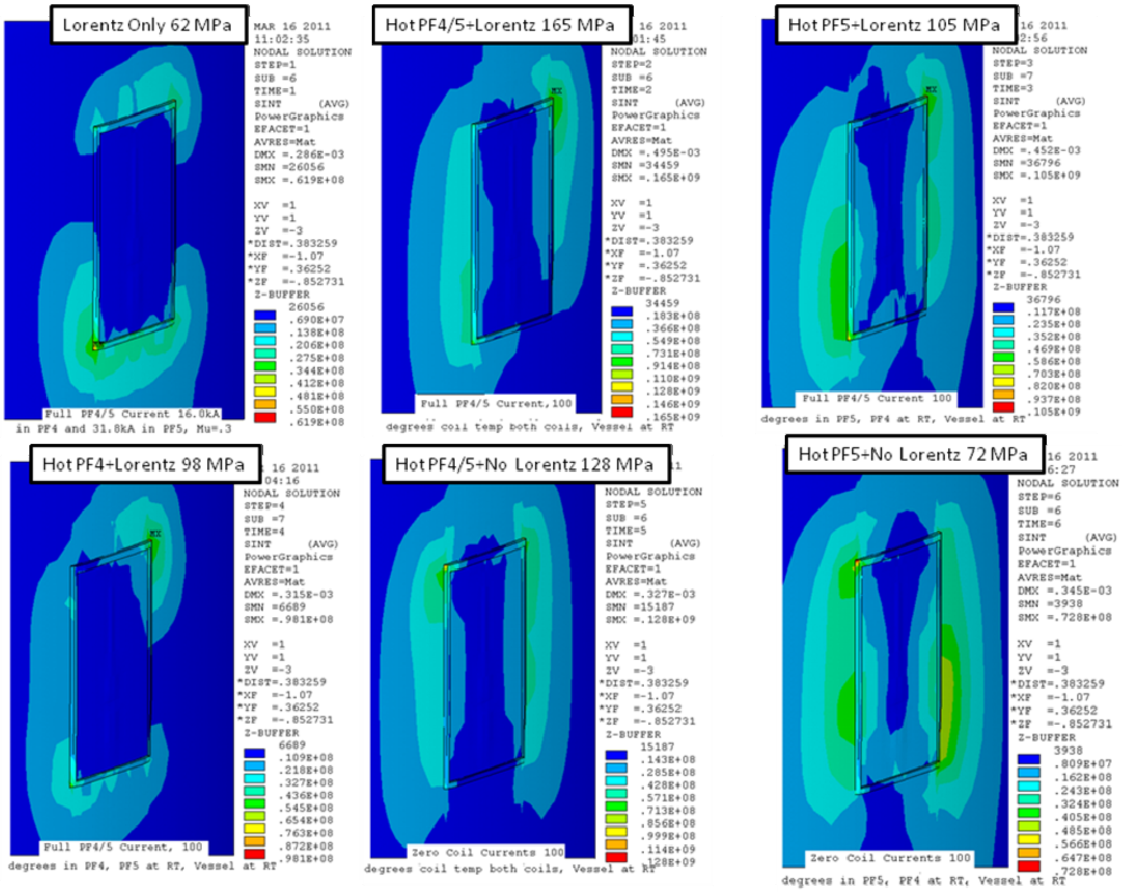


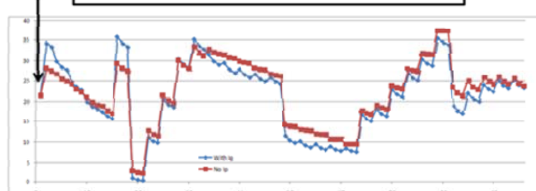
Figure 12.2-3 Weld Stresses from the Local Model of the Bracket

Weld Stresses Scaled From Coil Hoop Direction Stress Influence Coefficient

FEA Weld Multiplier

PF4/5 Weldment Nominal Weld = 5/16 In
QA Effective Weld =1/4
FEA Weld Model Thickness =10 mm
Weld Stress =
Sigma * (.01*39.37/.25/.707) =
Sigma * 2.22

Full Current in PF4 and 5, 16 and 32 kA, Produces 21 Mpa Smeared Stress from the influence coefficients



Multiply Influence Coefficient Results by 37/21 to get conductor stress

	FEA Lorentz Stress	Scenario Multiplier	Weld vs FEA Multiplier	Weld Stress Mpa	Weld Stress psi
Lorentz Only at Corner Peak	62	1.761904762	2.2	240.3238095	34854.79471
Lorentz Only Away from Corner	27.5	1.761904762	2.2	106.5952381	15459.78798
Lorentz +Hot Coils at Corner Peak	165	1.761904762	2.2	466.9238095	67719.1892
Lorentz +Hot Coils Away from Corner	54	1.761904762	2.2	164.8952381	23915.19044

Weld Allowable based on Visual weld inspection	Weld Allowable based on Visual Plus Penetrant weld inspection
14ksi	20ksi

Figure 12.2-4 Weld Stresses Scaled from the Local Model and Influence Coefficients

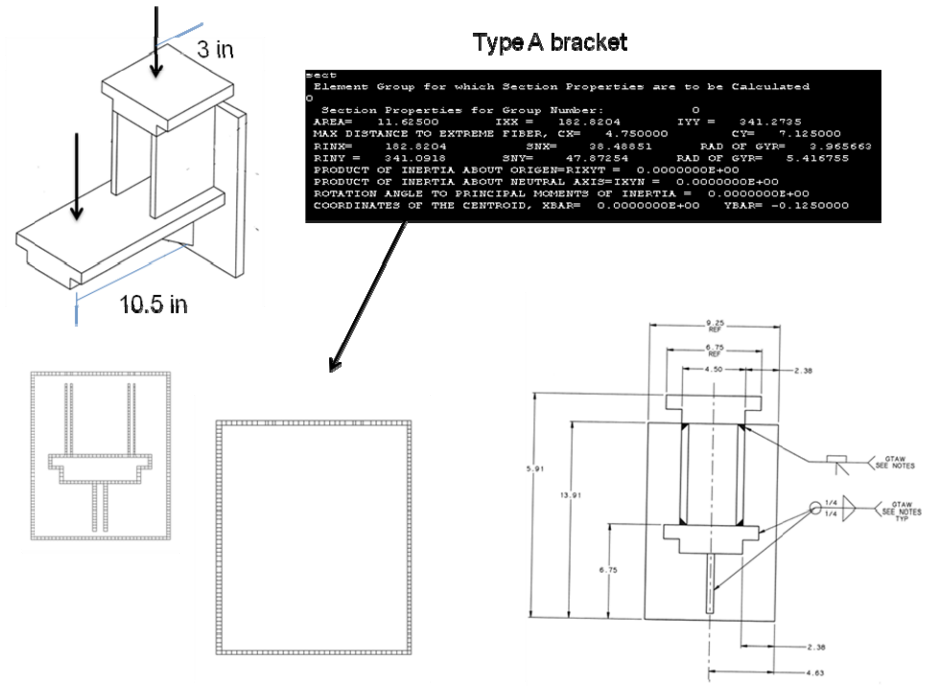


Figure 12.2-5 Weld Section Properties for the Type A Bracket

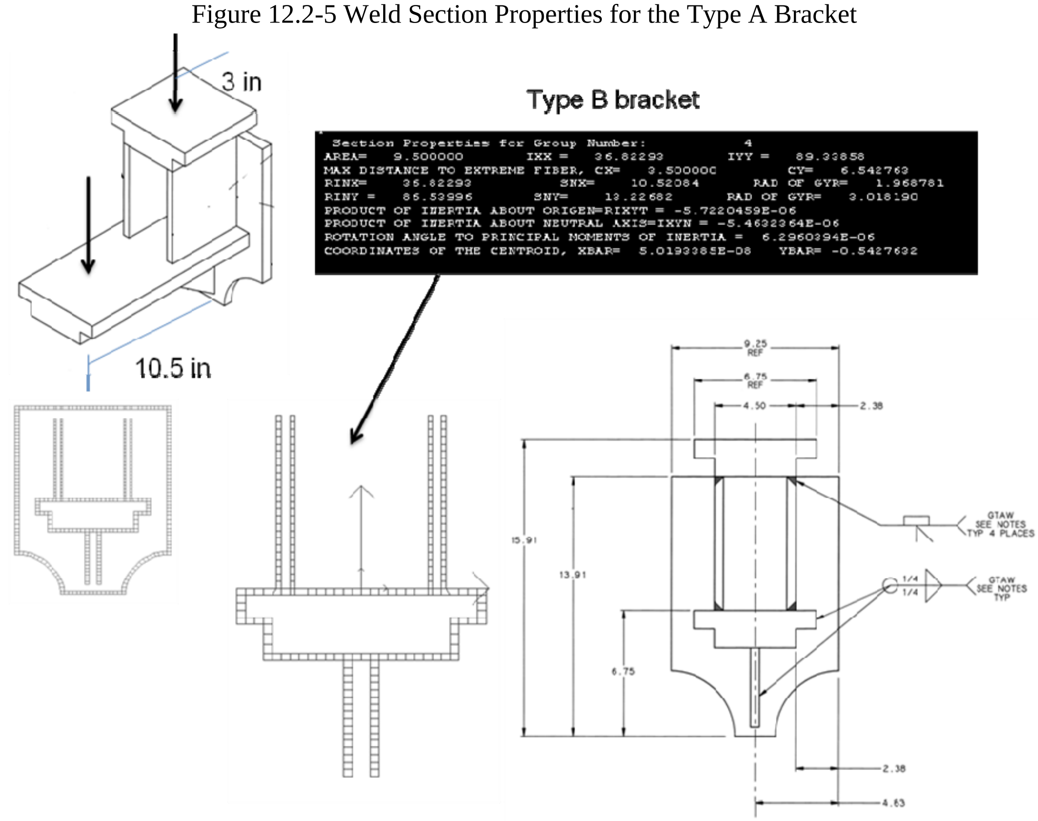


Figure 12.2-6 Weld Section Properties for the Type B Bracket

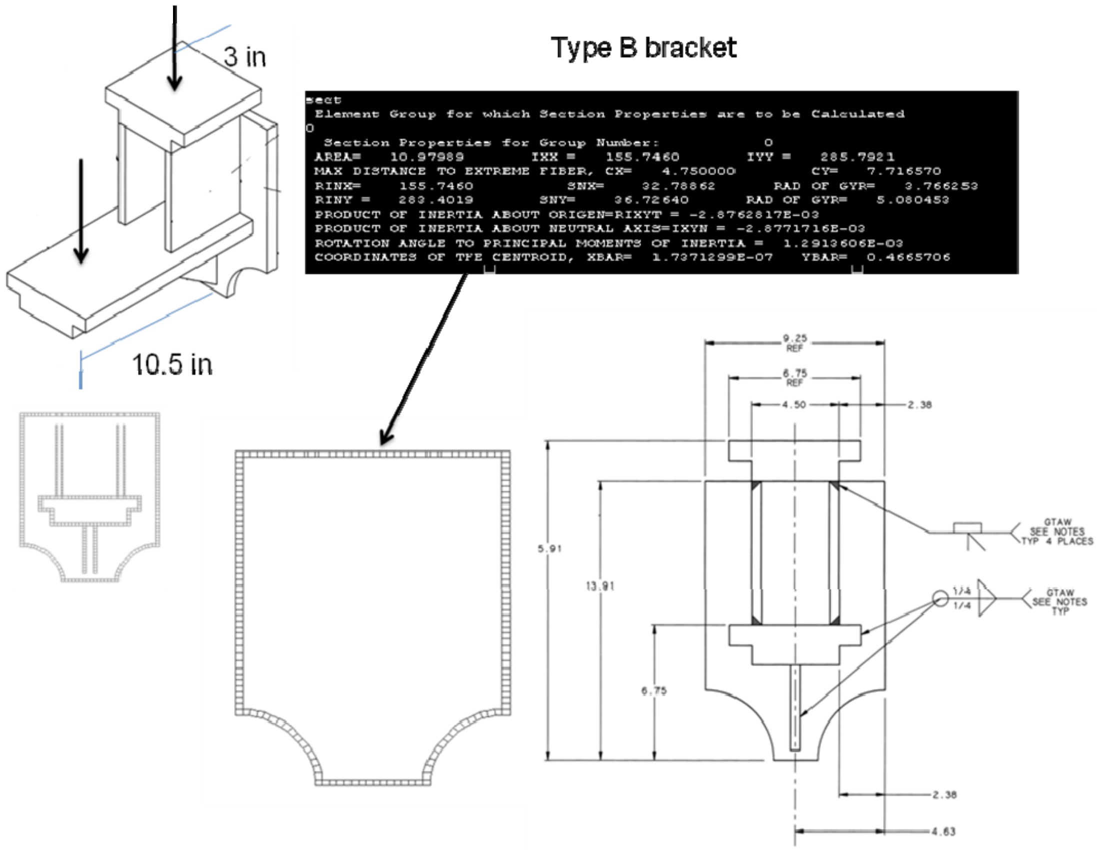


Figure 12.2-7 Weld Section Properties for the Type B Bracket

Weld Stresses Calculated From Weld Section Properties

	Worst Net PF4,5,U,L	Moment Sum for 6 Supports (12 U&L), 10.5" Lever	Section Modulus (in^3)	Bending Stress (psi)
psi Type A or B Bracket	-81953	-71708.875	13.22	-7672.237534
Type A Pad	-81953	-71708.875	47.87	-2118.800505
Type B Pad	-81953	-71708.875	36.7	-2763.677935

From Charlie's Design Point Spreadsheet

Fz(lbf)	(PF4U+PF5U)+(PF4L+PF5L)
Min w/o Plasma	-81947
Min w/ Plasma	-81953
Min Post-Disrupt	-58992
Min	-81953
Worst Case Min	-513255
Max w/o Plasma	0
Max w/ Plasma	17
Max Post-Disrupt	15
Max	17
Worst Case Max	513255

Conservatively uses PF5 moment arm and .707 factor on ¼ in weld

Figure 12.2-8 Net Loads on Bracket/Coil System

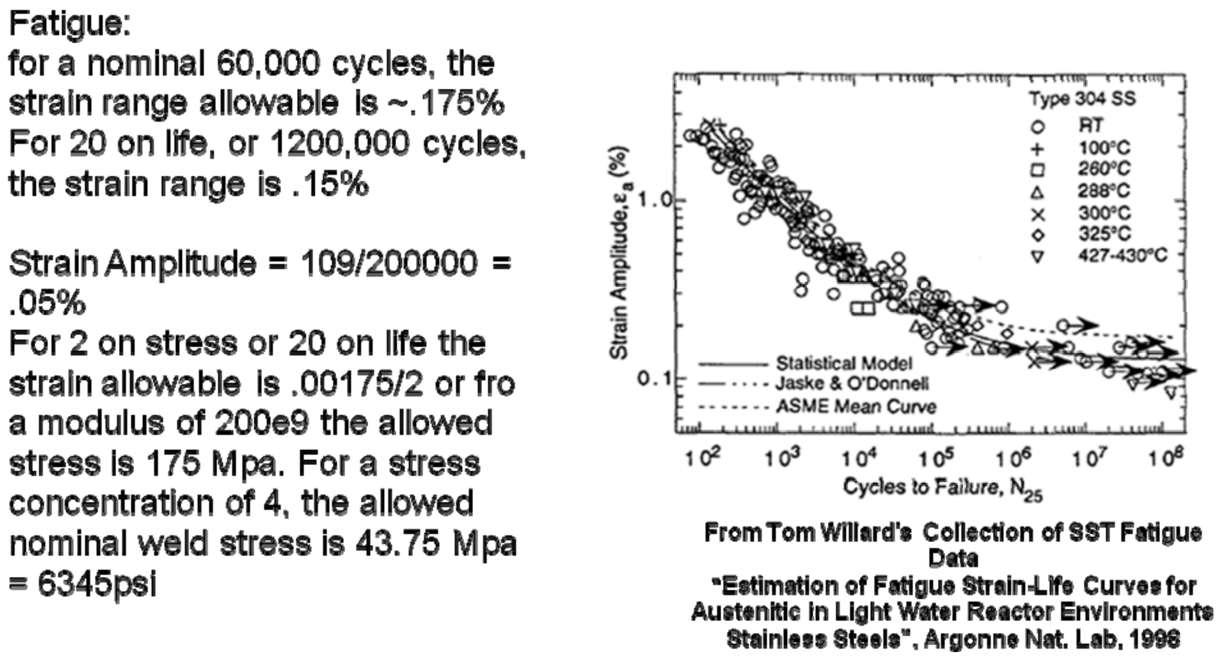


Figure 12.2-9 Fatigue Assessment

The weld stresses in the weld of the backing plate/pad to the vessel are 2118 psi and 2763 psi for the type A and B brackets, respectively. These are well below the fatigue allowable calculated above. This is consistent with the findings of the inspection described in Appendix A. The stress in the weld between the back plate or pad and the bracket was calculated to be 7672 psi based on the 1/8-inch fillets on the vertical legs of the bracket.

12.3 PF5 Bracket Support Plate and Weld, With and without Existing Column

The existing Support bracket for PF 4 and 5 includes an extension to support PF5. During the operation of NSTX, the support column between the existing upper and lower PF5 extensions buckled, and needed reinforcement. Early upgrade PF4/5 support concepts sought to remove this column because of its weakness, and to ease clearance issues. In this section, bracket stresses are considered with and without the column. The cantilever load principally derives from attractive loads to the lower PF4 and 5 coil pair. The final design, as of November 2011, has new, heavier columns between the upper and lower support brackets. This section is an exploration of why the new column was needed.