PPPL Calculation Form

Calculation # NSTXU-CALC-12-13-00 Revision # 0 ___ WP #, if any (ENG-032) 2320

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

Structural Qualification of E-DC11130, NSTX-U Casing Trial Asm Tool Fixture

Codes and versions: (List all codes, if any, used)

NSTX-U Structural Design Criteria, NSTX-CRIT-0001-02, Jan 2016

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

See attached

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

See attached

Calculation (Calculation is either documented here or attached)

See attached

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

The Casing Trial Asm Tool Fixture is qualified for:

16000 lbf of vertical load, which includes the clamping force of the locking studs

1000 lbf of side load, applied at the center of mass of the Casing

If the Casing is left installed on the Casing Jack overnight, some fixation must be present at both the top and bottom of the CS Casing, which directly reacts any sideloads, rather than transmitting them as bending moments through the Casing Jack itself. This fixation must increase the lateral stiffness of the {Casing + Tooling} by a factor of order 20x.

Cognizant Individual (or designee) printed name, signature, and date

Atiba Brereton Digitally signed by Atiba Brereton Date: 2018.05.22 08:58:36 -04'00'

Preparer's printed name, signature and date

Michael Mardenfeld Digitally signed by Michael Mardenfeld Date: 2018.05.02 17:33:34 -04'00'

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

Checker's printed name, signature, and date

Irving J. Zatz Digitally signed by Irving J. Zatz Date: 2018.05.03 10:04:36 -04'00'

Michael Mardenfeld
1 May 2018
Structural Qualification of E-DC11130, NSTX-U Casing Trial Asm Tool Fixture

Introduction

The NSTX-U Recovery project has planned a trial assembly, wherein the NSTX-U Centerstack Casing ("Casing") shall be installed on the NSTX-U TF/OH Bundle ("Bundle"). This trial assembly requires a particular geometric orientation between the Casing and the Bundle. A special purpose Tooling Fixture ("Fixture" or "Casing Jack") has been designed to support the structural load of the casing, allow fine adjustment of its positioning, and practically interface with lifting and metrology equipment. The purpose of this calculation is to structurally qualify this fixture.

Note that the trial assembly will occur in the South Highbay, away from NSTX-U proper. The Bundle will be supported by the Swing Fixture. The Centerstack Lower Support Weldments ("Skirt"), which normally supports the weight of the Casing, as well as the Inner PF Coils will not be installed during the Trial Assembly operation. The Fixture physically takes the place of these components and acts as a structural surrogate during the Trial Assembly.

Conclusion

The use of the Casing Jack is qualified to simultaneously react: 16000 lbf of vertical load, plus 1000 lbf of side load applied at the center of mass of the Casing.

The vertical load is an expected normal operating load: based on a slightly conservative assumption of 4000 lbf of gravity load, with 12000 lbf of clamping force from "locking studs" securing the Casing to the TF Bundle.

The 1000 lbf of side load is an assumed off normal event from, for instance, a seismic event. See attachment 1 for a discussion of Seismic Design Forces.

In the author's opinion these loads are acceptable, but marginal in four respects under superimposed vertical and side loads:

- The peak bending moment in the stud
- Buckling of the jacking leg
- Reaction of the side force, which is partially through friction across a Teflon slip plane
- Potential resonance of the {Casing + Tooling Fixture} with earthquake frequencies (See attachment 1)

Because the incremental cost is low, the risk reduction is high, and the assumptions in the calculation are difficult to verify, the recommendation is that a secondary fixation method be applied to secure the top of the CS Casing to either the Swing Fixture directly, or to the TF Bundle (which is secured to the swing fixture). This will significantly reduce the reacted bending moments at the base of the Casing Jack.

A similar fixation should be present at the bottom of the Casing, laterally connecting it to either the Swing Fixture or the TF/OH Bundle. The "Pusher Adjustment Mechanism" is sufficient to serve this purpose, but another technique could be acceptable as well.

This should be done any time the Casing is left on top of the Casing Jack for extended periods of time, e.g., overnight.

Requirements

- Loads the fixture must react:
  - Vertical dead weight of the (CS-Casing + PFCs), conservatively assumed to be **4000 lbm**
  - Side load representing a seismic event, applied at the center of mass of the Casing, assumed to be **1000 lbf**
  - Vertical Clamping Force from “Safety Studs”, E-DC11128-09, assumed to be 2000 lbf per 3/8” stud, or **12000 lbf total**
- Major Steps to qualification
  - Qualify the Casing Jack Main Assembly
    - Superimposed vertical loads and sideloads
    - Plate Stresses
    - Weld Stresses
    - Buckling of Legs
  - Qualify the Base Plate (E-DC11128-10)
    - Bending due to reaction from legs of Casing Jack Main Assembly
    - Bolt Reaction Forces
  - Qualify the Casing Support Plate (E-DC11128-6)
    - Bending Stresses
  - Qualify the Safety Studs
    - Reaction force of the floating locking plate
  - Discussion of Seismic Design Loads and Frequency Response (Attachment 1)

Assumptions

- Configuration
  - The assembly occurs in the South Highbay, away from NSTX-U proper
  - The TF/OH Bundle is standing vertically, supported by the Swing Fixture E-DC1740
  - The CS Casing weight includes the weight of all of the CS-PFCs, but not PF coils
  - The Swing Fixture has been previously qualified to support the TF/OH Bundle with and without the Casing installed

References, Drawings

E-DC11128	NSTX-U Casing Trial Asm Tool	Fixture being qualified
E-DC1443	Center Case Weldment and Final Machining	“Centerstack Casing”’
E-DC1740	Horizontal to Vertical Swing Fixture	TF/OH Support Tool
E-DC1454	Centerstack Lower Support Weldments	“Skirt”

References, Other

Machine Design Data Handbook	K Lingaiah	ISBN 0-07-037933-5
NSTXU-CALC-12-14-00	M Mardenfeld	Justification of Seismic Design Loads for E-DC11130, NSTX-U Casing Trial Asm Tool Fixture
NSTX-CRIT-0001-02	I Zatz	NSTX-U Structural Design Criteria, Jan 2016

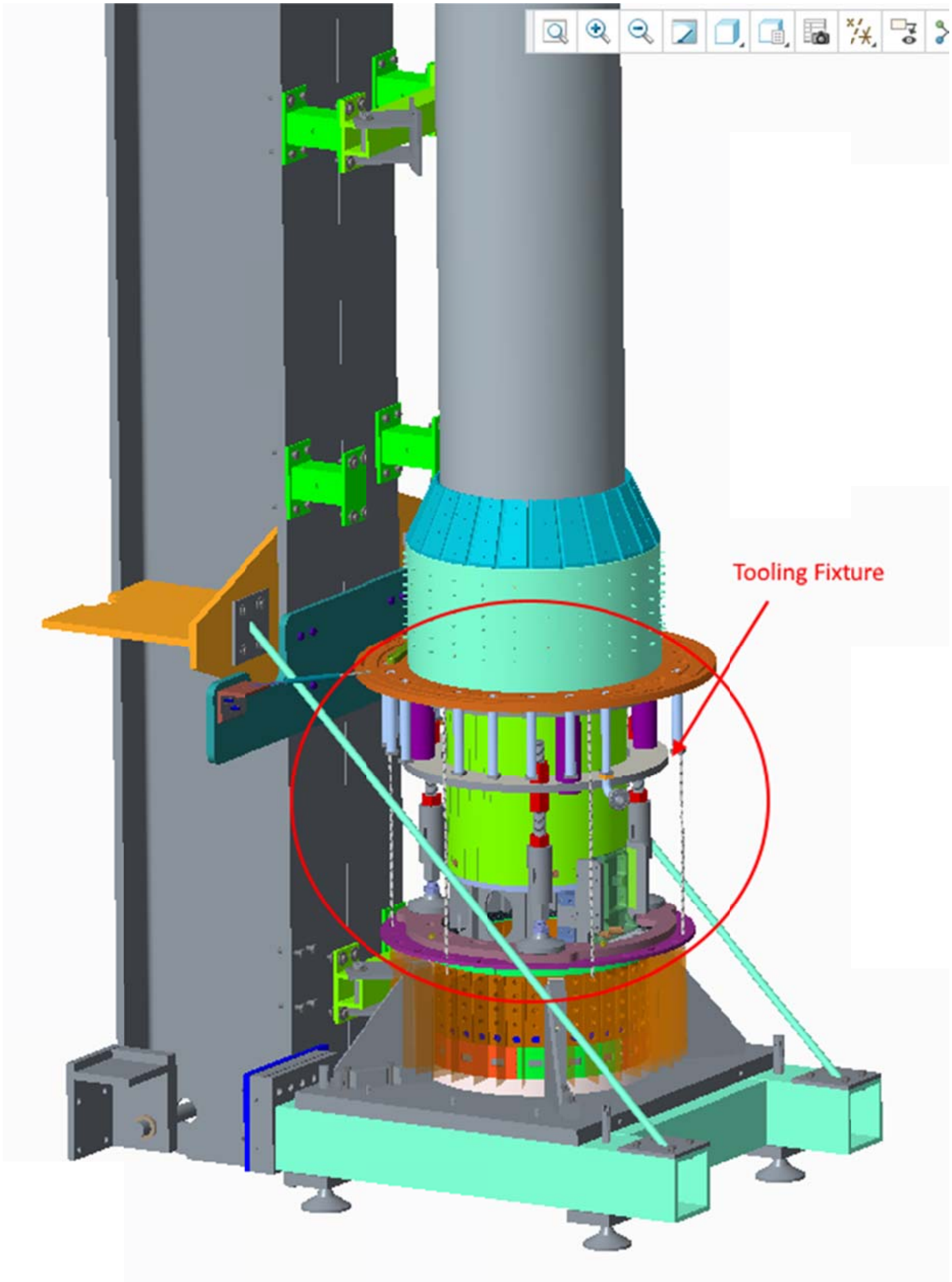


Figure 1: Tooling Fixture shown assembled on TF/OH Bundle and supporting CS Casing

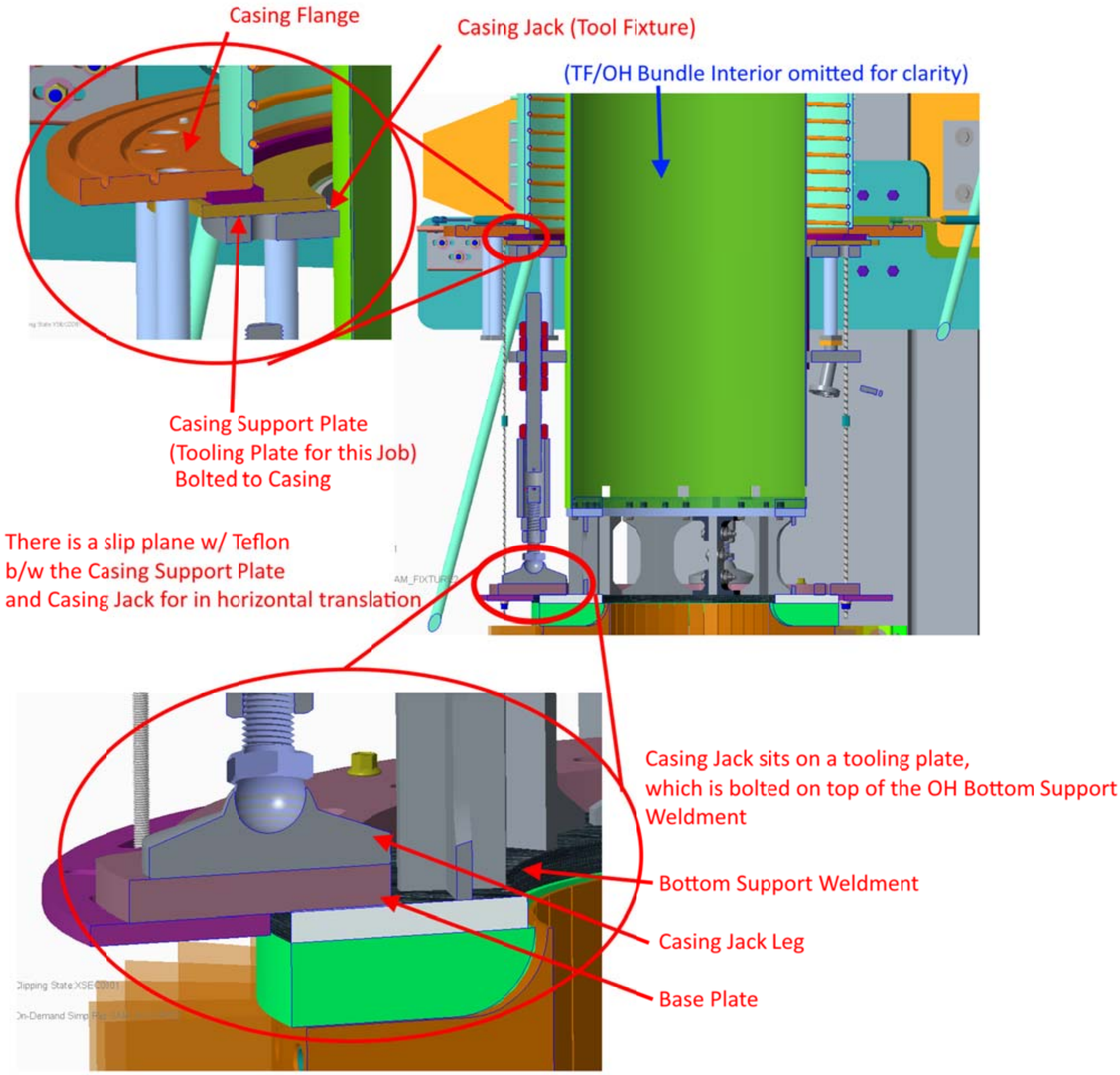


Figure 2: Cross section showing tooling fixture installed on TF/OH Bundle and Interface with Casing

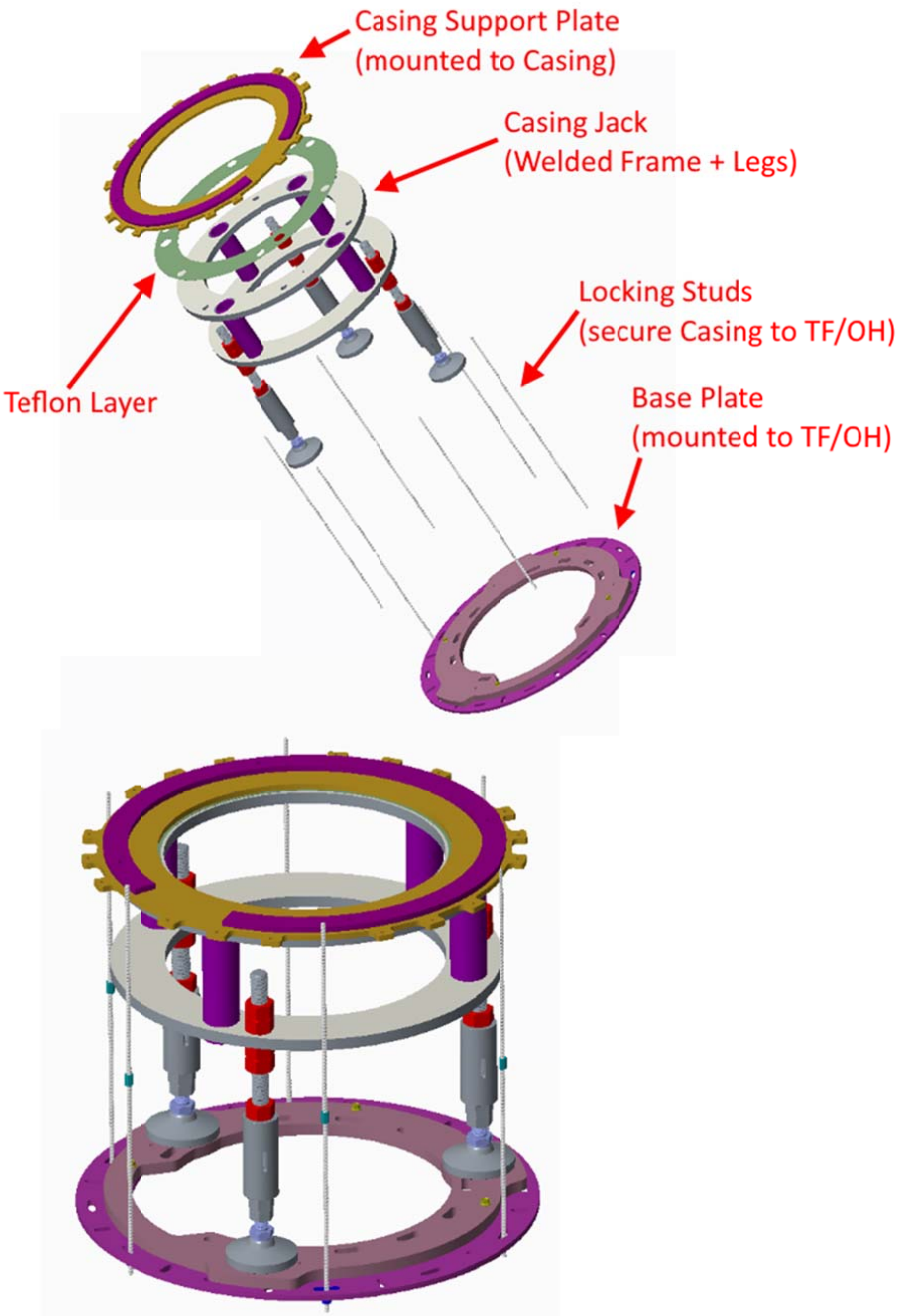


Figure 3: Components of the Casing Jack Assembly

Basic Design Features of the Casing Jack

The primary purpose of the Casing Jack is to structurally support the Casing, while allowing it to be moved about the TF/OH to a desired alignment in space. This is achieved by 3x jacking legs, which have length adjustment mechanisms to control the angular tilt and height of the Casing Jack. Following is a brief description of the assembly, component by component, starting from the bottom and working upwards.

The Base Plate is the bottom of the tooling fixture, and it sits upon the metal flange of the "permanently installed" OH Bottom Support Weldment. This plate, made of aluminum 6061 T6, serves as the platen to support the tooling fixture. It bears the entire load of the fixture and casing, and is bolted to the TF/OH Bundle through the existing holes which are intended for the Lower Support Weldment (the "skirt") during actual machine assembly. This plate is needed to spread the load of the jacking legs, which are radially outboard of the OD of the OH Bottom Support Weldment. It also serves as a load reaction or vertical fixation point for the "Floating Locking Plate".

The "Floating Locking Plate is simply a washer plate – it is a fixation point for quantity 6x 3/8-16 studs, which can be used to tie the Casing directly to the TF/OH Bundle via holes on the underside of the Casing Flange. This is a safety feature intended for more secure fixation of the Casing during periods where it may be left assembled on the Tooling Fixture. This is desirable because as described below, there are horizontal slip planes between the Casing and the Tooling Fixture, and the Tooling Fixture and the TF/OH Bundle. These safety studs allow a positive clamping force to lock the slip planes in place in addition to the gravity loads. The "Floating Locking Plate" is designed in such a way that it can react vertical loads by bearing upwards against the Base plate, while allowing easy fit up because it can move, or float, in a horizontal plane before the studs are tightened.

On top of the base plate rest the Casing Jack Legs. Note that they are not secured to the Base Plate except by friction and vertical loads. There are fabricated from mild steel studs, tubes, and nuts. These are essentially large studs with adjustable length. The mechanism for length adjustment is a differential screw. In other words, there is a "shuttle tube" in the center of the leg, with nuts welded on each end, and a threaded rod which screws into the nuts. Each end of the shuttle tube has a different thread pitch, which affects a different linear travel on the upper and lower studs for a rotation of the shuttle tube. This allows a simple mechanism for fine adjustment with large, structurally sized studs. At the bottom of each leg is a commercial swivel leveling mount with an integral spherical joint. These commercial mounts are load rated to 40,000 lbs each, and do not need to be qualified.

The Casing Jack Legs thread into nuts which are welded onto the bottom of the Casing Jack Welded Frame. This frame transfers the loads from the Bottom of the Casing Support Plate to the Jacking Legs. It is also a rigid moment frame in the regions of highest loads and bending moments. On top of the Casing Support Plate will lay a sheet of Teflon to allow in-plane sliding of the CS Casing. The Casing Jack Welded Frame is fabricated from mild steel plates and tubes welded together.

On top of the Teflon slip plane will sit the Casing Support Plate. This plate will be pre-bolted to the CS Casing before it is hoisted into place. It will be fabricated out of aluminum. It serves several purposes: to serve as the wearing surface at any sliding interface (rather than the CS Casing Flange itself), to fill the space which will be occupied by the PF1A/B during the real assembly but not during the trial fit, and also to increase the bearing area of the CS Casing on top of the Casing Jack. Note that the Casing Support Plate fit up is designed so that the load transfer path to the Casing mimics the actual machine assembly – the load is transferred across the step that the PF1B nests into.

Finally, there is a second tooling plate ("NSTX-U Casing Trial Asm Tool Fixture, Pusher"), which is shown in Figure 1. This plate mounts in a vertical orientation, and provides and adjustment capability for the in plane motion of the CS Casing via an adjustable 6 bar linkage mechanism. This is necessary because the Casing Jack can only adjust 3 degrees of freedom: two angles and a vertical height. ,Because it is not load bearing, the pusher mechanism does not need to be qualified by this calculation. However, it can and should be used as an additional fixation point to directly connect the Casing to the Swing Fixture.

Material Properties

Properties of Outline Row 3: Aluminum Alloy

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	172.93	lb ft^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Modulus and ...			
5	Young's Modulus	1.0298E+07	psi		
6	Poisson's Ratio	0.33			
7	Bulk Modulus	6.9608E+10	Pa		
8	Shear Modulus	2.6692E+10	Pa		

Figure 4: Aluminum Alloy Properties

Assume Aluminum 6061-T6 has:

- Ultimate Tensile Strength, 45 KSI
- Yield Strength, 40 KSI
- So Sm = ½ Ultimate = 22.5 KSI

Properties of Outline Row 4: Structural Steel

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	0.2836	lb in^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Modulus and ...			
5	Young's Modulus	2.9008E+07	psi		
6	Poisson's Ratio	0.3			
7	Bulk Modulus	1.6667E+11	Pa		
8	Shear Modulus	7.6923E+10	Pa		

Figure 5: Mild Steel Properties

Assume Mild Steel has:

- Ultimate Tensile Strength, 58 KSI
- Yield Strength, 36 KSI
- So Sm = 2/3 yield = 24 KSI

Qualification of the Casing Jack Legs and Casing Welded Frame

Assumptions

- Mild steel material properties
- Half symmetry model
- Welds are not modeled: monolithic contiguous mesh is modelled between welded components. Reaction forces and moments are extracted and qualified by hand. Load distribution is assumed to be unaffected by change in stiffness between welds and monolithic part
  - Consider that the difference in peak bending moment between a clamped/clamped beam and a pinned/pinned beam is a factor of 2x
  - So at worst, if the welded joint acted as a pinned connection the bending stress in the plate at midspan would increase by a factor of 2x. This would be acceptable based on calculated safety margins, but is likely unnecessarily conservative.
- Simplified modelling of Jacking Legs
  - Note for a moment bearing frame with pin connected legs, the peak bending moment occurs at the joint between the legs and the beam. So qualification of this joint ensures that the entire leg is strong enough
  - Jacking leg is modelled as a solid rod with cross sectional area equal to the stress area of a 1.5-6 UNC stud. (A_s = 1.41 in^2 → r = .67")
  - Bottoms are jacking legs are modelled with spherical joints fixed to ground

Loads

- Loads here enumerated for the entire frame, even though in the model they are applied at ½ value because of symmetry
- Vertical load of 16000 lbf applied to top face of Welded Frame (Teflon is not modelled)
  - Assume 6x safety studs, 3/8-16 UNC tensioned to 2000 lbf each
  - Assume 4000 lbs dead weight from the CS Casing
- Side load of 1000 lbf
  - Applied as a remote point: scoped to top face of frame, but applied at the center of mass of the CS casing (~67 in above top of Frame)
  - Represents an off normal sideload, for instance during a seismic event

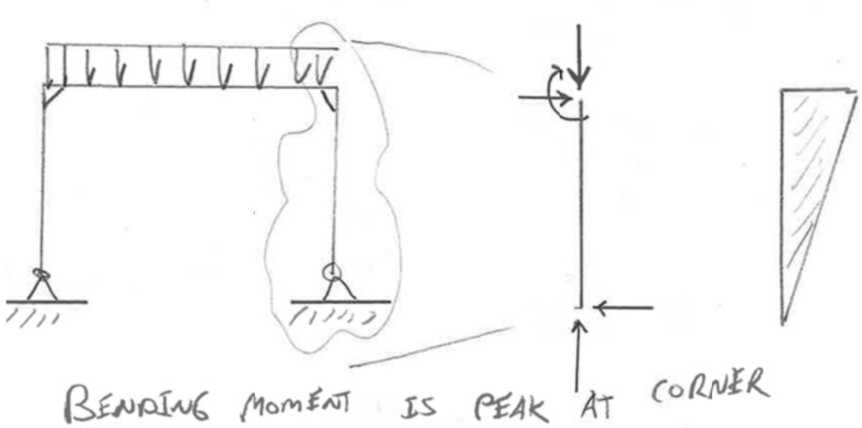


Figure 6: Peak Moment occurs at welded joint between leg and beam

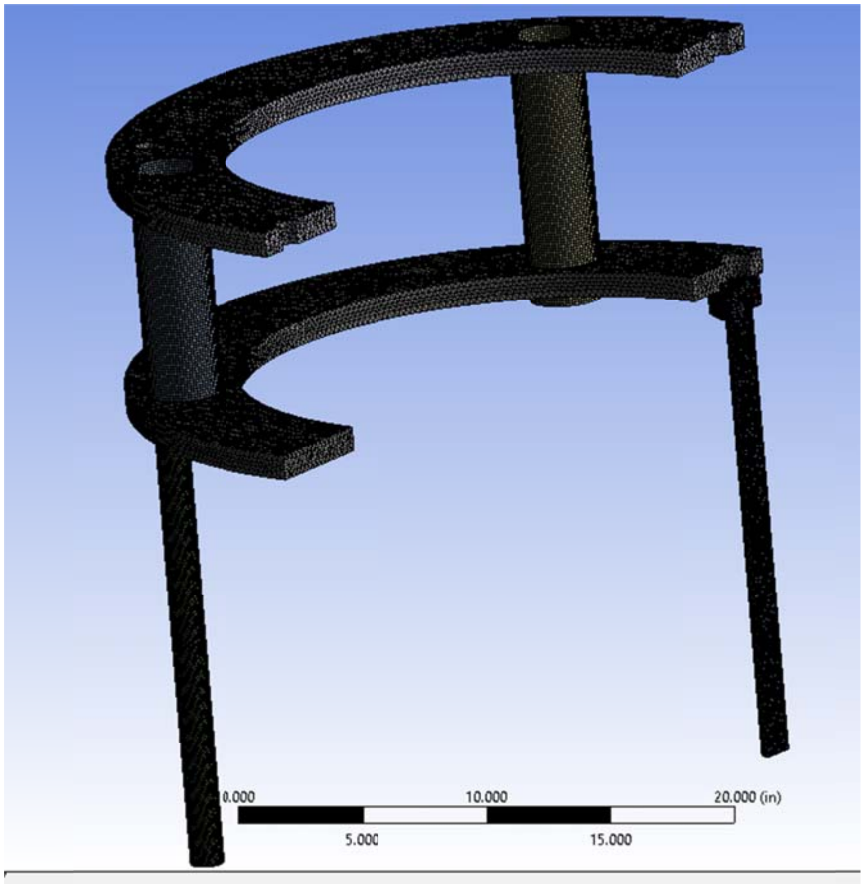


Figure 7: Half Symmetry Geometry and Mesh Density

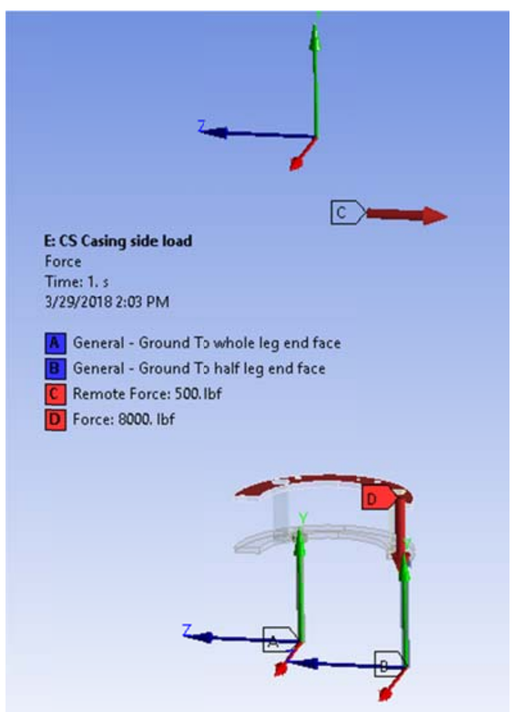


Figure 8: Loads and Spherical Joint Boundary Conditions

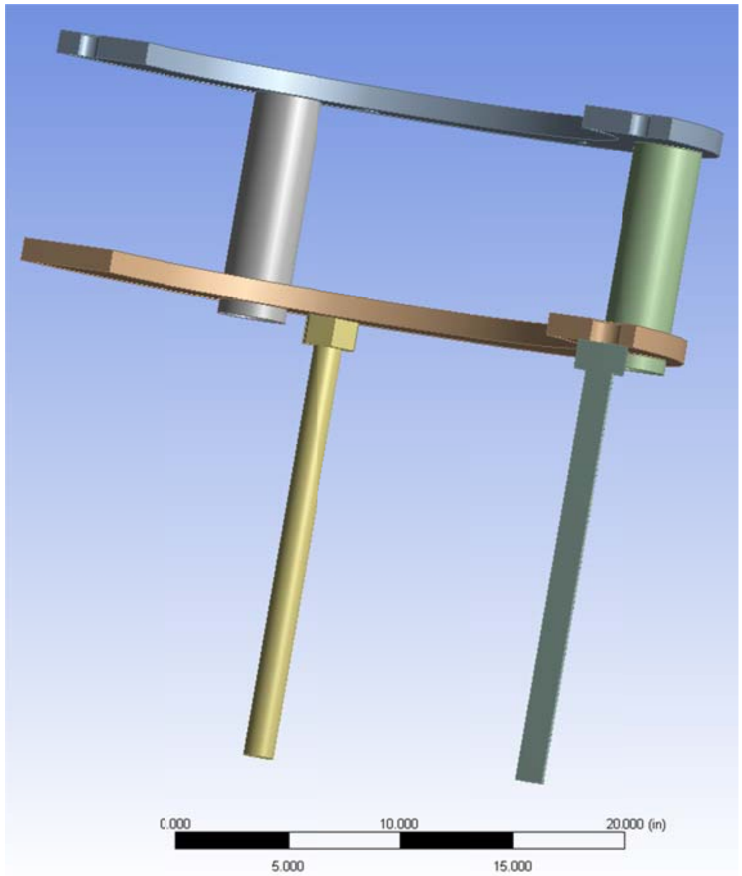


Figure 9: Geometry: Notice symmetry plane cuts 1 leg in half

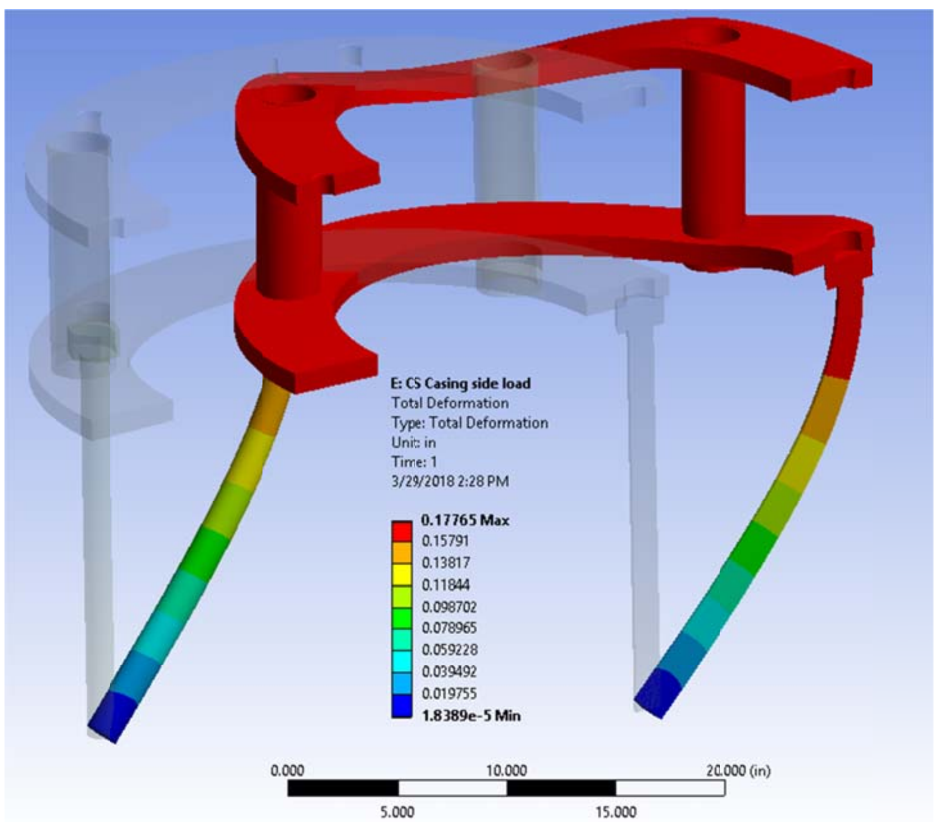
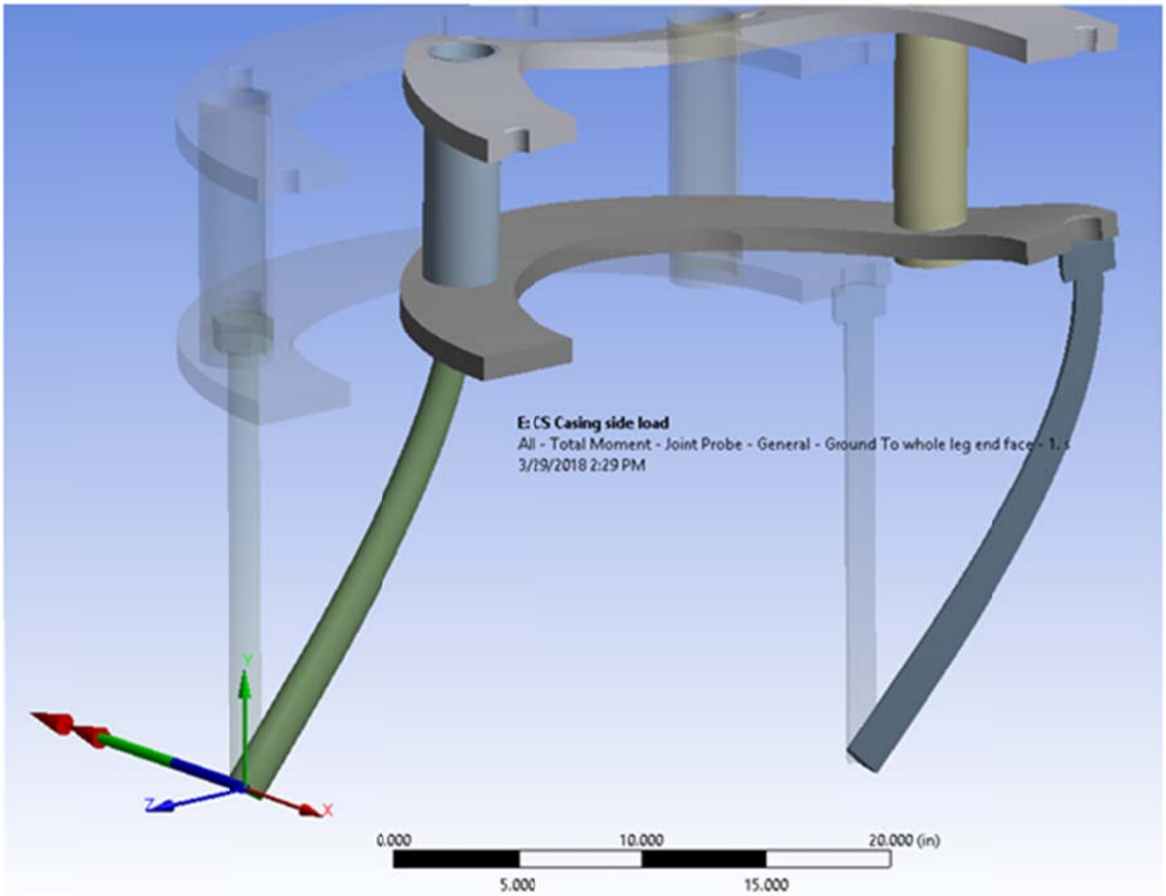


Figure 10: Displacement



Definition	
Type	Joint Probe
Boundary Condition	General - Ground To whole leg end face
Orientation Method	Joint Reference System
Suppressed	No
Options	
Result Type	Total Moment
Result Selection	All
Display Time	End Time
Results	
Maximum Value Over Time	
X Axis	-1.0233e-010 lbf·in
Y Axis	1.4392e-012 lbf·in
Z Axis	4.8128e-012 lbf·in
Total	1.0245e-010 lbf·in

Figure 11: Confirmation that joints do no react moment

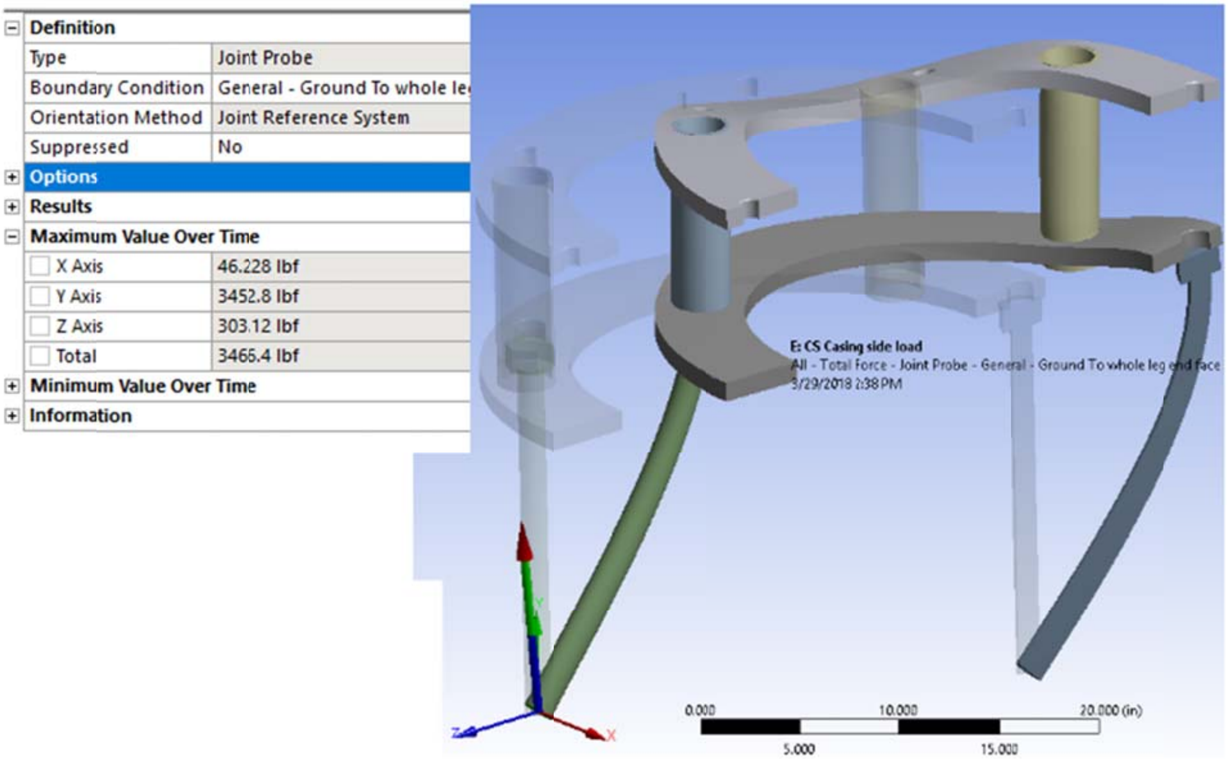


Figure 12: Ansys computation: Vertical Load on Left Leg is 3452 lbf

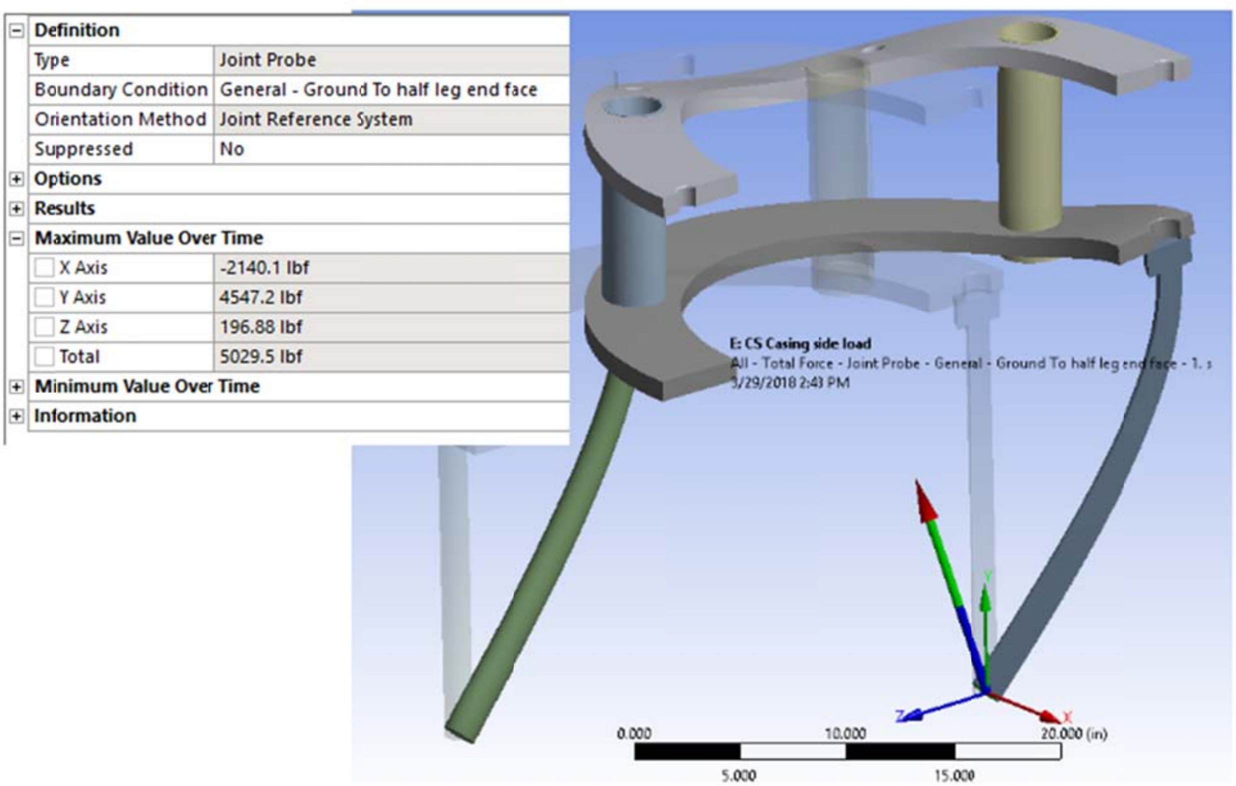


Figure 13: Ansys Computation: Vertical Load on Right Leg is 4,547*2=9,094 lbf

[Load reported by ansys is only for half leg, b/c it's split by the symmetry plane]

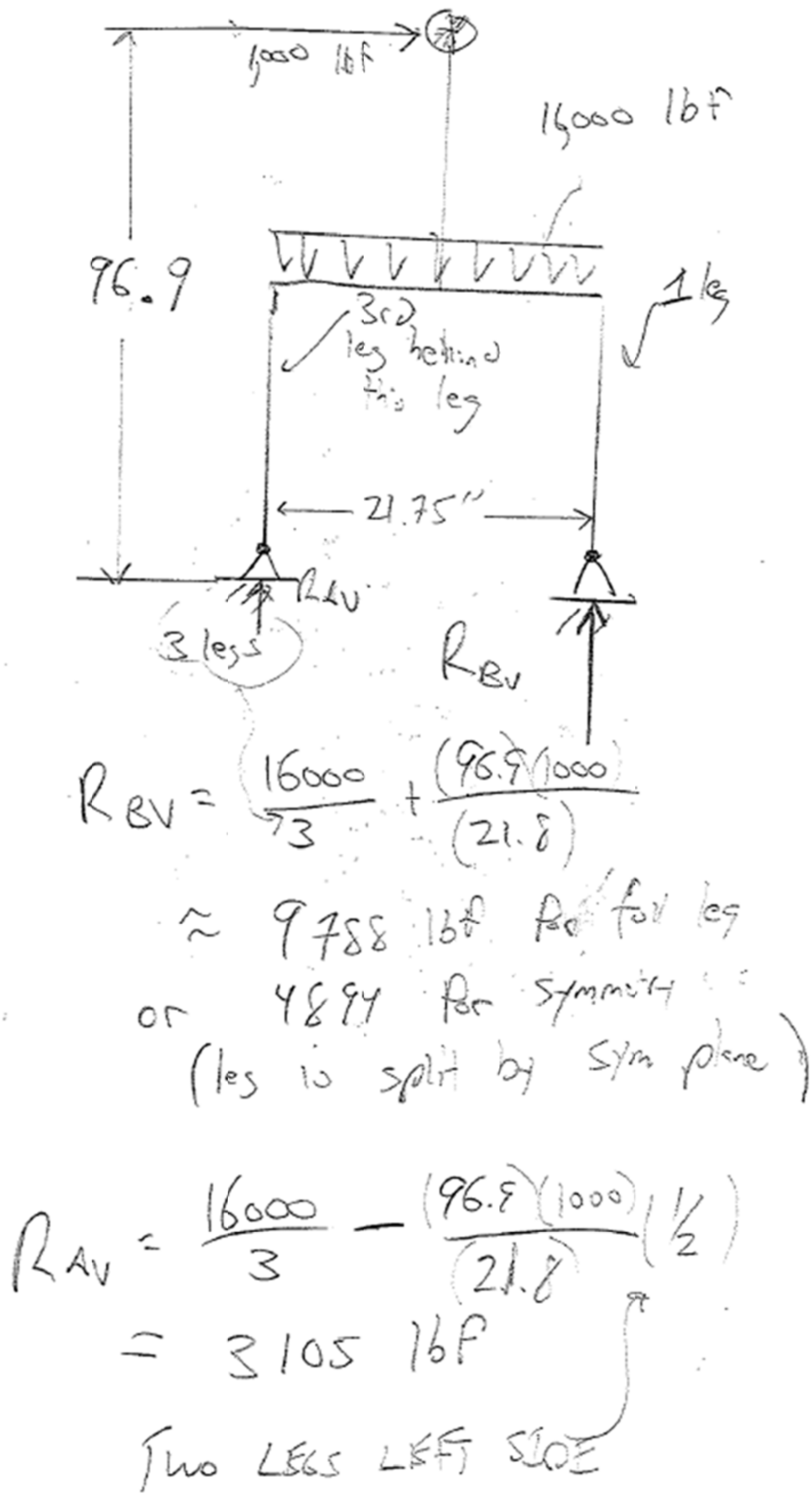


Figure 14: Sanity check on ansys reaction forces

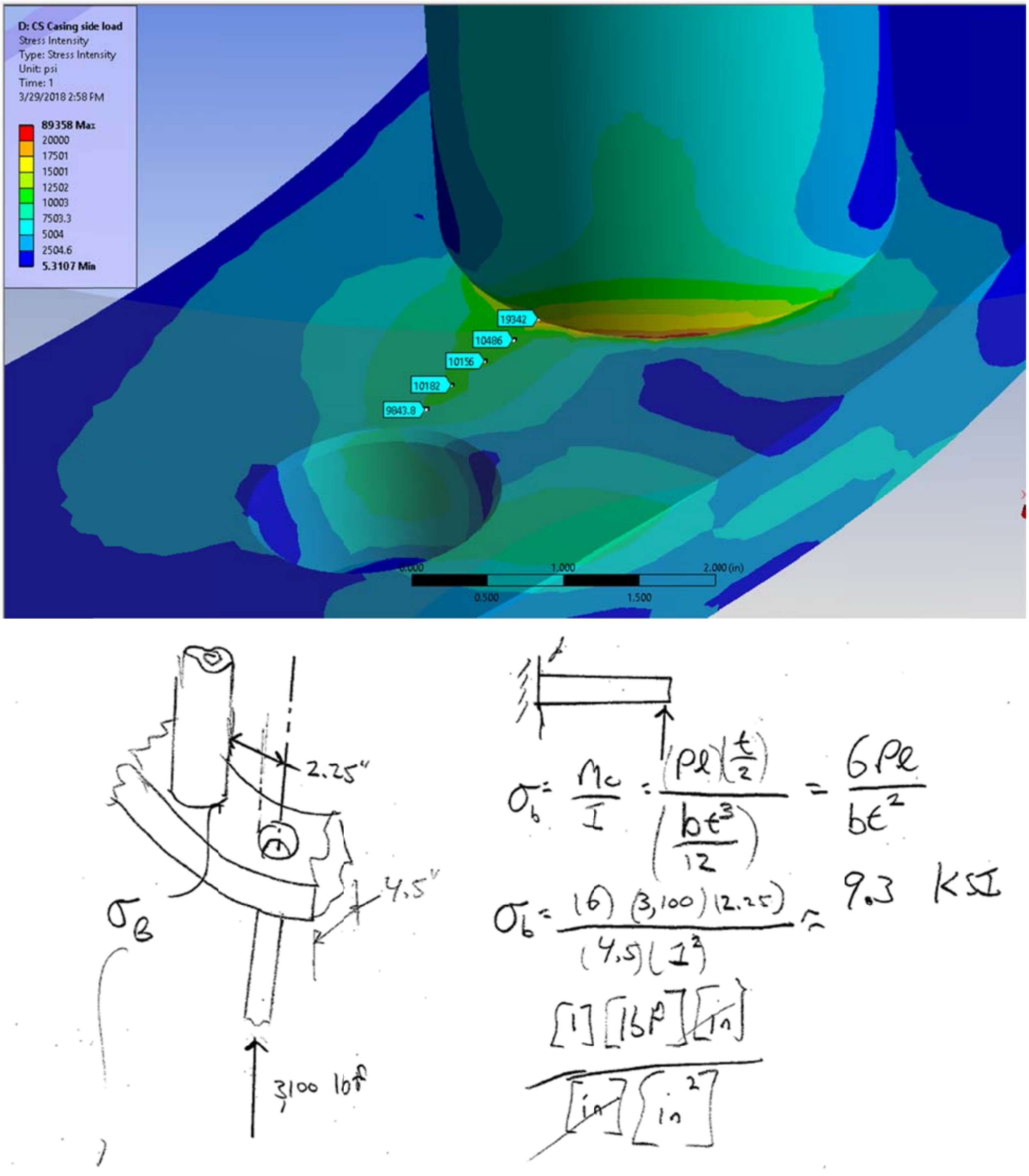


Figure 15: Spot Checking Local Bending Stress

Good Agreement between simple analytical results and ansys computation

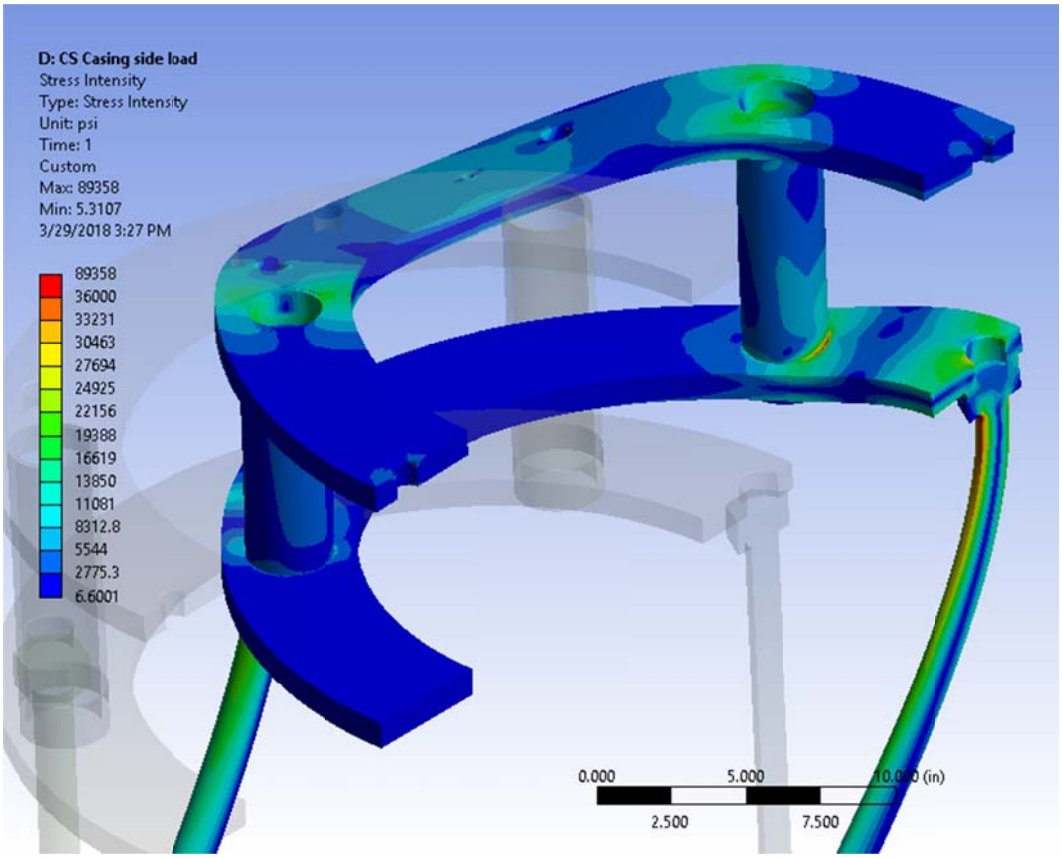


Figure 16: Stress Intensity

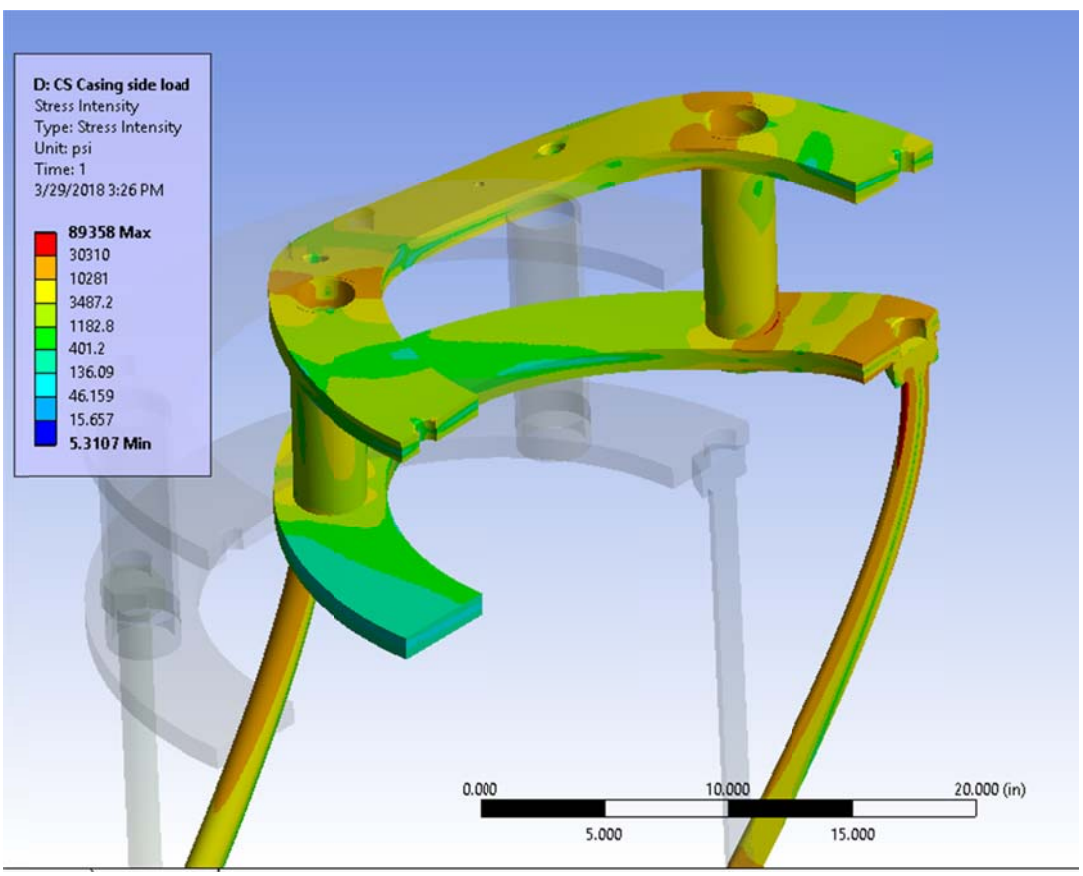


Figure 17: Stress Intensity

LOG SCALE!

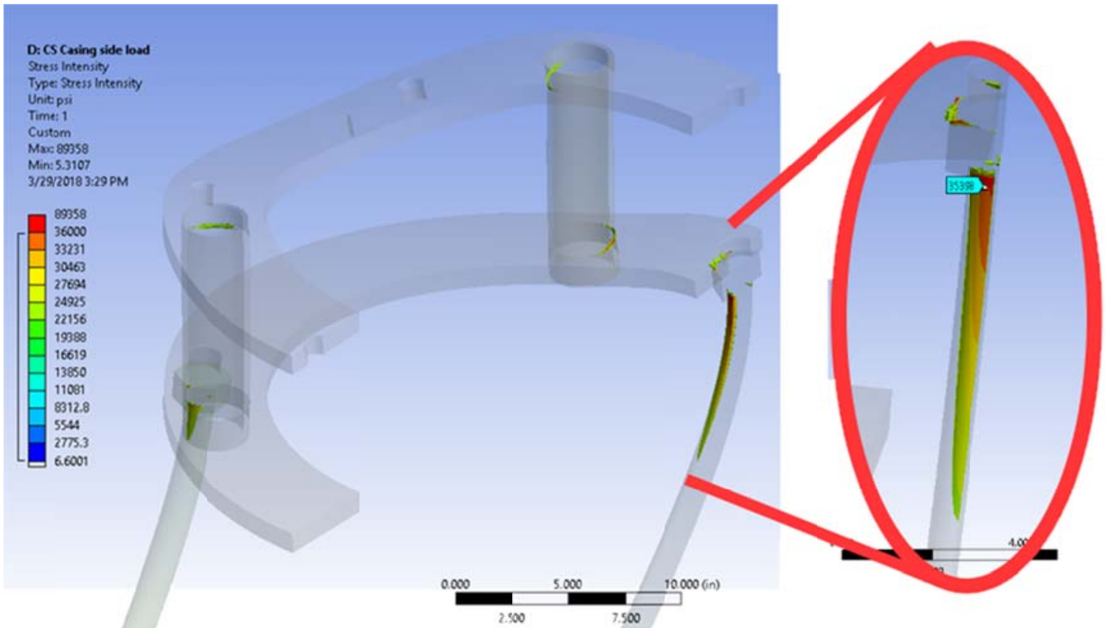


Figure 18: Stress Intensity, Regions above Sm

The figure above highlights all the stress regions above the membrane allowable, 24 KSI. Notice that these regions are all in bending or peak stresses, and are therefore the bulk of the fixture is acceptable.

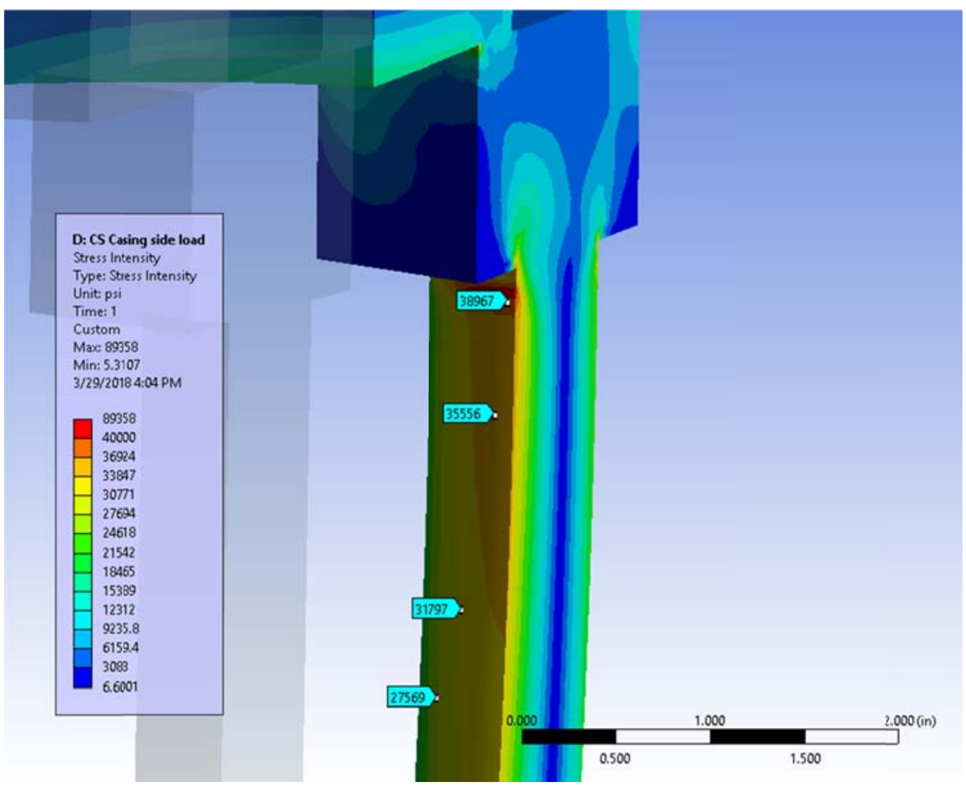


Figure 19: Close Up of Bending Stress in the Highly Stressed Leg

Note that the bending stress in the leg is below 1.5*Sm, 36 KSI, except at a local peak, and is therefore within allowable.

See further discussion following Figure 24.

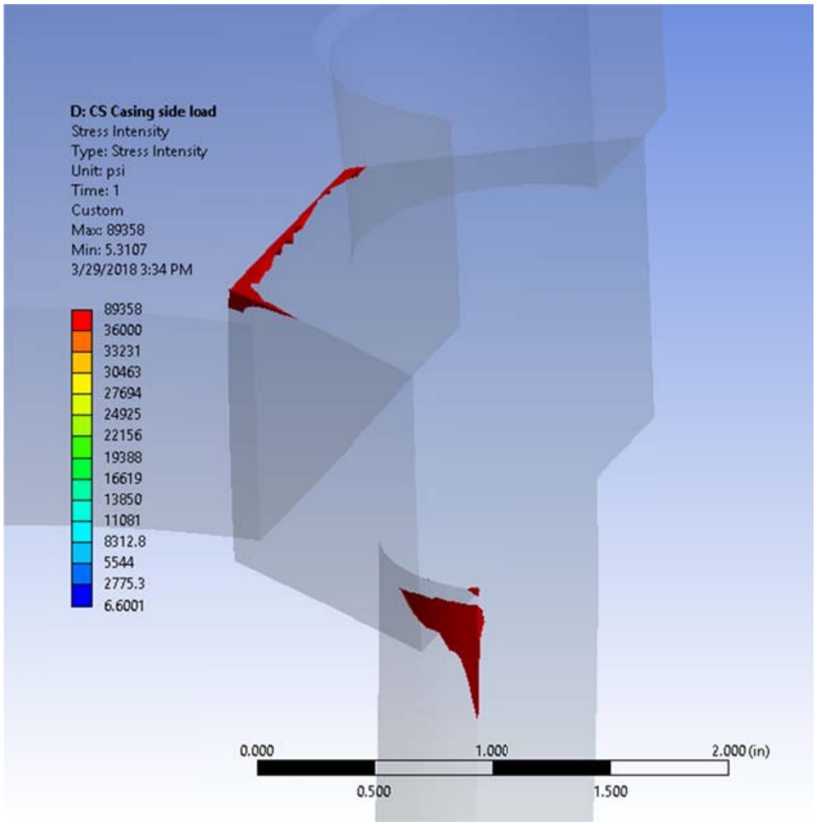


Figure 20: Peak Stresses

The figure above is typical of the regions with stresses above 36 KSI, the bending allowable. These local stresses are considered peak stresses, and therefore acceptable for static structures.

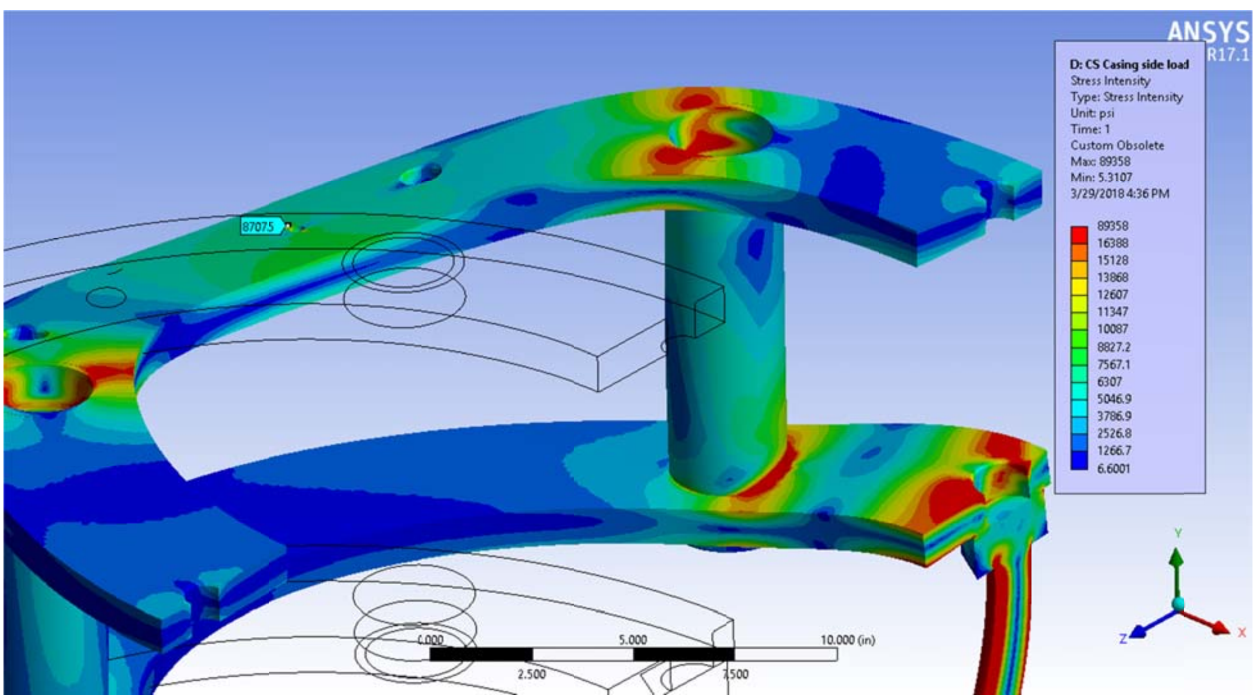


Figure 21: Peak stresses in the plates are extremely low, with safety factors of 3x+

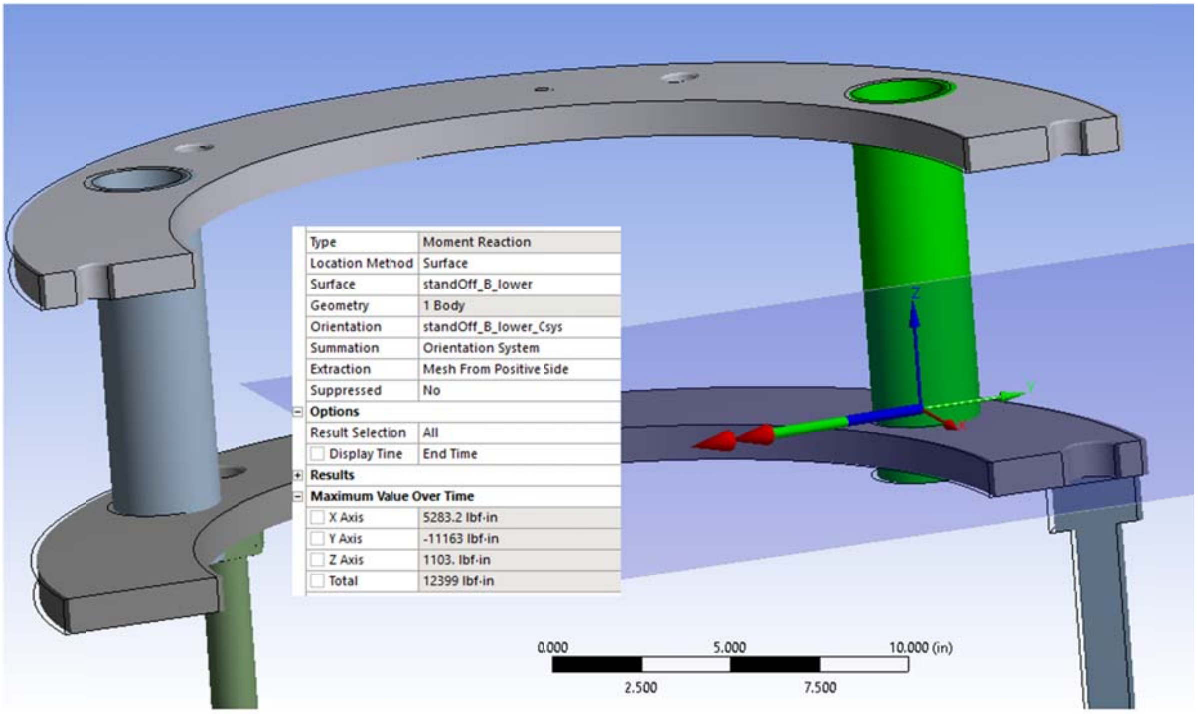
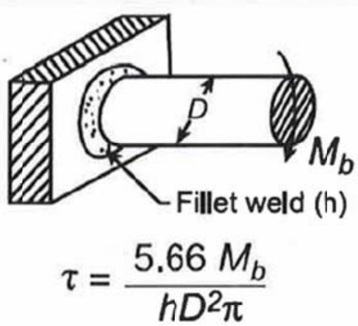


Figure 22: Peak Bending Moment between Plates and Tube Standoff

There are four welded joints between the "Tube Standoffs" (DC11128-5) and the Plates. Net bending moments were extracted from each of them, and the highest value bending moment is shown in the figure above. The peak bending moment is 12400 in*lbf and the peak force is 5250 lbf (not shown in figure).



$$\tau = \frac{5.66\,M_b}{hD^2\pi}$$

Figure 23: Handbook formula for round fillet weld in bending

Table 12.1
Machine Design Data Handbook
K. Lingaiah
ISBN 0-07-037933-5

FOR WELD: ASSUME SHEAR ACROSS THROAT

$$\tau_{AL} = \left[\tfrac{2}{3}\sigma_y\right] .57 \approx .38\,\sigma_y \approx 13.6 \text{ KSI}$$

ASSUME .25" FILLET WELD

$$\tau_{TOT} = \tau_B + \tau_S = \frac{(5.66) M_b}{h D^2 \pi} + \frac{\sqrt{2}P}{\pi D h}$$

$$\frac{[1][in \cdot lbf]}{[in][in^2][1]} + \frac{[1][lbf]}{[1][in][in]} = \frac{(5.66)(12500)}{(.25)(3)^2\pi} + \frac{(\sqrt{2})(5250)}{(\pi)(3)(.25)}$$

$$\approx 13.1 \text{ KSI}$$

A single 0.25" fillet weld is qualified, although it is likely that 0.375" fillet will be used on both sides of the plate.

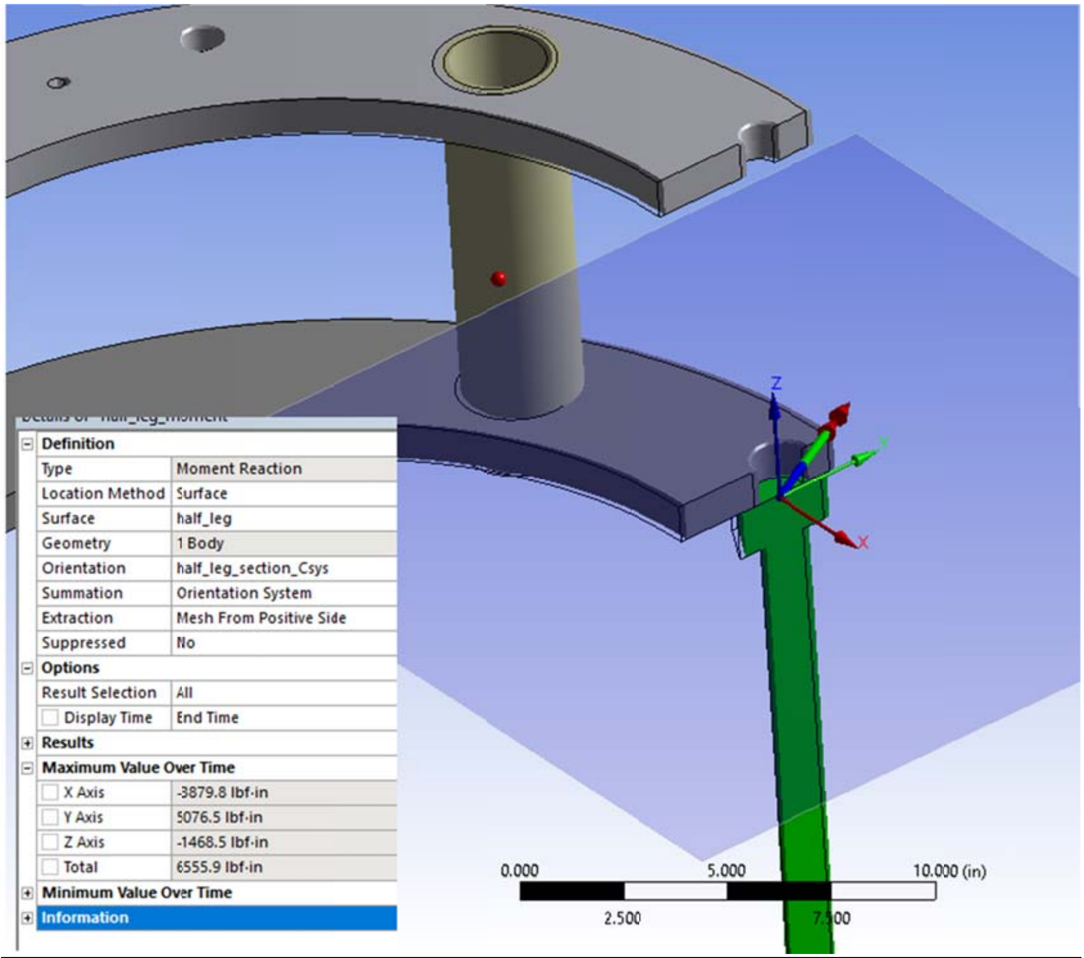


Figure 24

The peak bending moment occurs at the "right hand side" leg, both because this leg is on the side where the reaction force from the side load superimposes on the vertical dead load, and because on this side the entire load is reacted by a single leg (rather than 2 of the three legs). Note that because this reaction occurs at a symmetry boundary normal to the X axis of the local coordinate system, the moments about the Z and Y axis should not be considered. They are internally reacted by the half of the leg on the other side of the boundary condition, and do not contribute to the net force on the weld. However, the moment about the X axis must be doubled, and would be approximately 7800 in lbf for the entire leg. The vertical load on this leg was previously shown in figure 13 to be 9100 lbf.

Both the weld at the nut and the stud itself must be qualified for the bending moment and vertical loads. These computations are shown on the following page.

Note that the bending stress in the stud is slightly above the allowed stress for (Bending+Membrane), with a computed result of 39.6 KSI vs the allowable of 36 KSI. This is driven by the aggressive assumption of 1000 lbf side load: the stress in the same location with only vertical loads applied, although not plotted here, is only about 7.5 KSI. Because the locking safety studs were modelled as constant force, rather than as solid geometry, their contributory stiffness was neglected. In reality, they will absorb some of the reaction force of the upending moment and decrease the local bending stress in the leg. Therefore this load condition is deemed acceptable even with the 39.6 KSI local bending stress. Since there are no cyclical life requirements, local peak stresses may be above yield per NSTX structural criteria.

The stress in the weld attaching the nut to the weldment is also computed on the following page.

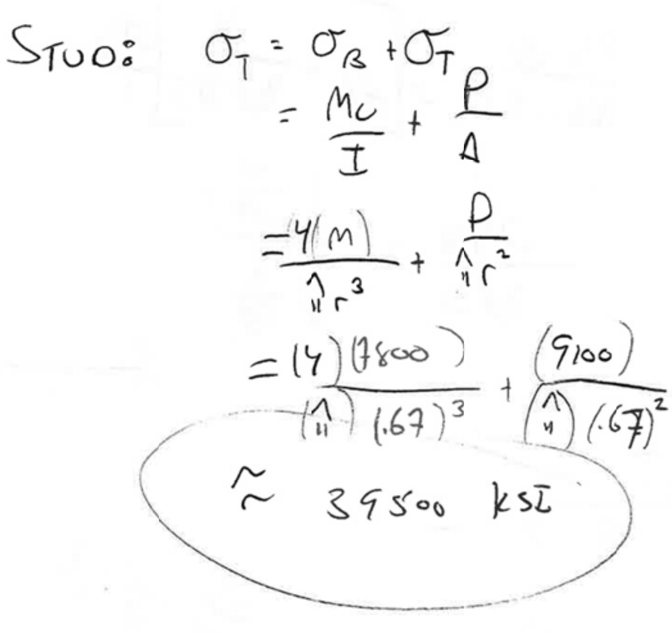


Figure 25: Computation of bending+tension stress in high stress leg

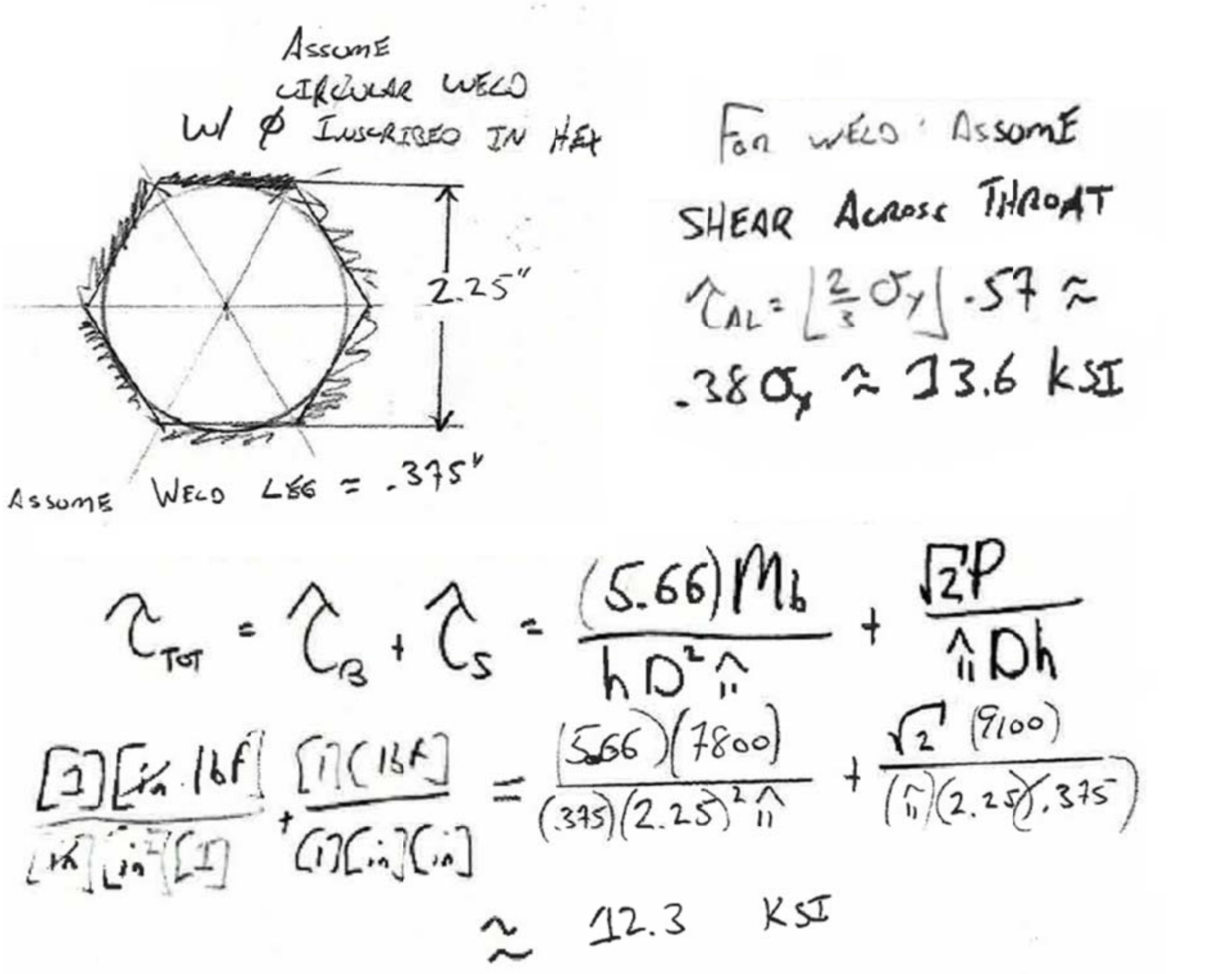
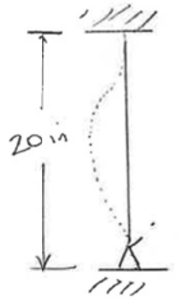


Figure 26: Computation of bending+tension in weld at nut

Euler buckling is also checked below as a crude metric of stability. Note that the bottom of each Jack Leg is pinned and the top is a rigid, moment bearing connection to the plate. If there was a single Jack Leg, this upper connection would act as a fixed rotation w/ free translation end condition, because the entire plate could translate laterally. However, because there are 3x Jack Legs, and only one of these is highly loaded (~9100 lbf vs 3500 lbf), the lightly loaded legs will prevent a lateral translation of the highly loaded leg, and we can claim that this end condition is built in (fixed rotation, fixed translation). The computed factor of safety of 7.5x on Euler Buckling is sufficient.

This treatment neglects the bending moment at the end of the column which will decrease the critical load.



$$F_{cr} = \frac{\pi^2 E I}{(KL)^2} = \frac{(\pi^2)(29E6)(0.077)}{[(.9)(20)]^2} \approx 68,000 \text{ lbf}$$

$$\frac{[1]\left[\frac{lbf}{in^2}\right][in^4]}{[1][in^2]}$$

1 1/4-7 UNC

STRESS AREA $\approx .97 \text{ in}^2$

$$R_{eff} = \sqrt{\frac{4(.97)}{\pi}} \approx 0.56 \text{ in}$$

$$I = \frac{\pi r^4}{4} = \frac{(\pi)(0.56)^4}{4} = .077 \text{ in}^4$$

ACTUAL LOAD: 9,100 lbf

CRITICAL LOAD: 68,000 lbf

$$FoS = \frac{68,000}{9,100} = 7.5$$

The assumptions appear reasonable and result in calculated design loads which are acceptable. However, because the assumptions are difficult to verify, it is recommended that if the CS Casing is left installed on top of the Casing Jack for extended periods of time, that some secondary fixation method be applied at the top of the Casing. This secondary fixation will react the overturning moment from any potential seismic loads through a much more structurally efficient load path due to the increase moment arm, and will significantly decrease the reaction forces at the Casing Jack. Although it may be argued that this secondary fixation might not be strictly necessary, it can be done in such a way that the incremental cost is negligible and it retires an unnecessary risk.

A sketch on the following page illustrates a concept for choking or shimming between the CS Casing and the TF Bundle which is relatively simple to implement. Other methods, which either secure the CS Casing to the Swing Fixture, or the CS Casing to the TF Bundle (with the TF Bundle already being secured to the swing fixture) would also be acceptable.

This choking or shimming has a secondary benefit of reaction the side force directly, rather than through a frictional traction applied across the Teflon slip plane.

The bottom of the Casing should also have fixation to the Swing Fixation. A practical and sufficient way of achieving this would be to leave the “Pusher Adjustment Mechanism” in place, and have its studs act as lateral stabilizers.

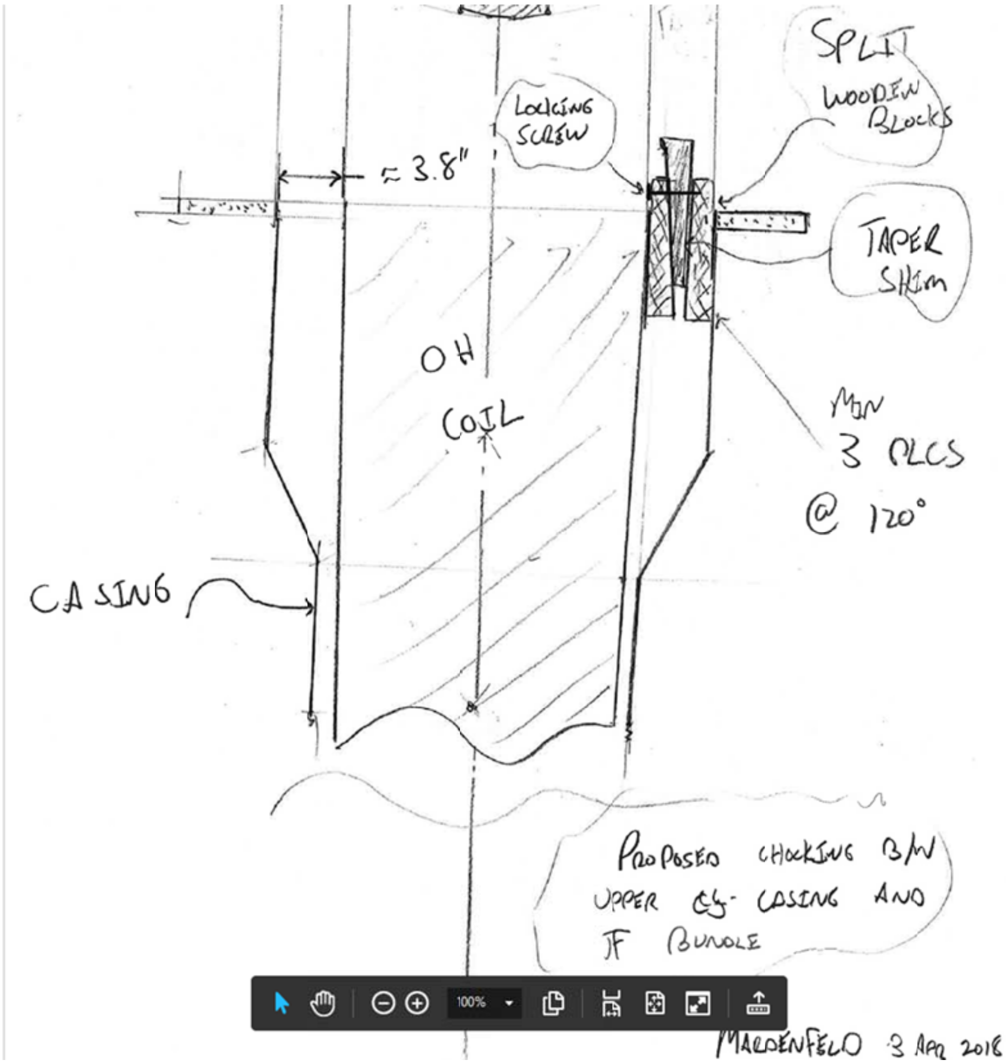


Figure 27: Example secondary fixation scheme between the CS Casing and TF Bundle

Comments

- Notice that the deflected shape in FEA plots is as expected, the displacement at the spherical joints is zero, and there is "zero" moment near the spherical joint. This confirms the model is performing as expected.
- Sanity checks confirm several key metrics, for instance, reaction forces at the bottom of the feet and some bending stresses
- "Safety Studs" to clamp the CS Casing in place were assumed to be loaded to 2000 lbf for qualification purposes, but this is not necessary in practice. They were modelled as applied loads, with no contributory stiffness or reactions. While clamping is recommended, there is no necessary minimum load.
- The lateral force reaction from a seismic load is not explicitly calculated. Although there may be some contribution from the clamping force of the safety studs across the Teflon slip plane, due to the inherently low coefficient of friction, this is not counted on for load reaction. Lateral load reaction will be taken by the "chocks" or shims shown in Figure 27, and partially by the "In Plane Pusher Adjustment Mechanism", E-DC11128-6.

Qualification of the Base Plate (E-DC11128-10)

Assumptions

- Aluminum material properties
- Note 0.75 in thick plate
- Half symmetry model
- Compression only support on the part of the plate which is supported by the OH Bottom Support Weldment (E-DC1482)
- Bolts are not explicitly modelled, but rather two bounding end conditions are used:
  - Case 1: QTY 4x 5/8 bolt holes have applied a constant force of 1500 lbf each on the lateral faces of the bolt hole slots. This is a low preload of about 6.5 KSI.
  - Case 2: QTY 4x 5/8 bolt holes have displacement in the vertical direction clamped to zero on the lateral faces of the bolt holes

Loads

- The worst case vertical force from any Jacking Leg (approximately 9100 lbf) is applied to the plate on the area the reaction would occur
- For Case 1, the bolt holes have a constant force applied

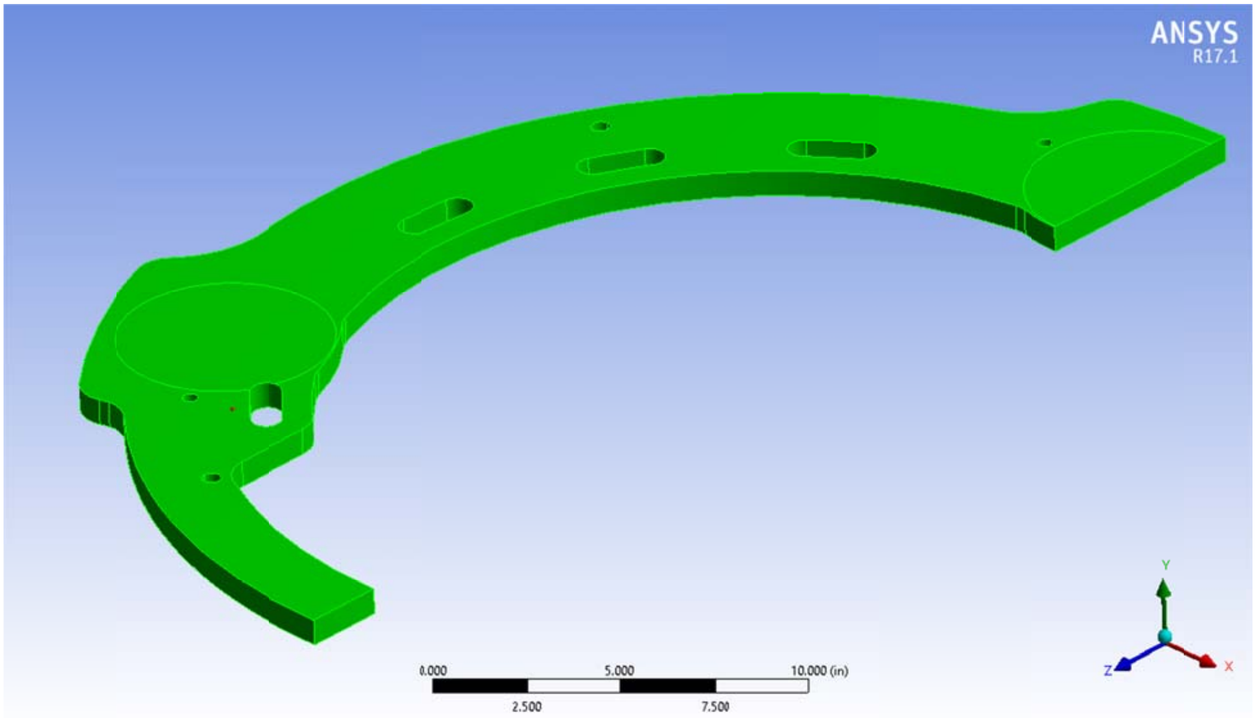


Figure 28: Geometry

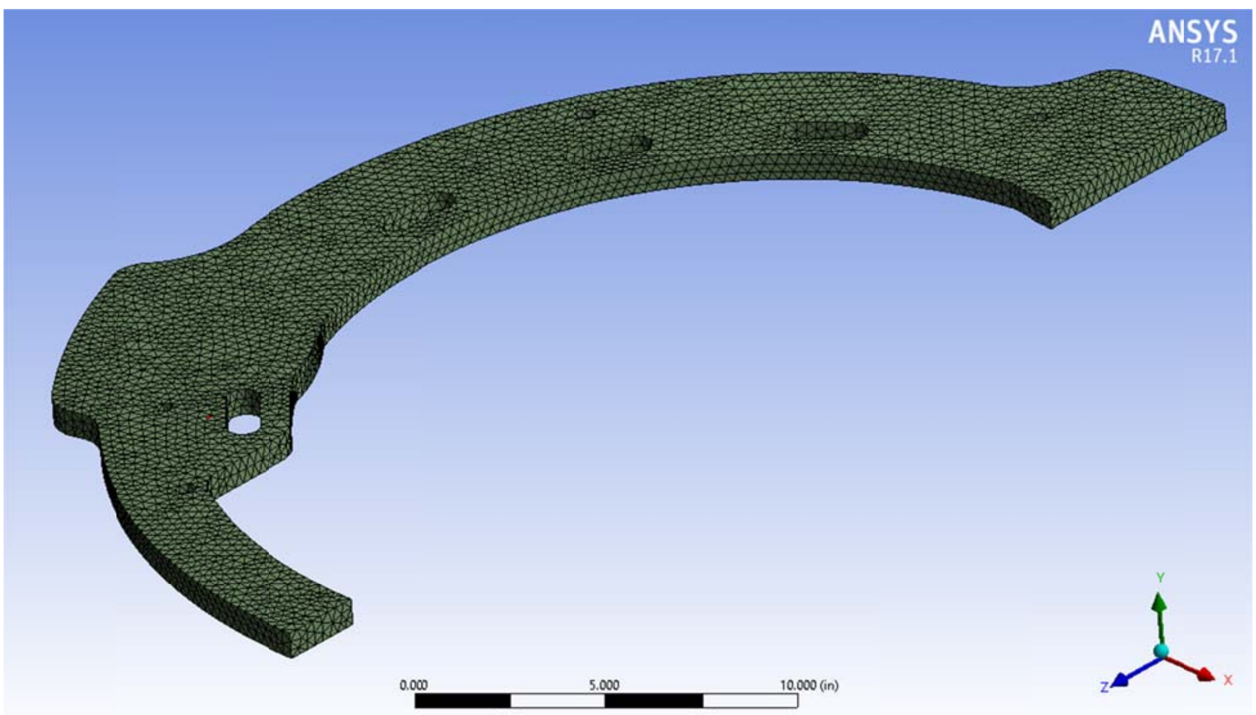


Figure 29: Mesh

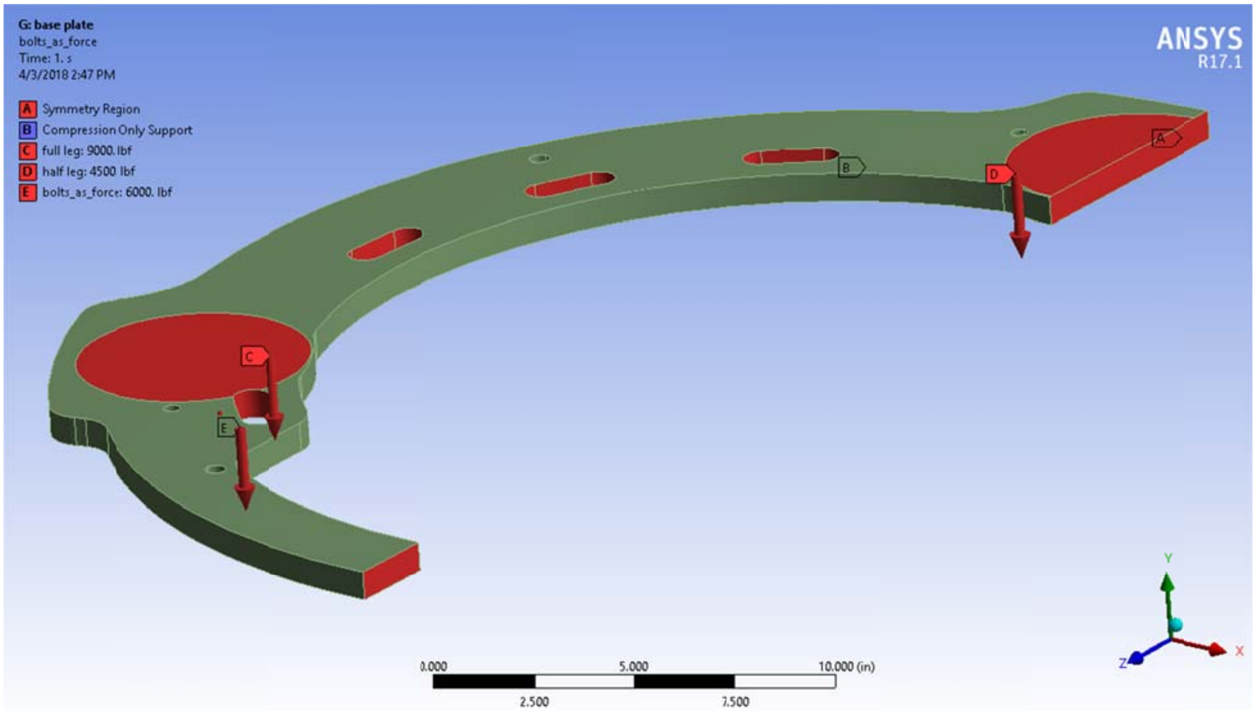


Figure 30: Loads and Reaction Forces, seen from above (Case 1)

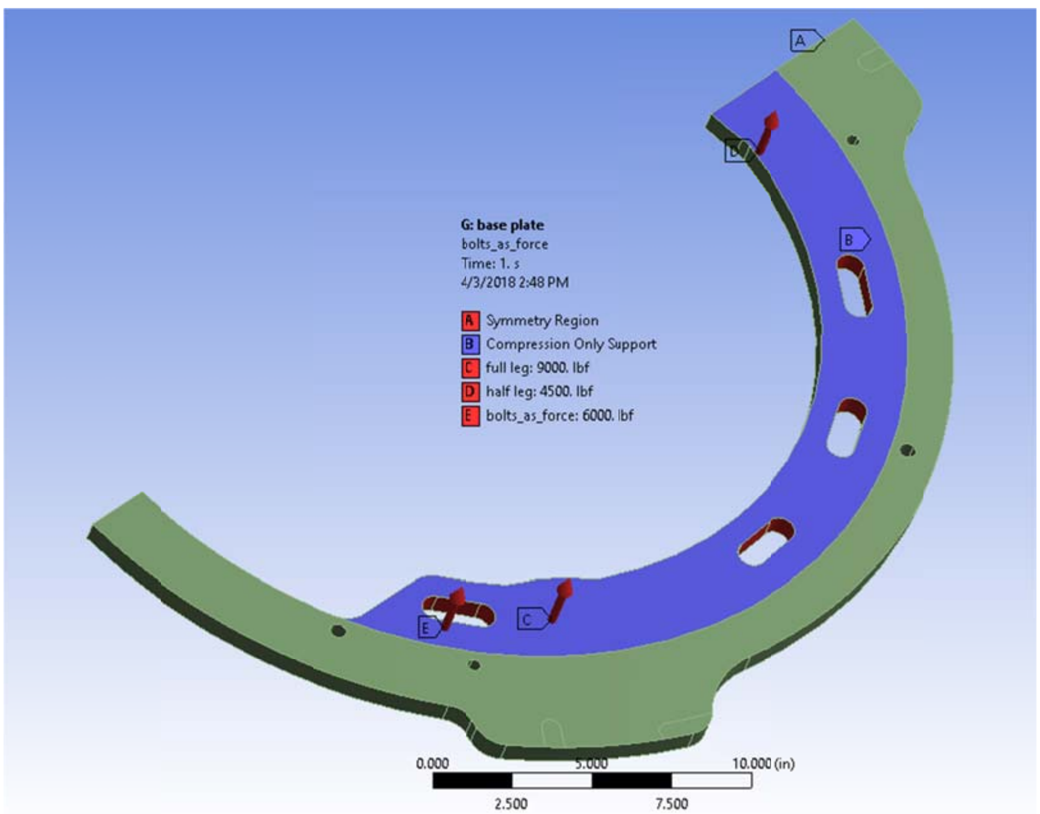


Figure 31: Loads and Reaction Forces seen from below (Case 1)

Case 2, not shown, replaces the 6000 lbf load with a zero displacement condition in the vertical direction.

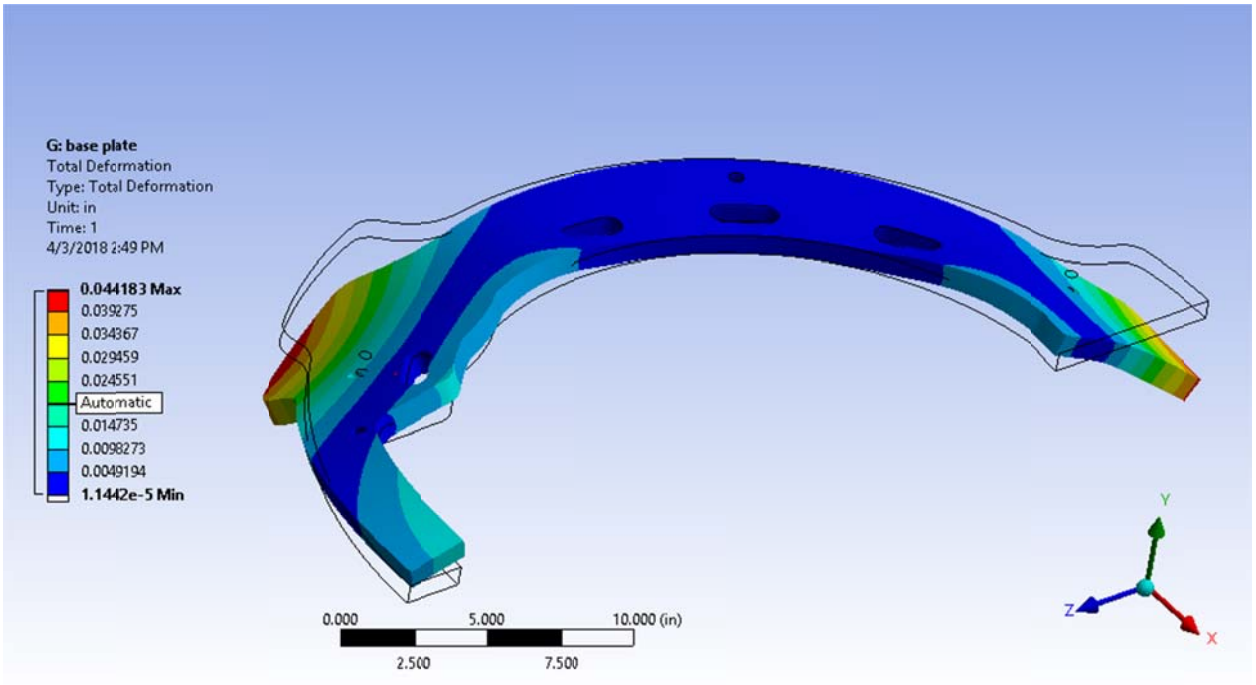


Figure 32: Displacement, Case 1

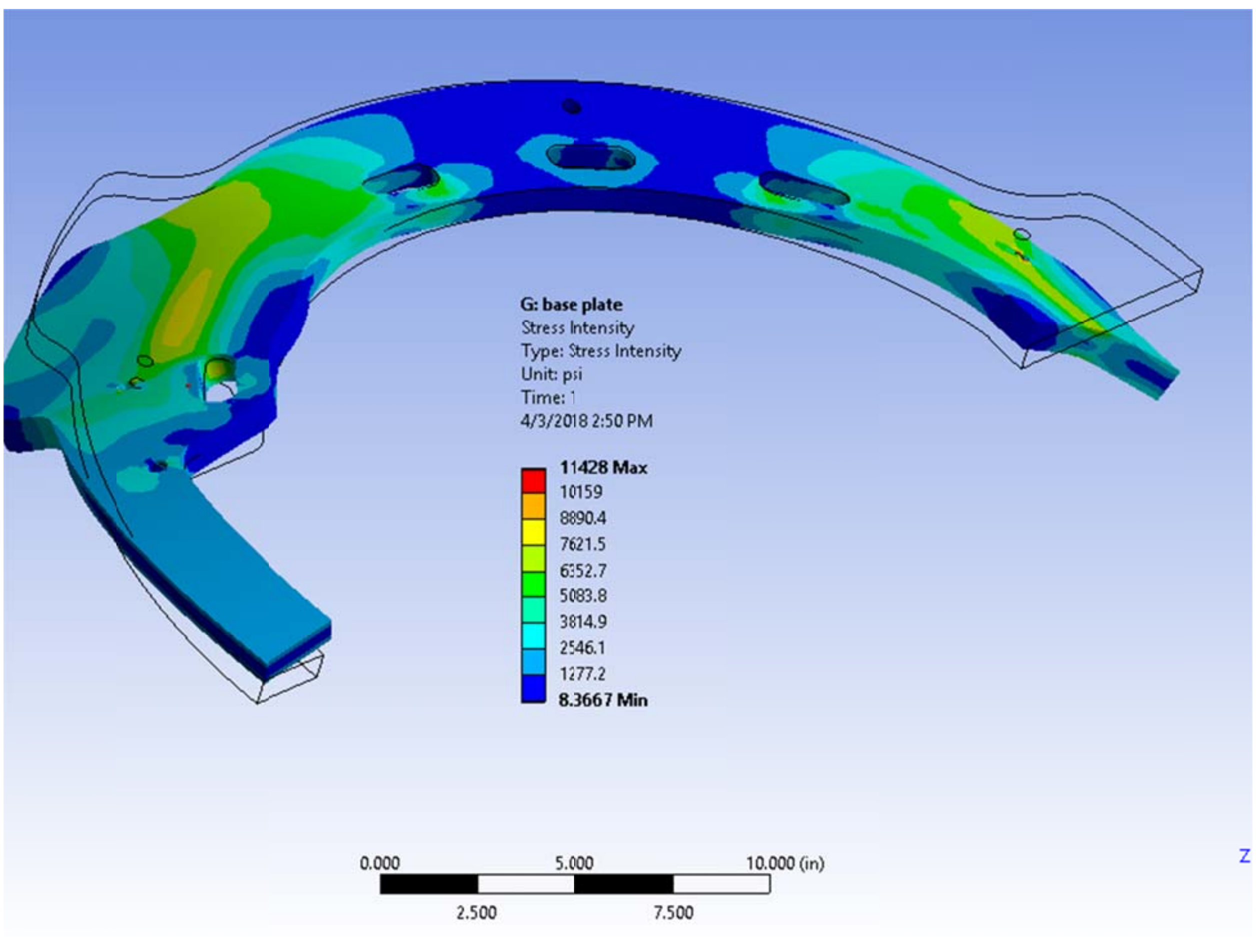


Figure 33: Stress Intensity, Case 1

Note that for Case 1, the stresses are very low. Even the local peaks are well below Sm = 22.5 KSI

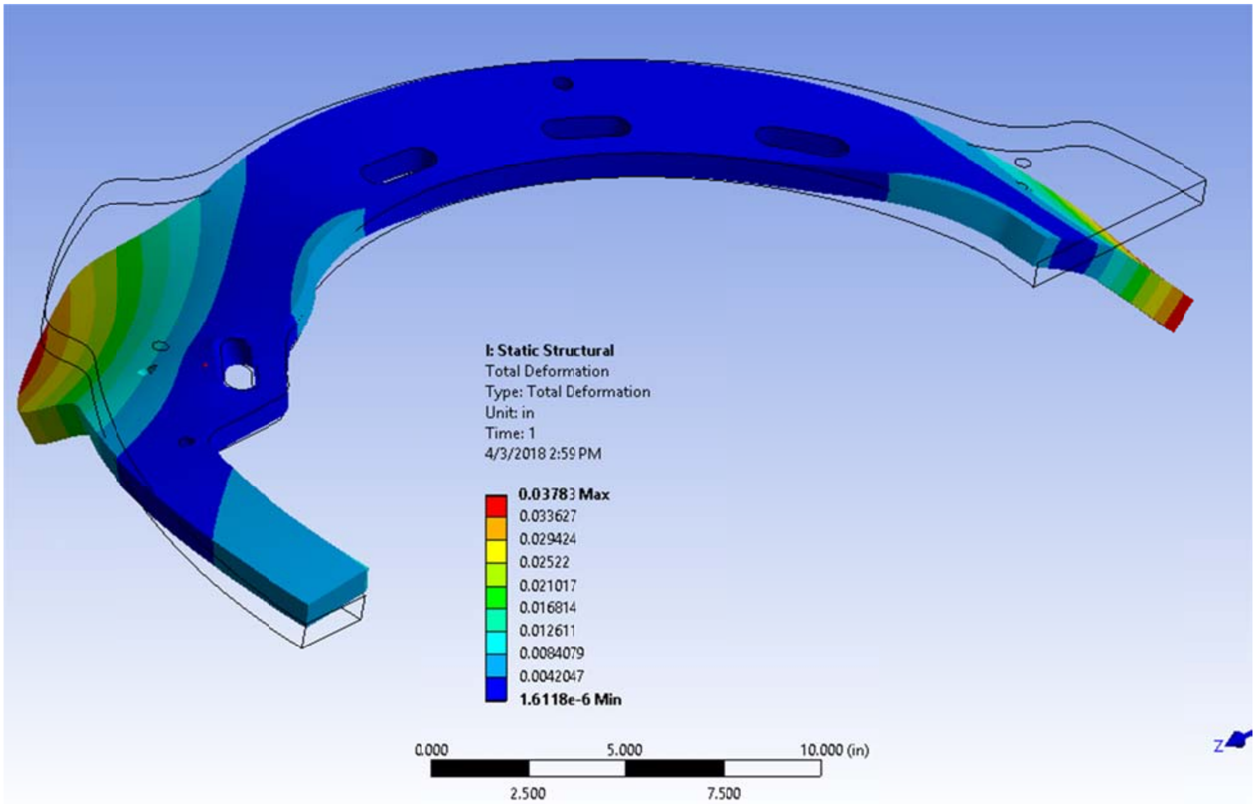


Figure 34: Displacement, Case 2

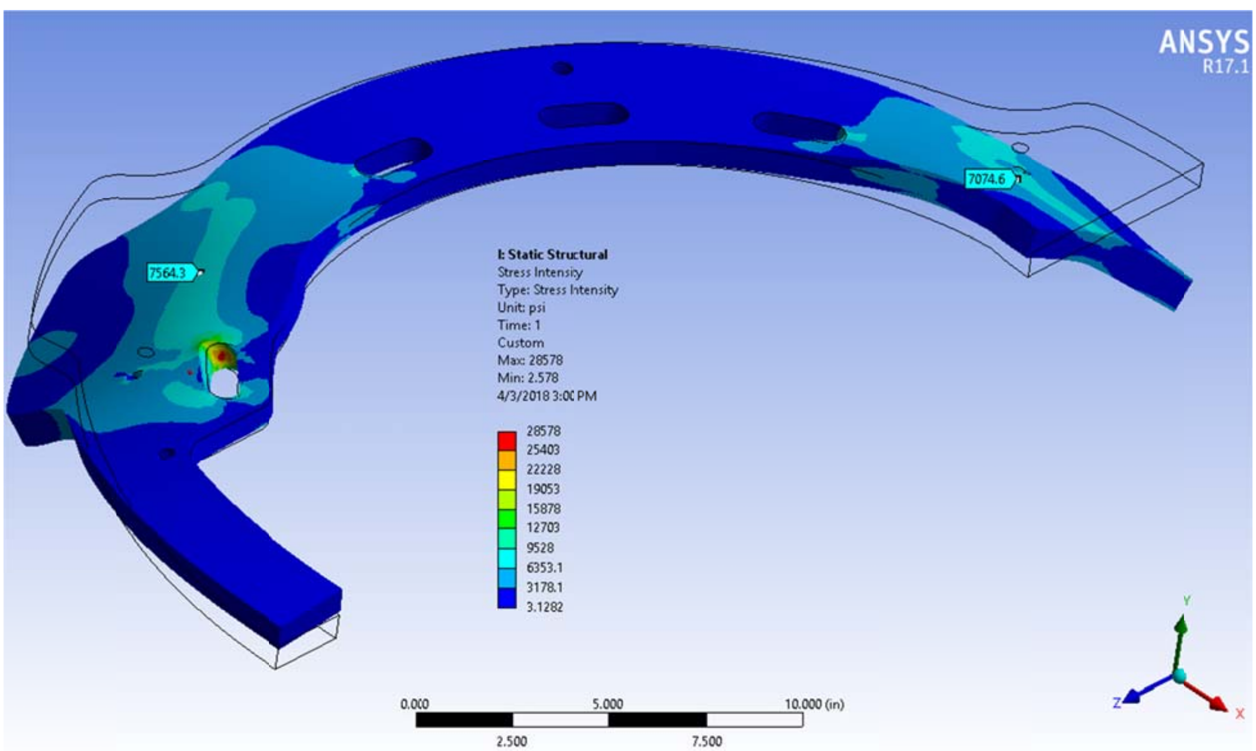


Figure 35: Stress Intensity, Case 2

Notice that stresses in the bulk remain unchanged or even slightly lower than Case 1.

Some local peak stresses approach Sm, but this is below allowable for peak, and are artifacts of boundary condition assumptions.

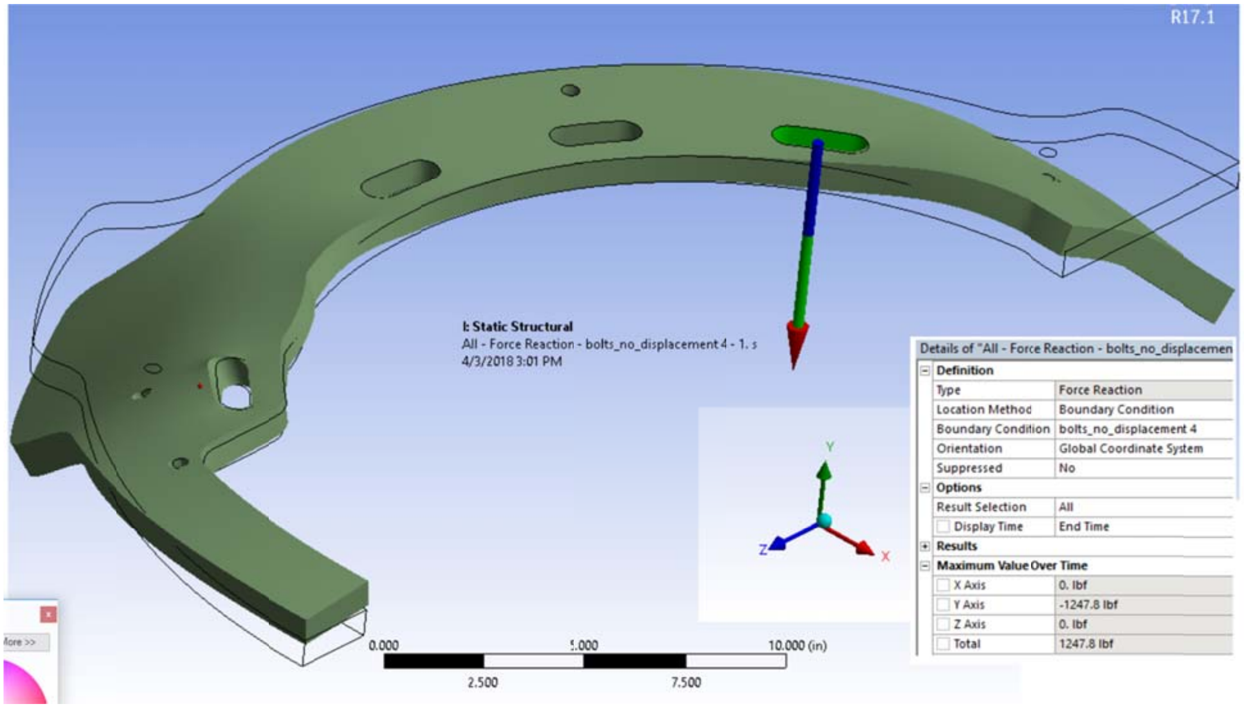


Figure 36: Reaction Force at Highest Loaded Bolt, Case 2

Reaction force from the highest loaded bolt for case 2 = 1250 lbf

Performance Data

Internal Thread Size (in)	(metric)	Effective Shear Area (in)²	Pull-Out Resistance (lb) Phenolic (9,500 PSI Shear)	380 Die Cast Aluminum (26,000 PSI Shear)	2024 T4 Wrought Aluminum (40,000 PSI Shear)	Tensile Strength (lb) of 160,000 PSI Heat-Treated Cap Screw (in)	(metric)
2	2	.040	380	1040	1600	–	510
4	3	.060	570	1560	2400	910	1250
6	3.5	.090	860	2340	3600	1370	1680
8	4	.130	1290	3380	5200	2120	2180
10	5	.170	1620	4420	6800	2825	3520
1/4	6	.270	2570	7020	10800	4800	4980
5/16	8	.410	3900	10660	16400	7900	9080
3/8	10	.610	5700	15860	24400	11700	14320
7/16	–	.780	7410	20280	31200	16050	–
1/2	12	1.040	9880	27040	41600	21550	20910
9/16	14	1.230	11590	31720	48800	27200	28520
5/8	16	1.610	15300	41860	64400	34200	38940
3/4	18	2.360	22420	61360	94400	50500	–

** Representative performance data for regular length. Preproduction prototype testing recommended for your application.*

Figure 37: Pull out Strength Values for Tap-Lok Threaded Inserts

http://www.groov-pin.com/tap-lok-hole-series.html

For a 5/8" Tap Lok threaded insert, in phenolic substrate, the pull out resistance is approximately 15,300 lbf

Comments

- Two bounding cases were examined to simplify boundary conditions of the bolts.
  - For Case 1, with bolt influence modelled as an applied force all stresses are extremely low, with even local peaks about ½ of the membrane allowable
  - For Case 2, with bolt influence modelled as a zero displacement boundary, the bulk stresses remain the same or slightly lower than Case 1. Some local peak stresses approach Sm, but they are allowed to go significantly higher than this, and thus are still acceptable. Note that these are artificially amplified by the zero displacement boundary condition.

- Case Two allows an estimation of the reaction forces which will be applied to the bolt, with the highest loaded bolt having approximately 1,250 lbf in tension.
  - This is lower than the assumed bolt pretension of 1500, which can be achieved easily and without torque wrenches. This indicates a good structural joint without lift off.
  - Drawing DC1523-2 specifies that the threaded inserts, TAP-LOK HOLE SERIES INSERT NO. H-62518-50, inserted into a G10 plate, react the loads from these bolts. Although detailed information on the strength is not available, the vendor cites an expected pull out strength of 15,300 lbf in phenolic material. This has ample margin, and it is furthermore expected that the through thickness shear strength of fiber reinforced G10 FR-4 exceed phenolic material.

- From these results, the Base Plate greatly exceeds minimum requirements.

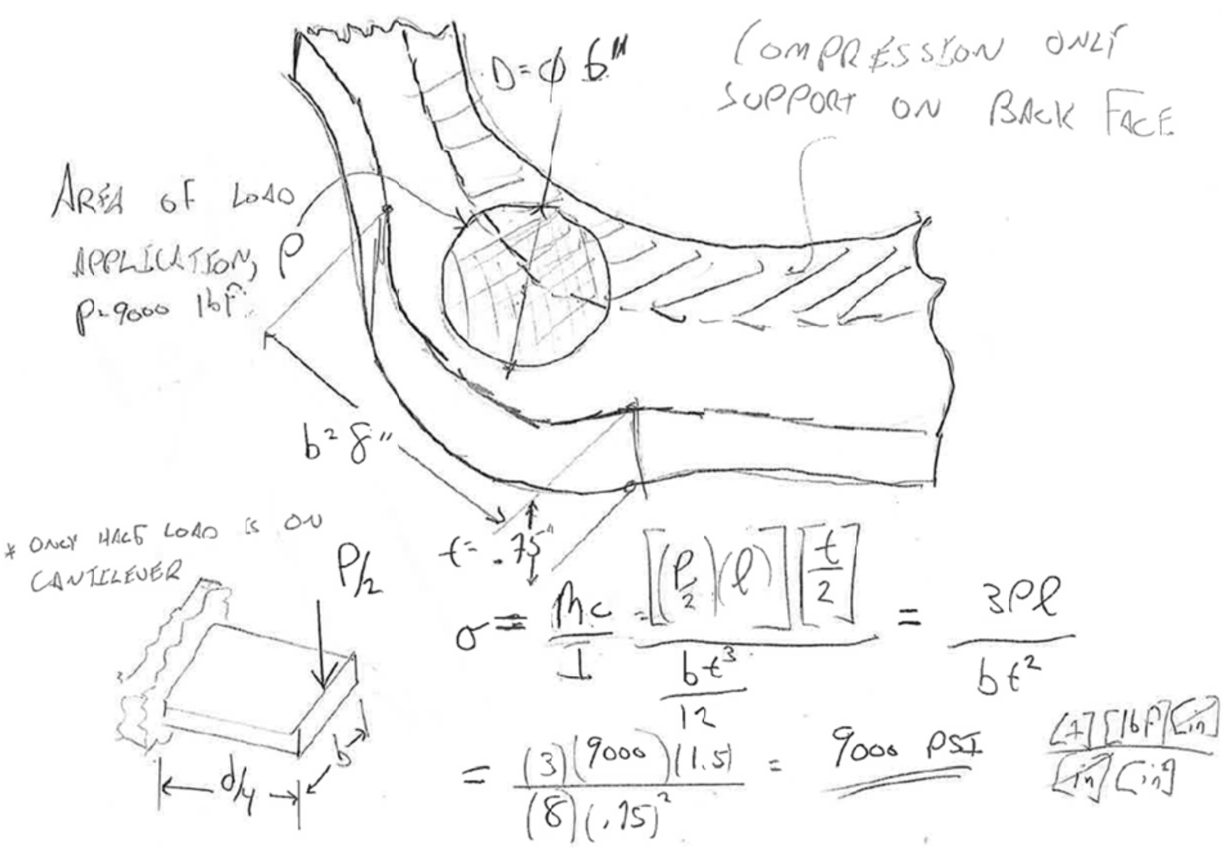


Figure 38: Sanity Check, Compare 9 KSI here to 7.5 KSI in Figures 33 and 35

Qualification of the Casing Support Plate, E-DC11128-03

Assumptions

- Aluminum steel material properties
- Quarter symmetry model
- Simplified model
    - Only the plate bearing in bending is modelled explicitly
    - The standoff plate, which transmits the bearing force of the casing through compression, is replaced with a zero displacement boundary condition at the contact point
    - An upward force (equal and opposite to the download load from the casing weight + locking studs), is applied to the vertical face at the ID of the support plate. This is a conservative assumption: in reality, the load is distributed over a larger area which results in a lower effective moment arm.
    - The bolts which fix the casing plate to the underside of the Casing are modelled as constant force

Loads

- Vertical load of 4000 lbf in quarter symmetry (16000 lbf total) is applied to the vertical face of the ID of the plate
    - Based on assumption of total Casing weight of 4000
    - Based on assumption of QTY 6x 3/8 in locking studs at 2000 lbf each
- Bolt Loads
    - The bolts which hold the plate to the underside of the Casing are assumed to have 2000 lbf each
    - This is equivalent to about 25 KSI, or the rated torque for low strength 3/8-16 UNC
    - In reality these only need to be finger tight, they serve only to hold the plate against the Casing during the lift, but overestimating the bolt is conservative with respect to plate bending stresses

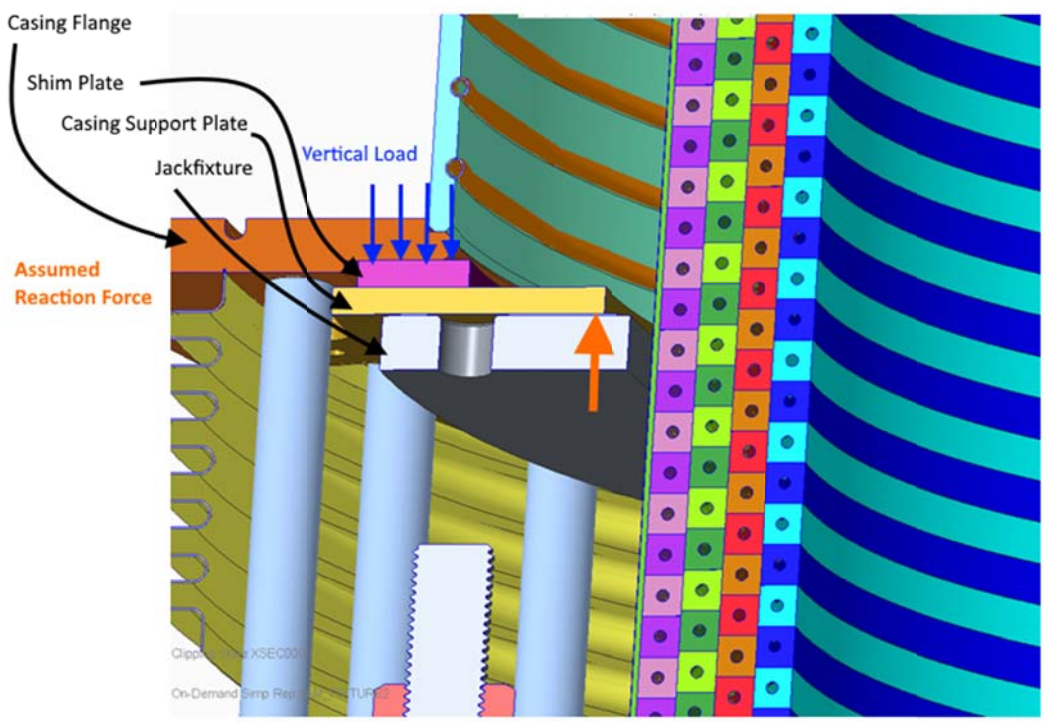


Figure 39: Casing Support Flange Load Path

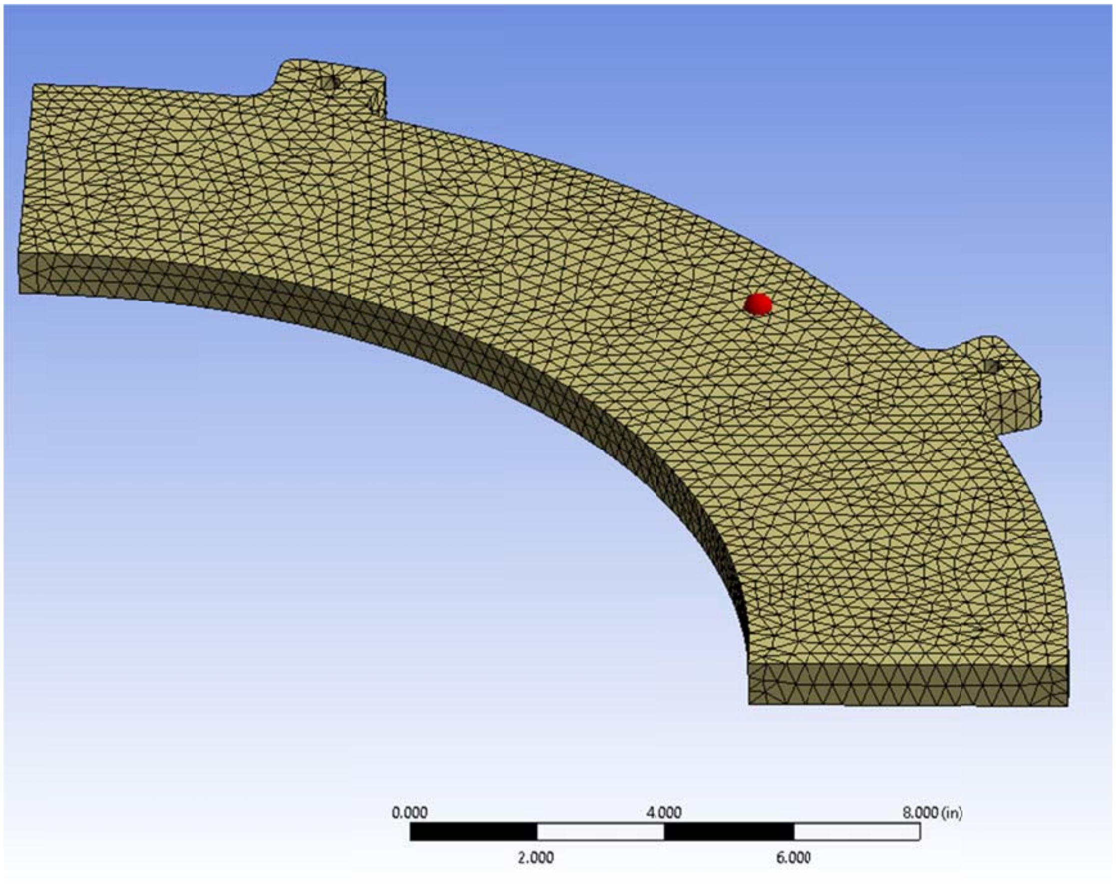


Figure 40: Mesh

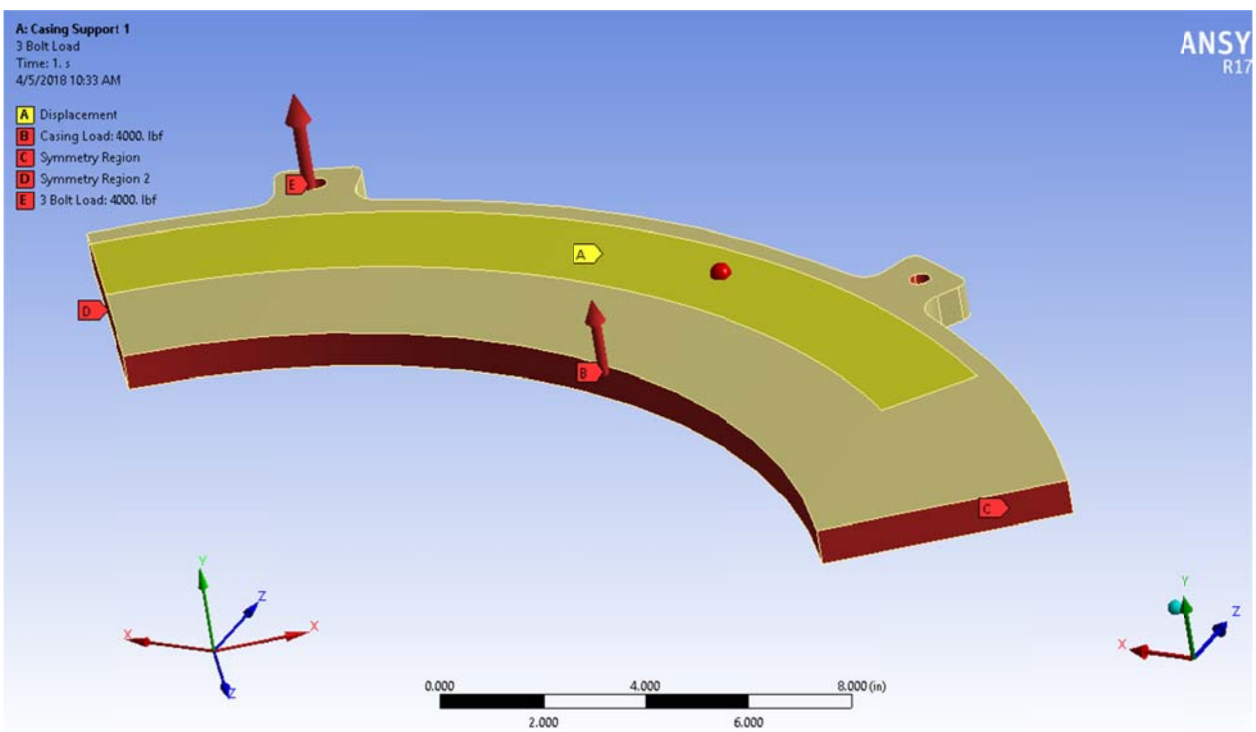


Figure 41: Boundary Conditions and Loads

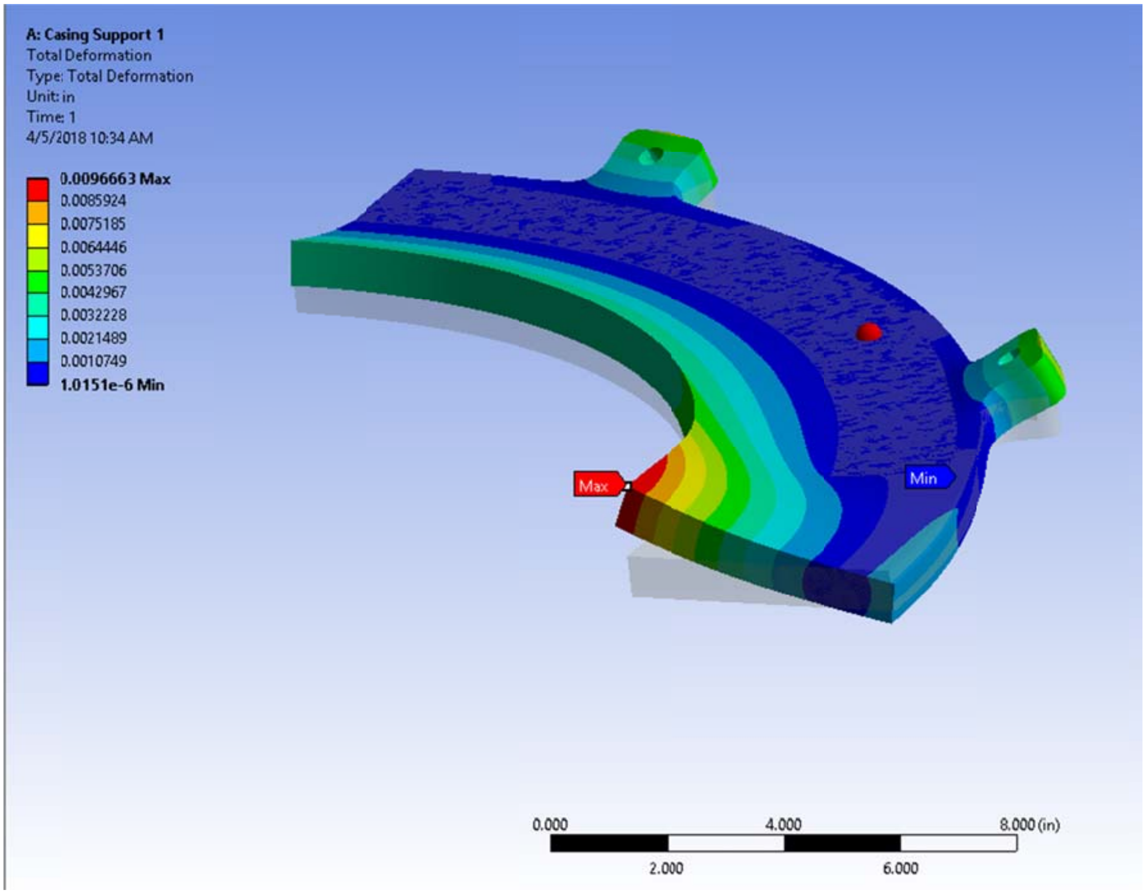


Figure 42: Deflected Shape

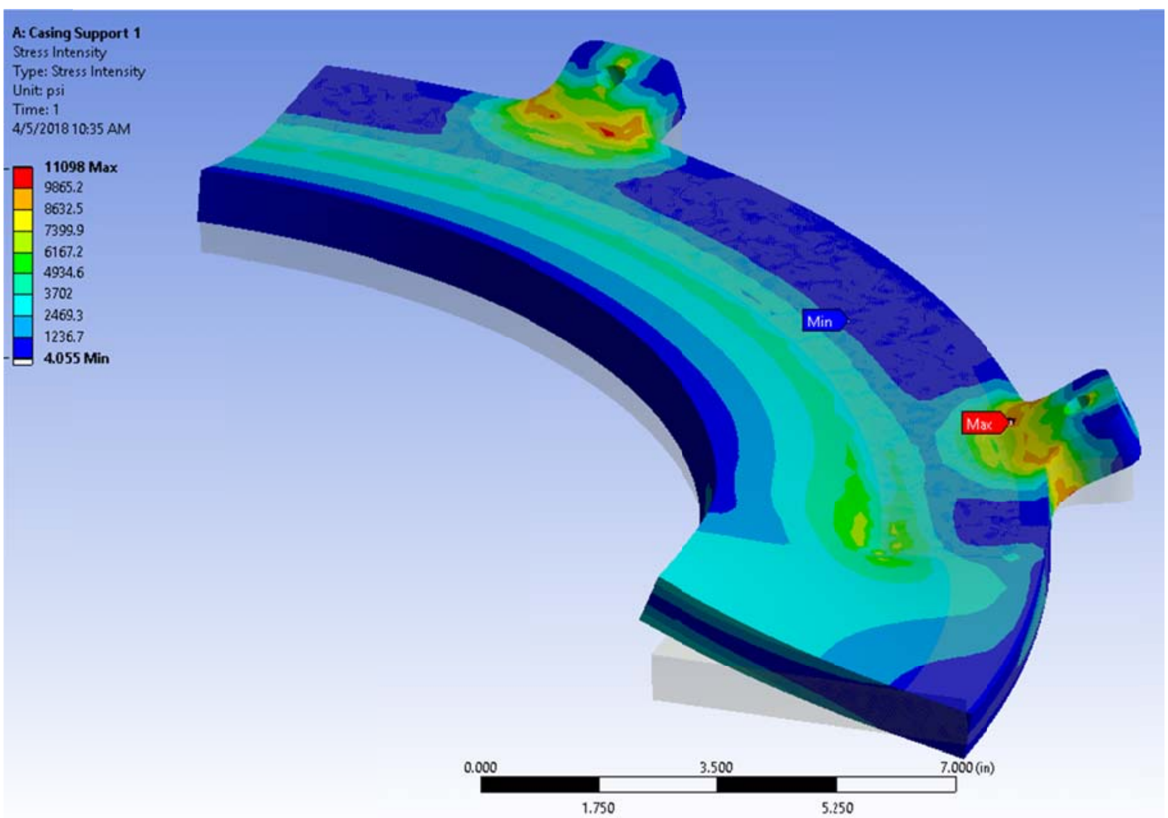
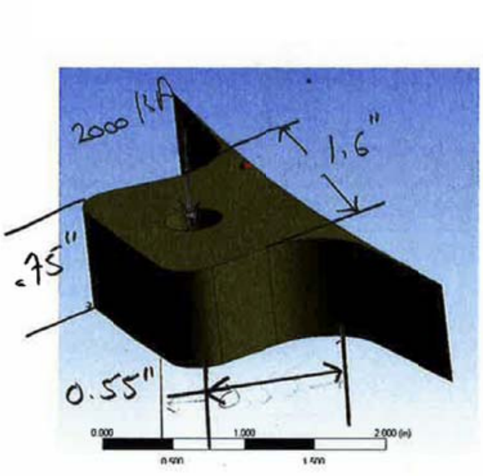


Figure 43: Peak Stress is 11 KSI

Note that the peak stress from FEA is less than half of Sm = 22.5 KSI. This is also driven by local bending stresses from conservatively assumed bolt torques, so the plate has very large margins.



$$\sigma = \frac{Mc}{I} = \frac{(Pl)\left(\frac{t}{2}\right)}{\left(\frac{bt^3}{12}\right)} = \frac{6Pl}{bt^2} = \frac{(6)(2000)(0.55)}{(1.6)(.75)^2} \qquad \frac{[1][lbf][in]}{[in][in^2]}$$

$$\sigma \approx 7.3 \text{ KSI} \checkmark$$

Figure 44: Sanity Check on Bending Stress in Plate

Qualification of the Floating Locking Plate, E-DC11128-05

Assumptions

- Mild steel material properties
- Half symmetry model
- Simplified model
    - The base plate, which serves as an upward restraint on the locking plate, is modelled as a zero displacement boundary condition in the vertical direction
    - Since 6x total locking studs are planned on being used, 3x are shown on the half sym model
        - The positions of the 3x locking studs are chosen to be those furthest away from the bearing force reaction between the locking plate and the base plate

Loads

- Bolt Loads
    - The locking sutds are assumed to have 2000 lbf each, applied to the inner surface of the bolt holes
    - This is equivalent to about 25 KSI, or the rated torque for low strength 3/8-16 UNC
    - In reality these may not need to be this tight, but are modelled at the highest normal load expected for their size

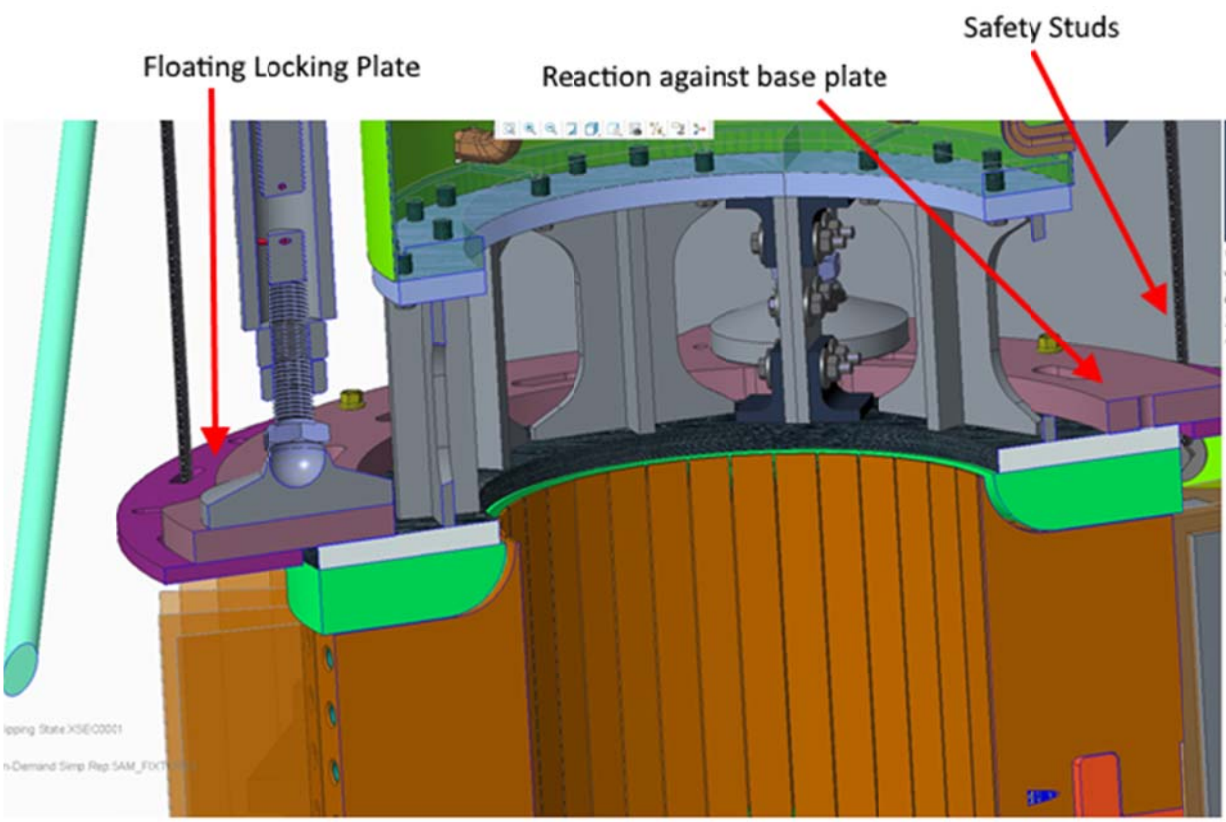


Figure 45: Floating Locking Plate Load Path

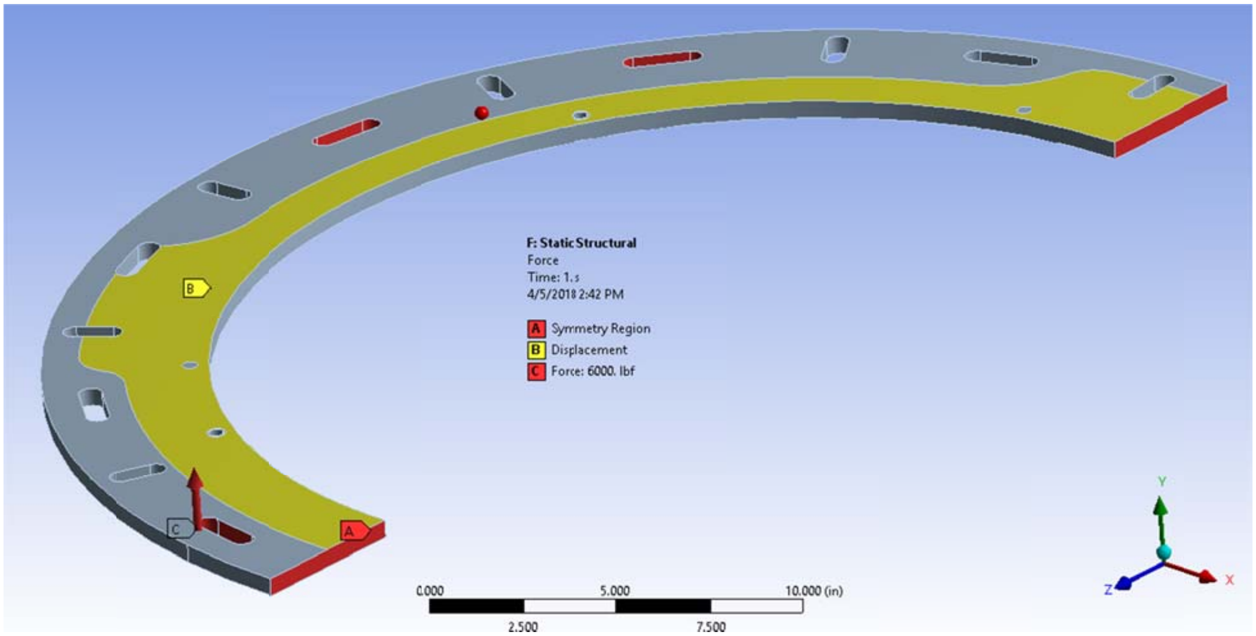


Figure 46: Boundary Conditions and Loads on Locking Plate

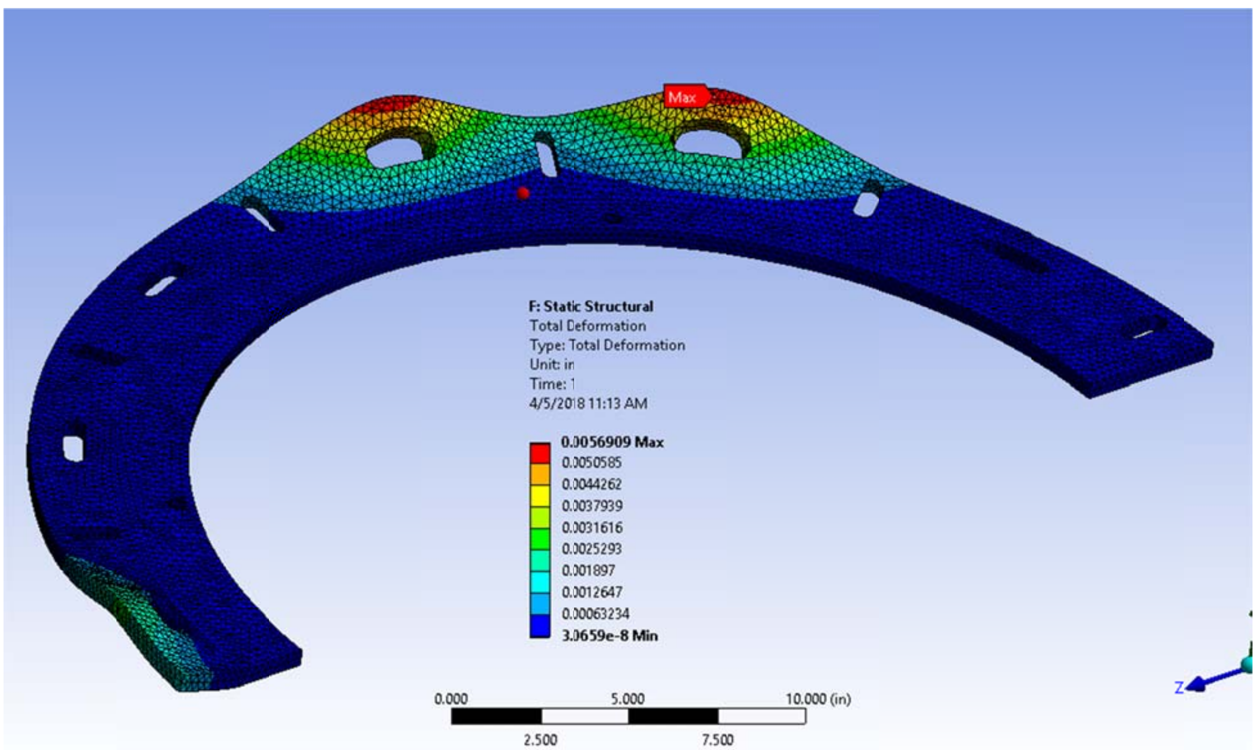


Figure 47: Displacement Results

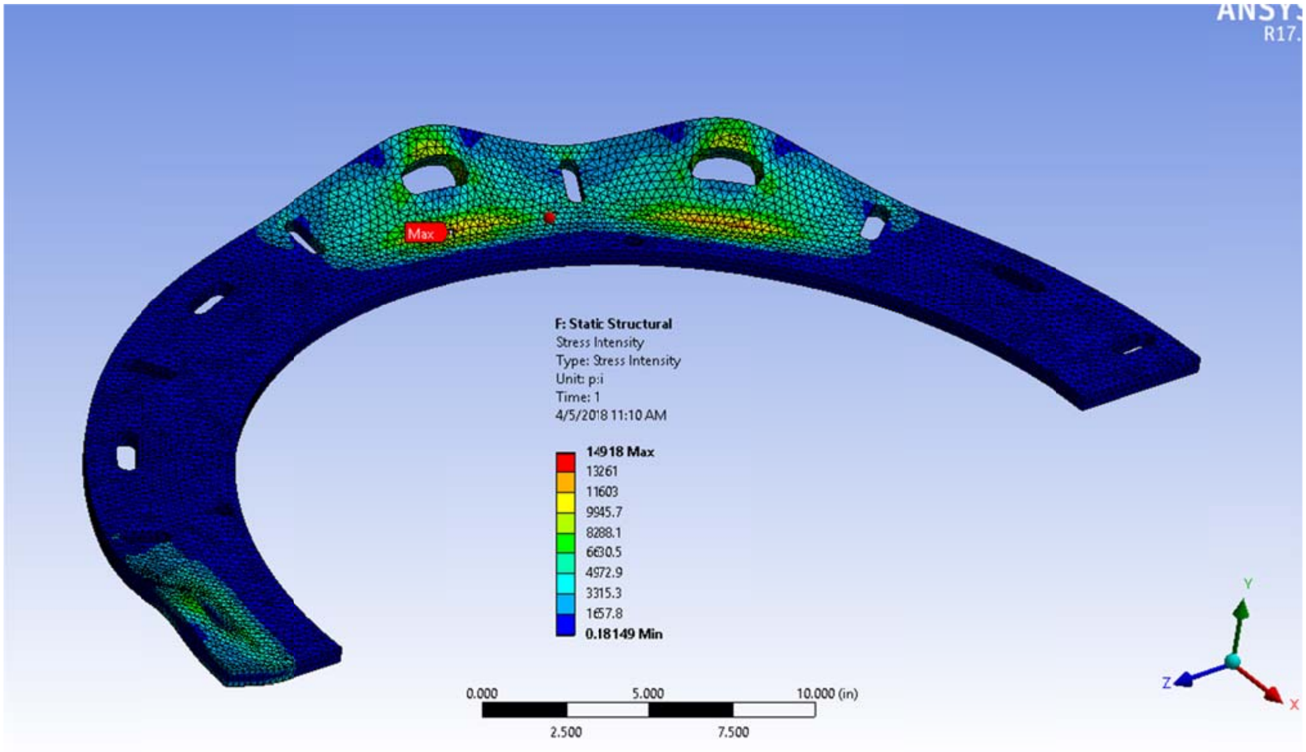


Figure 48: Stress Intensity

Figure 49

Peak stress of 15 KSI is << than membrane allowable of 24 KSI and is acceptable.

Michael Mardenfeld
2 May 2018
Structural Qualification of E-DC11130, NSTX-U Casing Trial Asm Tool Fixture

Comments on Seismic Design Loads

This calculation, NSTXU-CALC-12-13-00, assumes an "off normal" horizontal load of 1000 lbf, applied at the center of mass of the CS Casing. This is a conservative assumption intended to envelope unusual loads - particularly seismic loading from earthquakes. This commentary justifies that assumption while a site wide standard for earthquake loading is being finalized.

NSTX-U-CALC-12-14-00, Justification of Seismic Design Loads for E-DC11130: NSTX-U Casing Trial Asm Tool Fixture, traces the PPPL site obligations related to earthquakes from DOE-STD-1020-2016: Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities. For the components in question, the requirement is to follow ASCE-7: "Minimum Design Loads and Associated Criteria for Buildings and Other Structures". Application of ASCE-7 results in the following requirements:

Seismic Design Loads:Earthquake Loads[1]

- "Earthquake Loads"
  - Equivalent static loads applied at the center of mass of components
    - 285 lbf lateral (horizontal side load)
    - 113 lbf vertical load, applied in the worst direction
- Load Combinations which must be sustained
  - 100% of Dead Load + 70% of Earthquake Load
  - 60% of Dead Load + 70% of Earthquake Load
- Dynamic Effects
  - "Consideration shall be given to the dynamic effects of the components, their contents, and where appropriate, their supports and attachments…"

Note that the finite element analysis assumes {100% of Dead Load + 100% Stud Clamping Force + 350% Earthquake Load}, and finds that the failure mode of the system with the least margin is bending stress and/or buckling of the most highly loaded Jacking Leg in a worst case load direction. This is clearly conservative from the point of view of strength, and fulfills the first load combination case.

The second load combination case requires that upending does not occur, even with credit taken for only 60% of the Dead Load resisting an overturning moment. Although the clamping force from the studs would prevent overturning regardless, on the following page it is shown that overturning would just barely be prevented even without consideration of the studs or secondary lateral supports. Therefore a specified clamping force and torque control of the studs is not required, as any resistance from the studs is sufficient to prevent overturning. Despite this, studs shall be installed whenever the Casing is not being actively moved.

Note that since the total vertical applied load in the detailed FEA was 16,000 lbf, the superposition of +/- 113 lbf vertical load is a variation of less than 1%. It is negligible and can be ignored without any change in conclusions.

---

1 Although the main body if the calculation conservatively assumes 4000 lbf weight, the actual weight is closer to 3000 lbf because the PF1B Coils are not presently installed.

Finally, as computed in NSTX-U-CALC-12-14-00, the lateral stiffness of the {Casing + Tooling} leads to a vibration mode which is very close to the design basis earthquake's dominant frequencies. The following simple calculation shows that an increase of the lateral stiffness of the {Casing + Tooling} by a factor of approximately 10x reduces the amplification factor to manageable levels. It assumes 2% damping of the structure and yields amplification factors of approximately 1.05x. Increasing the lateral stiffness by using members which react through compression rather than bending, as has already been recommended in the calculation, should accomplish this.

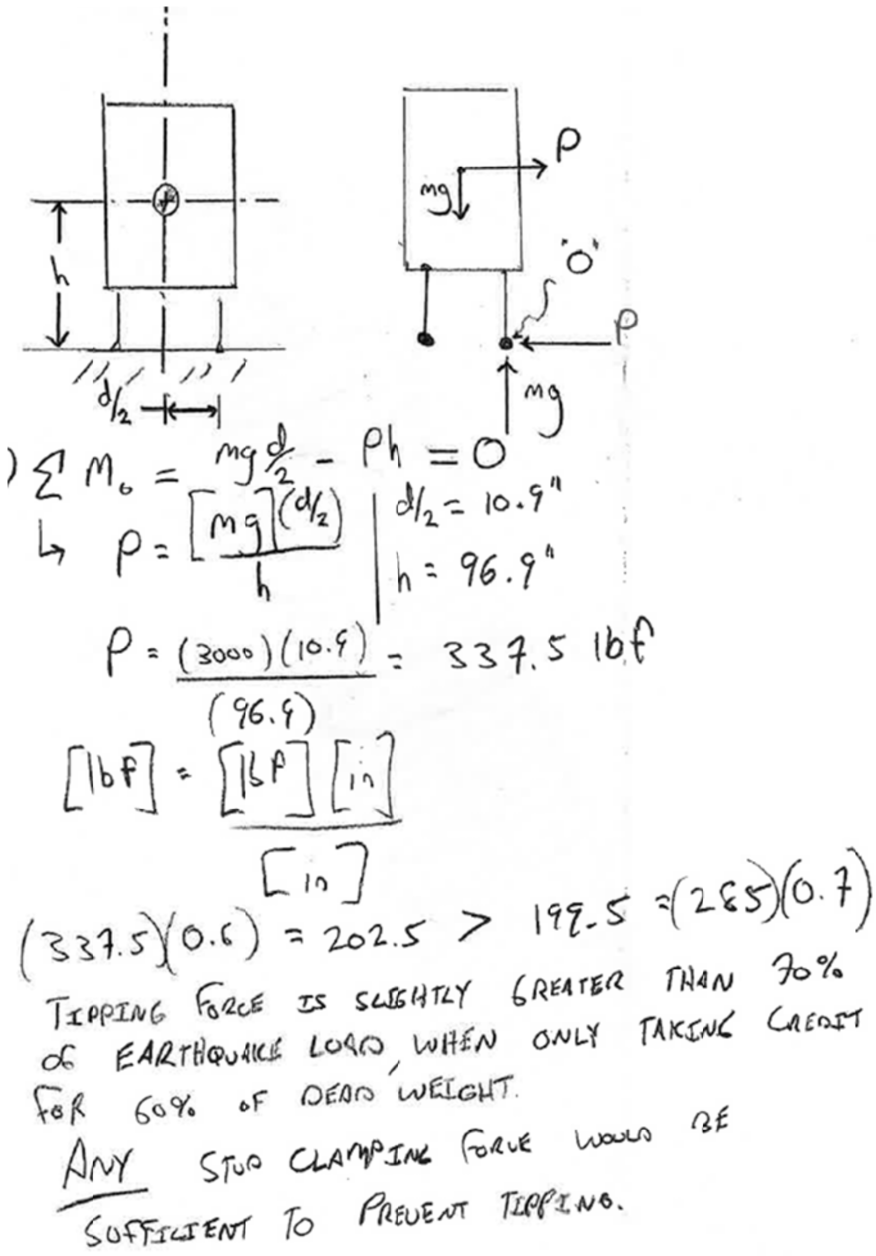


Figure 1: Moment Balance to Computer Overturning Load

Note that 60% of Dead Weight is just sufficient to resist overturning from 70% of Earthquake Load, without taking credit for stud tension or lateral supports. With consideration of these, there will be ample margin.

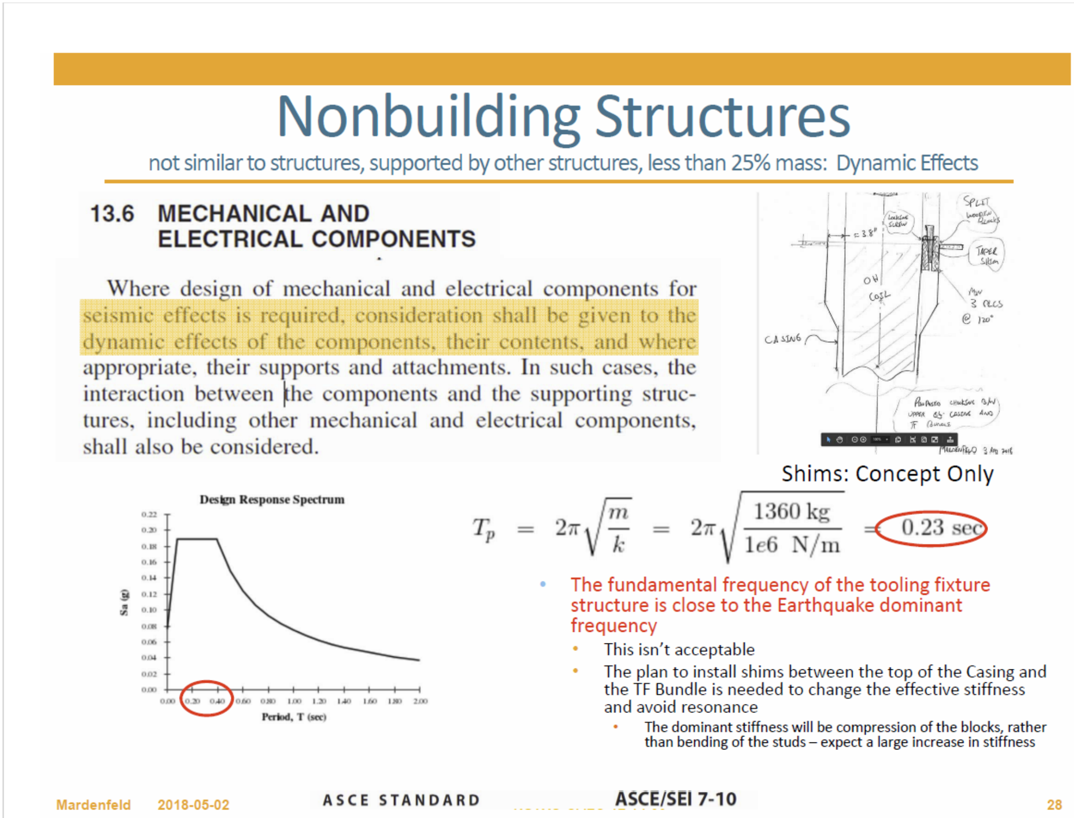


Figure 2: Excerpt from NSTXU-CALC-12-13-00 Showing Fundamental Frequency of {Casing+Tooling}

$$\beta_d = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} \quad \text{with} \quad r = \frac{\omega_{forced}}{\omega_{parts}}$$

Assume $\zeta = .02$, $r = 1 \rightarrow \beta_0 = 25$ RESONANCE

$\zeta = .02$, $r = .22 \rightarrow \beta_0 = 1.05$ SMALL AMPLIFICATION OK.

Assume $\zeta = .02$

So if unbuttressed component is near resonance, what stiffness increase is required to reduce amplification factor to 1.05?

We want: $\frac{r'}{r} = \frac{.22}{1} = .22$

$$\frac{r'}{r} = \frac{\frac{\omega_{forced}}{\omega_{part}'}}{\frac{\omega_{forced}}{\omega_{part}}} = \frac{\omega_f \sqrt{\frac{m}{k'}}}{\omega_f \sqrt{\frac{m}{k}}} = \sqrt{\frac{k}{k'}}$$

$$\text{So} \quad k' = \left(\frac{r}{r'}\right)^2 k = \left(\frac{1}{.22}\right)^2 k = 20.7\ k$$

NEED TO INCREASE LATERAL STIFFNESS BY APPROXIMATELY A FACTOR OF 20x

Figure 3: Computation showing 20x Stiffness Increase eliminates resonance risk by reducing amplification factor to 1.05x

The magnification factor is

$$\beta = \left|\frac{1}{1-\left(\frac{\omega_f}{\omega}\right)^2}\right| = \left|\frac{1}{1-\left(\frac{104.7\ \frac{\text{rad}}{\text{sec}}}{68.09\ \frac{\text{rad}}{\text{sec}}}\right)^2}\right|$$

$$= 0.733$$

The amplitude of oscillation is calculated from Eq. 60.50.

$$D = \beta\left(\frac{F_0}{k}\right) = (0.733)(0.00667\ \text{in})$$

$$= 0.00489\ \text{in}$$

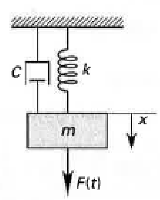
16. DAMPED FORCED VIBRATIONS

If a viscous damping force, $Cv = C(dx/dt)$, is added to a sinusoidally forced system, as in Fig. 60.15, the differential equation of motion is

$$m\frac{d^2x}{dt^2} = -kx - C\frac{dx}{dt} + F_0\cos\omega_f t \qquad \text{[SI]} \qquad 60.52(a)$$

$$\frac{m}{g_c}\frac{d^2x}{dt^2} = -kx - C\frac{dx}{dt} + F_0\cos\omega_f t \qquad \text{[U.S.]} \qquad 60.52(b)$$

Figure 60.15 *Damped Forced Oscillations*



The solution to Eq. 60.52 has several terms. As a result of the damping force, the complementary solution has decaying exponentials. Therefore, the complementary solution is also known as the *transient component* because its contribution to the system performance decreases rapidly. However, the transient terms do contribute to the initial performance. For this reason, initial cycles may experience displacements greater than the steady-state values. The particular solution is known as the *steady-state component.*

Equation 60.53 defines the damped magnification factor, β_d, for steady-state damped forced vibrations. (See Fig. 60.16.) The magnification factor for the undamped case (see Eq. 60.50) can be derived by setting $\zeta = 0$.

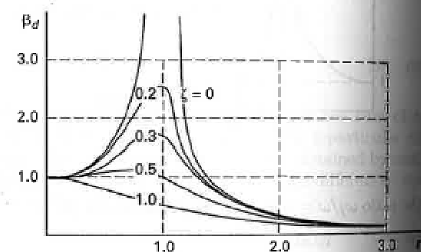
$$\beta_d = \left|\frac{D}{\frac{F_0}{k}}\right| = \frac{1}{\sqrt{\left(1-\left(\frac{\omega_f}{\omega}\right)^2\right)^2 + \left(\frac{C\omega_f}{m\omega^2}\right)^2}} \qquad \text{[SI only]}$$

$$= \frac{1}{\sqrt{\left(1-\left(\frac{\omega_f}{\omega}\right)^2\right)^2 + \left(\frac{2C\omega_f}{C_{\text{critical}}\omega}\right)^2}} \qquad \text{[U.S. and SI]}$$

$$= \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} \qquad \text{[U.S. and SI]} \qquad 60.53$$

$$r = \frac{\omega_f}{\omega} \qquad 60.54$$

Figure 60.16 *Damped Magnification Factor*



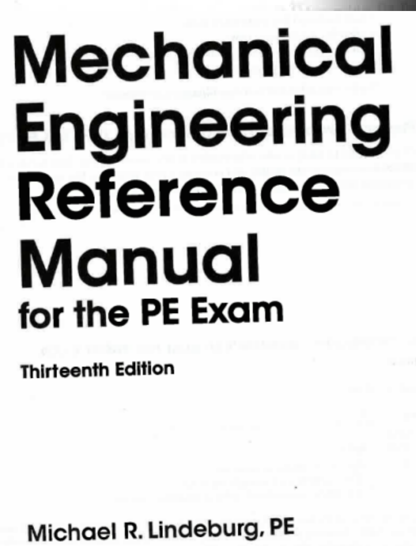


Figure 4: Reference for Dynamic Magnification Factor