LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Stress and Deflection Analysis of the TMS Large Motion Restraint Design

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1 Abstract

The Transmission Monitor Suspension (TMS) is restrained from large motion (swinging) by an assembly which attaches to the BSC chamber. The BSC chamber deflects during pump down due to the large atmospheric pressure loads. An analysis was conducted to insure that the TMS large motion restraint system (a) does not deflect so much that it contacts the suspended TMS payload and (b) is not over-stressed.

2 The Large Motion Restraint Assembly for the Transmission Monitor Suspension

The Transmission Monitor Suspension (TMS) assembly is positioned behind the End Test Mass (ETM) quadruple pendulum suspension assembly ("quad") on the optics table in the BSC end chambers (as depicted in Figure 1). The TMS is prevented from swinging too far, in the event of an earthquake, or a bump by personnel, by a Seismic Safety Stop Assembly (aka Earthquake Stop Assembly, D0901787), which is shown in Figure 2. Two brackets, which are welded to the interior wall of the BSC chamber, support the EQ Stop Assembly. The interfacing brackets on the EQ Stop Assembly extend down below the chamber brackets by 3.4 inches (as depicted in Figure 3).

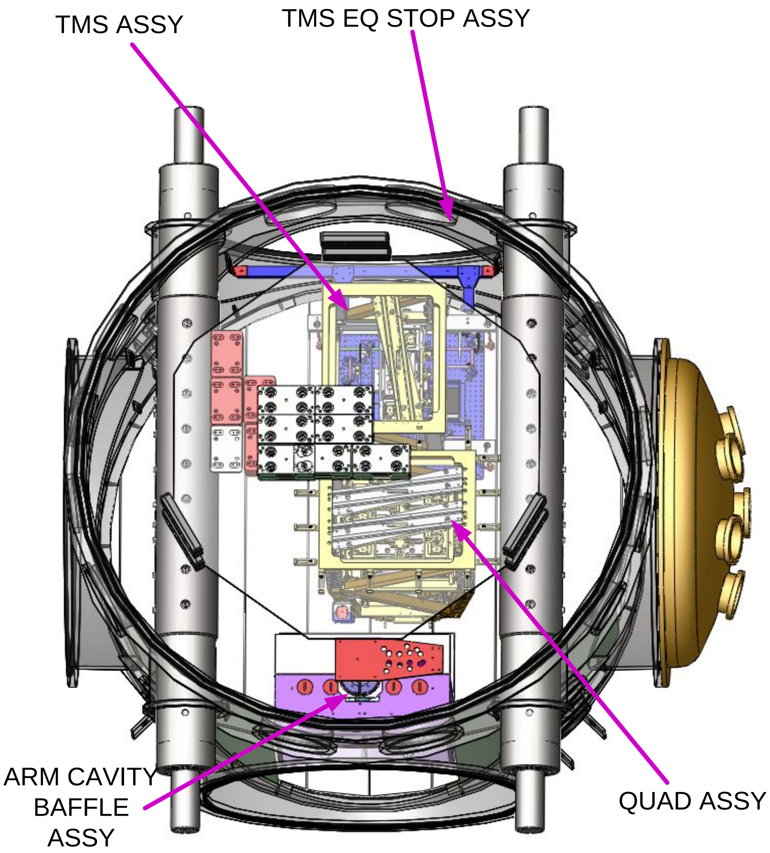


Figure 1: TMS Assembly shown in the WBSC6 chamber

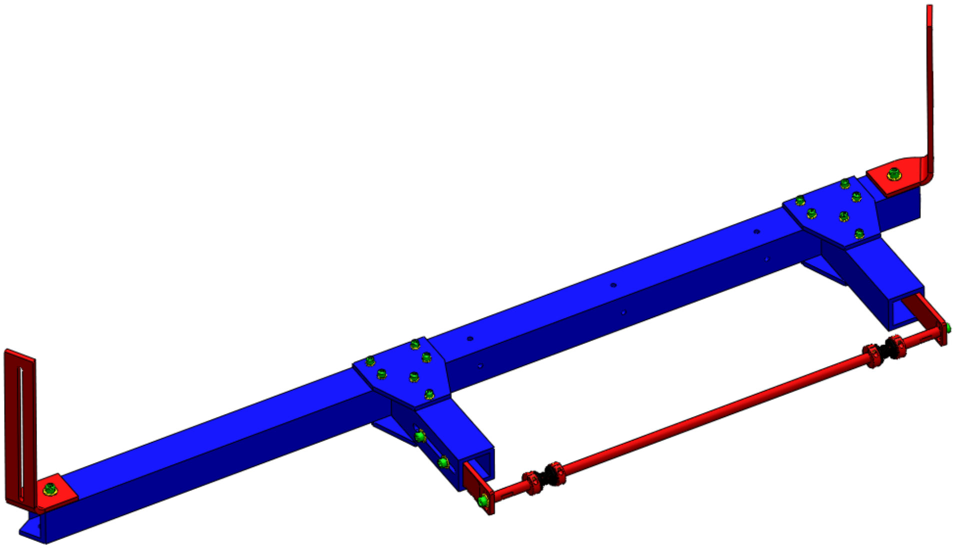


Figure 2: TMS Seismic Stop Assembly (D1001781)

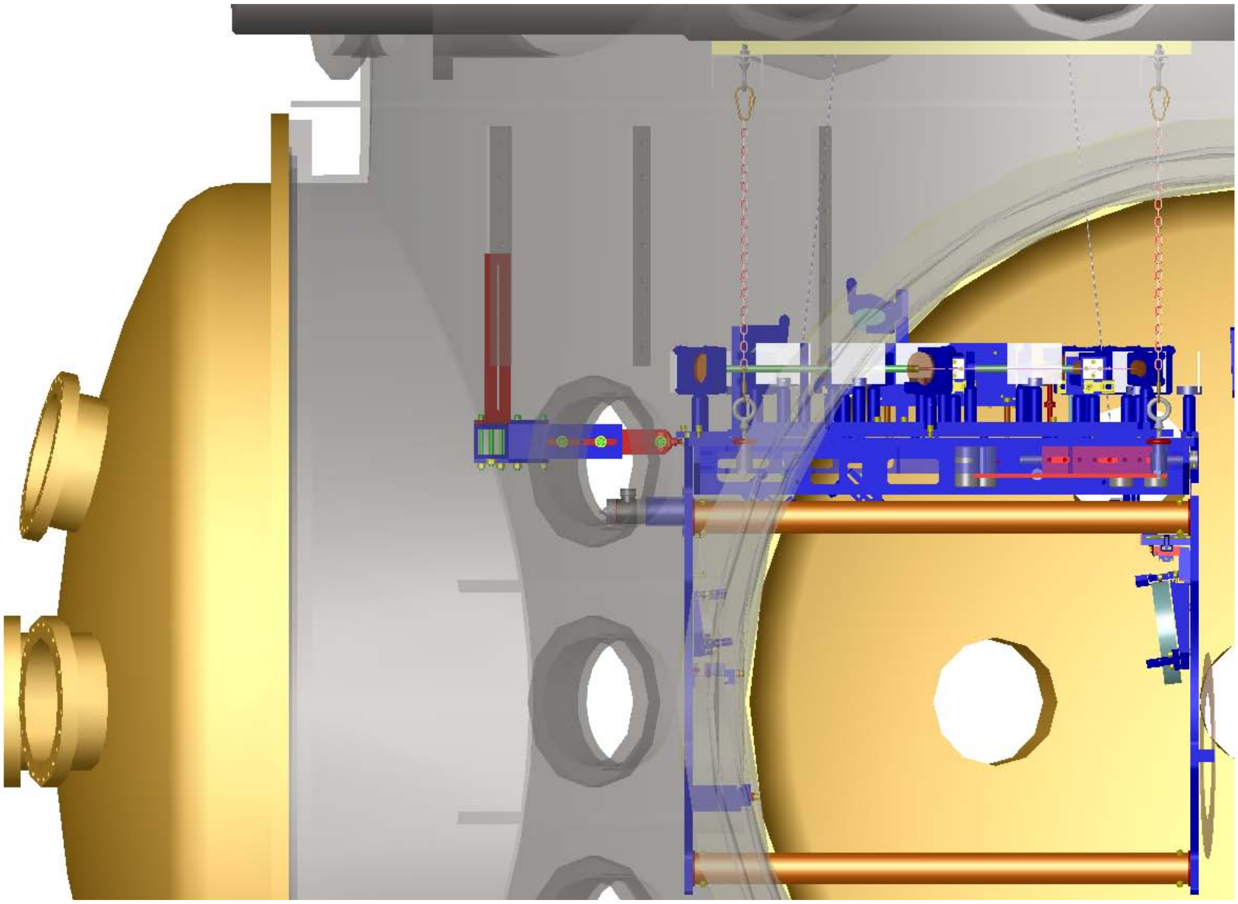


Figure 3: Cross-section of WBSC6 showing TMS Earthquake Restraint Assembly attachment to the chamber bracket. The free length of TMS EQ stop bracket extension below the chamber bracket is 3.4 inches.

3 BSC Chamber Deflections

The deflection of the chamber due to vacuum loads has been calculated by the designer and manufacturer, PSI (LIGO-C960964-01, PSI V049-1-22, Rev. 0: BSC FE Analysis of Lower Section). The maximum load case considered in the document LIGO-C960964-01 is when the chamber has atmospheric pressure on all external surfaces (load case 1). In this case, as shown in Figure 4 below, the maximum deflection is 0.15 inch (3.8 mm), in a radial direction, near the chamber viewports. However, when the reaction forces from the support structure is included in the analysis (load case 3) , the maximum deflection is 0.13 inch (3.3 mm) in the radial direction. Load case 1 is similar to the end BSC chambers (WBSC5, WBSC6, LBSC4 and LBSC5).

The maximum asymmetric load case considered (load case 2) has atmospheric loads from two opposing doors, but not from the other two doors. In this case the maximum deflection near the chamber viewports is 0.13 inch (3.3mm), as shown in Figure 6 and Figure 7 (showing the deflection in the two horizontal directions). Load case 2 is similar to the H1 ETM chambers (WBSC9 and WBSC10).

It should be noted that the support frame for the end BSC chambers (WBSC5, WBSC6, LBSC4 and LBSC5) will also deflect due to the large unbalanced vacuum loads; which will cause the BSC chamber to tilt as a rigid body; this deflection is not part of the finite element analysis conducted by PSI and will result in more- relative deflection of the TMS Seismic Safety Stop Assembly (D1001781) relative to the suspended TMS payload.

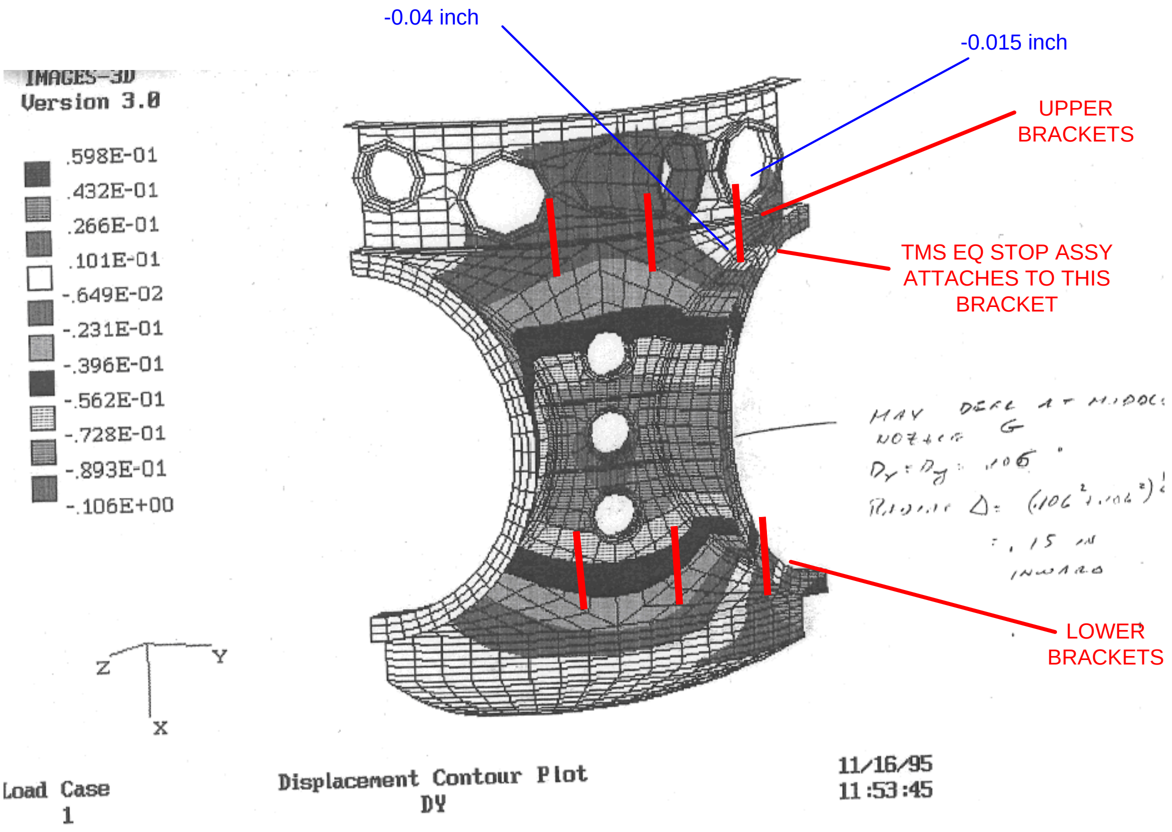
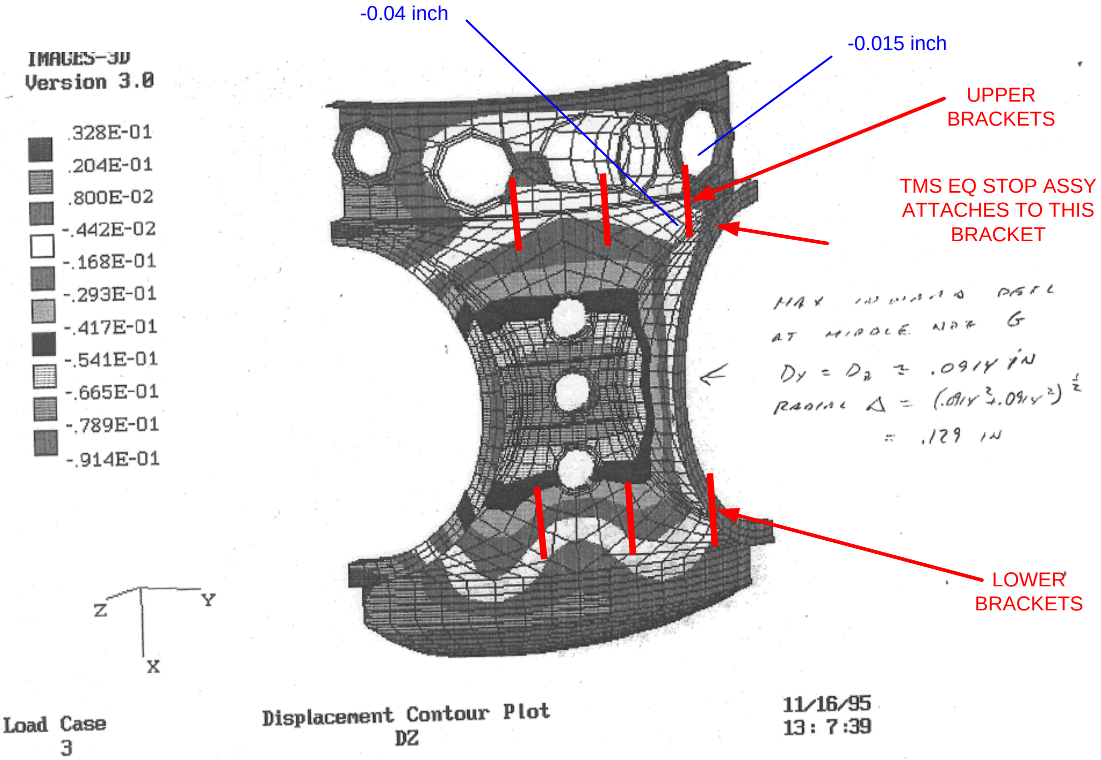
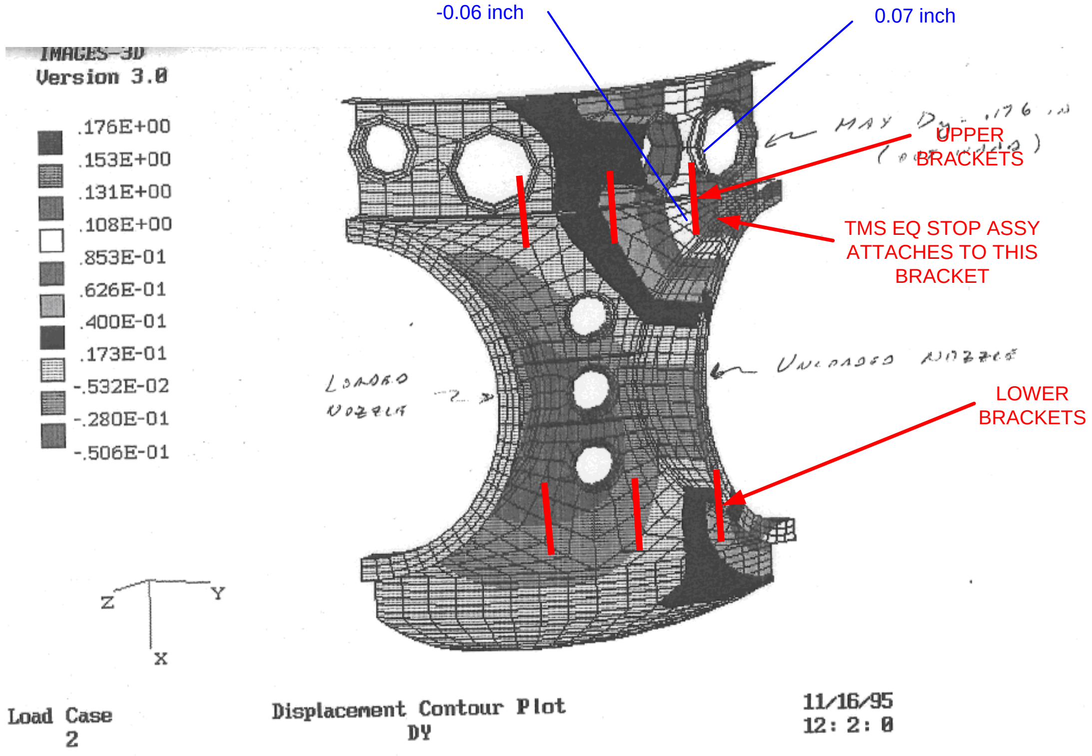


Figure 4 Displacement Contour Plot for the BSC Chamber Shell (Load Case 1)



MAX INWARD DEFL
AT MIDDLE NOZ G
$D_y = D_z \approx .0914$ IN
RADIAL $\Delta = (.0914^2 + .0914^2)^{\frac{1}{2}}$
$\approx .129$ IN

Figure 5 Displacement Contour Plot for the BSC Chamber Shell (Load Case 3)



MAX D_y = .176 IN
(OUTWARD)

UNLOADED NOZZLE

LOADED NOZZLE

Figure 6 Displacement (DY) Contour Plot for the BSC Chamber Shell (Load Case 2)

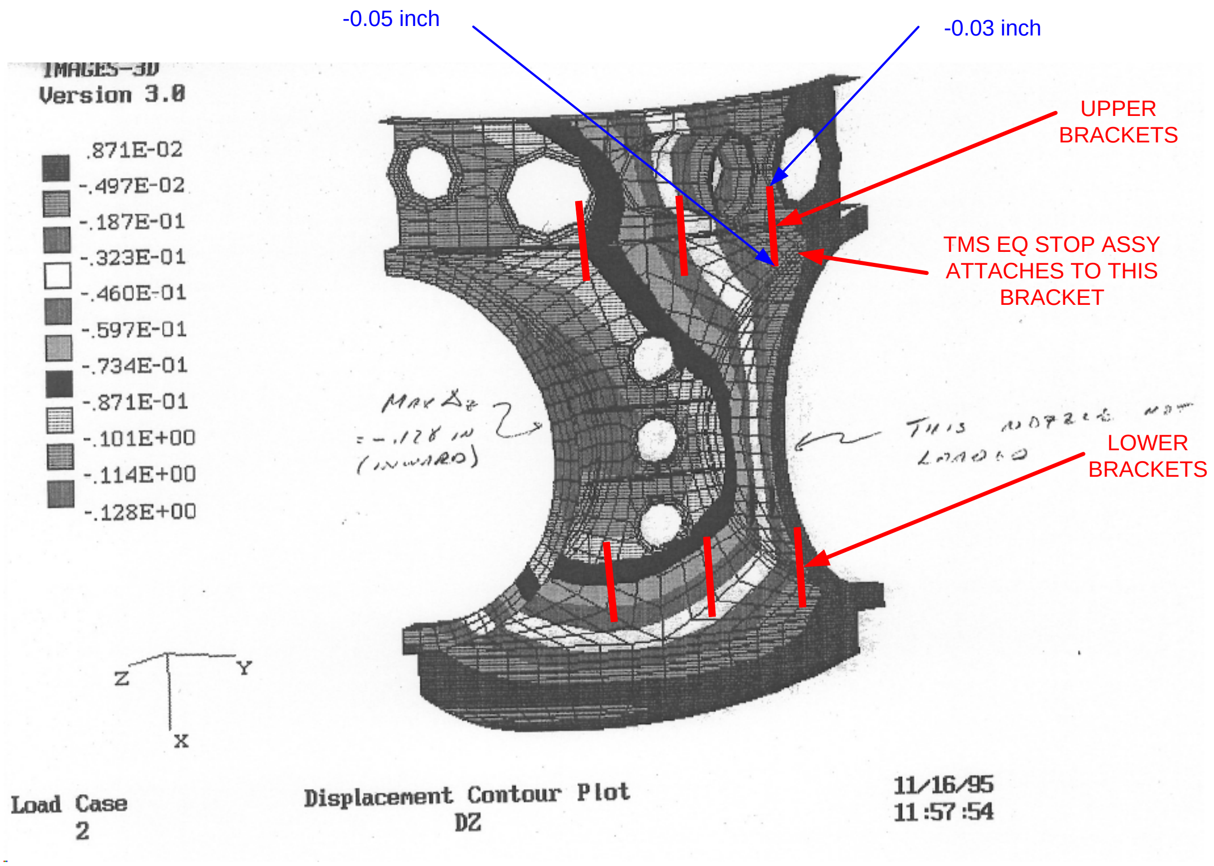


Figure 7 Displacement (DZ) Contour Plot for the BSC Chamber Shell (Load Case 2)

The worst case (conservative) deflection is load case 2 with about 0.06 inch deflection in both horizontal directions (Y and Z directions in Figure 6 and Figure 7). This is assumed for the analysis in the following section. The worst case rotation is taken from load cases 1 and 3 where the bottom of the bracket moves 0.025 inch more than the top of the bracket (0.040 – 0.015 inch).

4 Structural Analysis of the TMS Earthquake Stop Assembly

4.1 Rigid Body Deflection

Consider first the deflection of the EQ Stop Assy as a rigid body (without elastic deflection). As indicated in Figure 8, if the interfacing bracket of the EQ Stop Assy spanned the entire length of the chamber bracket and did not extend below, then the lever arms are about equal. In this case the rod which interfaces to the retaining eyes in the payload would move about 0.05 inch total. In fact the interfacing bracket does not span the entire length of the welded chamber bracket, but it does extend about 3.4 inches below (which increases the lever arm). Nonetheless the resulting translation of the TMS EQ Stop Assy relative to the suspended payload by rigid body motion is small.

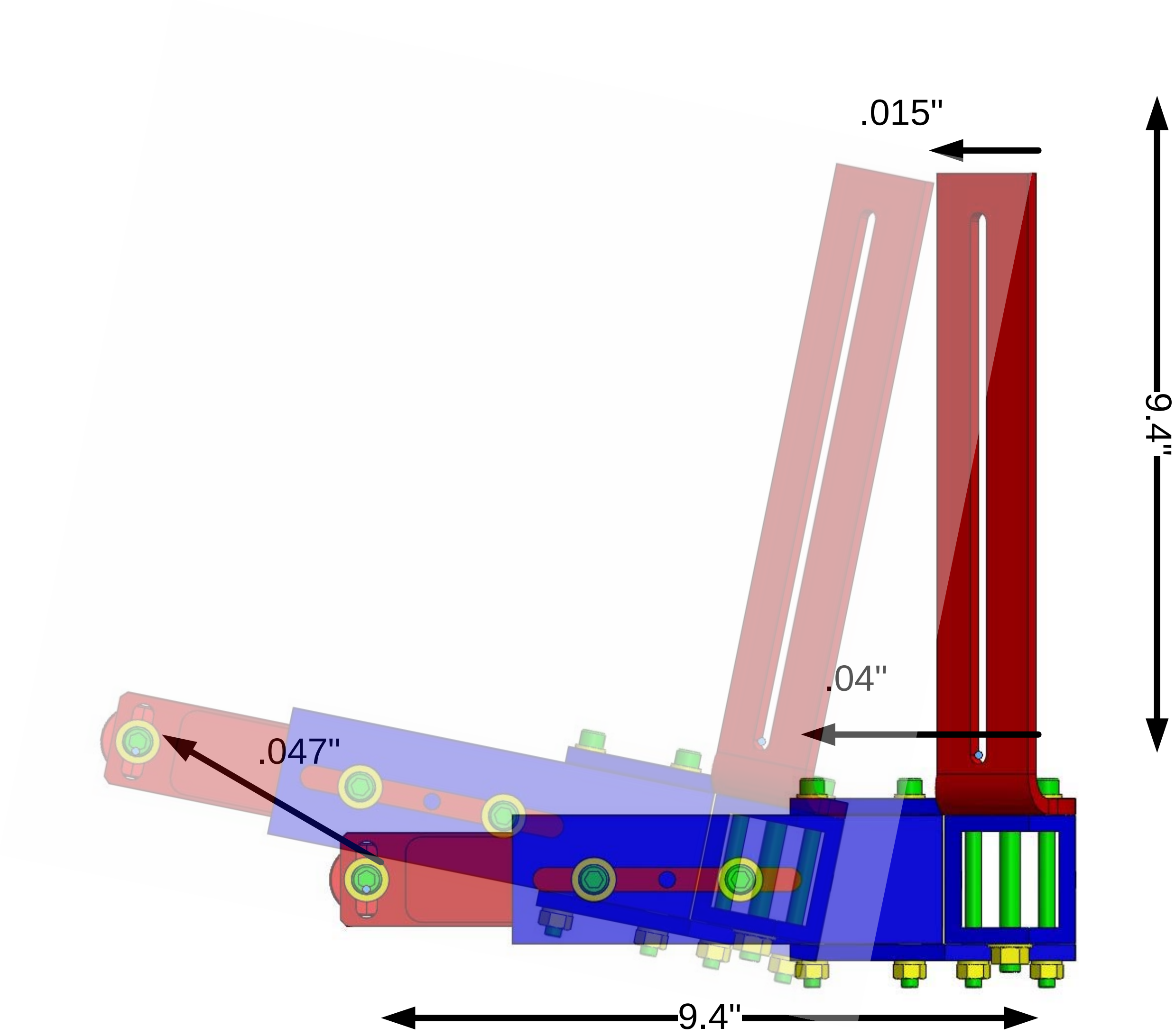


Figure 8: Rigid body deflection of the TMS EQ Stop Assy

4.2 Elastic Deflection

The extension of the TMS EQ Stop Assembly Bracket below the chamber bracket acts as a compliant spring. At the time of writing this document, the bracket thickness is 0.25 inch. This compliance considerably reduces the magnitude of bending in the aluminum box section (which spans between the chamber bracket attachments) from what it would be without this compliant section. The maximum deflection of the rod which threads though the eyes attached to the TMS payload is 0.1 inch, as indicated in Figure 9.

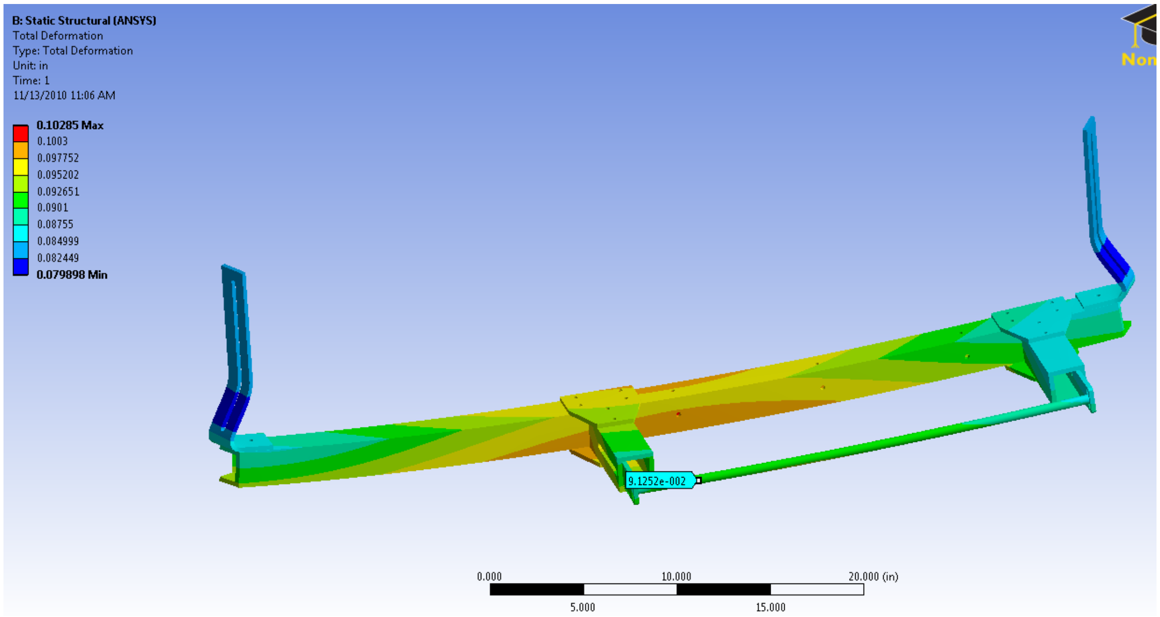


Figure 9: Deflection of the TMS EQ Stop Assy with nominal (0.25 inch) thickness brackets

This compliant member also reduces the stresses compared to a more direct connection. However the stresses in the 302 stainless steel bracket (shown in Figure 10) are too high (93 ksi localized maximum and 47 ksi to 68 ksi elsewhere) may be too high. The material callout on the drawing (D1001938-v1) is “302 SSTL”. The tensile yield stress of annealed 302 is only 39.9 ksi. However cold rolled (work hardened) 302 can have a sufficiently high tensile yield to work in this application. The other alternative is to reduce the thickness of the bracket.

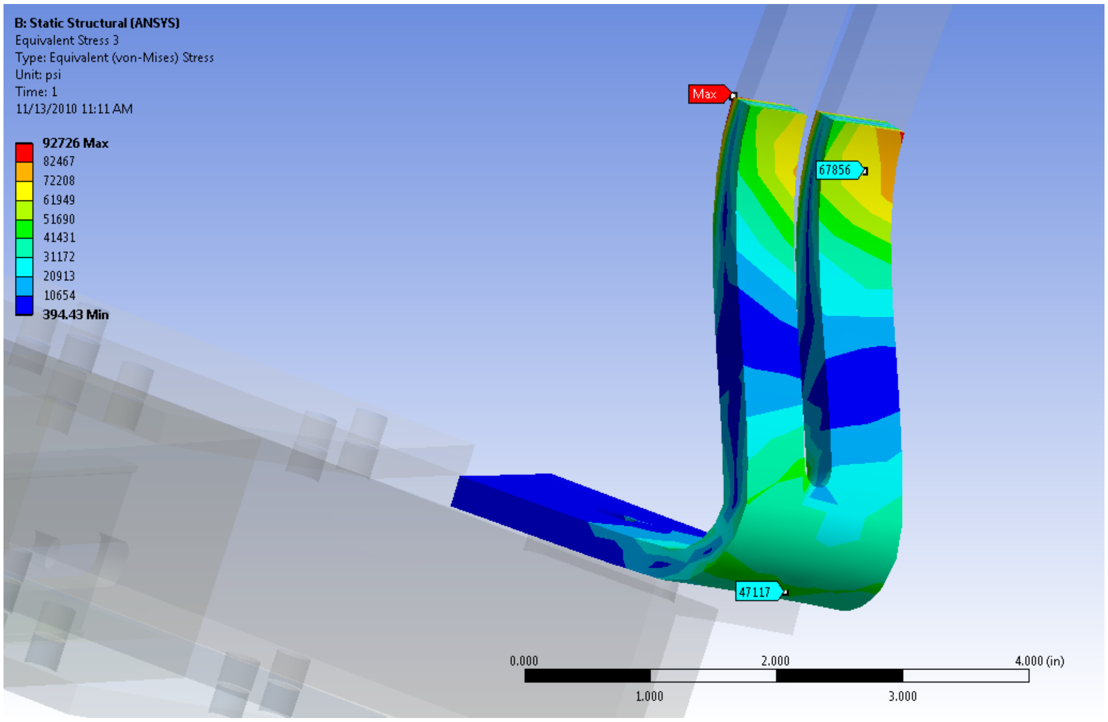


Figure 10: Stress in the lower (flexural) portion of the interfacing bracket (0.25 inch thick)

The deflection for a simple beam clamped at one end and guided at the other is given by[1]:

$$y = W L^3 / (12 E I)$$

where W is the load imposed by the interface bracket to force the deflection, L is the length of the flexure (beam), E is the elastic modulus and $I = b h^3/12$ is the moment of inertia of the flexure cross-section, with a flexure width b and a flexure thickness h. We are imposing a deflection, y, of 0.06 inch. This permits us to solve for the load, W. The bending moment of the flexure, $M = W L/2$, and the maximum stress is $s = M h/(2 I)$. So the stress is given by:

$$s = 3 E h y / L^2$$

Note that the stress only varies linearly with the thickness of the flexure but with the inverse square of the length. Although we cannot change the relative position of the EQ Stop to the chamber welded bracket, we could increase the flexure length by use of a standoff shim between the welded bracket and the flexure. However since this is a redesign (although a minor one) I first seek to make the design work by material choice and flexure thickness, as shown in Table 1. The required minimum factors of safety[2] are 1.25 on yield and 1.4 on ultimate.

Table 1: Factor of Safety for the Bracket Flexural Stress

0.06	in	deflection, y
3.4	in	flexure length, L
1.615	in	flexure width, b
3.00E+07	psi	elastic modulus, E
0.002102865	in^4	moment of Ineteria, I

		Thickness, h (in)		
		0.25	0.125	0.0625
	beam formula force (lbf)	1156	144	18
	beam formula stress (ksi)	117	58	29
	FEA stress (ksi)	93	60	38
Material	**tensile yield stress (ksi)**	**Yield Factors of Safety:**		
annealed 302	36.3	0.39	0.61	0.96
10% cold reduction	92.1	0.99	1.54	2.42
20% cold reduction	106	1.14	1.77	2.79
30% cold reduction	120	1.29	2.00	3.16
40% cold reduction	133	1.43	2.22	3.50
	tensile ult. stress (ksi)	**Ultimate Factors of Safety:**		
annealed 302	92.8	1.00	1.55	2.44
10% cold reduction	117	1.26	1.95	3.08
20% cold reduction	123	1.32	2.05	3.24
30% cold reduction	137	1.47	2.28	3.61
40% cold reduction	152	1.63	2.53	4.00

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[1] W. Young, Roark's Formulas for Stress and Strain, 6th Ed., McGraw-Hill Inc., 1989, Table 3, case 1b.

[2] D. Coyne, "Generic Requirements & Standards for Detector Systems", E010613-v1, section 3.4.1

As indicated in Table 1, the original design with 0.25 inch thick brackets can work if 30% (or greater) cold rolled 302 SSTL is called out. Alternatively 10% cold rolled 302 SSTL with either 0.125 inch or 0.0625 inch thickness would also work.

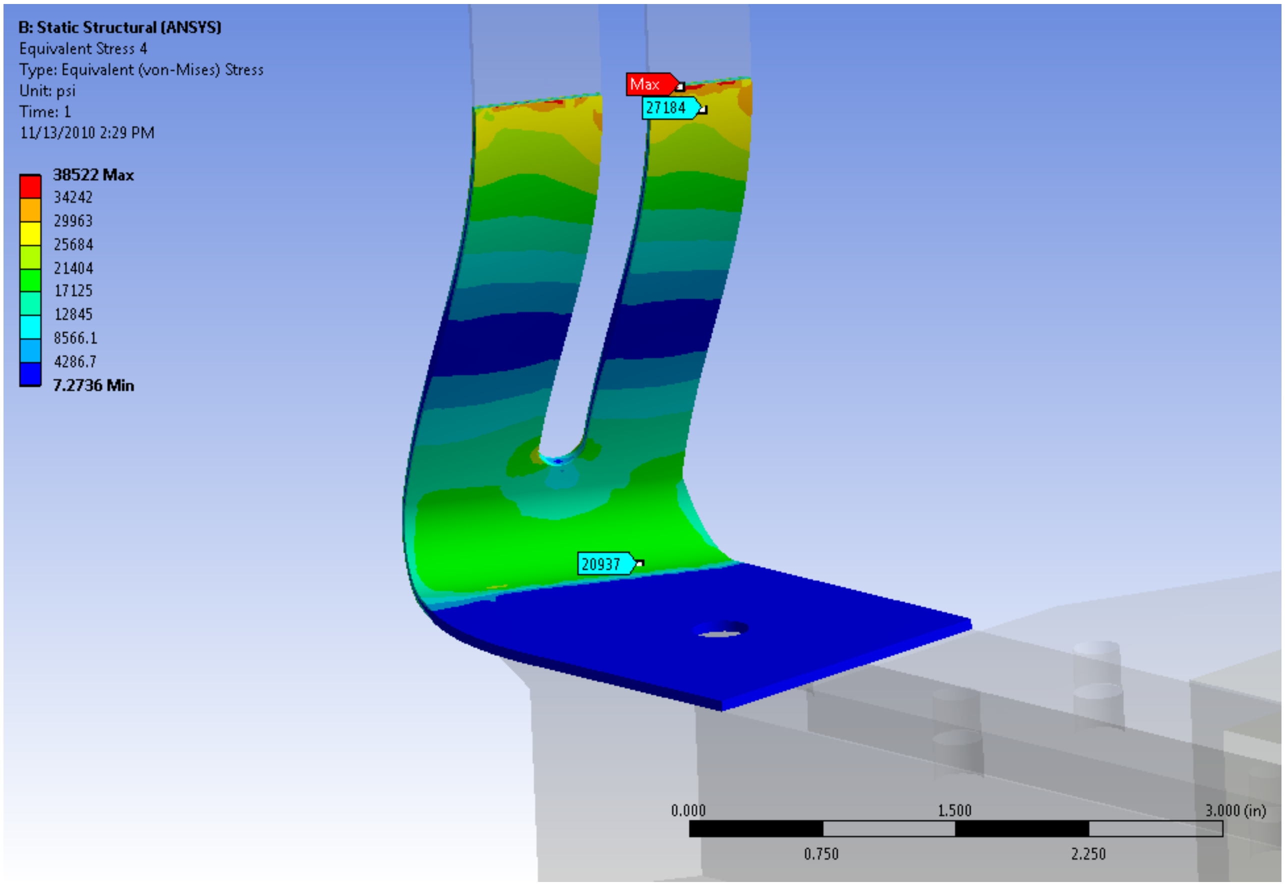

Figure 11: Stress in the lower (flexural) portion of the interfacing bracket (0.0625 inch thick)

4.3 Bolted Joint Slippage

In the elastic deflection analysis in the previous section, it was assumed that the forces transmitted through the bolted joints are low enough that slippage does not occur. If the lateral force exceeds the friction force due to the pre-load in the joint, then the parts will slip relative to each other. Although bolted joint slippage would relieve the stress in the assembly, it could also lead to loose, rattling parts with repeated vent and pump-down cycles; Bolted joint slippage should be avoided.

The force transmitted through the single 5/16-18 UNC bolt/joint between the 302 SSTL bracket and the aluminum box section (which spans between the welded chamber brackets) is shown in Table 1, according to the beam formula (I did not calculate this with the finite element analysis). Without more analysis (or test data) I do not know the allowable lateral (shear) force on this bolted joint. However, the ~1200 lbf load for the 0.25 inch thick baseline design seems too high. A bracket thickness of 0.125 inch would be preferable.

5 Summary

It is recommended that the TMS Seismic Safety Stop Chamber Brackets (D1001929-v1, Left and D1001938-v1, Right) be no greater than 0.125 inch thick and that they be comprised of 10% (or greater) cold rolled 302 stainless steel.