Fermilab

Particle Physics Division

Mechanical Department Engineering Note

Number: MD-ENG-545 Date: 9th December 2015

Project: DESI

Project Internal Reference:

Title: DESI VERTICAL FIXTURE FLIPPING RING

Author(s): Drew Stefanik

Reviewer(s):

Key Words: DESI, Below-the-hook lifting device

Abstract/Summary: Calculations to show conformance with ASME B30.20 for the lifting fixture used to flip the DESI Corrector Barrel's individual sections

Applicable Codes: FESHM 10110, ASME B30.20, ASME BTH-1-2014

10110TA

BELOW-THE-HOOK LIFTING DEVICE
Engineering Note Cover Page

Lifting Device Numbers:

FNAL Site No. ________________ Div. Specific No. ________________ Asset No. ________________

If applicable   If applicable   If applicable

ASME B30.20 Group: (check one)

[X] Chapter 20-1 Structural and Mechanical Lifting Devices
[ ] Chapter 20-2 Vacuum Lifting Devices
[ ] Chapter 20-3 Close Proximity Operated Lifting Magnets
[ ] Chapter 20-4 Remotely Operated Lifting Magnets
[ ] Chapter 20-5 Scrap and Material Handling Grapples

Device Name or Description DESI – VERTICAL FIXTURE FLIPPING RING

Device was (check all applicable)

[ ] Purchased from a Commercial Lifting Device Manufacturer. Mfg Name ________________
[X] Designed and Built at Fermilab
Assy drawing number F10044013
[ ] Designed by Fermilab and Built by a Vendor. Assy drawing number ________________
[ ] Provided by a User or other Laboratory
[ ] Other: Describe ________________

Engineering Note Prepared by DREW STEFANIK Date 11TH NOV 2015

Engineering Note Reviewed by ________________ Date ________________

Lifting Device Data:

Capacity 10,000 LBS = 4,535 KG

Fixture Weight 85.4 KG = 190 LBS

ASME BTH -1 Design Category: [ ] Category A [X] Category B
(See ASME BTH-1 Section 2-2)

ASME BTH -1 Service Class: [X] 0 [ ] 1 [ ] 2 [ ] 3 [ ] 4
(See ASME BTH-1 Section 2-3)

Duty Cycle _______ 8, 16 or 24 hour rating (applicable to groups III, and IV)

Inspections Frequency BEFORE EACH USE

Service (refer to B30.20 for definitions) [X] normal [ ] heavy [ ] severe

Rated Load Test by FNAL (if applicable) Date ________________ Load ________________

[ ] Check if Load Test was by Vendor and attach the certificate

Satisfactory Load Test Witnessed by: ________________

Signature (of Load Test Witness) ________________

Notes or Special Information:

Introduction

The Vertical Fixture Flipping Ring (VFFR) will be used to lift and flip four of the DESI corrector barrel's sections (aft, front, mid, and FPD, see Figure 1) by 180°, and then set them back down. This fixture is to be used for flipping the barrel sections only, and only with unloaded barrel sections (i.e., without the cells, lenses, bearings, etc.). The aft section connects to the lifting fixture differently than the other three sections. Among the remaining three sections, the front section has the highest mass. Thus, two main cases will be analyzed, the Aft Case (see Figure 2) and the Front Case (see Figure 3). For the Mid Case and the FPD Case, only the lifting points will be analyzed, to ensure the center of gravity is aligned with the lifting axis. All other conclusions from the Front Case will be valid for the Mid and FPD cases.

The main structure of the VFFR consists of a large stiffener ring through which a series of lifting cylinders are welded. Threaded rods are used to connect the barrel sections to the stiffener ring through three lifting cylinders, which are fastened to the stiffener ring by nuts and self-aligning washers. Two of the lifting cylinders are used to attach the crane's lifting points.

The threaded rods, weld joints, stiffener ring, and lifting points are analyzed according to the procedure in FESHM 10110.

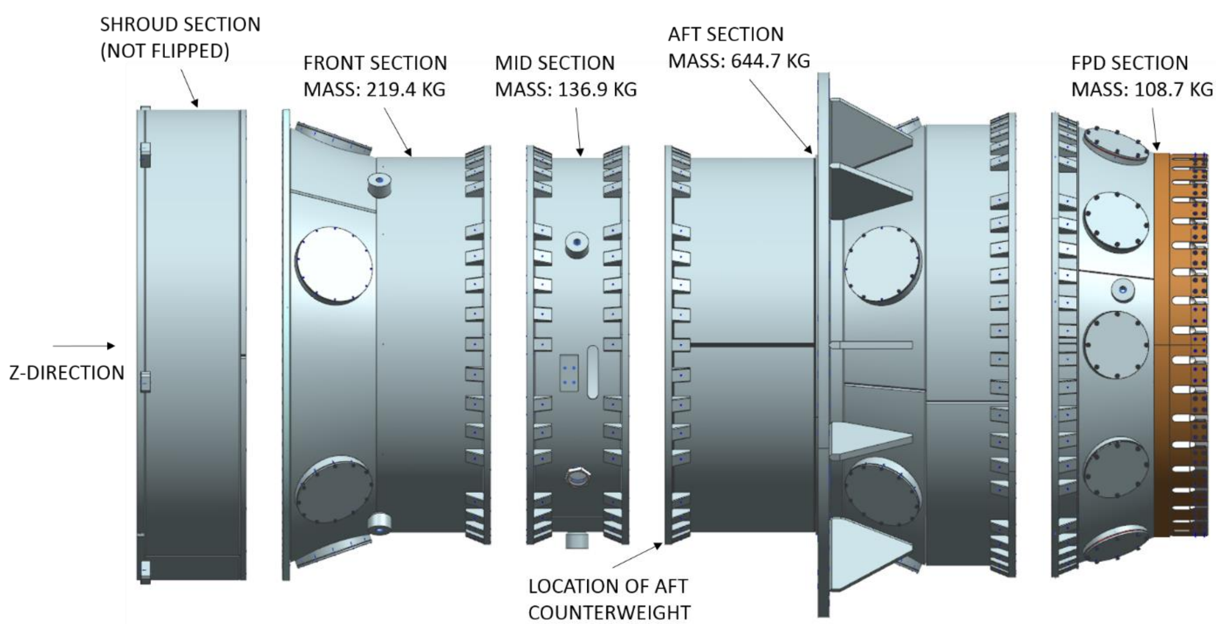


Figure 1 – The Five DESI Barrel Sections

Test

The VFFR shall be tested according to the procedure in FESHM #10110. There are two cases for which the fixture must be tested: the Aft Case and the Front Case.

In the Aft Case, a test load must be attached to the lifting fixture through the three axial 3/4-10 ASTM A193 Grade B7 threaded rods. The test load is:

$$L_{aft} = 1.25 * 9.81 * 877.9 = 10{,}765\ N = 2{,}420\ lbf$$

The aft section and its counterweight will be used in the test, for a total of 7774 N (1748 lbf). The remaining 2991 N (672 lbf) must be attached to the fixture such that it remains balanced about the lifting axis. The test involves picking the up the ring, rotating it 180°, and setting it back down. Both clockwise and counter-clockwise rotations should be tested, and both directions should be repeated multiple times.

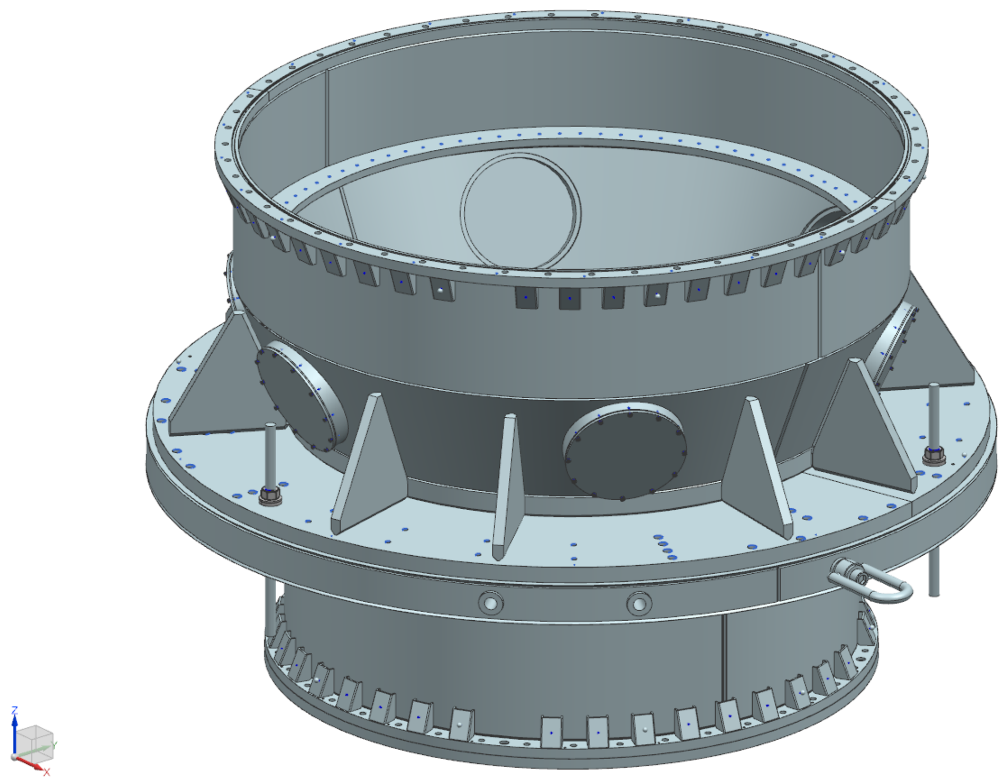


Figure 2 – The Aft Case

In the Front Case, a test load must be attached to the ring through the three radial 3/4-10 ASTM A193 Grade B7 threaded rods with self-aligning washers. The test load is:

$$L_{front} = 1.25 * 9.81 * 219.4 = 2690\ N = 605\ lbf$$

The front section will be used in the test, for a total of 2152 N (484 lbf). The remaining 538 N (121 lbf) must be attached to the fixture such that it remains balanced about the lifting axis. The test involves picking the up the ring, rotating it 180°, and setting it back down. Both clockwise and counter-clockwise rotations should be tested, and both directions should be repeated multiple times.

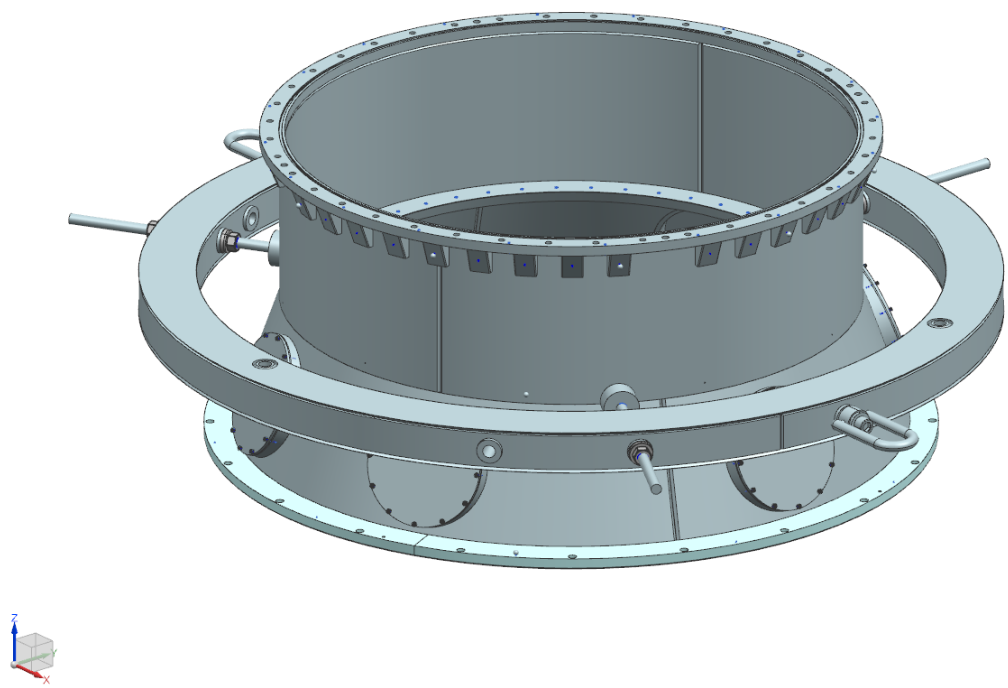


Figure 3 – The Front Case

Installation Notes

Three of the barrel sections, the FPD, aft, and front sections, have a constraint when attaching the ring to them. The inner radius of the flipping ring is too small to fit over the "wide end" (see Figure 4) of these sections. This means that when attaching the ring, it must always come over the "narrow end". When the narrow end is closer to the floor, the sections can be lowered via the crane into the center of the ring, and the ring can then be lifted to the appropriate height to install the threaded rods. When the wide end is closer to the floor, the barrel sections can be lowered to and rest on the floor, and then the ring can be lifted above the sections and lowered over the narrow end, at which point the threaded rods can be installed.

An additional constraint for the FPD section only is that the flexures on the narrow end are fragile, and the weight of the FPD section cannot rest on the flexures. In other words, the FPD section cannot be placed on the floor when the narrow end is facing the floor. A solution to attach the ring in this case would be to place shims under the ring so that it is at a height appropriate to install the threaded rods without the flexures touching the floor, and then to install the threaded rods there while the crane holds the FPD section.

The mid section has neither of these constraints.

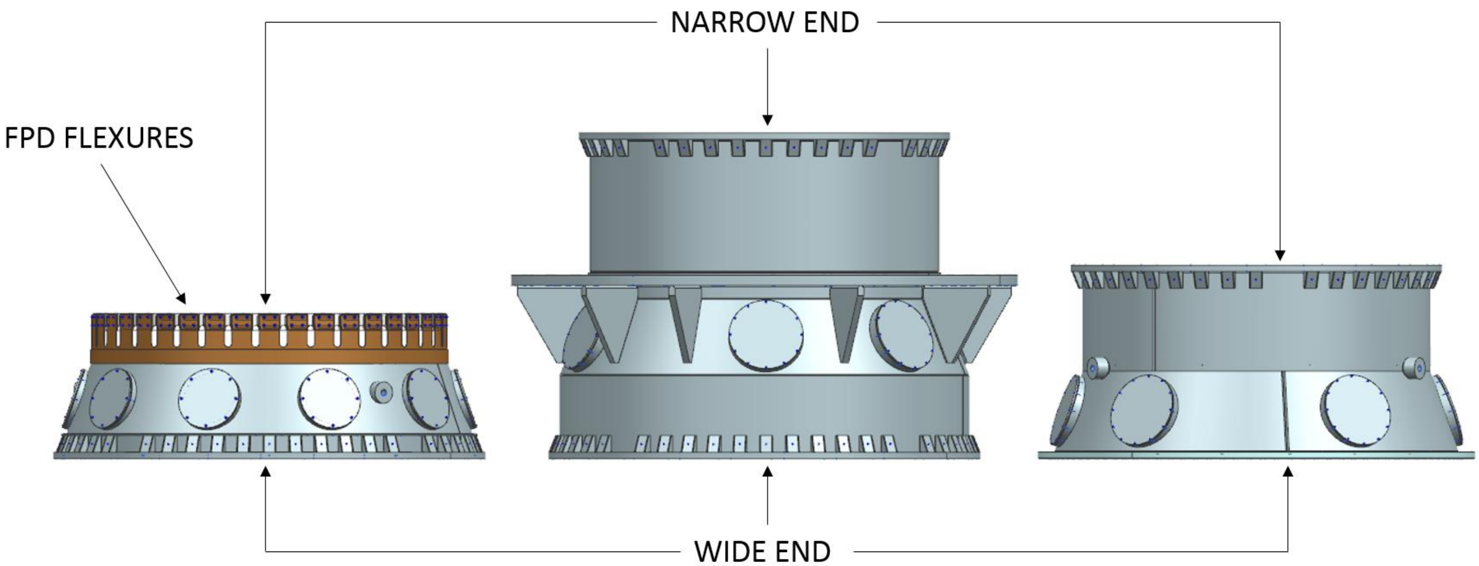


Figure 4 – Installation Notes

Flipping Procedure

Once the ring has been attached to a barrel section, the actual flipping process can begin. First, straps should be looped around the ring, at least one on each side of the lifting axis. While the load is properly weight balanced, this is an additional precautionary measure and allows for more control when flipping the sections. After the straps are added, the ring should be lifted by the crane to a height such that the rotating ring will not impact the floor. The straps should then be manipulated to rotate the section 180°. After the rotation, the section can be lowered, the straps removed, and the ring removed from the barrel section.

AFT CASE

In the Aft Case, there are three different positions of import: when the aft section hangs below the ring (the lower position), when it rests on top of the ring (the upper position), and when it has rotated 90° from either the lower or upper positions (the normal position). See Figures 5a, 5b, and 5c in Appendix 2.

Center of Gravity

The total mass of the fixture, which includes the aft section and the lifting fixture, is:

$$m_{aft} = 644.7\ kg$$

$$m_{fixture} = 85.4\ kg$$

$$m_{cog} = m_{aft} + m_{fixture} = 730.1\ kg$$

The center of gravity of the system is 77.6 mm from the lifting axis in the z-direction (towards the FPD section). Because of this, a counterweight must be installed on the aft section on the opposite end of the section (towards the mid section). The distance from this end of the aft section to the lifting axis is 383.2 mm (see Figures 1 and 6 for clarity).

$$d_{cog} = 77.6\ mm$$

$$d_{cwt} = -(383.2 + l_{cw})\ mm$$

$$l_{cw} = 19.5\ mm$$

The moment created by the center of gravity not being aligned to the lifting axis must be offset by an equal but opposite moment. This allows the mass of the counterweight to be calculated:

$$M_{cwt} = -M_{cog}$$

$$m_{cwt} * d_{cwt} = -m_{cog} * d_{cog}$$

$$m_{cwt} * -383.2 = -730.1 * 77.6$$

$$m_{cwt} = 147.8\ kg = 326\ lbs$$

Therefore, the total mass of the fixture plus the load is:

$$m_{total} = m_{cog} + m_{cwt} = 730.1 + 147.8 = 877.9\ kg$$

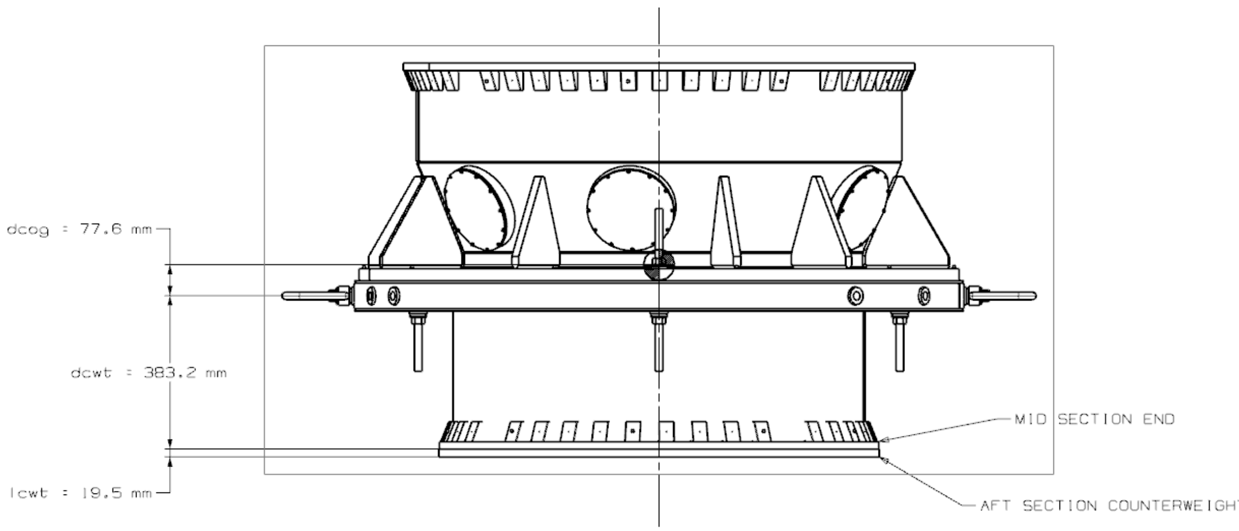


Figure 6 – Aft Section Counterweight

Threaded Rods

Bolted Connection

Tensile Stress

The three threaded rods function as bolts that connect to the stiffener ring's three axial lifting cylinders and the hexapod mounting ring. The maximum tensile stress in a bolt occurs when the fixture is in the lower position, and f_t is:

$$f_t = \frac{\frac{(m_{aft} + m_{cwt})}{3} * g}{A} = \frac{\frac{644.7 + 147.8}{3} * 9.81}{2.0 * 10^{-4}} = 13.0\ MPa$$

$$\frac{f_t}{F_{t,b}} = \frac{13.0}{239.4} = 0.05 \leq 1.0$$

The bolts satisfy the allowable tensile stress equation.

Shear Stress

The maximum shear stress in a bolt occurs when the fixture is at the shear positions and is:

$$f_v = \frac{\frac{(m_{aft} + m_{cwt})}{3} * g}{A} = \frac{\frac{644.7 + 147.8}{3} * 9.81}{2.0 * 10^{-4}} = 13.0\ MPa$$

$$\frac{f_v}{F_{v,b}} = \frac{13.0}{148.5} = 0.09 \leq 1.0$$

The bolts satisfy the allowable shear stress equation.

Combined Tensile and Shear Stress

When a bolt is subjected to combined tensile and shear stresses, the allowable tensile stress changes as a function of the shear stress:

$$F_t' = \sqrt{F_{t,b}^2 - 2.60 * f_v^2}$$

Using the maximum tensile and shear stresses as a conservative value, rather than checking at each angle of rotation:

$$F_t' = \sqrt{239.4^2 - 2.60 * 13.0^2} = 238.5\ MPa$$

The adjusted allowable tensile stress only lowered by 0.9 MPa, and is still much greater than the maximum tensile stress of 13.0 MPa, and is thus still satisfied.

Welded Connections

Weld joints 1 and 2 (see Figure 8 in Appendix 2) are 4 *mm* equal leg fillet welds, and weld joint 3 is a 4 *mm* 60° bevel groove weld. All three weld joints have a diameter of 44.4 *mm*. This gives all three welds the same effective length, and weld joints 1 and 2 have the same effective throat. In this analysis, it is assumed that only half of the weld joint will carry the load at any one time:

$$t_{e,12} = 0.707 * 4 * 10^{-3} = 2.8 * 10^{-3}\ m$$

$$l_e = \frac{\pi * 44.4 * 10^{-3}}{2} = 0.07\ m$$

A 60° bevel groove weld has an effective throat thickness equal to the depth of the groove:

$$t_{e,3} = 4 * 10^{-3}\ m$$

Weld joints 1 and 3 will take a maximum of a third of the barrel section’s weight as shear force through it. Meanwhile, weld joint 2 will take a maximum of half of the entire fixture’s weight as shear force through it. The maximum shear stress in weld joint 2 is:

$$f_{v,w2} = \frac{\frac{m_{total}}{2} * g}{t_{e,12} * l_e} = \frac{\frac{877.9}{2} * 9.81}{0.0028 * 0.07} = 22.0\ MPa$$

$$\frac{f_{v,w2}}{F_v} = \frac{22.0}{80.4} = 0.27 \leq 1.0$$

Weld joint 2 satisfies the allowable stress equation. Because weld joint 1 will take less force and has the same effective area as weld joint 2, it is also satisfactory.

The maximum shear stress in weld joint 3 is:

$$f_{v,w3} = \frac{\frac{m_{total}}{3} * g}{t_{e,3} * l_e} = \frac{\frac{877.9}{3} * 9.81}{0.004 * 0.07} = 10.3\ MPa$$

$$\frac{f_{v,w3}}{F_v} = \frac{10.3}{80.4} = 0.13 \leq 1.0$$

Weld joint 3 satisfies the allowable stress equation.

Stiffener Ring

Combined Normal and Shear Stress

Due to the complexity of the formulas for curved members, FEAs were run in lieu of hand calculations. The three cases (lower, upper, and normal) were all analyzed. See Appendix 3 for the results.

The ring is under combined normal and shear stress, and must therefore satisfy the following equation:

$$f_{cr} = \sqrt{f_x^2 - f_x f_y + f_y^2 + 3f_v^2} \leq F_{cr}$$

For the lower, upper, and normal positions, respectively:

$$f_{cr,l} = \sqrt{24^2 - 24 * 33.7 + 33.7^2 + 3 * 10.9^2} = 35.5\ MPa \leq 83.3\ MPa$$

$$f_{cr,u} = \sqrt{24^2 - 24 * 33.7 + 33.7^2 + 3 * 10.9^2} = 35.5\ MPa \leq 83.3\ MPa$$

$$f_{cr,n} = \sqrt{5.4^2 - 5.4 * 6.2 + 6.2^2 + 3 * 4.8^2} = 10.2\ MPa \leq 83.3\ MPa$$

In all three positions, the stiffener ring satisfies the allowable stress equations.

Welded Connections

The stiffener ring is a welded piece, and the weakest weld joints were also analyzed with the FEA (those on the inner radius of the ring). The calculated shear stress must be less than the allowable shear stress:

$$f_v \leq F_v$$

For the lower, upper, and normal positions, respectively:

$$f_{v,wl} = 7.4\ MPa \leq 80.4\ MPa$$

$$f_{v,wu} = 7.4\ MPa \leq 80.4\ MPa$$

$$f_{v,wn} = 0.54\ MPa \leq 80.4\ MPa$$

In all three positions, the weakest welds satisfy the allowable stress equations. Therefore the stronger welds also satisfy the allowable stress equations.

FRONT CASE

In the front case, there are three different positions of import: when the front section has not yet been rotated (the neutral position), and rotating 90° from the neutral position in either direction gives two unique positions (the tensile normal and compressive normal positions). See Figures 7a, 7b, and 7c in Appendix 2.

Center of Gravity

In the Front Case, the total mass of the fixture, which includes the front section and the lifting fixture, is:

$$m_{front} = 219.4\ kg$$

$$m_{fixture} = 85.4\ kg$$

$$m_{total} = m_{aft} + m_{fixture} = 304.8\ kg$$

The center of gravity of the system is -3.3 mm from the lifting axis in the -z-direction (towards the shroud section). This is a negligible amount, so a counterweight is not needed.

Threaded Rods

Bending

In the neutral position, the front section is supported by all three threaded rods. Due to the way the rods are distributed around the lifting axis, as a conservative estimate it will be assumed that 50% of the load is on each side of the lifting axis, and thus must be taken by a single rod. The required flexural strength of a single rod taking 50% of the front section's weight is:

$$M_a = \frac{M_{max}}{4} = \frac{103.7}{4} = 25.9\ N-m$$

$$\frac{M_a}{M_n/\Omega_b} = \frac{25.9}{278.9} = 0.09 \leq 1$$

The threaded rods satisfy the required flexural strength equations.

Tension and Compression

As the fixture rotates from the neutral position, there will be less bending stress on the rods, but there will instead be increasing tensile or compressive stress. In the tensile normal and compressive normal positions, there will be no bending stress in the rods and tensile/compressive stress will be at its maximum. In the worst case, these stresses will be taken by a single rod:

$$f_t = f_a = \frac{m_{front} * g}{A} = \frac{219.4 \ * 9.81}{2.0 * 10^{-4}} = 10.8\ MPa$$

$$\frac{f_t}{F_t} = \frac{10.8}{241.3} = 0.04 \leq 1.0$$

$$\frac{f_a}{F_a} = \frac{10.8}{168.6} = 0.06 \leq 1.0$$

The threaded rods satisfy the allowable tension and compression equations.

Combined Bending and Tension or Compression

As the fixture rotates from the neutral position, the threaded rods will be under combined stress. As the fixture rotates to the tensile normal position, it will add tensile stress. It is assumed that the maximum bending stress occurs at the neutral position, and likewise, the maximum tensile stress occurs at the tensile normal position. The maximum stresses for each are used as a worst case to check the allowable stress. The maximum bending stress is:

$$f_b = \frac{M_{max}}{S_x} = \frac{103.7}{4.02 * 10^{-7}} = 258.0\ MPa$$

The allowable bending stress is:

$$F_b = 0.6 * F_y = 0.6 * 724 = 434.4\ MPa$$

Additionally, there is only bending stress in one direction. Therefore, the combined stresses must satisfy:

$$\frac{f_t}{F_t} + \frac{f_b}{F_b} \leq 1.0$$

$$0.04 + \frac{258.0}{434.4} = 0.04 + 0.59 = 0.63 \leq 1.0$$

As the fixture rotates to the compressive normal position, it will add compressive stress. As above, it is assumed that the maximum bending stress occurs at the neutral position, and the maximum compressive stress occurs at the compressive normal position. The maximum stresses for each are used as a worst case to check the allowable stress. Additionally, there is only bending stress in one direction and $f_a/F_a < 0.15$. Therefore, the combined stresses must satisfy:

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1.0$$

$$0.06 + \frac{258.0}{434.4} = 0.06 + 0.59 = 0.65 \leq 1.0$$

The threaded rods satisfy the allowable combined stress equations.

Bolted Connection

Tensile Stress

The threaded rods function as bolts that connect to the stiffener ring's lifting cylinders. The maximum tensile stress in the bolt occurs when the fixture is in the tensile normal position, where f_t = 10.8 MPa:

$$\frac{f_t}{F_{t,b}} = \frac{10.8}{239.4} = 0.05 \leq 1.0$$

The bolts satisfy the allowable tensile stress equation.

Shear Stress

The maximum shear stress in the bolt occurs when the fixture as at the neutral positions and is:

$$f_v = \frac{M_{max}}{l_{bolt} * A} = \frac{69.2}{0.15 * 2.0 * 10^{-4}} = 2.3\ MPa$$

$$\frac{f_v}{F_{v,b}} = \frac{2.3}{148.5} = 0.02 \leq 1.0$$

The bolts satisfy the allowable shear stress equation.

Combined Tensile and Shear Stress

When a bolt is subjected to combined tensile and shear stresses, the allowable tensile stress changes as a function of the shear stress:

$$F_t' = \sqrt{F_{t,b}^2 - 2.60 * f_v^2}$$

Using the maximum shear stress as a worst case scenario:

$$F_t' = \sqrt{239.4^2 - 2.60 * 2.3^2} = 239.37\ MPa$$

The adjusted allowable tensile stress is functionally the same as before, and thus it is still satisfied.

Welded Connections

Weld joints 1 and 2 (see Figure 8 in Appendix 2) have the same physical properties:

$$t_e = 0.707 * 4 * 10^{-3} = 2.8 * 10^{-3}\ m$$

$$l_e = \frac{\pi * 44.4 * 10^{-3}}{2} = 0.07\ m$$

Weld joint 1 will take a maximum of a third of the barrel section's weight as shear force through it. Meanwhile, weld joint 2 will take a maximum of half of the entire fixture's weight as shear force through it. The shear stress in weld joint 2 is:

$$f_{v,w2} = \frac{\frac{m_{fixture}}{2} * g}{t_e * l_e} = \frac{\frac{304.8}{2} * 9.81}{0.0028 * 0.07} = 7.6\ MPa$$

$$\frac{f_{v,w2}}{F_v} = \frac{7.6}{80.4} = 0.09 \leq 1.0$$

Weld joint 2 satisfies the allowable stress equation. Because weld joint 1 will take less force and has the same effective area as weld joint 2, it is also satisfactory.

Stiffener Ring

Combined Normal and Shear Stress

As in the Aft Case, due to the complexity of the formulas for curved members, FEAs were run in lieu of hand calculations. The three cases (neutral, tensile normal, and compressive normal) were all analyzed. See Appendix 3 for the results.

The ring is under combined normal and shear stress, and must therefore satisfy the following equation:

$$f_{cr} = \sqrt{f_x^2 - f_x f_y + f_y^2 + 3f_v^2} \leq F_{cr}$$

For the neutral, tensile normal, and compressive normal positions, respectively:

$$f_{cr,n} = \sqrt{24^2 - 24 * 33.7 + 33.7^2 + 3 * 10.9^2} = 35.5\ MPa \leq 83.3\ MPa$$

$$f_{cr,t} = \sqrt{5.4^2 - 5.4 * 6.3 + 6.3^2 + 3 * 4.8^2} = 10.2\ MPa \leq 83.3\ MPa$$

$$f_{cr,c} = \sqrt{5.4^2 - 5.4 * 6.3 + 6.3^2 + 3 * 4.8^2} = 10.2\ MPa \leq 83.3\ MPa$$

In all three positions, the stiffener ring satisfies the allowable stress equations.

Welded Connections

The stiffener ring is a welded piece, and the weakest weld joints were also analyzed with the FEA (those on the inner radius of the ring). The calculated shear stress must be less than the allowable shear stress:

$$f_v \leq F_v$$

For the neutral, tensile normal, and compressive normal positions, respectively:

$$f_{v,wn} = 7.4\ MPa \leq 80.4\ MPa$$

$$f_{v,wt} = 0.54\ MPa \leq 80.4\ MPa$$

$$f_{v,wc} = 0.54\ MPa \leq 80.4\ MPa$$

In all three positions, the weakest welds satisfy the allowable stress equations. Therefore the stronger welds also satisfy the allowable stress equations.

MID CASE

Center of Gravity

In the Mid Case, the total mass of the system, which includes the mid section and the lifting fixture, is:

$$m_{mid} = 136.9\ kg$$

$$m_{fixture} = 85.4\ kg$$

$$m_{total} = m_{mid} + m_{fixture} = 222.3\ kg$$

The center of gravity of the system is 0.9 mm from the lifting axis in the z-direction (towards the aft section). This is a negligible amount, so a counterweight is not needed.

FPD CASE

Center of Gravity

In the FPD Case, the total mass of the system, which includes the FPD section and the lifting fixture:

$$m_{fpd} = 108.7\ kg$$

$$m_{fixture} = 85.4\ kg$$

$$m_{total} = m_{fpd} + m_{fixture} = 194.1\ kg$$

The center of gravity of the system is 0.3 mm from the lifting axis in the -z-direction (towards the aft section). This is a negligible amount, so a counterweight is not needed.

Appendix 1 (Allowable Stress)

From ASME BTH-1_2014, Chapter 3-2: Member Design

Design Factor:

$N_d = 3$ Design Category B

Mechanical Properties of ASTM A36:

$F_y = 36.3\ ksi = \ 250\ MPa$ Tensile Strength, Yield

$F_u = 58\ ksi = 400\ MPa$ Tensile Strength, Ultimate

$E = 29000\ ksi = 200000\ MPa$ Modulus of Elasticity

Mechanical Properties of ASTM A193 Grade B7 with Diameter less than 2.5":

$F_y = 105\ ksi = 724\ MPa$ Tensile Strength, Yield

$F_u = 125\ ksi = 862\ MPa$ Tensile Strength, Ultimate

$E = 29000\ ksi = 200000\ MPa$ Modulus of Elasticity

Properties of Threaded Rod, 3/4-10 UNC-2B:

$l_{bolt} = 0.15\ m$ Length Between Supports

$ø_{min} = 0.627\ in = 16\ mm$ Minor Diameter

$r = 8mm = 0.008\ m$ Radius

$I = \frac{\pi}{4} r^4 = 3.2x10^{-9}\ \ m^4$ Second Area Moment of Inertia

$A = \pi r^2 = 2.0x10^{-4}\ m^2$ Cross Sectional Area

$K = 2.0$ Effective Length Factor (Worst Case)

$l_{unbraced} = 96.4\ mm$ Unbraced Length

$r_g = \sqrt{\frac{I}{A}} = \sqrt{\frac{3.2x10^{-9}}{2.0x10^{-4}}} = 4\ mm$ Radius of Gyration

$$M_{max} = \frac{m_{front} * g}{2} * l_{unbraced} = \frac{219.4 * 9.81}{2} * 0.0964 = 103.7\ N - m$$

Maximum Moment on a Rod,

Neutral Position

Section 3-2.1: Tension Members

ASTM A193 Grade B7

The allowable tensile stress, on both the gross area and the net tensile area, is:

$$F_t(grossArea) = \frac{F_y}{N_D} = \frac{724}{3} = 241.3\ MPa$$

$$F_t(netArea) = \frac{F_u}{1.20N_D} = \frac{862}{1.20 * 3} = 239.4\ MPa$$

Section 3-2.2: Compression Members

ASTM A193 Grade B7

$$C_C = \sqrt{\frac{2\pi^2 E}{F_y}} = \sqrt{\frac{2\pi^2 * 200000}{724}} = 73.8$$

$$\frac{Kl}{r_g} = \frac{2.0 * 96.4}{4} = 48.2$$

Since Kl/r < C_C, the allowable axial compressive stress is:

$$F_a = \frac{[1 - \frac{(Kl/r)^2}{2C_C^2}]F_y}{N_d[1 + \frac{9(Kl/r)}{40C_C} - \frac{3\,(Kl/r)^3}{40C_C^3}]} = \frac{\left[1 - \frac{(48.2)^2}{2 * 73.8^2}\right] * 724}{3 * [1 + \frac{9 * (48.2)}{40 * 73.8} - \frac{3 * (48.2)^3}{40 * 73.8^3}]} = 168.6\ MPa$$

Flexural Strength – Round Bars

ASTM A193 Grade B7

Geometric Properties:

$$S_x = \frac{\pi * d^3}{32} = \frac{\pi * 0.016^3}{32} = 4.02x10^{-7}\ m^3$$

$$Z_x = \frac{d^3}{6} = \frac{0.016^3}{6} = 6.83x10^{-7}\ m^3$$

Nominal Flexure Strength, M_n:

$$M_n = F_y Z_x \leq 1.6 F_y S_x$$

$$1.6F_y S_x = 1.6 * 724x10^6 * 4.02x10^{-7} = 465.8\ N - m$$

$$F_y Z_x = 724x10^6 * 6.83x10^{-7} = 494.3\ N - m > 465.8\ N - m$$

Therefore, M_n = 465.8 $N - m$

Available Flexural Strength:

$$\Omega_b = 1.67$$

$$\frac{M_n}{\Omega_b} = \frac{465.8}{1.67} = 278.9\ N - m$$

Section 3-2.5: Combined Normal and Shear Stress

ASTM A36

The allowable critical stress due to combined shear and normal stresses is:

$$F_{cr} = \frac{F_y}{N_d} = \frac{250}{3} = 83.3\ MPa$$

Section 3-3.2: Bolted Connections

ASTM A193 Grade B7

The allowable tensile stress on the threaded rods is:

$$F_{t,b} = \frac{F_u}{1.20 * N_D} = \frac{862}{1.20 * 3} = 239.4\ MPa$$

The allowable shear stress on the threaded rods is:

$$F_{v,b} = \frac{0.62 * F_u}{1.20 * N_D} = \frac{0.62 * 862}{1.20 * 3} = 148.5\ MPa$$

Section 3-3.4.1: Welded Connections – General

The allowable shear stress in a weld is:

$$Exx(E7018) = 70\ ksi = 482.7MPa$$

$$F_v = \frac{0.60Exx}{1.20N_d} = \frac{0.60 * 482.7}{1.20 * 3} = 80.4\ MPa$$

Appendix 2 (Figures)

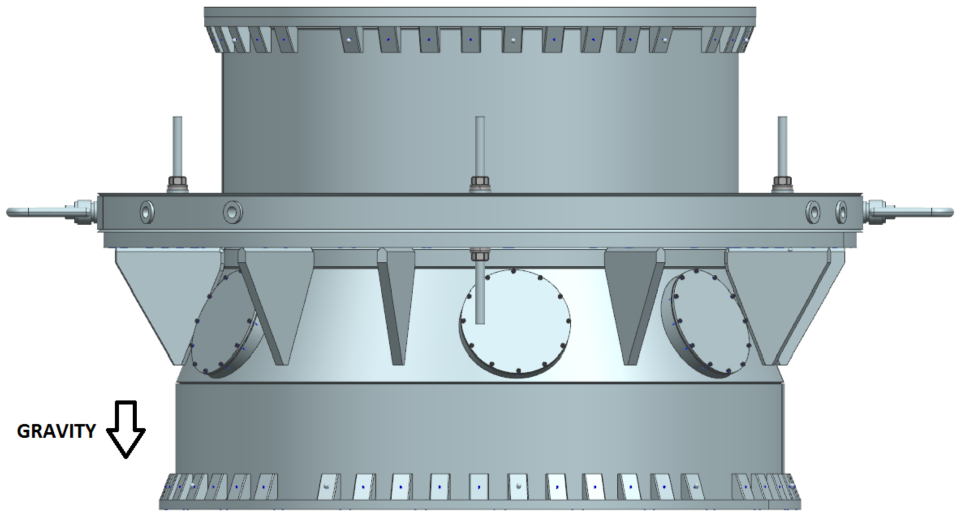


Figure 5a – The Aft Lower Position

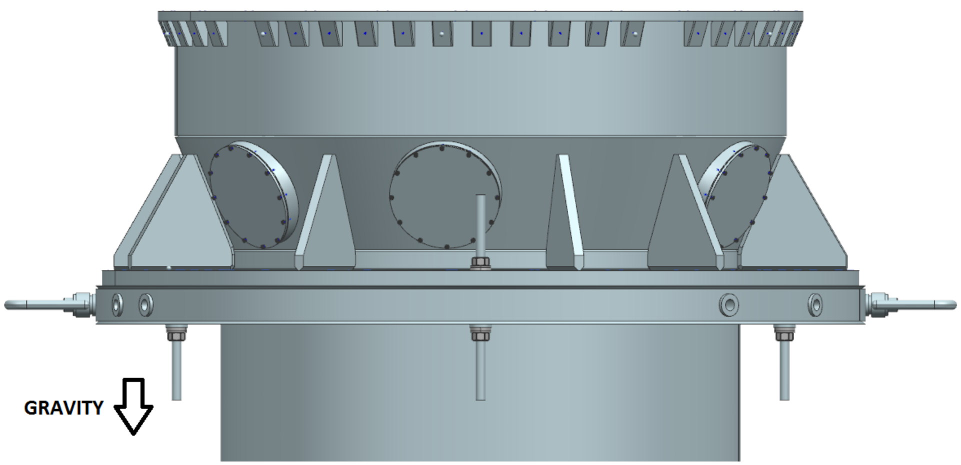


Figure 5b – The Aft Upper Position

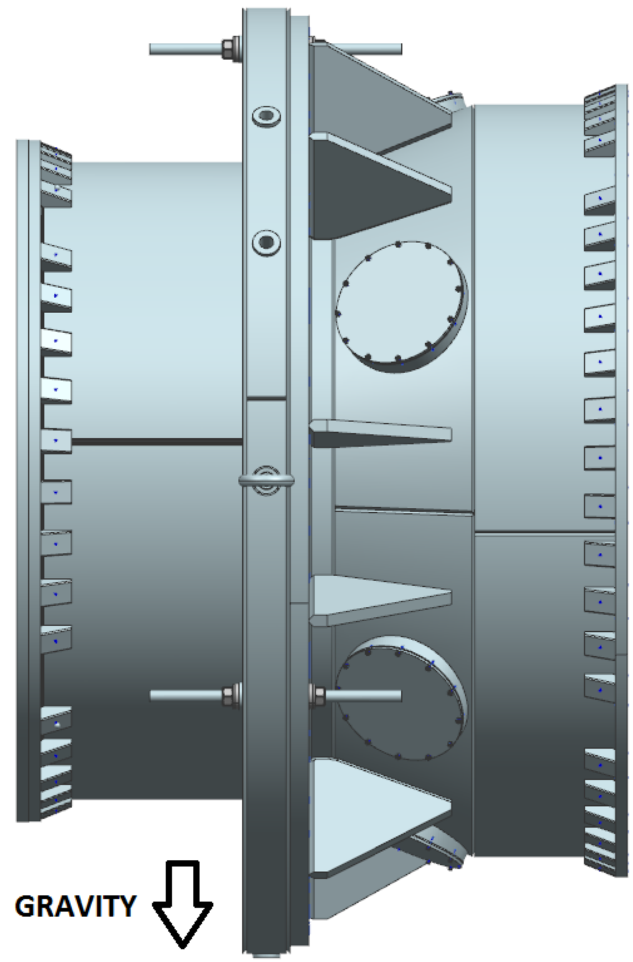


Figure 5c – The Aft Normal Position

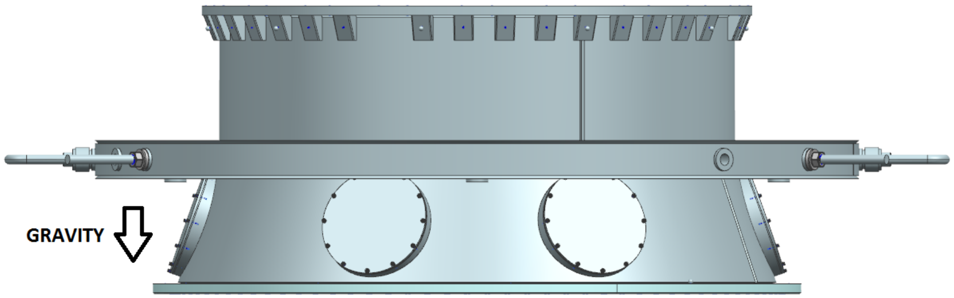


Figure 7a – The Front Neutral Position

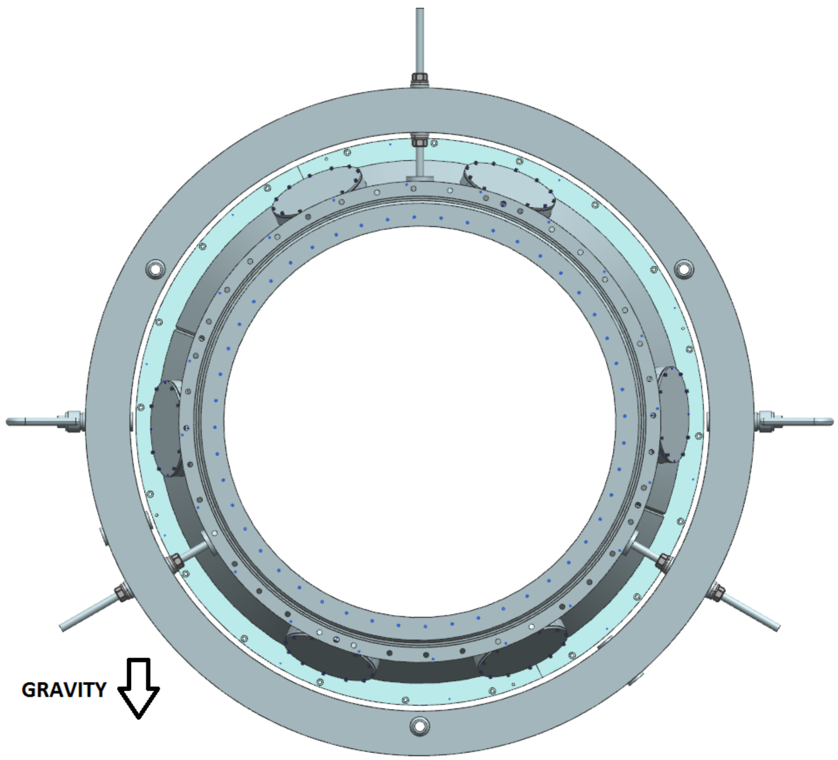


Figure 7b – The Front Tensile Normal Position

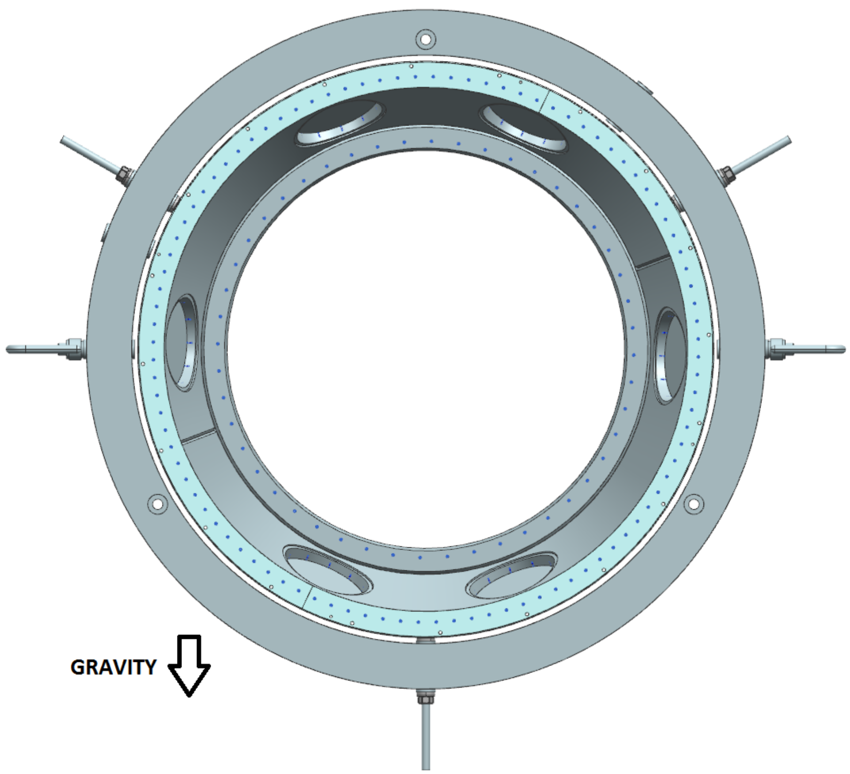


Figure 7c – The Front Compressive Normal Position

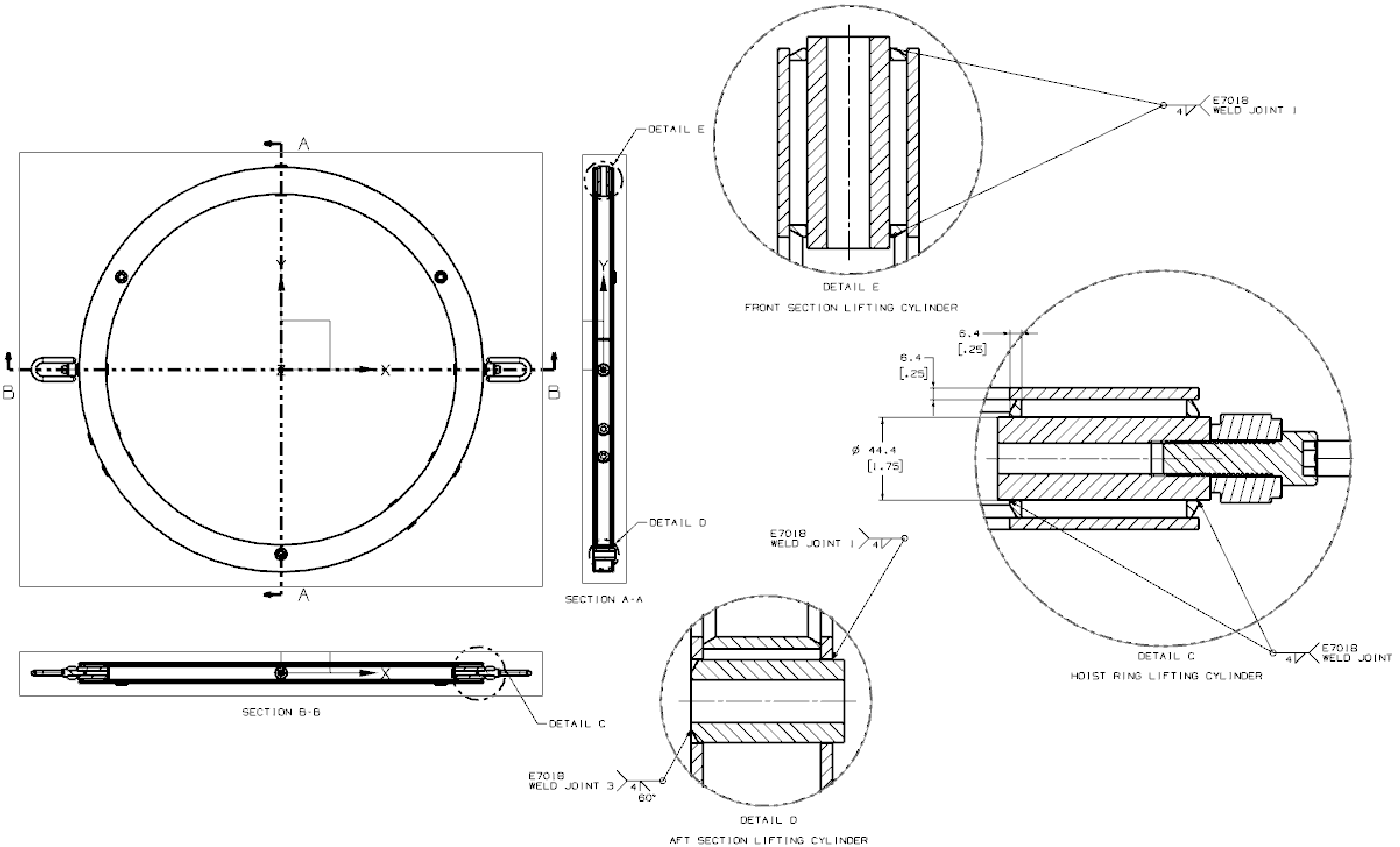
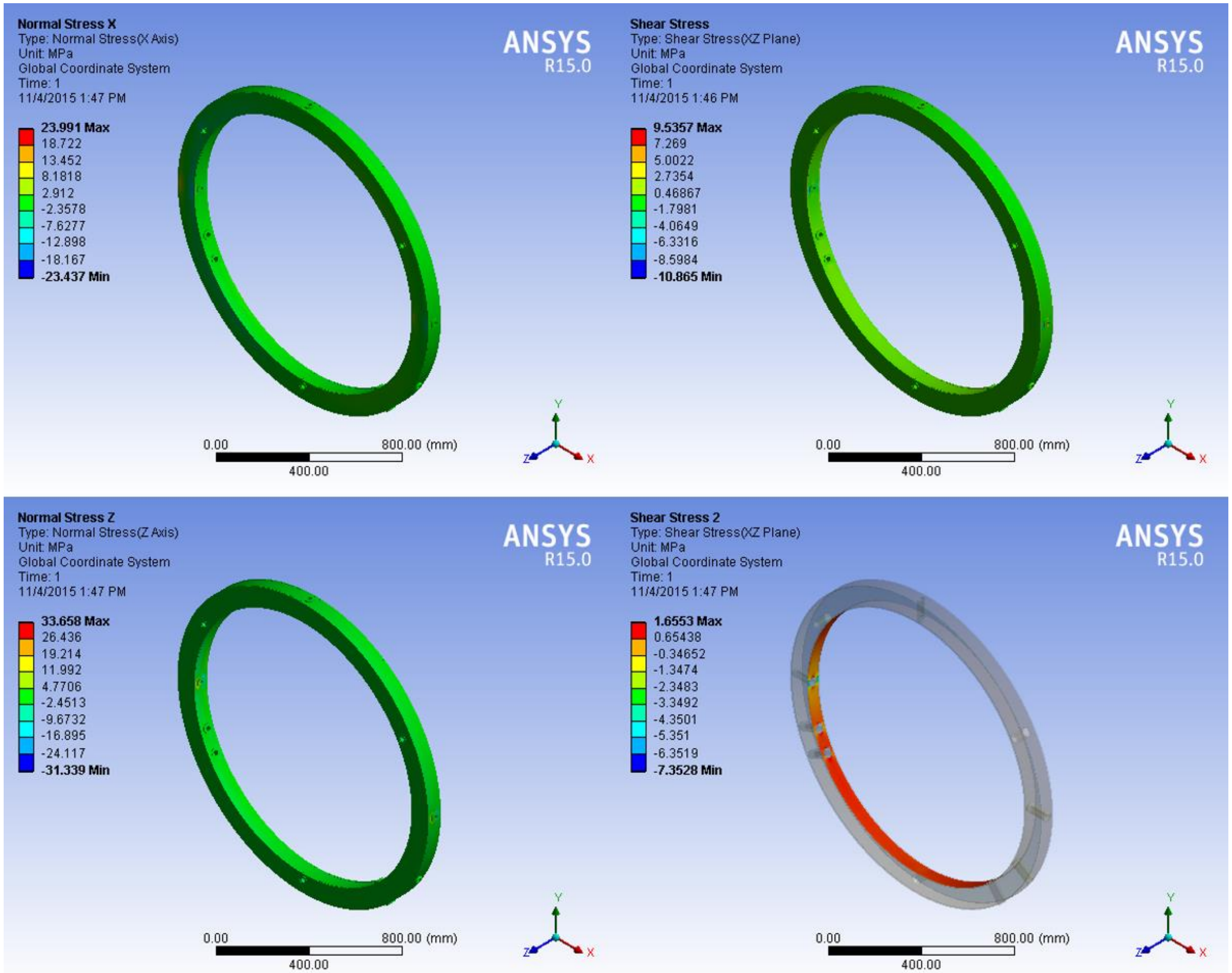
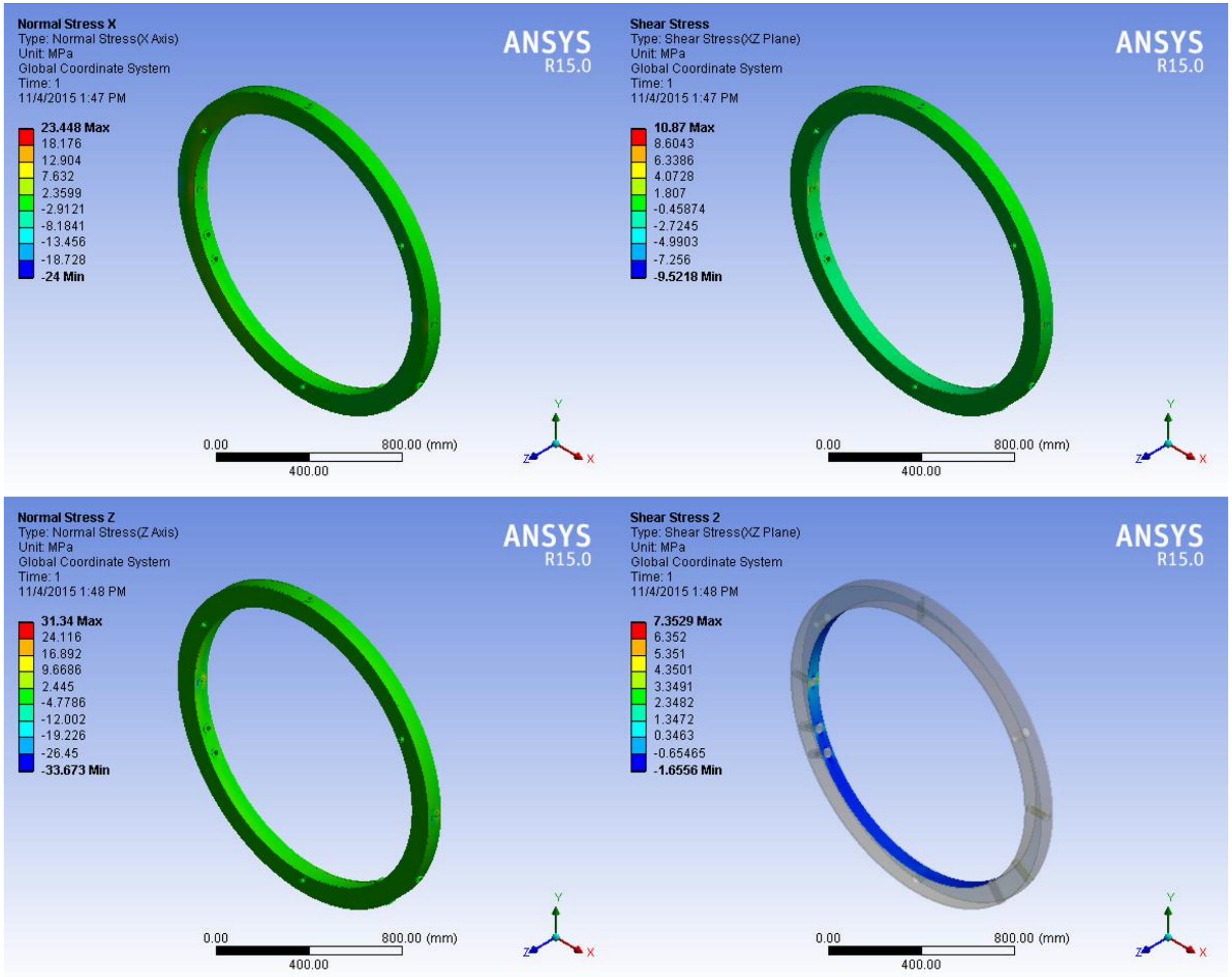


Figure 8 – Weld Joints

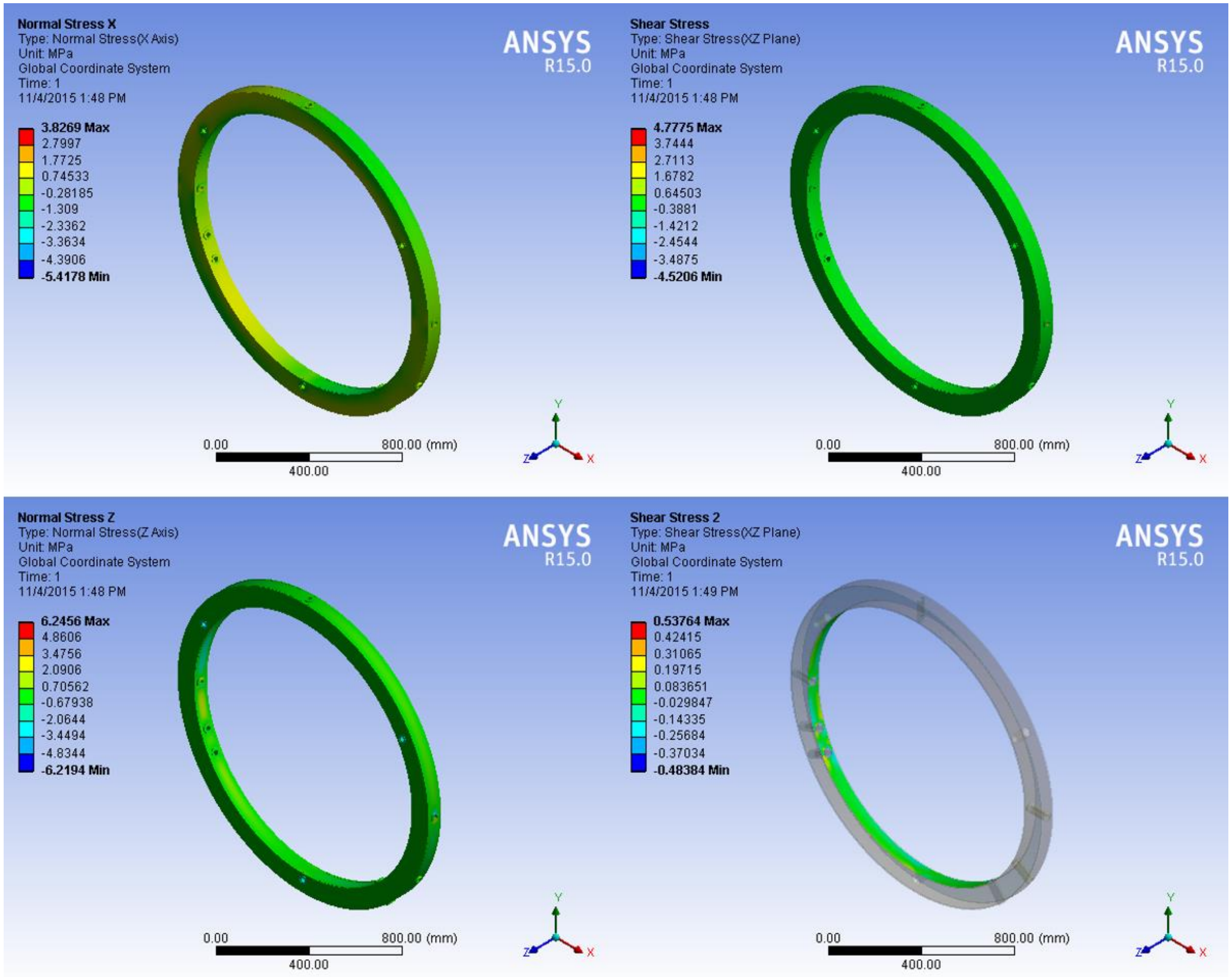
Appendix 3 (FEA Results – Aft Case, Lower Position)



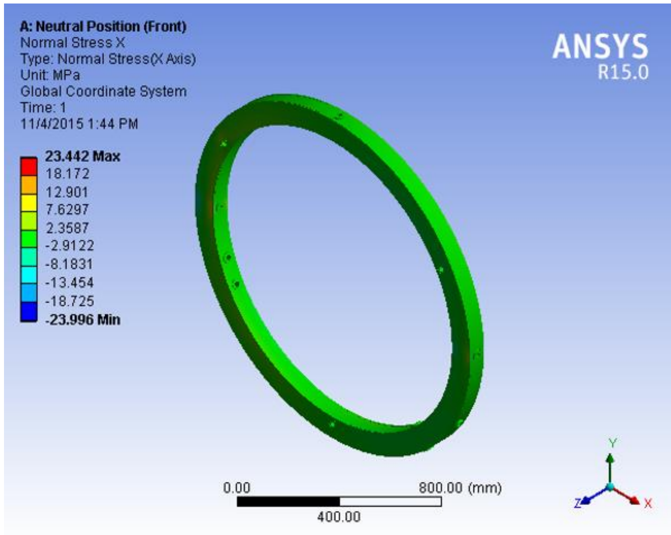
Aft Case, Upper Position

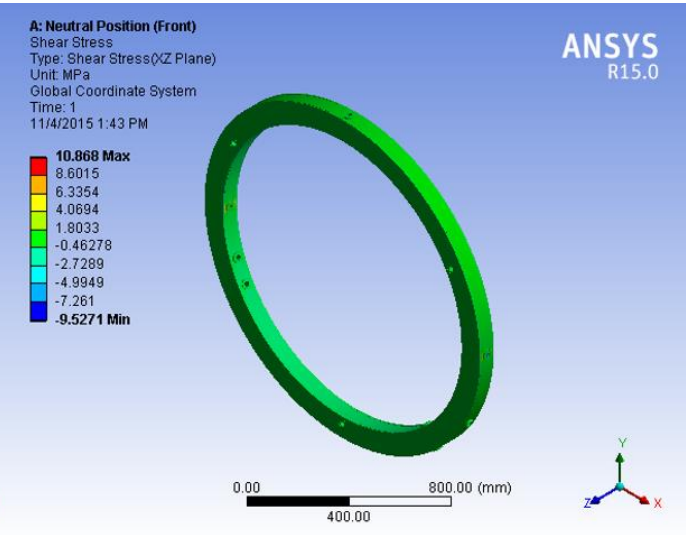


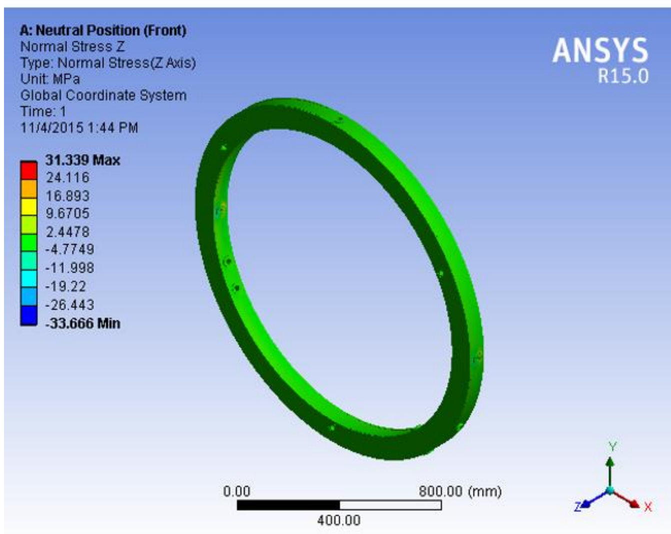
Aft Case, Normal Position

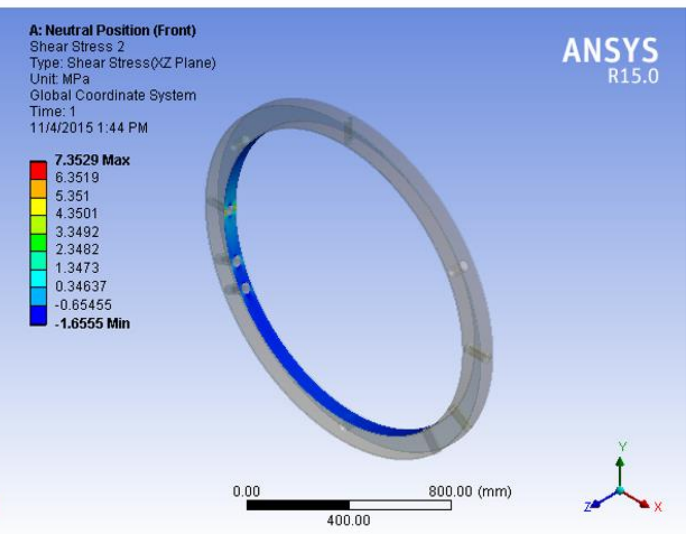


Front Case, Neutral Position

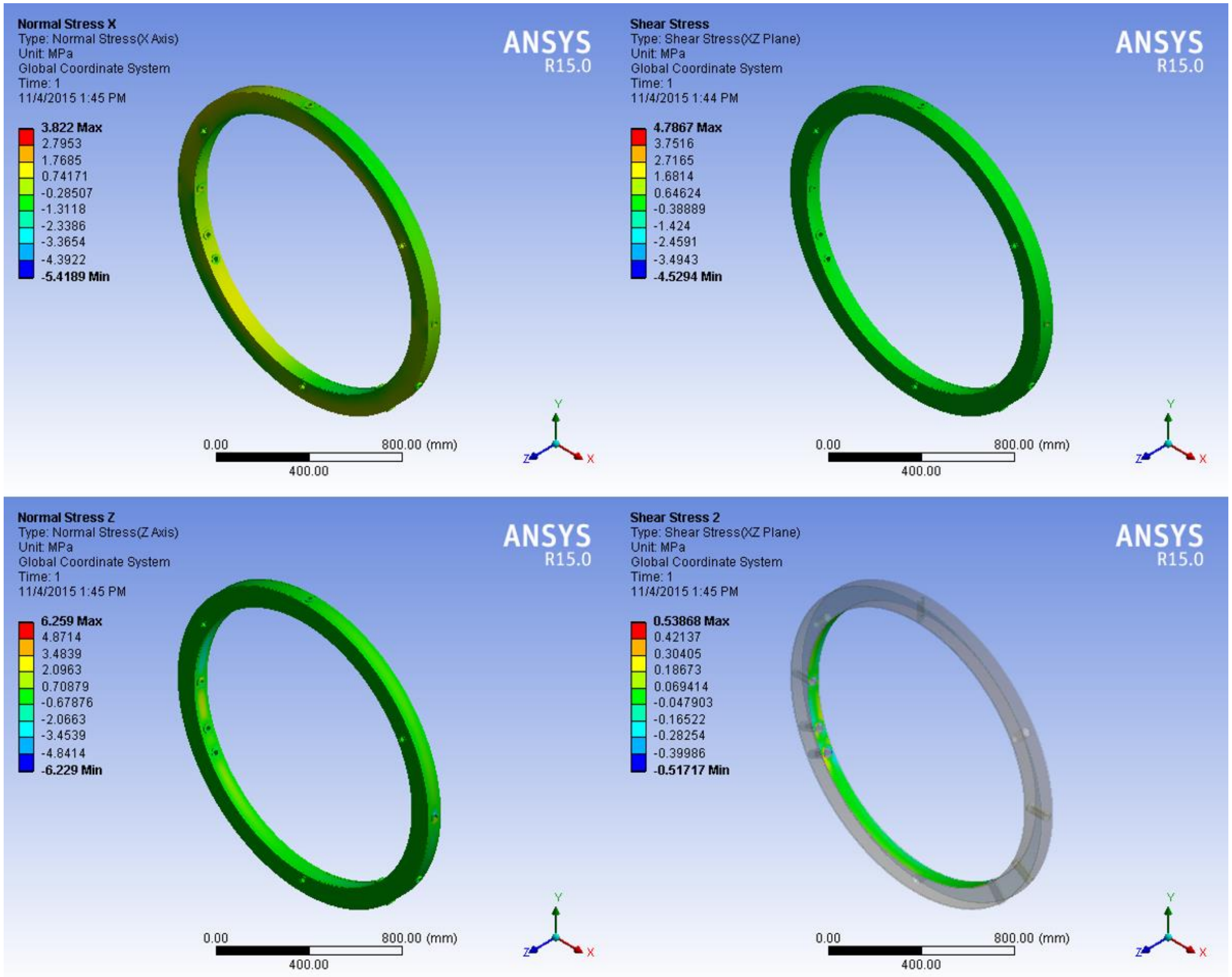








Front Case, Tensile Normal Position



Front Case, Compressive Normal Position