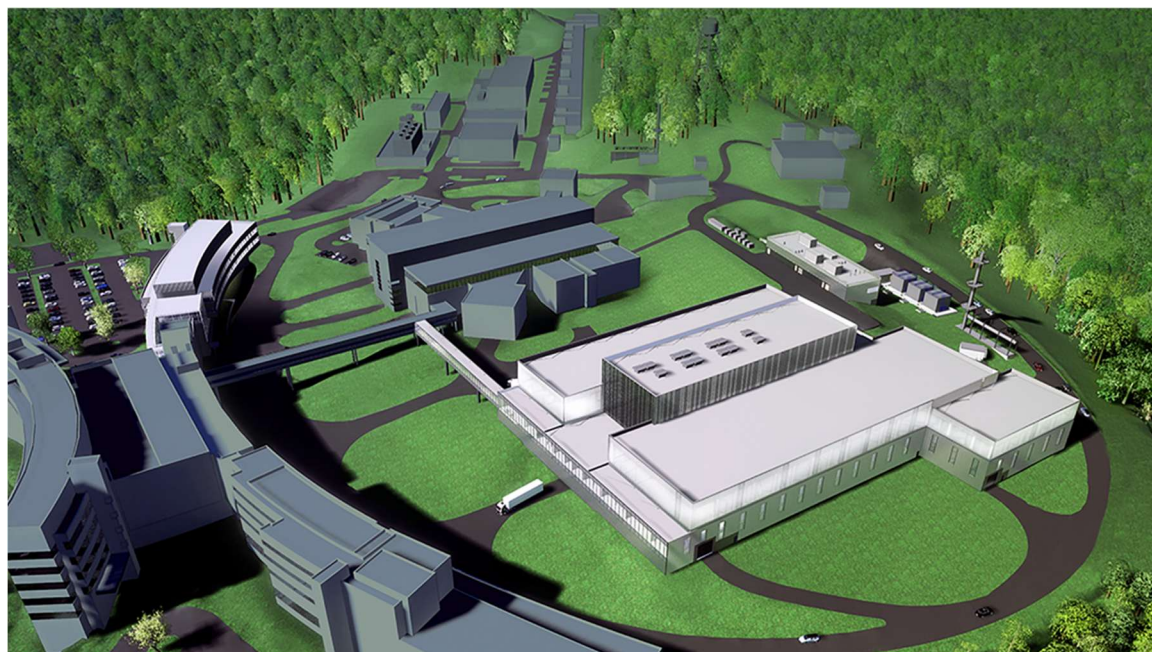


Second Target Station Project: Target Assembly Structural Analysis



Seth Schlotfeldt

March 2026

**Draft. Document has not been
reviewed and approved for
public release.**



Second Target Station Project

TARGET ASSEMBLY STRUCTURAL ANALYSIS

Seth Schlotfeldt PE

March 2026

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

Contents	iii
List of Acronyms	5
1. Introduction.....	6
2. Assumptions	11
3. Physical Model Definition.....	13
3.1 Geometry.....	13
3.1.1 Target Assembly	13
3.1.2 Target Segment	18
3.1.3 Target Shaft.....	23
3.1.4 Crown and Drive.....	30
3.2 Material Properties.....	35
3.3 Requirements and Loads.....	56
3.3.1 Load Parameters.....	56
3.3.2 Weld Strength	68
3.3.3 Fastener Calculations	70
3.3.4 Fatigue Analysis.....	70
3.3.5 Snubber Ring Load	73
4. Numerical Model or Simulation	74
4.1 Software	74
4.2 Unit System.....	75
4.3 Discretization	75
4.3.1 Target Assembly	75
4.3.2 Target Segment	153
4.3.3 Target Shaft.....	174
4.3.4 Crown and Drive.....	195
4.4 Boundary Conditions	221
4.4.1 Target Assembly	221
4.4.2 Target Segment	221
4.4.3 Target Shaft.....	222
4.4.4 Crown and Bearings.....	223
4.5 Contact Conditions.....	225
4.5.1 Target Assembly	225
4.5.2 Target Segment	227
4.5.3 Target Shaft.....	235
4.5.4 Crown and Drive.....	240
4.6 Load Definitions	244
4.6.1 Target Assembly	245
4.6.2 Target Segment Load Cases.....	264
4.6.3 Target Shaft Load Cases	295
4.6.4 Crown and Drive.....	320
4.7 Solution Methodology	345
4.7.1 Target Assembly Analysis Settings	345
4.7.2 Target Segment Analysis Settings	349
4.7.3 Target Shaft Analysis Settings.....	354
4.7.4 Crown and Drive Analysis Settings.....	359
5. Results.....	362
5.1.1 Target Assembly	362
5.1.2 Target Segment	380

5.1.3	Target Shaft.....	424
5.1.4	Crown and Drive.....	462
5.1.5	Result Summary.....	541
6.	Conclusions.....	544
7.	References.....	545
	Appendix A. Supplemental calculations.....	546

LIST OF ACRONYMS

AISC – American Institute of Steel Construction
ASCE – American Society of Civil Engineers
ASME – American Society of Mechanical Engineers
BPVC – Boiler and Pressure Vessel Code
CAD – Computer Aided Design
CG – Center of Gravity
CJP – Complete Joint Penetration
CTE – Coefficient of Thermal Expansion
DoF – Degree of Freedom
FEA – Finite Element Analysis
EP - Elastic Plastic
LoF – Life of Facility
MAWP – Maximum Allowable Water Pressure
MPC - Multi Point Constraint
MRA – Moderator Reflector Assembly
ORNL - Oak Ridge National Laboratory
RCSC – Research Council on Structural Connections
SNS - Spallation Neutron Source
STS - Second Target Station
F - Fahrenheit
in - inch
lbf - pound force
m - meter
mm - millimeter
psi - pound per square inch
rad - radian
rpm – revolutions per minute
s - second
S_a – Stress Amplitude

1. INTRODUCTION

The STS Project is to design and build the world's brightest source of cold wavelength neutrons for cutting edge science. To achieve this goal, the tungsten spallation target will receive 1.3 GeV proton pulses at a rate of 15 Hz, totaling 700 kW beam power. The focused nature of the proton beam and the decay heat have necessitated a target assembly that consists of 20 individual target segments rotating at approximately 45 rpm so that each target segment receives a proton pulse every $4/3$ seconds. The top of the assembly consists of a drive system and a coolant distribution system. It is connected to a large shaft around which 20 target segments are held. The target segment is 14 ft 5 inches in height. A concentric system of pipes carries coolant in and out. All materials are 316L stainless steel.

This STS Target Assembly structural analysis evaluates code-relevant limits (elastic stress/plastic strain margins) and fatigue usage under combined mechanical and thermal cycling. Using project-based requirements along with multiple codes and standards the Target Assembly is checked against seismic, pressure, live, dead, and thermal loads. Figure 1 shows the Core Vessel with the upper Target Assembly visible.

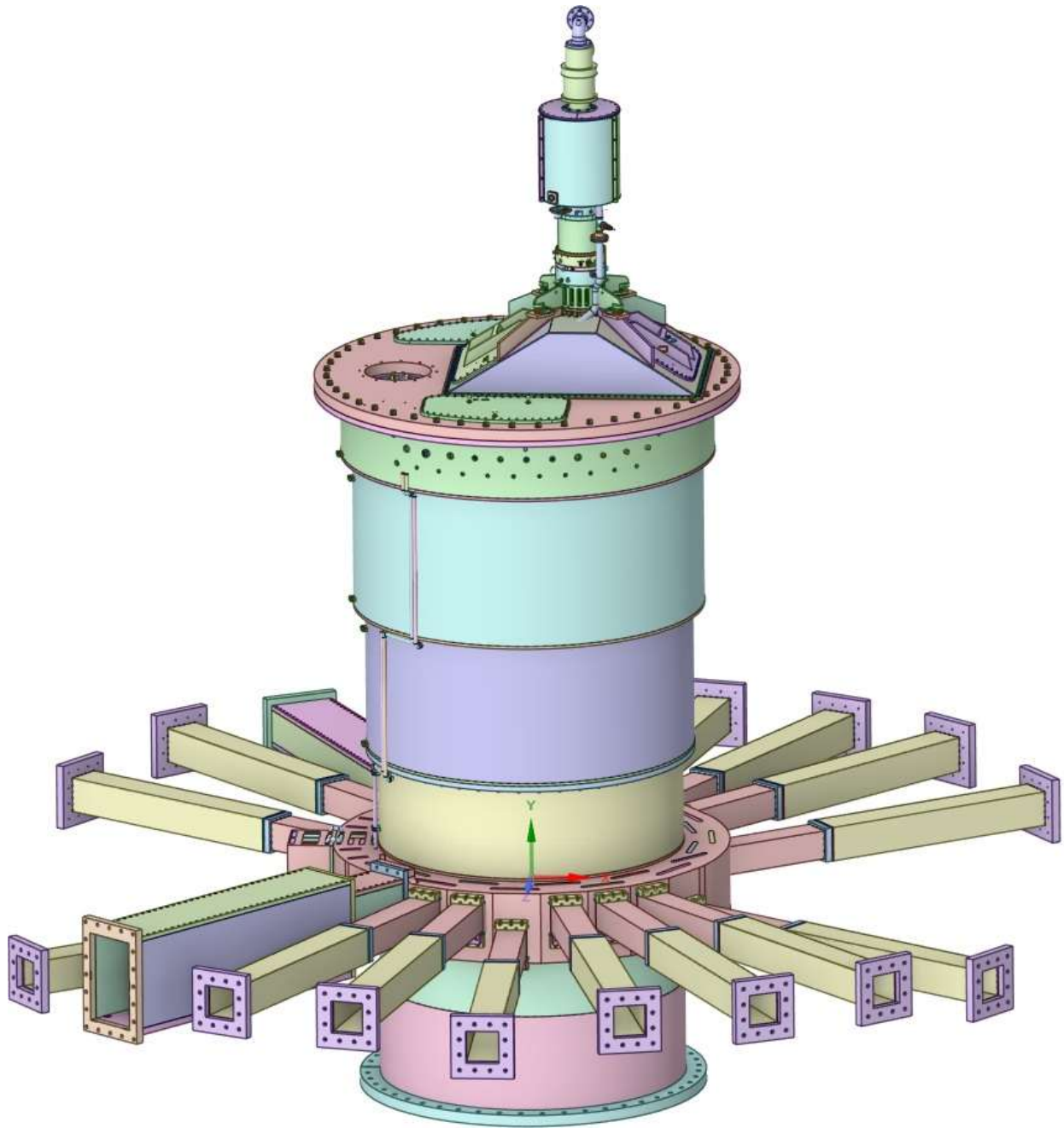


Figure 1 Target and Core Vessel Assembly

The Target Assembly is supported at the Core Vessel lid. Figure 2 shows the cross section and separation of the two assemblies by color.

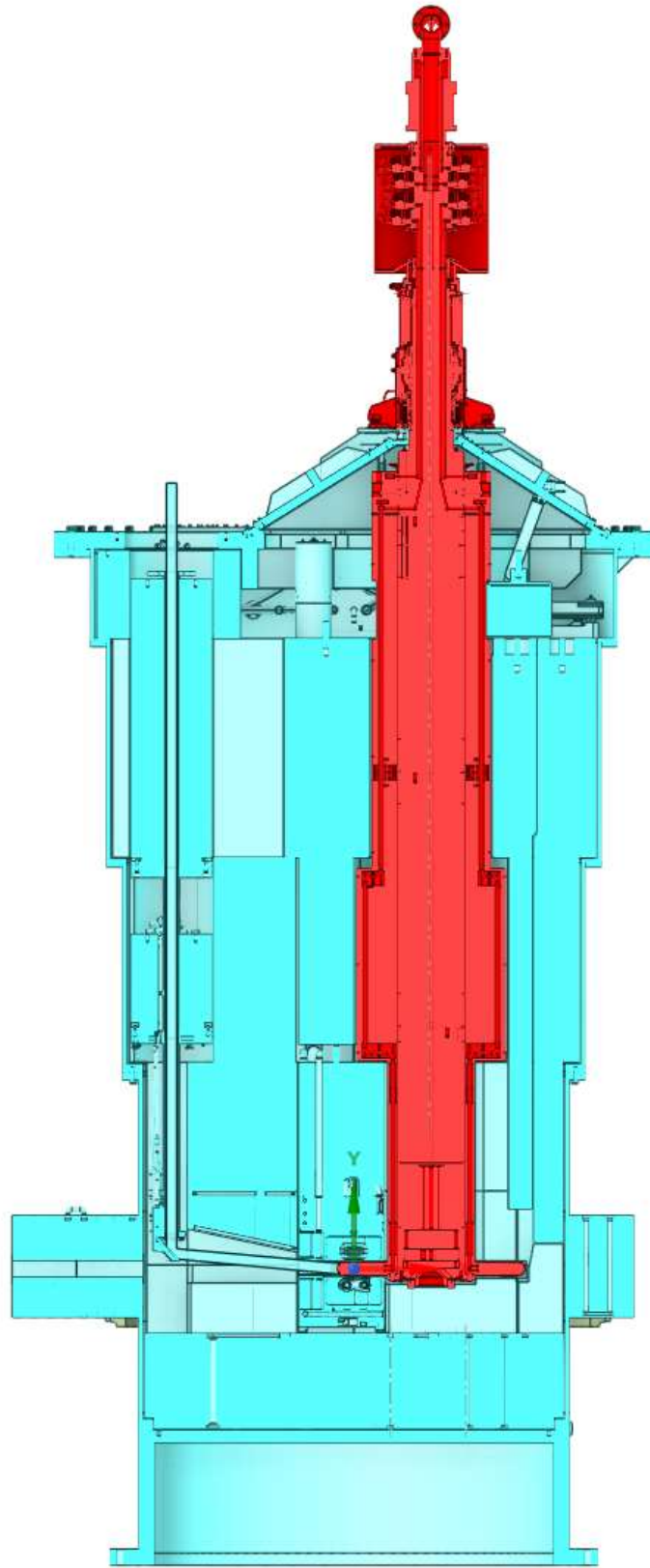


Figure 2 Target Assembly in Red

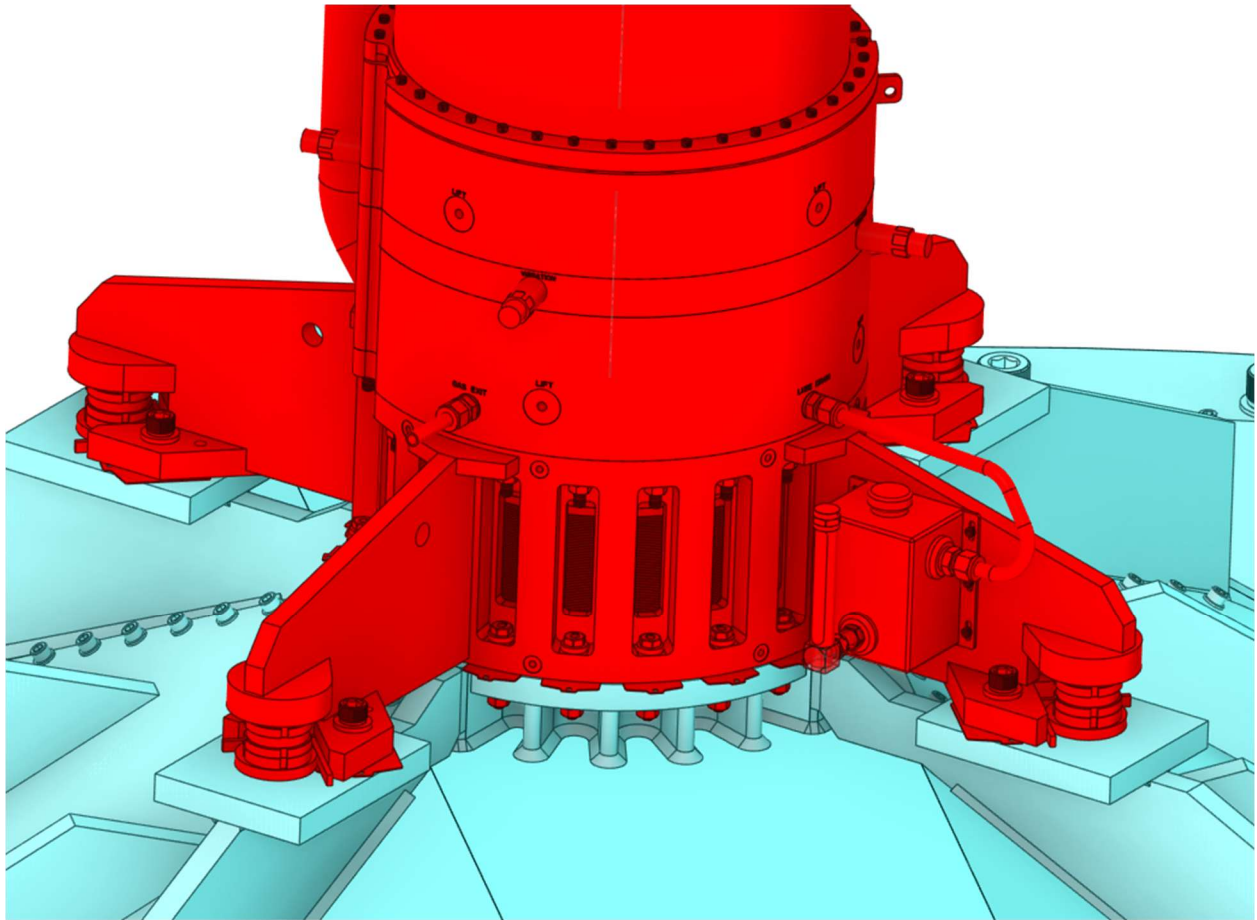


Figure 3 Target / Core Vessel Bolted Interface

Figure 3 shows a close up of where the Target Assembly mounts to the Core Vessel lid. Figure 4 shows the lower end of the Target Assembly where it interfaces with the MRA and Snubber ring. The Snubber ring is the seismic restraint for the bottom of the Target Shaft, this provides a captive feature that limits the lateral movement but does not directly contact the Target Shaft.

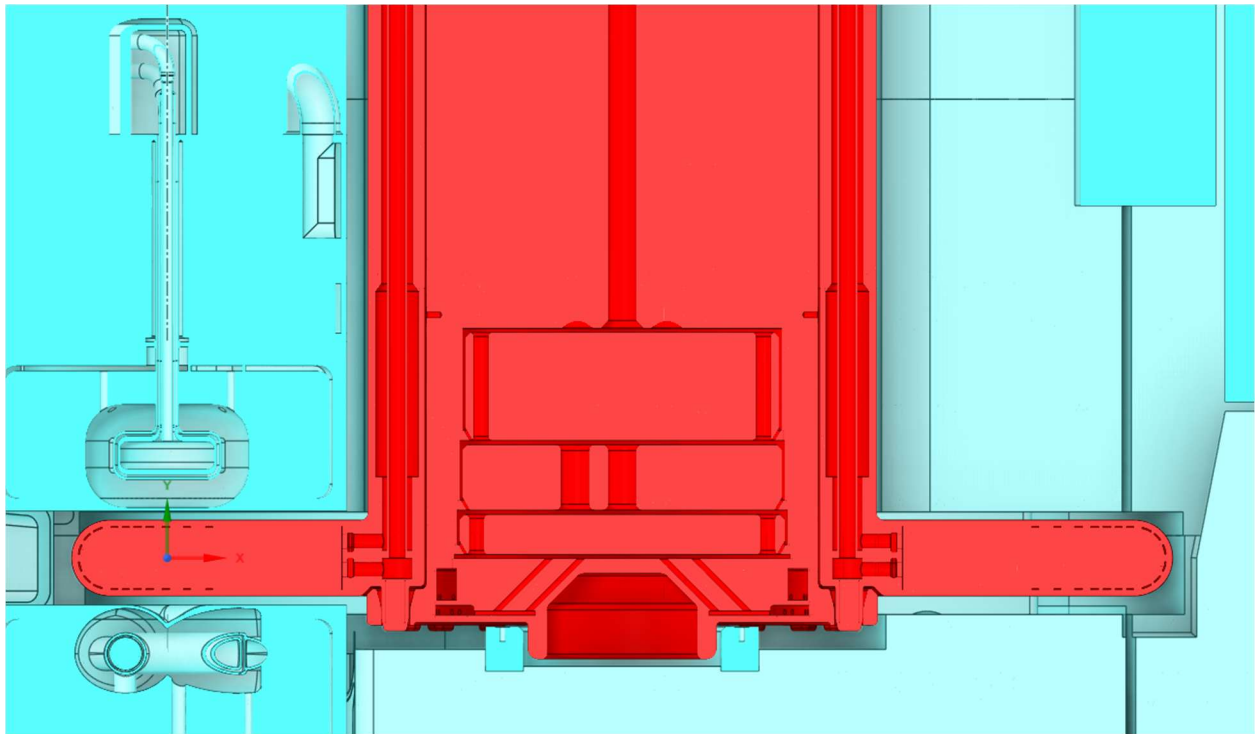


Figure 4 Snubber Interface and MRA Clearance View

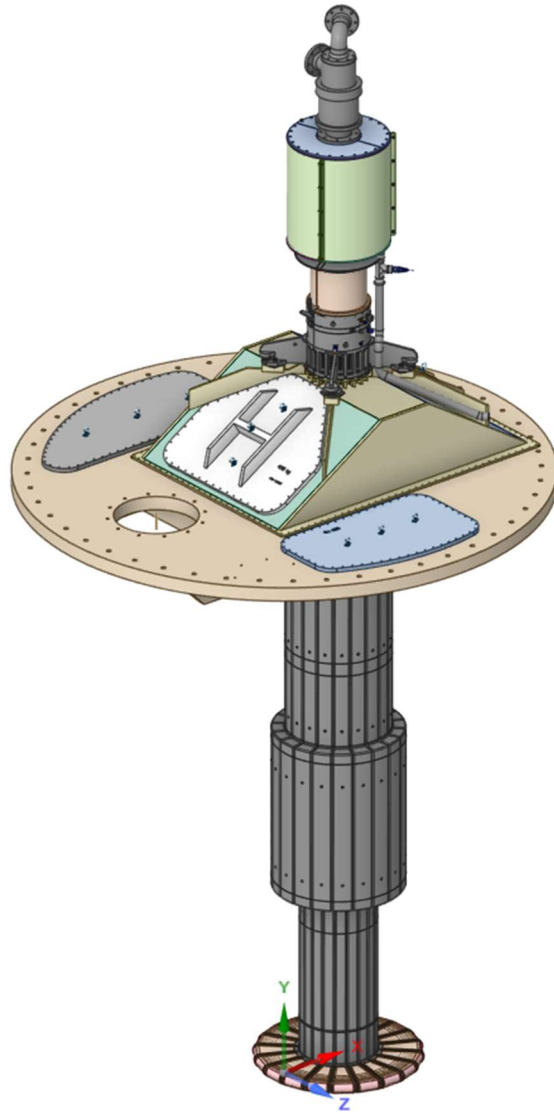


Figure 5 Target Assembly with Core Vessel Lid

2. ASSUMPTIONS

- The attachment point at the core vessel lid is rigid.
- No additional heat is transferred to the Target from other sources inside the core vessel.
- Rotating equipment assumed to be balanced except for eccentric loads.
- Steady state operation is assumed for both mechanical and thermal loads.

- Welds are ground and polished.
- Tolerance stack up is not considered when evaluating displacement.
- Buckling is ignored in this analysis.
- An Imbalanced Target is the equivalent of the Target Shaft with only 19 Segments.

3. PHYSICAL MODEL DEFINITION

3.1 GEOMETRY

The Target Assembly CAD model begins in Creo, part number 0000004343.ASM version 187. The model is exported as an STP file and moved into ANSYS Workbench. The STP file was then opened in Spaceclaim for editing. Due to the size of the model a complete assessment of the Target Assembly isn't feasible with one model. Three subassemblies were created to focus on the Target Segment, the Target Shaft/Tie Rods, and the Crown/Bearings assemblies.

3.1.1 Target Assembly

The full Target Assembly is very large and complex, the height of from the bottom of the shaft to the top of the pipe union is just under 26 feet (7.8m). The FEA model includes the Core Vessel Lid and Tent as part of the analysis. The Target Assembly is mounted on the Tent, which is mounted on the Lid. This combination gives overall deflections which are needed to verify that during operations or upset load conditions that there is no part interference with other components inside the Core Vessel. The CAD model is fully detailed with fasteners, sensors, electronics, etc. These components were deleted out of the assembly, as well as any component that was not part of the load bearing structure. O Rings, glands, and gaskets were removed. Shims and alignment features were removed. All the stenciled or etched text was removed. The piping was converted to 2D bodies, the shroud around the water manifold is a sheet metal design and those components were also converted to 2D bodies.

Figure 2 is a view of the initial step file opened in Spaceclaim before any simplifications were made.

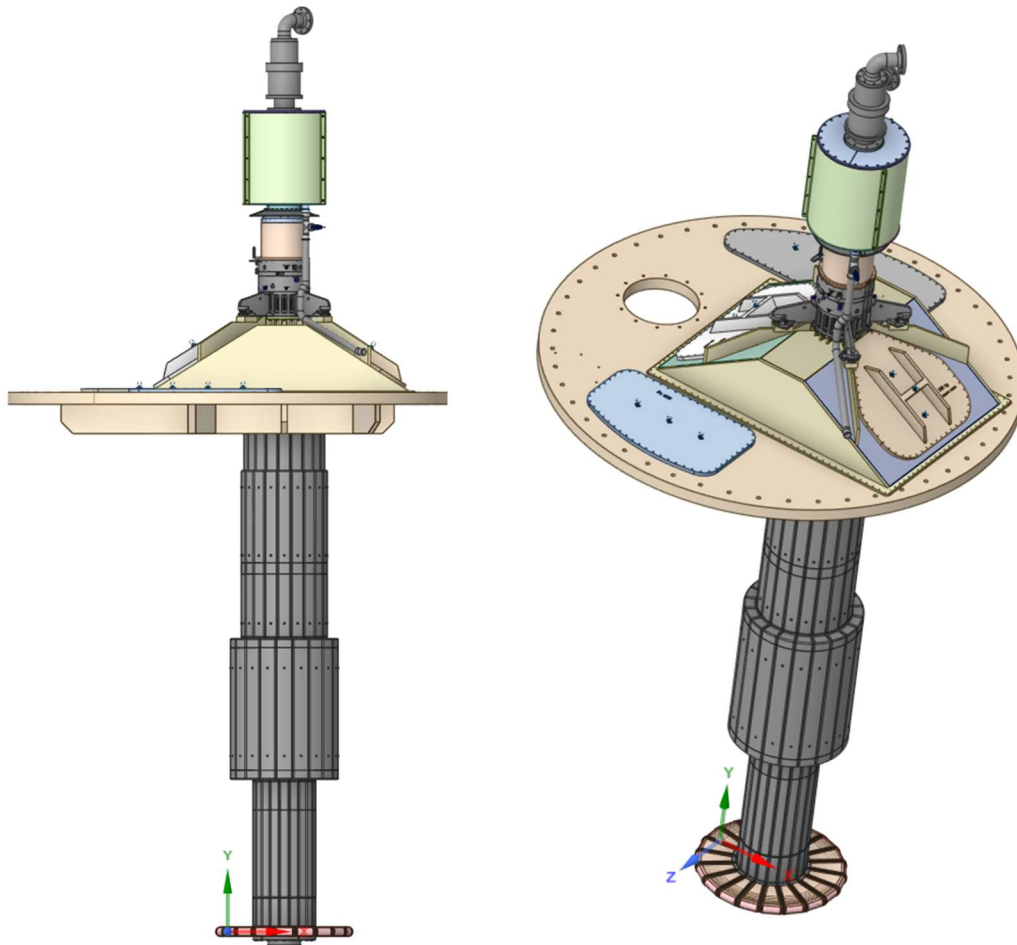


Figure 6 Target Assembly CAD Model

Figure 3 shows the FEA model after simplification.

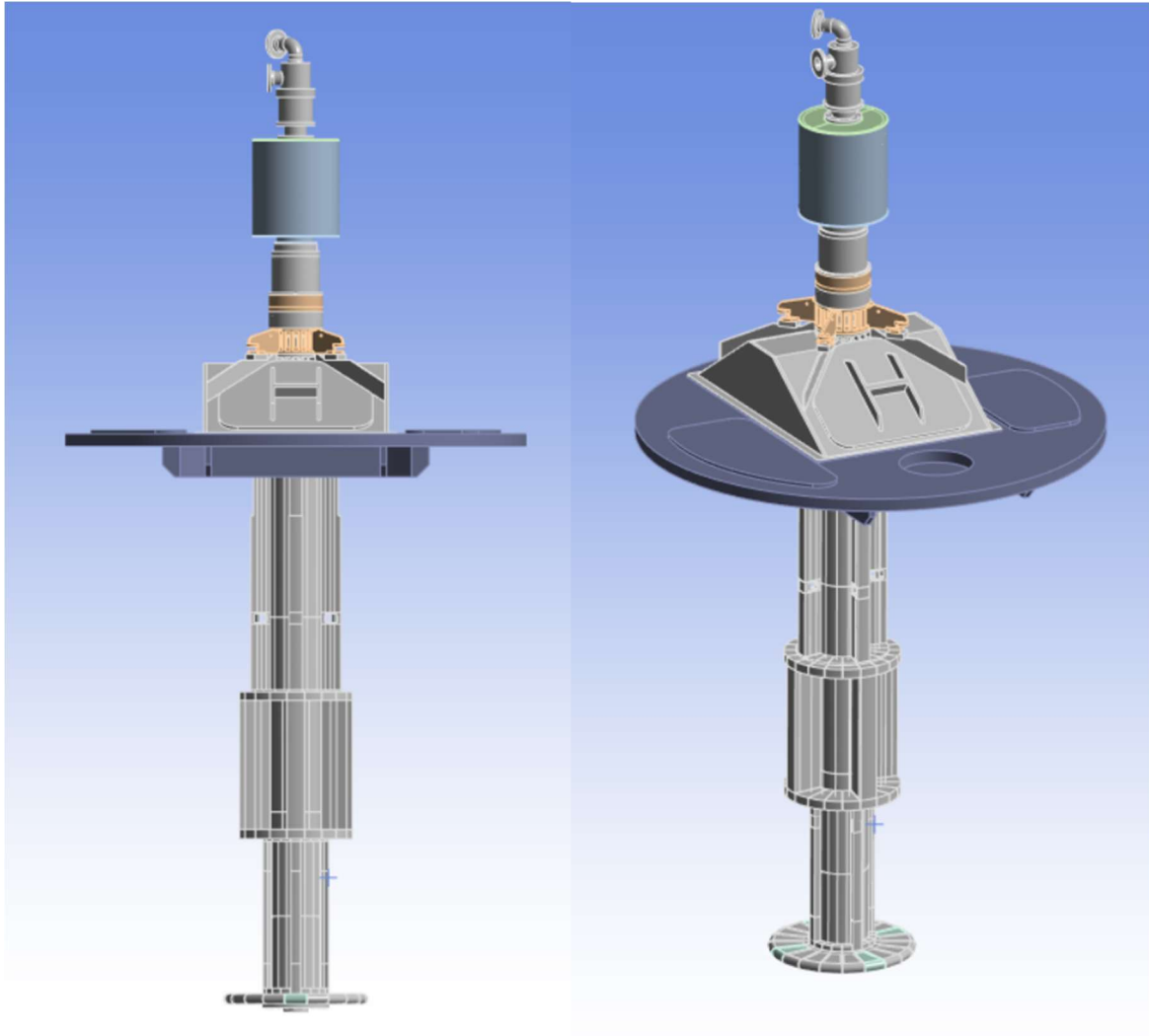


Figure 7 Target Assembly ANSYS Model

Figure 4 shows an example of simplified components. There are 20 Segments in the assembly, since they are all the same and require a complex mesh, only 4 are used in this model. The remaining segments are replaced with ‘dummy’ Segments that are mostly 1D beam models that replace the constant cross section areas with beam sections and solid bodies where the cross section changes. The solid bodies are a place to anchor the beam ends. Figure 3 shows there are 4 full Segments, one at each of the principal directions, -X, +X, -Z and +Z. The load conditions are all applied in one of those principal directions so the worst of the load would act on one of those Segments.

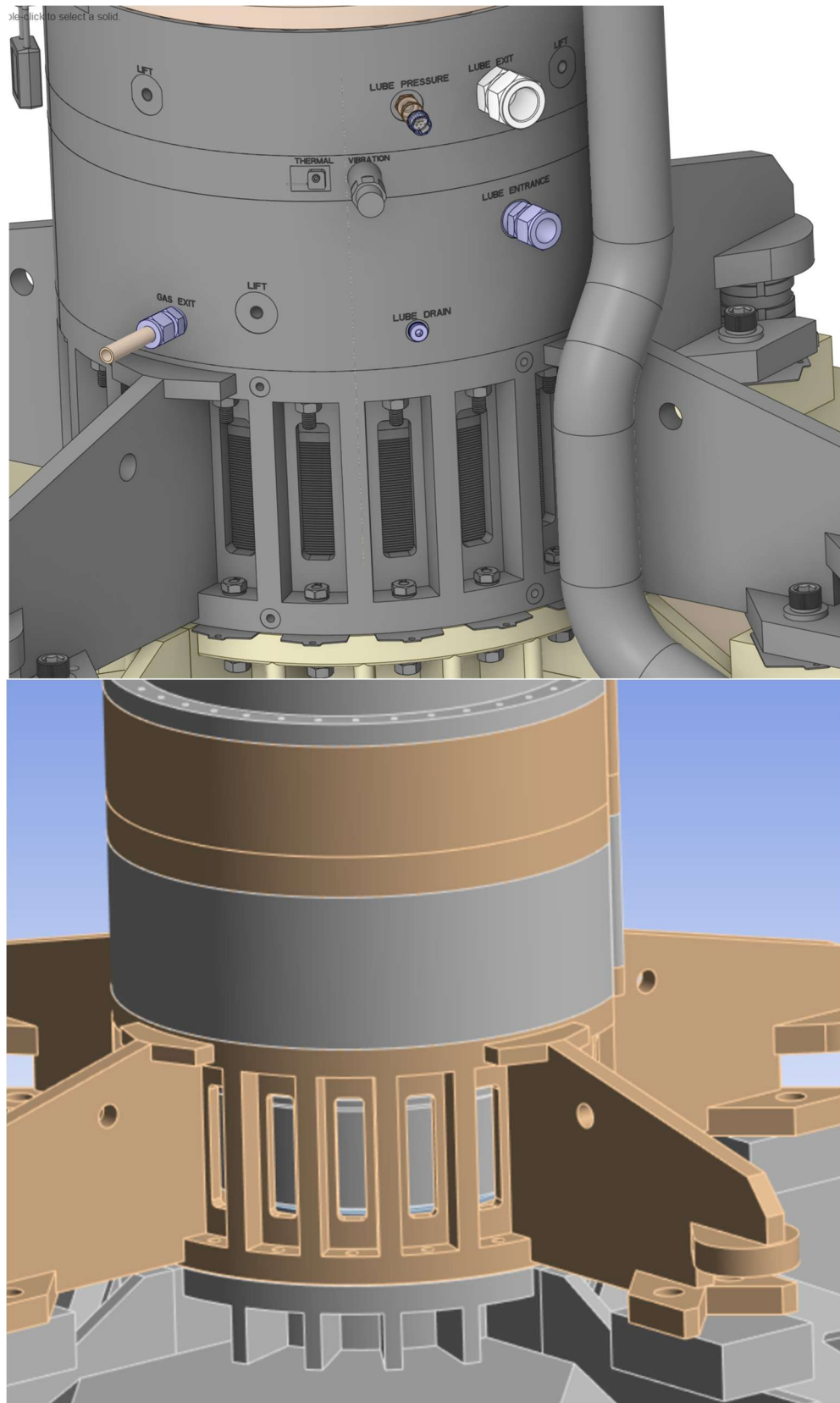


Figure 8 Target Assembly Example of Simplified Areas

Figures 5 and 6 show the two main coordinate systems used, the coordinate system in Figure 5 is located where the beam hits the Target in the MRA, it is the global origin for everything in the Core Vessel. A second coordinate system is required for the inertia loads that is on the center axis of the rotating components. The principal directions stayed consistent, the origin was just moved as seen in Figure 6.

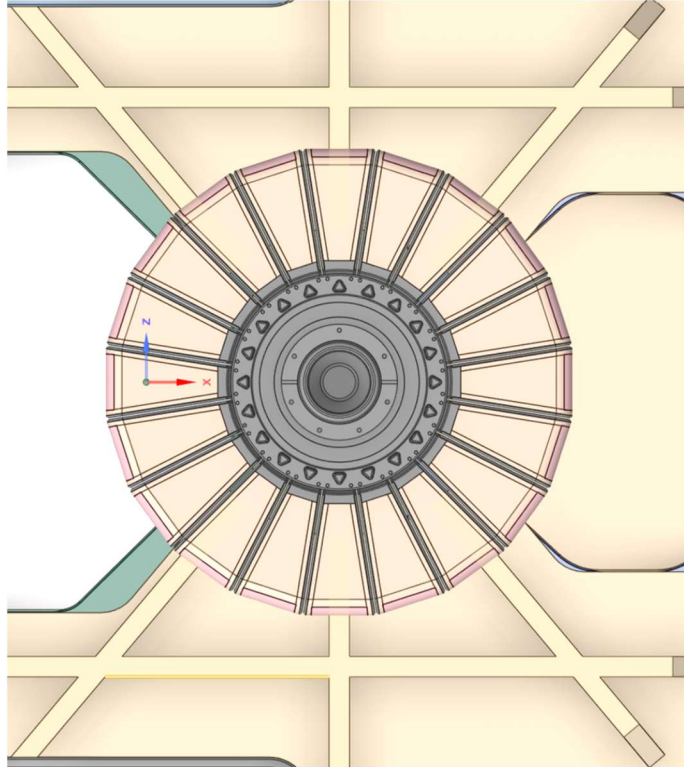


Figure 9 Target Assembly Default Coordinate System

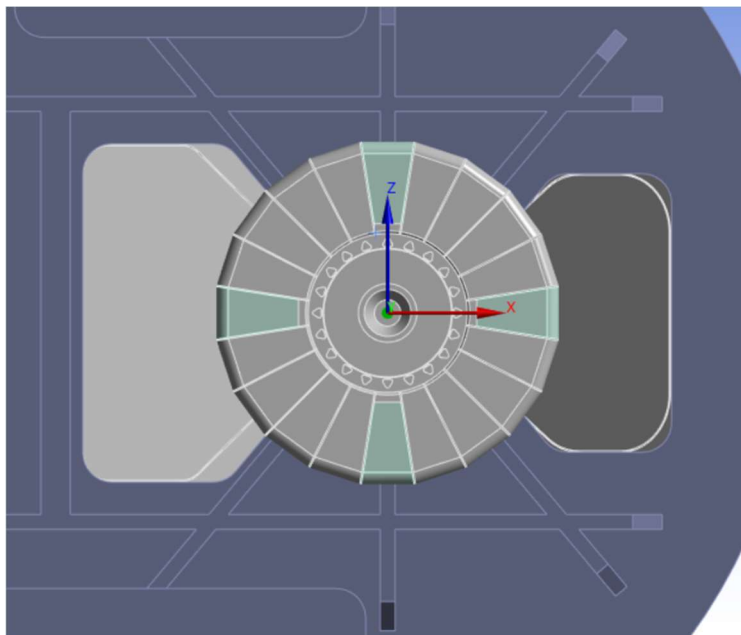


Figure 10 Coordinate System for Inertia Loads

3.1.2 Target Segment

The Segment is a critical component and has its own analysis to focus on key features. The Segment body is a weldment with both 2D and 3D elements, the 2D elements being internal piping. There is a single bolt at the top of the Segment, this bolt is replaced with a beam connection. The bolted joint is also a water connection for cooling the Segment Foot, there are two O Rings the require this joint to stay compressed to prevent any leaking. A cutout of the Crown is included in the Segment model to provide both sides of the sealing interface. The second point of constraint for the Segment is at the foot, a triangular pin. The Segment model was simplified by removing all the of the rounds. The weld thickness for each joint was imprinted and only the weld size was used for the bonded interface. The split sections are stitch welded together, for this connection the parts were modeled with a repeating feature the size and length of the weld and then the two halves were merged into one body. Finally, there are some plugs for the piping that are welded in, those plugs also were merged into the parent body.

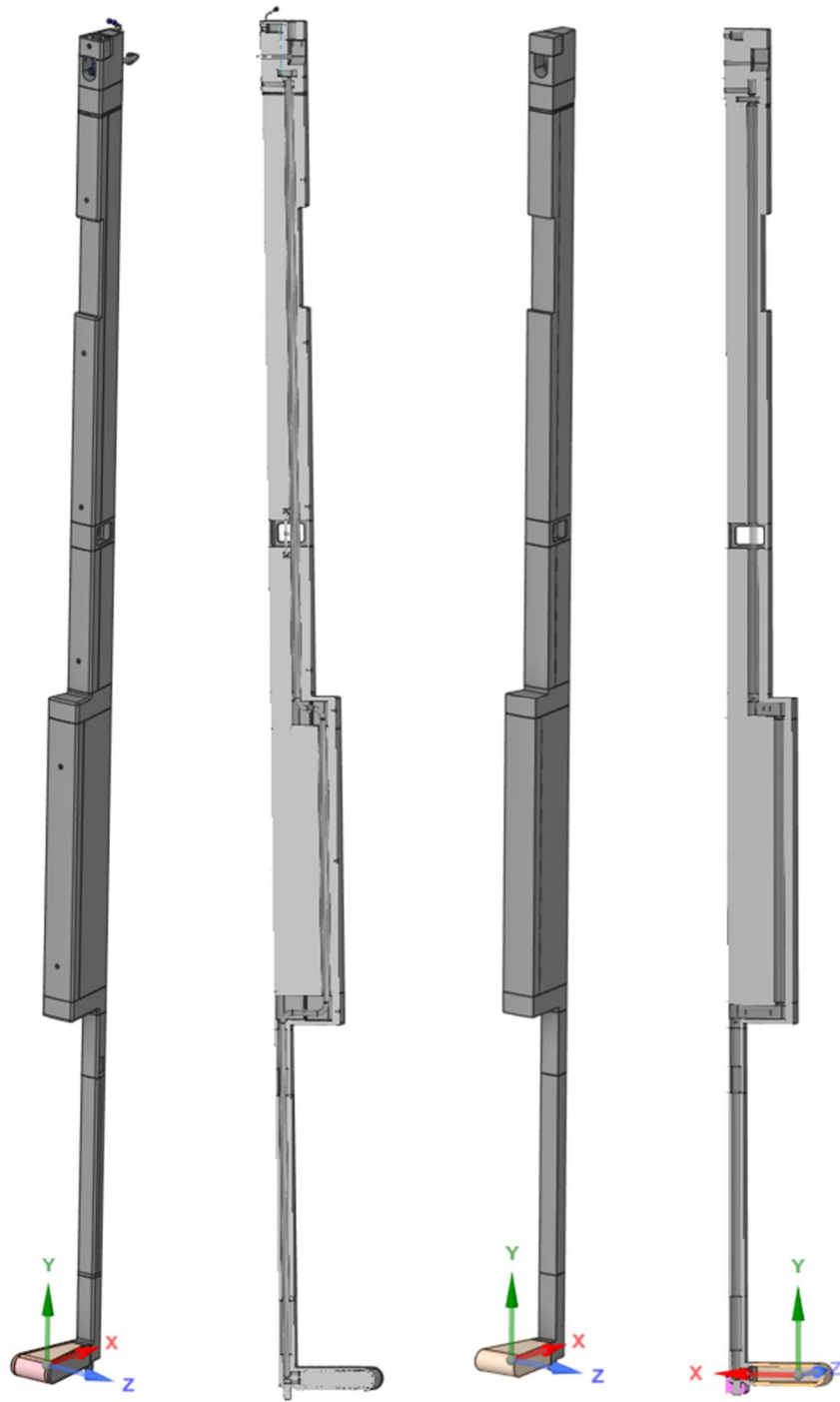


Figure 11 Segment CAD Model vs FEA Model

Figures 11 and 12 show an overall view and a close up view of the CAD model, starting on the left, and it's cross section then a comparison view of the simplified FEA model and it's cross section view is shown on the right.

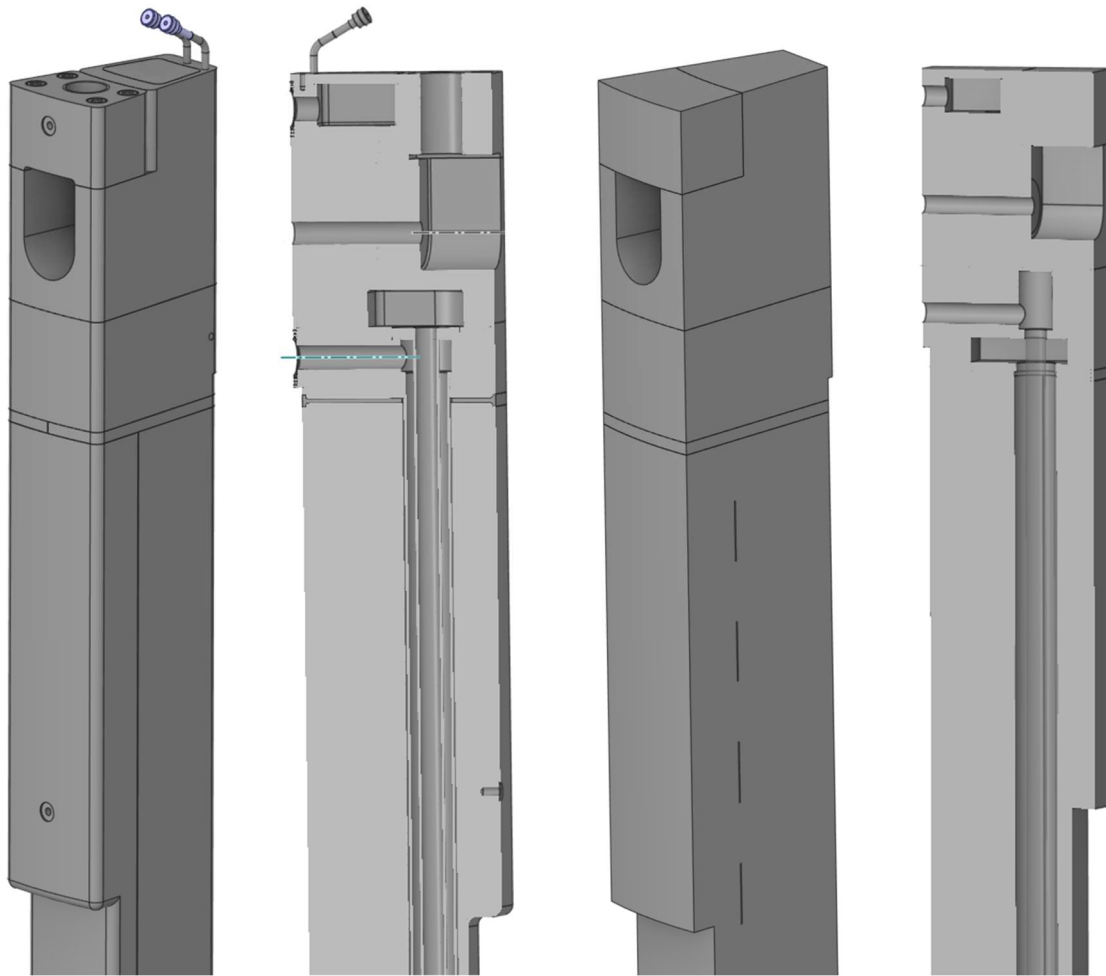


Figure 12 CAD Model vs FEA Model

The ‘foot’ of the Segment, which contains the actual Target, has been evaluated separately in document. The foot is included in this model but only to serve as weight. Figure 13 shows simplified foot on top with the just the Inconel shell used. The Inconel density is adjusted so the weight is equivalent to the actual foot. Below the FEA foot is the actual Target foot with the stack of Tungsten shown.

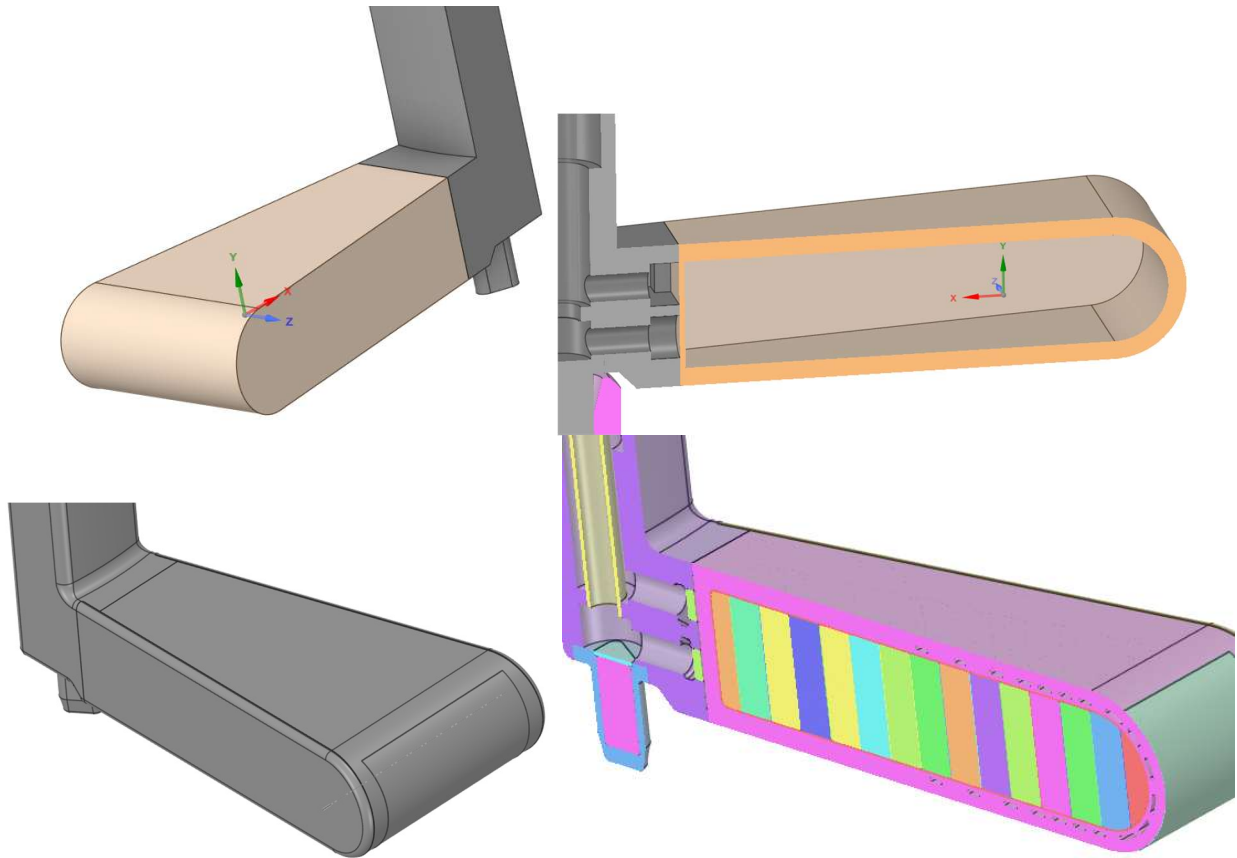


Figure 13 Target Foot Comparison

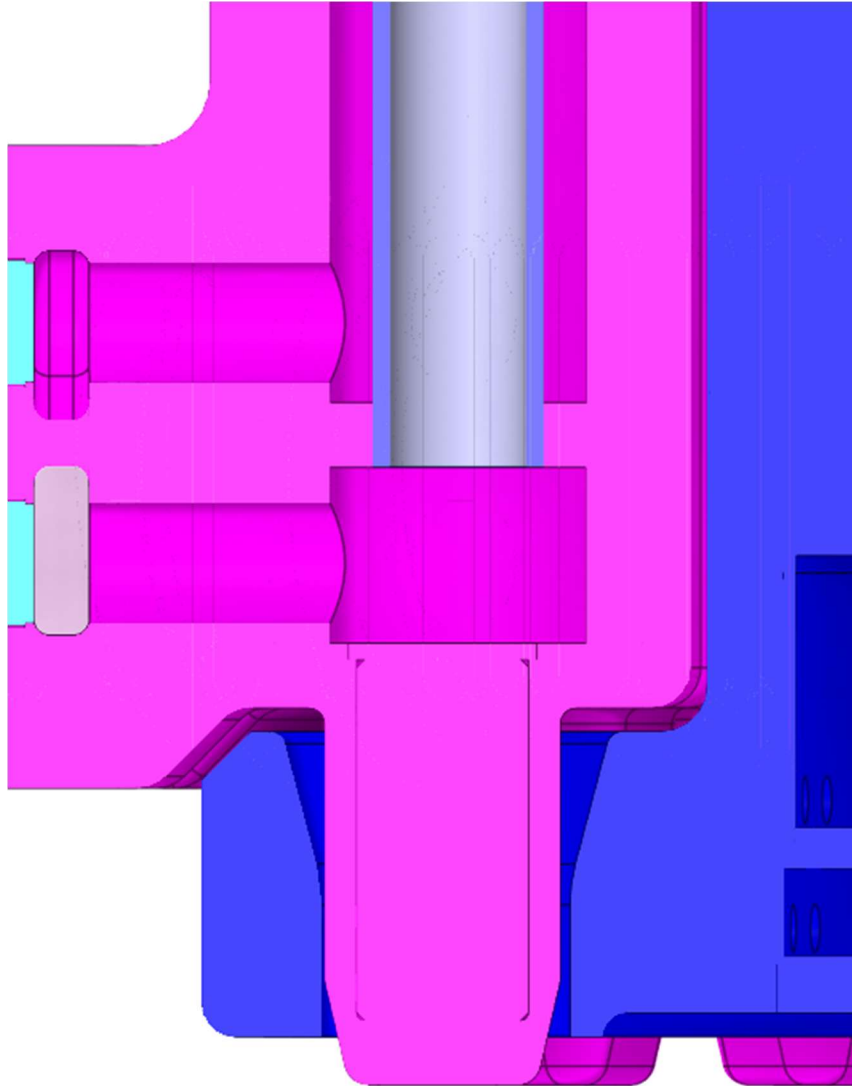


Figure 14 Segment Foot Pin, Side View

The Segment foot pin is a critical point in the analysis as it is one of two connections hold the Segment in place. When a Segment is replaced, it is lowered by crane until this pin (purple component) has aligned and engaged in the feature on the Shaft (blue component). The tapered fit helps with installation and the triangular feature, Figure 15, keeps the Segment from rotating about it's vertical axis.

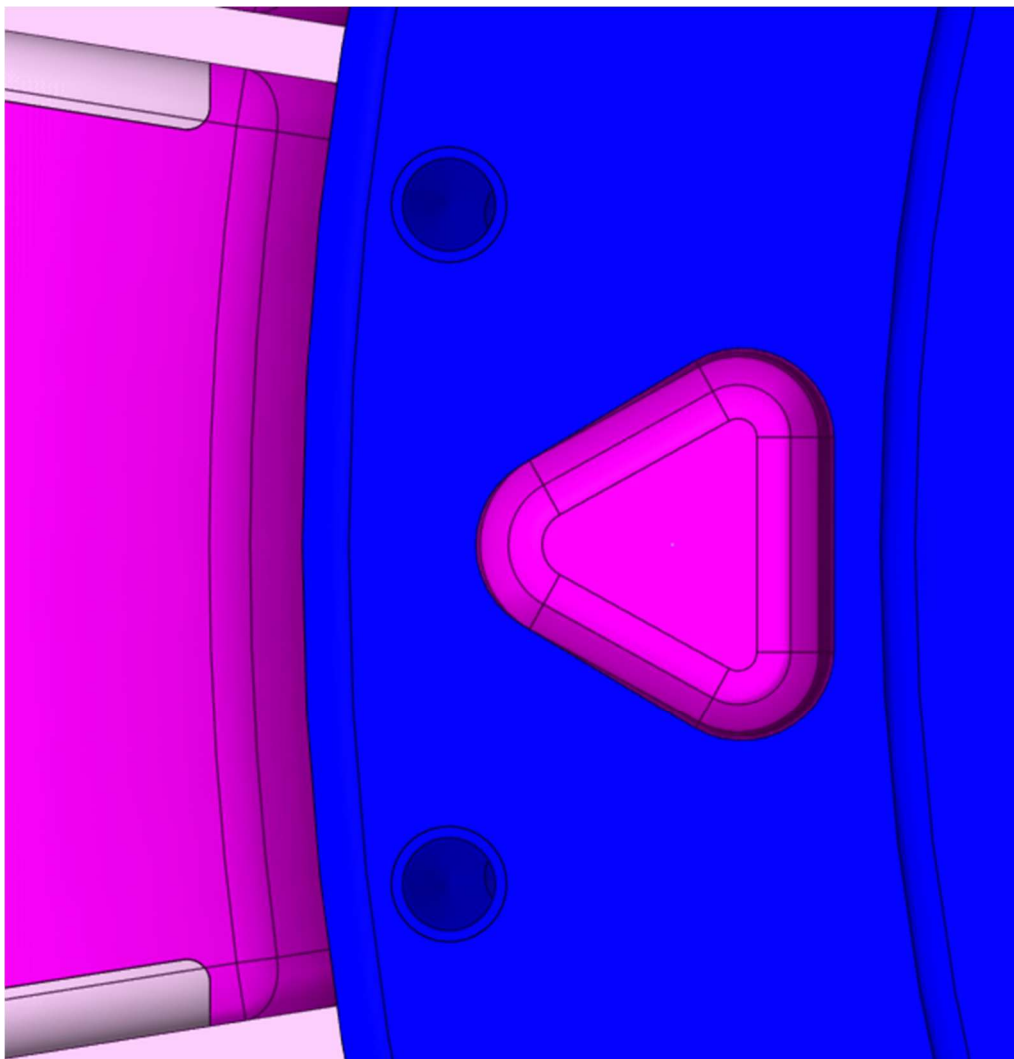


Figure 15 Segment Foot Pin Bottom View

3.1.3 Target Shaft

The Shaft is singled out as well for a closer evaluation. The Shaft is held together by 10 Tie Rods that use a preload force to clamp three sections together, part of the Crown is included in the model and all the Segments are used. The Crown is simplified and cut to use just the lower section, enough for the Tie Rods. The Segments are also simplified to down to be mostly beam sections that represent the constant cross section lengths with solid bodies at the transition areas to anchor the beams. The lower section of the Shaft contains water cooling channels with several welded in components. The holes have been removed from this area, and the welded components are bonded to the shaft.

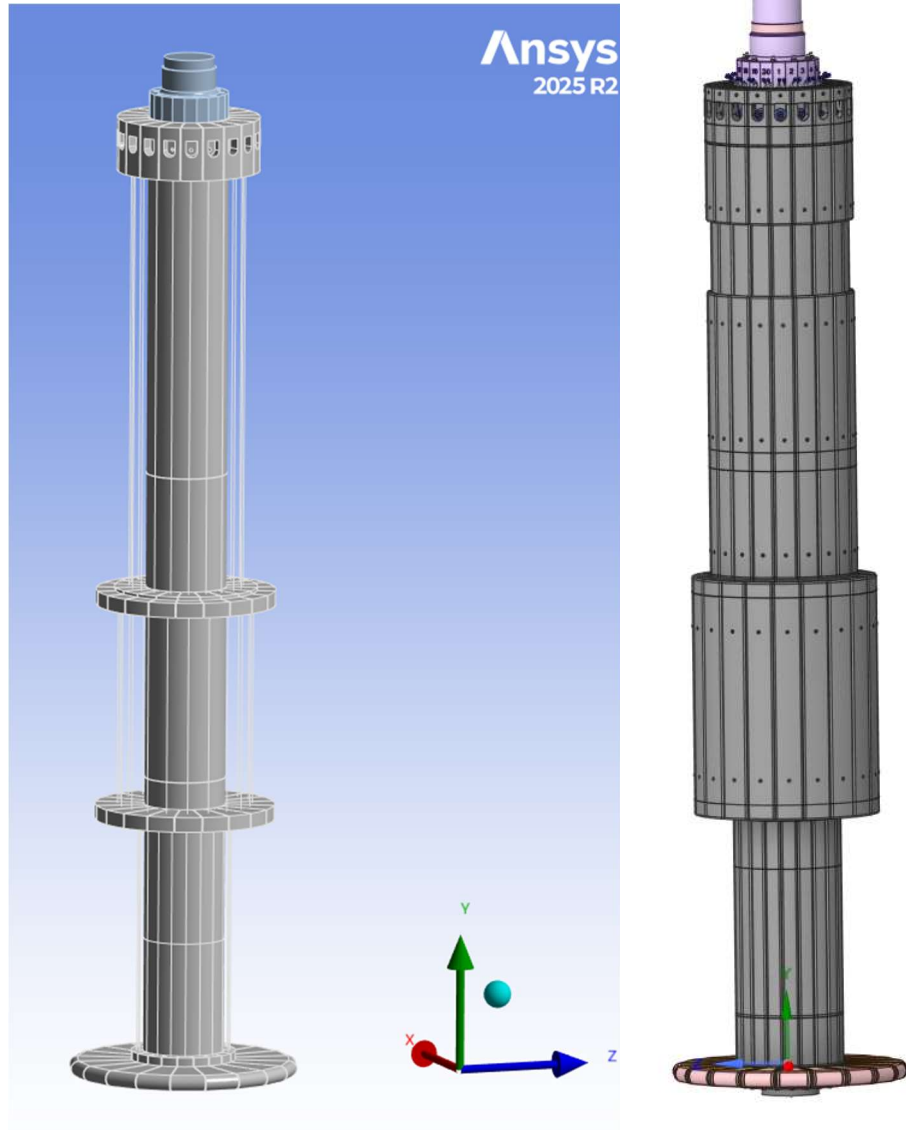


Figure 16 Target Shaft Model

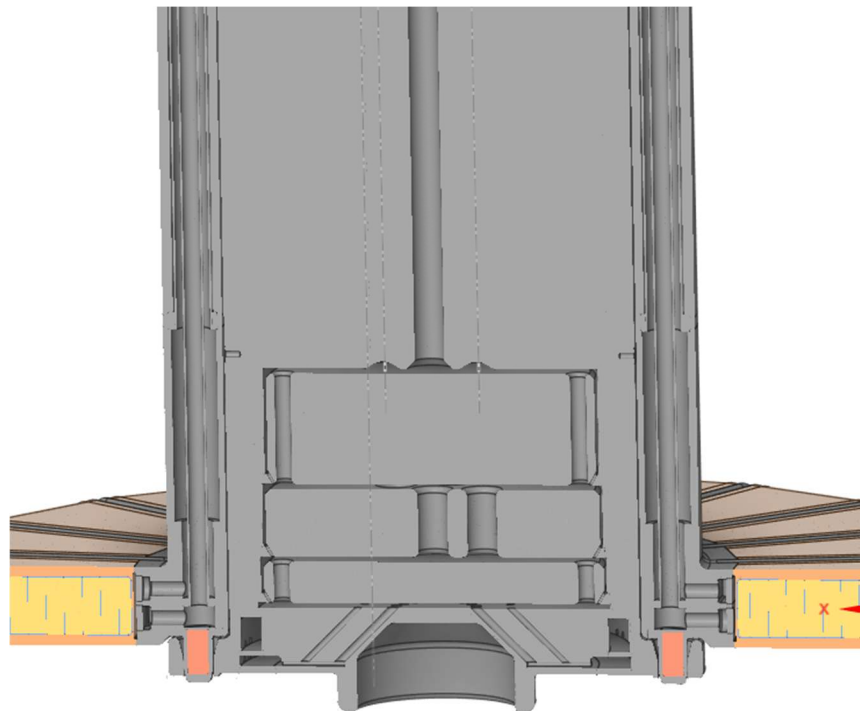
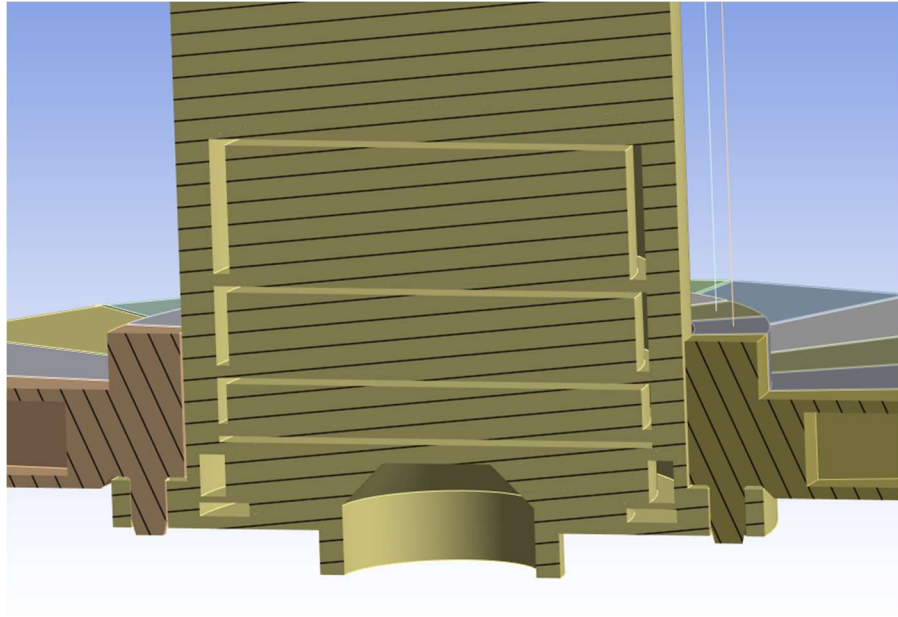


Figure 17 Shaft Cooling Channels Simplified

The Tie Rods are imported from Spaceclaim as beam elements so they will be included here, they are M16 threads made with Inconel 718.

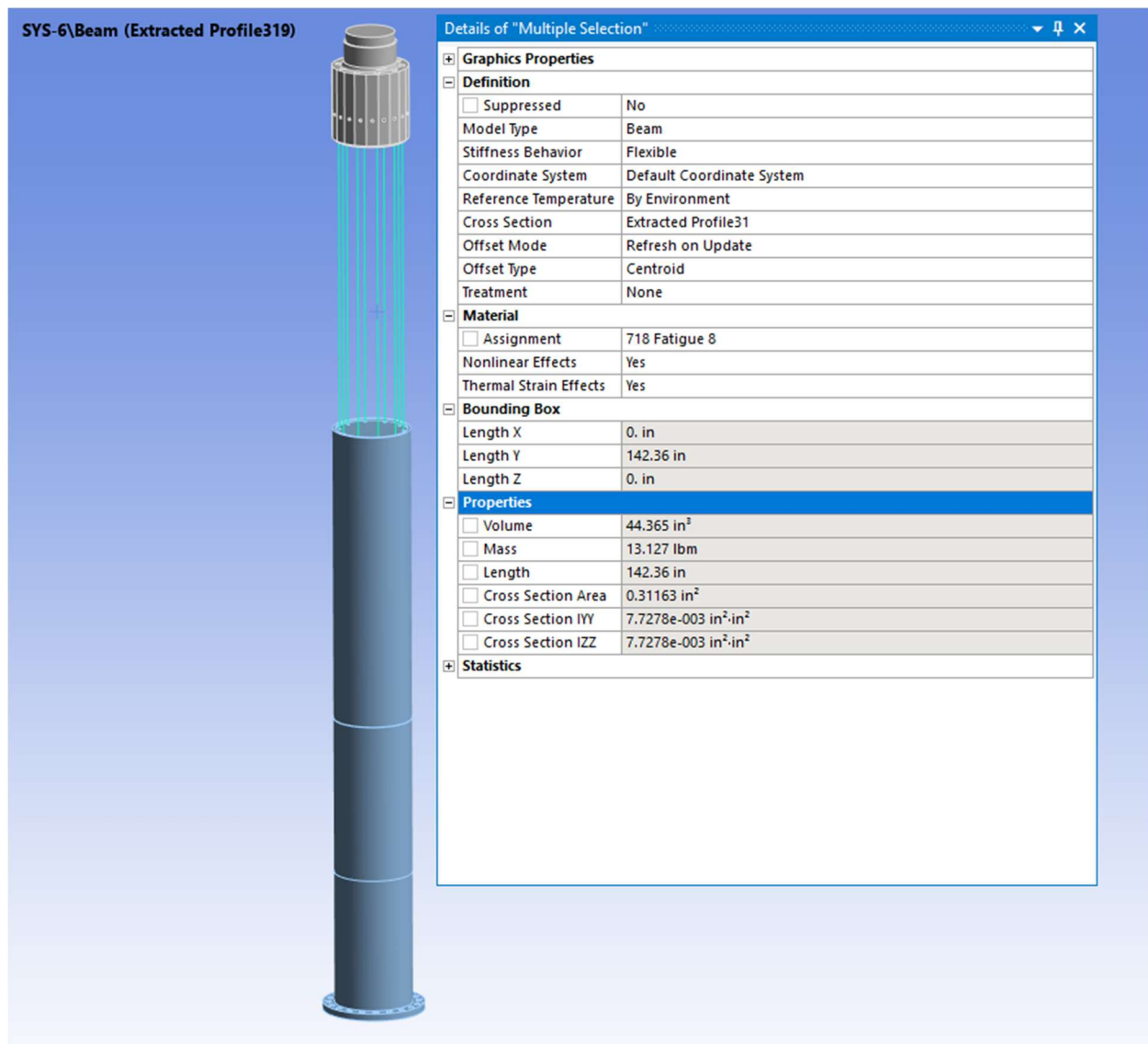


Figure 18 Tie Rod Material and Properties

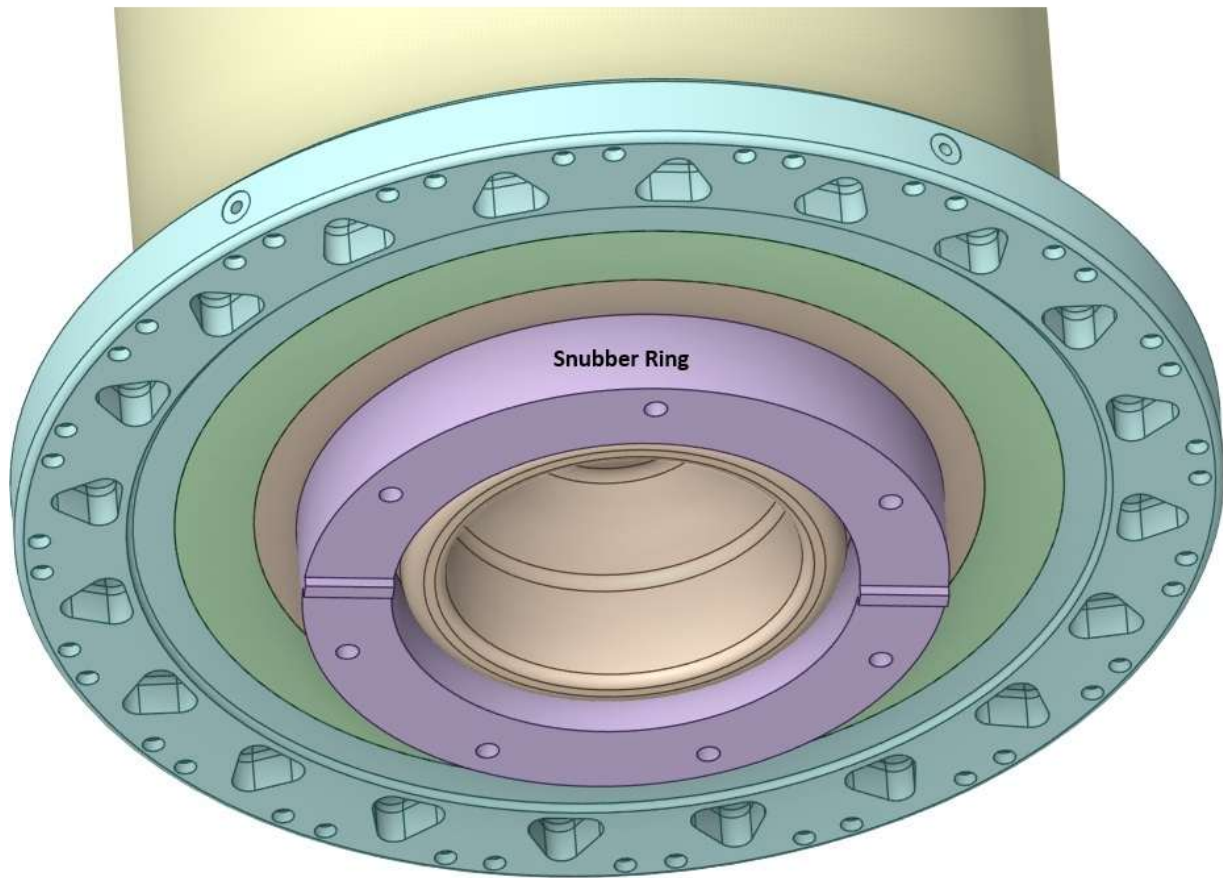


Figure 19 Snubber Ring Interface

The Snubber Ring is the seismic restraint feature for the lower end of the Target Shaft. It is bolted to the shield blocks below the Shaft. In normal operation the Shaft should not interfere with the Snubber Ring.

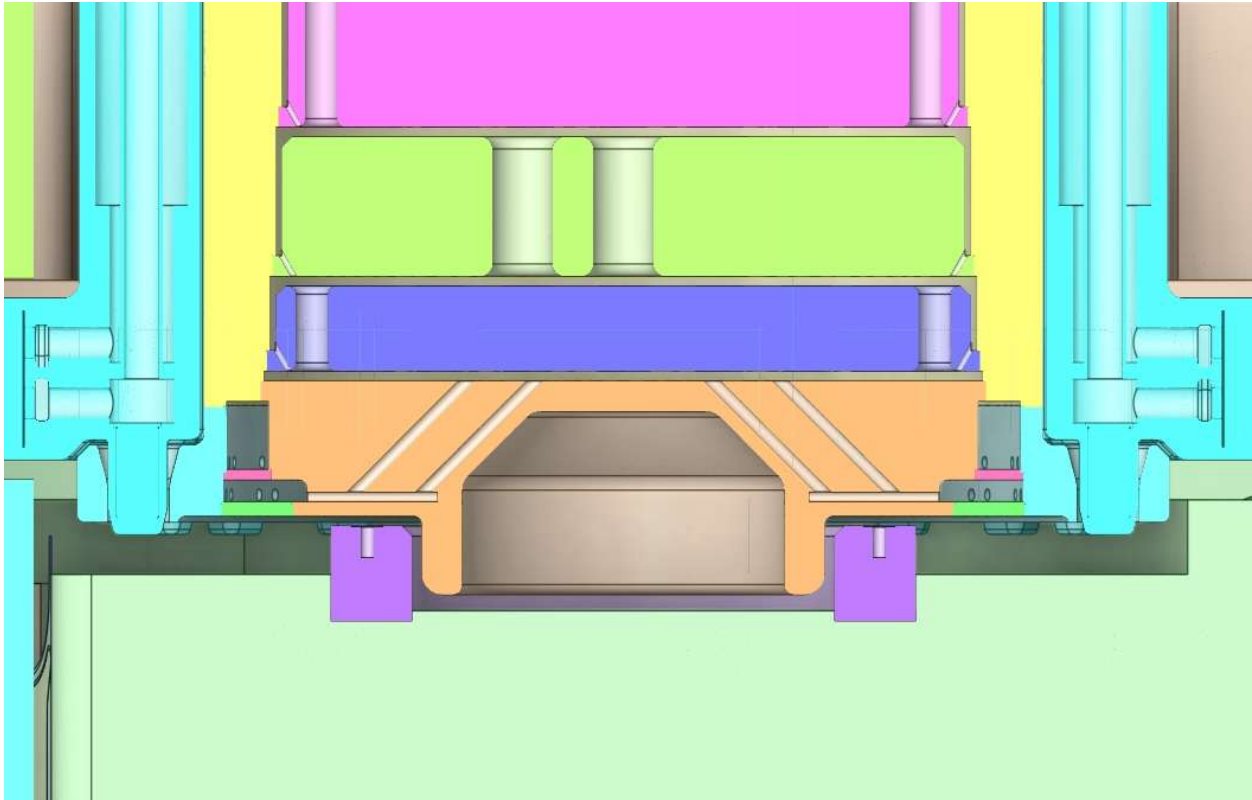


Figure 20 Snubber Ring Interface, Side View

3.1.3.1 Snubber Ring Analysis

The model for the Snubber Ring analysis is just the ring itself with a simplified version of the lower shaft. In this model the Snubber ring is moved in contact with the shaft. The water channels in the main body are removed except for the component that is in contact with the ring. The welded in water channel bodies are removed for simplicity.

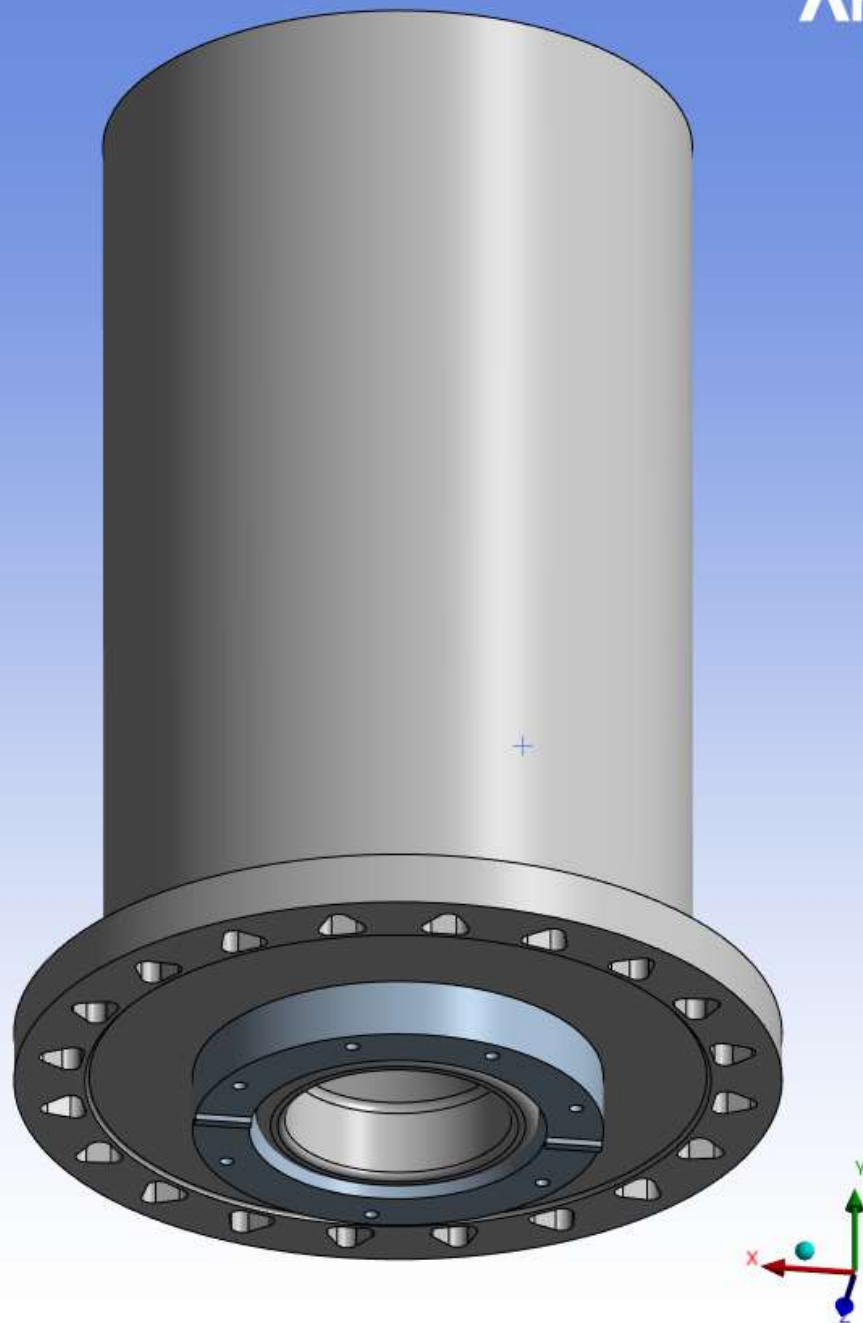


Figure 21 Snubber Ring Model

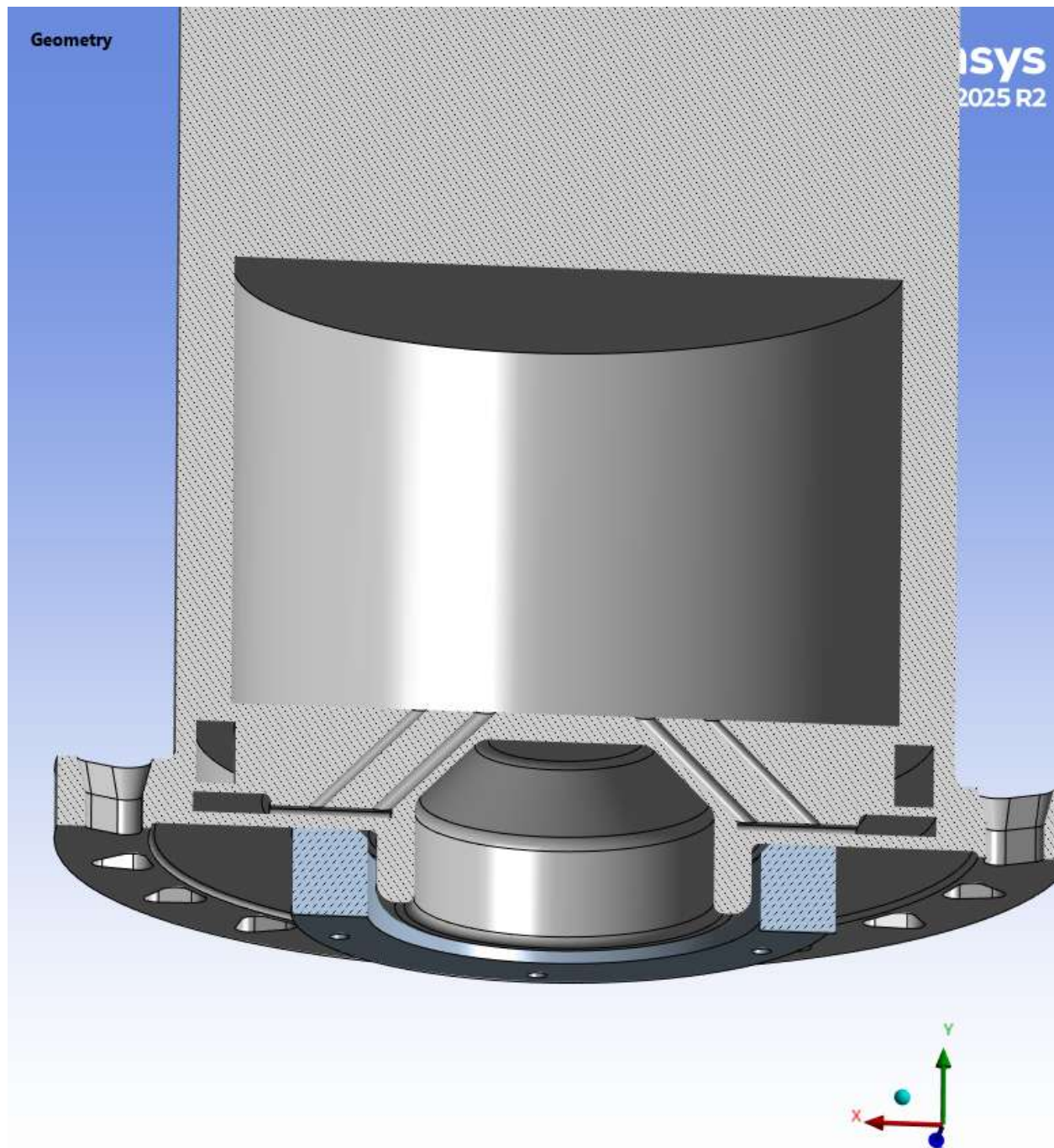


Figure 22 Snubber Ring Model, Section View

3.1.4 Crown and Drive

The final subassembly is to focus on the Crown and the drive bearings, a portion of the Crown is included in the other subassemblies because it is a key component in the Target Assembly's design. This model

also includes all the nonlinear material properties. The geometry of the Drive model is simplified down to just the main components around the bearing assembly. The components above and below the Crown were simplified down to basic shapes for a simpler mesh.



Figure 23 Crown and Drive Model Geometry

Figure 22 shows, by color, the components that are stationary and the rotating components in the Drive assembly. The mounting point at the Core Vessel lid is the fixed point to resist rotation of the Target. The drive uses 3 bearings for rotation and the motor is located above the bearings and provides the torque for rotation.

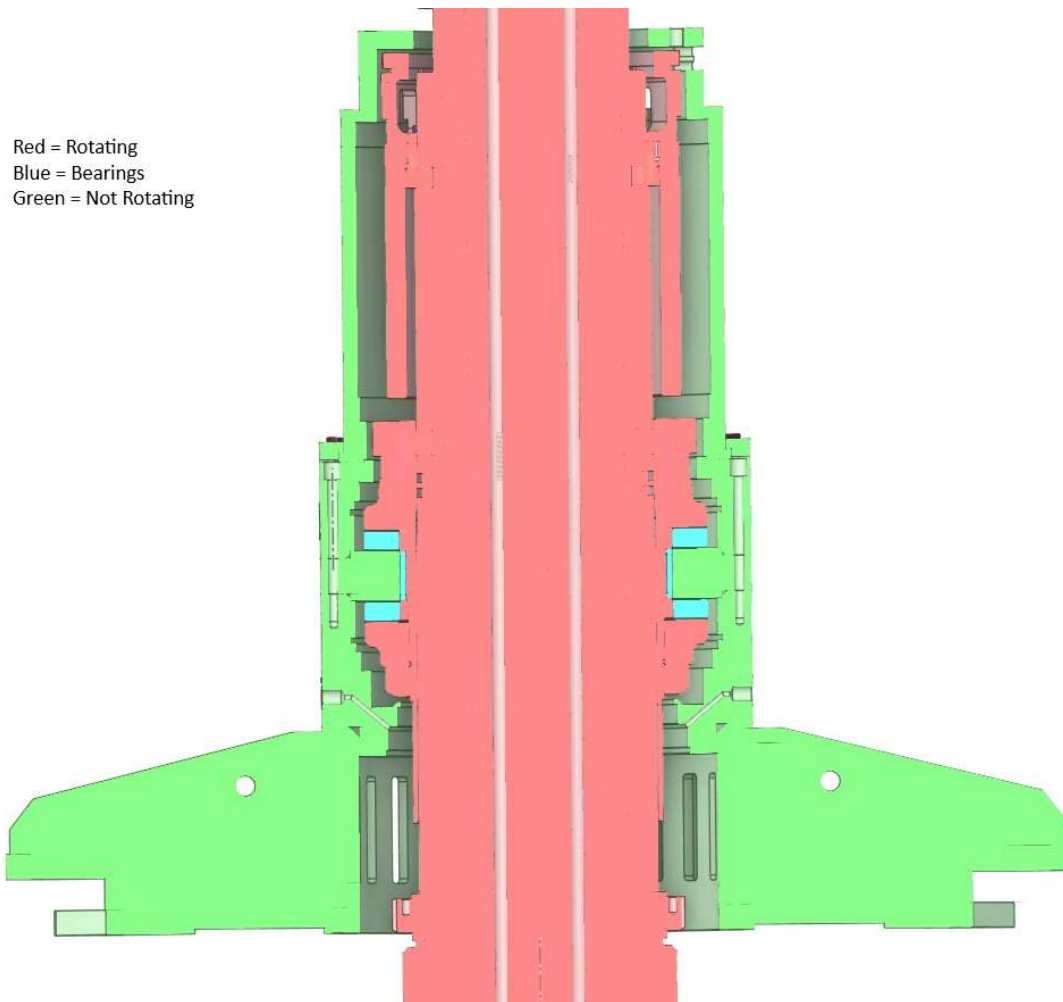


Figure 24 Drive Assembly Rotating Components

Figure 23 gives a simple view of how the load is transferred from the Crown/Shaft/Segments through the bearings and into the Core Vessel lid. This attachment point at the Crown is the only area supporting the entire Shaft and 20 Segments, essentially the part of the assembly below this attachment point is a pendulum. This reinforces the importance of the Snubber ring to help restrain any seismic movement.

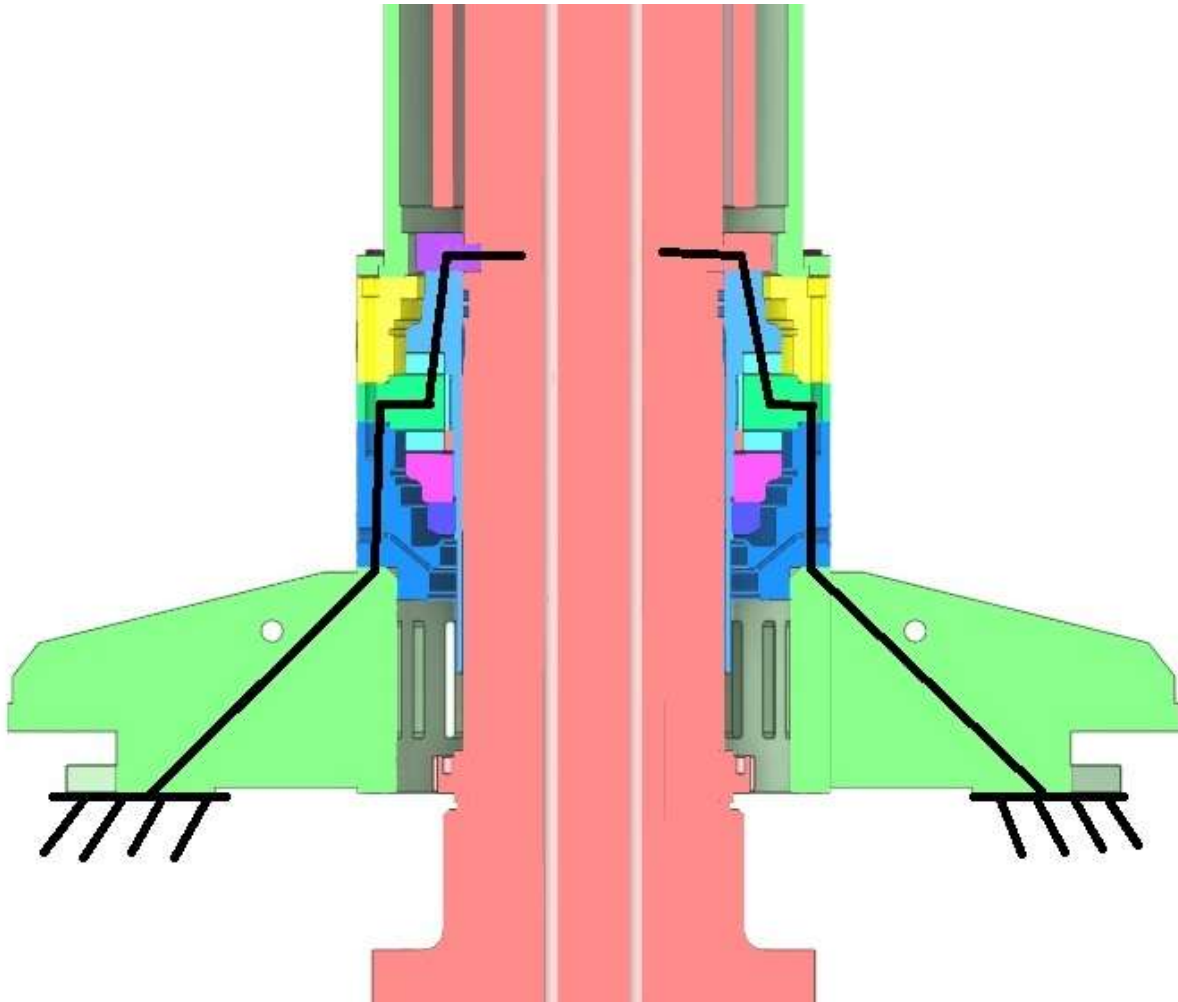


Figure 25 Drive Assembly Load Path

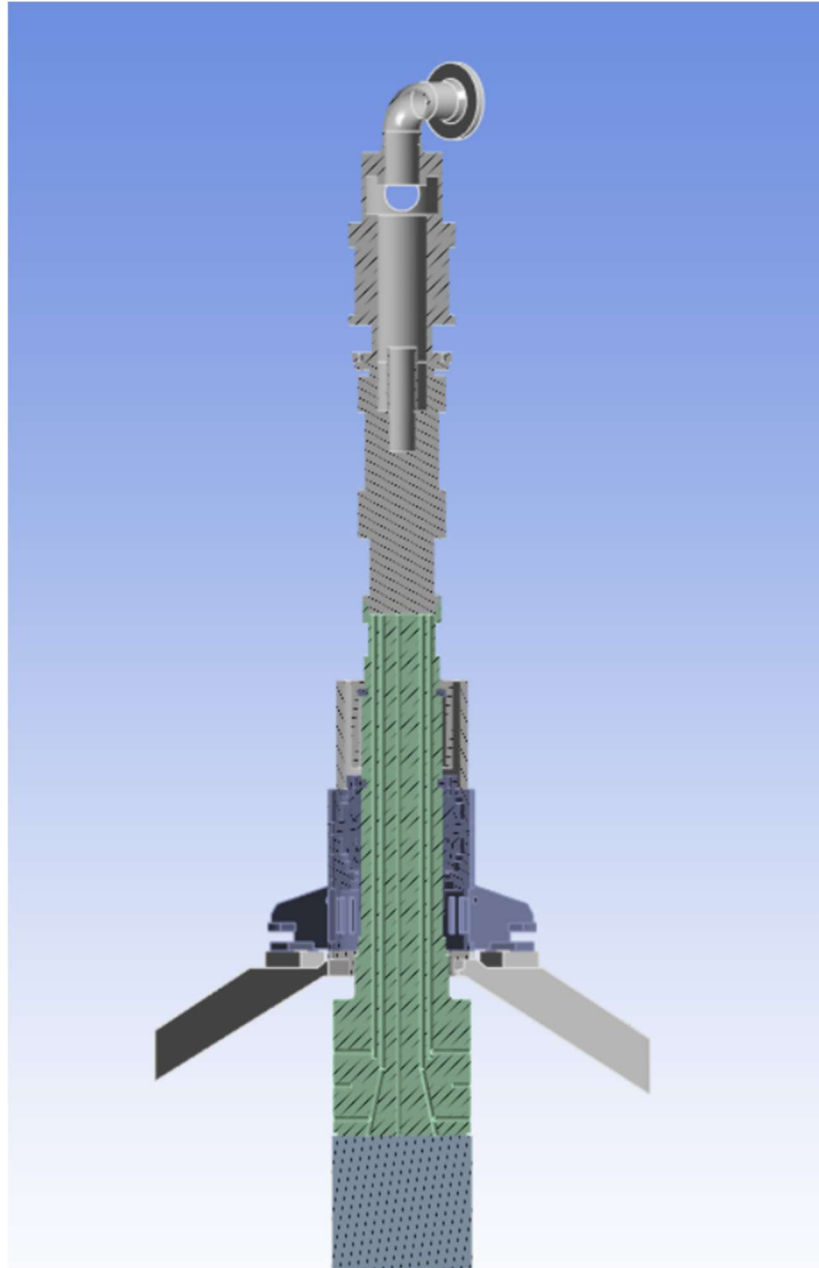
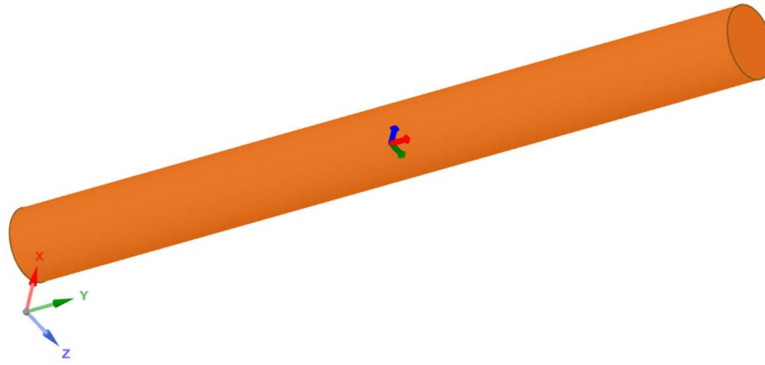


Figure 26 Crown and Drive Model Geometry

Figure 15 shows how the Shaft was simplified, the weight of the shaft and segments were combined, and the density of a simple cylinder was adjusted to match the combined weight. The shaft and segments are symmetric about the center axis so the CG was left alone.



Mass	16211603.296 g
Volume	648464131.8392mm ³
Center of mass	(483, 2314.5, 0)mm
Total surface area	6507067.766mm ²
Principal moment and axis	350689402498.629 g·mm ² (0, 1, 0)
Principal moment and axis	30926649996260.9 g·mm ² (1, 0, 0)
Principal moment and axis	30926649996260.9 g·mm ² (0, 0, 1)

Simplified Shaft and Segments Weight:	
Shaft	$5115 \text{ kg} \cdot g = 11277 \text{ lbf}$
Segment	$543 \text{ kg} \cdot g = 1197 \text{ lbf}$
20 Segments	$1200 \cdot \text{lbf} \cdot 20 = 24000 \text{ lbf}$
Shaft + Segments	$24000 \cdot \text{lbf} + 11300 \cdot \text{lbf} = 35300 \text{ lbf}$
Simplified Part	$16211603 \cdot \text{gm} \cdot g = 35740 \text{ lbf}$

Figure 27 Shaft Weight Comparison

3.2 MATERIAL PROPERTIES

The Target Assembly uses several different materials, Table 1 lists the materials and properties while Figures 26, 27, and 28 show where on the assembly, by part number, each of the components are located. The materials were taken from the Creo model [8].

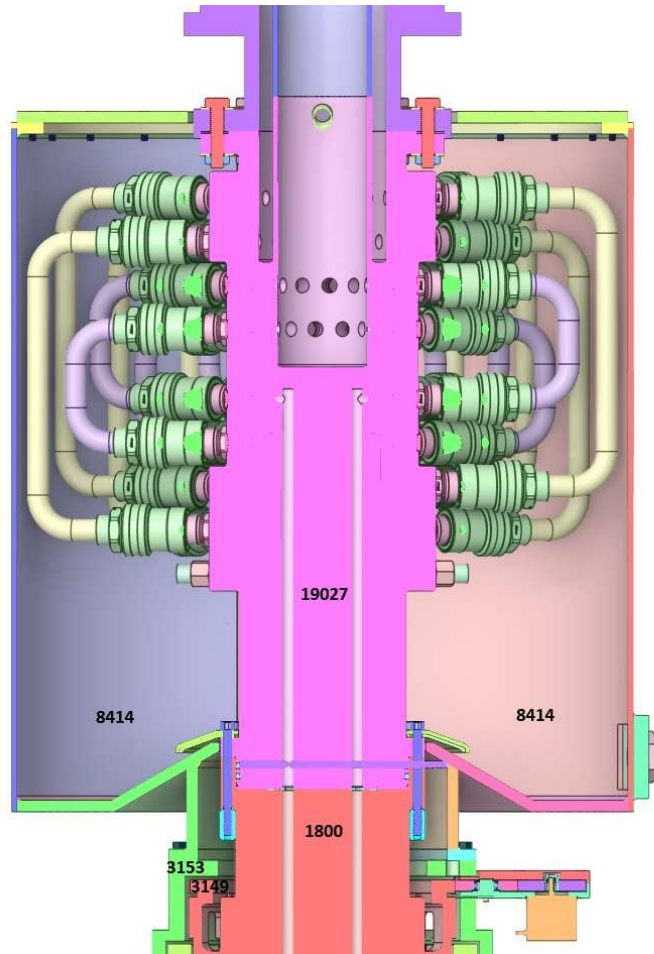


Figure 28 Manifold Area Components

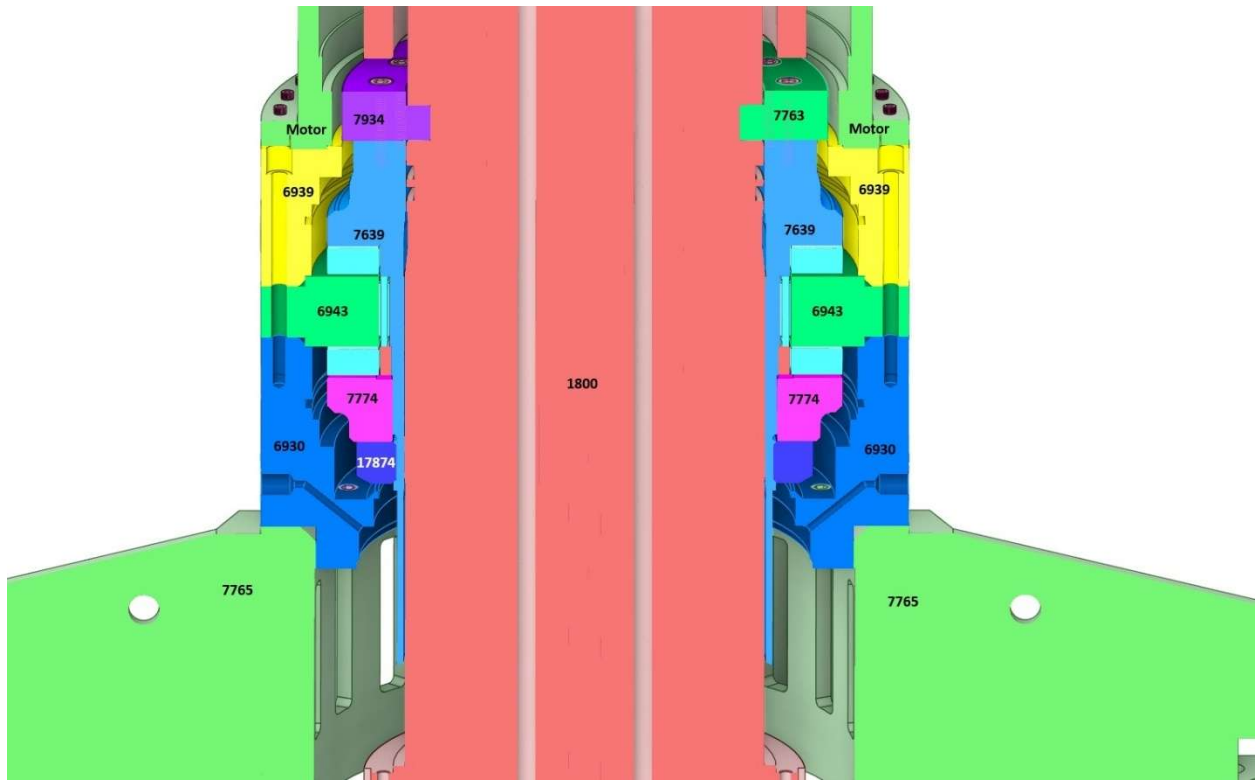


Figure 29 Drive Area Components

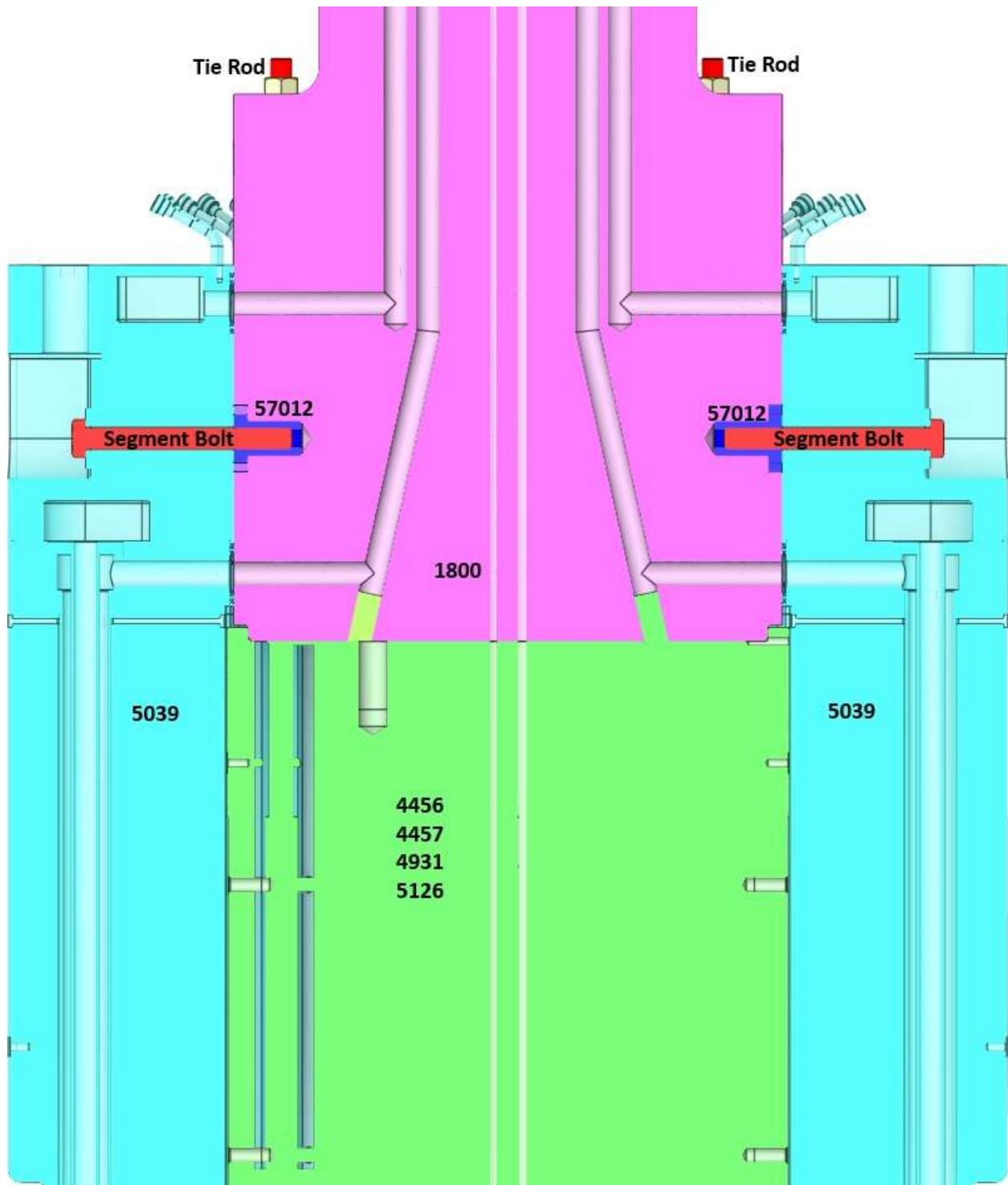


Figure 30 Shaft / Segment Area Components

Table 1 Material Properties

Component, Part Number	Material/Spec	Allowable Strength (BPVC)[2]	Yield Strength (BPVC)[2]	Ultimate Shear Strength for Thread Pullout (RCSC) [1]	Ultimate Strength (BPVC)[2]
Tie Rod Bolts, Segment Bolts	Inconel 718, ASTM B637	S=37ksi	S _y =150ksi	S _v =88ksi	S _u =160ksi
Crown, 1800	Inconel 625, AMS 5666	S=33.3ksi	S _y =50ksi	S _v =60ksi	S _u =120ksi
Segment, 5039 Manifold, 19027 Sensor Ring, 3153	SS316L, ASTM A276	S=16.7ksi	S _y =25ksi	S _v =38ksi	S _u =70ksi
Bearing Locknut, 17874	9310 Steel, ASTM A29	S=33.3ksi (A36)	S _y =64ksi		S _u =179ksi
Manifold Shroud, 8414 Reluctor Drive, 3149	6061 T6, ASTM B221	S=8ksi	S _y =36ksi		S _u =45ksi
Crown Sleeve, 7639 Lower Race, 7774 Center Housing, 6943	100 CrMo7-3	S=33.3ksi (A36)	S _y =67ksi	S _v =60ksi	S _u =101ksi
Upper Housing, 6939 Lower Housing, 6930	ASTM A830 GR1045	S=33.3ksi (A36)	S _y =45ksi	S _v =49ksi	S _u =82ksi
Rocket Fins, 7765	ASTM A572 Gr 50, Plate ASTM A830 GR1045	S=33.3ksi (A36)	S _y =50ksi		S _u =65ksi
Vertical Ring Transfer, 7943, 7763 Motor Ring, 19457, 3151 Manifold Nutplate, 19396	AISI 4130 Steel	S=33.3ksi (A36)	S _y =45ksi	S _v =48ksi	S _u =81ksi

Crown Insert, 57012	Nitronic 60 ASTM A276	S=16.7ksi (316L)	S _y =50ksi	S _v =52ksi	S _u =95ksi
---------------------	--------------------------	---------------------	-----------------------	-----------------------	-----------------------

Note that for steel alloys not listed in Section II-D [2] the allowable stress value for A36 Steel will be used in place. The alloys used in the Target Assembly are higher strength steel and A36 strength is a conservative value. The same is true for Nitronic 60, a conservative 316L strength is used in its place.

Table 2 Fasteners

Fastener Location	Grade / Yield Strength	Size	Part Number
Rocket Fin to Tent (Circular pattern)	CLASS 12.9 Steel, 136ksi, ISO 4762, 898-1	M10X1.5, 70	91310A650
Rocket Fin to Lower Housing	CLASS 12.9 Steel, 159ksi	M10X1.5, 220	91290A160
Upper Housing to Lower Housing	CLASS 12.9 Steel, 159ksi	M10x1.5, 140	91290A556
Rocket Fin to Tent	CLASS 12.9 Steel, 159ksi	M16X2, 50	91290A820
Vertical Load Ring to Crown Sleeve	CLASS 12.9 Steel, 159ksi	M10x1.5, 50	91290A218
Motor to Motor Ring	CLASS 12.9 Steel, 159ksi	M6X1, 30	91290A332
Segment to Crown Insert	Inconel 718, 150ksi	M16X2, 153	
Crown to Shaft	Inconel 718, 150ksi	M16X2, 3685	
Manifold to Crown	CLASS 12.9 Steel, 159ksi	M10x1.5, 120	91290A129
Center Race to Lower Housing	CLASS 12.9 Steel, 159ksi	M10x1.5, 34	

Table 3 Threaded Components

Threaded Component	Material	Thread Size	Depth
Crown Sleeve	100 CrMo7-3	M10x1.5	25mm
Lower Housing	ASTM A830 GR1045	M10x1.5	24mm
Tent	316L	M16x2	20mm
Motor Ring, 19457, 3151	316L	M6x1	16mm
Bearing Locknut, 17874, HM 52T	9310 Steel / 100 CrMo7-3	TR260x4	36mm
Crown Locknut, 17606, HM 3052	9310 Steel / 625	TR260x4	34mm

Manifold Nutplate	8620 Steel	M10x1.5	29mm
Shaft	718 / 316L	M16x2	60mm
Crown Insert	Nitronic 60 / 625	M24x3, M16x2	38mm, 30mm

Material properties from Section II D [2] are shown below:

Table TM-1
Moduli of Elasticity E of Ferrous Materials for Given Temperatures

Materials	Modulus of Elasticity E = Value Given $\times 10^6$ psi, for Temperature, °F, of																	
	-325	-200	-100	70	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
Carbon steels with C $\leq$ 0.30%	31.4	30.8	30.3	29.4	28.8	28.3	27.9	27.3	26.5	25.5	24.2	22.5	20.4	18.0	...	...	...	...
Carbon steels with C > 0.30%	31.2	30.6	30.1	29.2	28.6	28.1	27.7	27.1	26.4	25.3	24.0	22.3	20.2	17.9	15.4	...	...	...
Ductile cast iron	...	...	...	24.5	23.4	22.5	21.9	21.2	20.5	19.9	19.2	...	...	...	...	...	...	...
Material Group A [Note (1)]	31.1	30.5	30.0	29.0	28.5	28.0	27.6	27.0	26.3	25.3	23.9	22.2	20.1	17.8	15.3	...	...	...
Material Group B [Note (2)]	29.6	29.0	28.6	27.8	27.1	26.7	26.2	25.7	25.1	24.6	23.9	23.2	22.4	21.5	20.4	19.2	17.7	...
Material Group C [Note (3)]	31.6	30.9	30.5	29.6	29.0	28.5	28.0	27.4	26.9	26.2	25.6	24.8	23.9	23.0	21.8	20.5	18.9	...
Material Group D [Note (4)]	32.6	31.9	31.4	30.6	29.9	29.4	28.8	28.3	27.7	27.0	26.3	25.6	24.7	23.7	22.5	21.1	19.4	...
Material Group E [Note (5)]	33.0	32.4	31.9	31.0	30.3	29.7	29.2	28.6	28.1	27.5	26.9	26.2	25.4	24.4	23.3	22.0	20.5	...
Material Group F [Note (6)]	31.2	30.7	30.2	29.2	28.4	27.9	27.3	26.8	26.2	25.5	24.5	23.2	21.5	19.2	16.5	...	...	...
Material Group G [Note (7)]	30.3	29.7	29.2	28.3	27.5	27.0	26.4	25.9	25.3	24.8	24.1	23.5	22.8	22.0	21.2	20.3	19.2	18.1
Material Group H [Note (8)]	...	...	...	30.2	29.0	28.2	27.5	27.0	26.4	26.0	25.5	25.1	...	...	...	...	...	...
Material Group I [Note (9)]	27.8	27.1	26.6	25.8	25.1	24.6	24.1	23.6	23.1	22.6	22.1	21.6	21.1	20.6	20.1	19.6	19.1	18.6
Material Group J [Note (10)]	31.1	30.3	29.7	28.6	27.8	27.2	26.6	26.0	25.4	24.7	24.1	23.5	22.9	...	...	...	...	...
S13800 [Note (11)]	31.5	30.9	30.3	29.4	28.7	28.1	27.5	26.9	26.3	25.7	25.0	24.4	...	...	...	...	...	...
S15500 [Note (12)]	30.5	29.9	29.4	28.5	27.8	27.2	26.7	26.1	25.5	24.9	24.3	23.7	...	...	...	...	...	...
S45000 [Note (13)]	31.6	31.0	30.4	29.5	28.8	28.2	27.6	27.0	26.4	25.8	25.1	24.5	...	...	...	...	...	...
S17400 [Note (14)]	30.5	29.9	29.4	28.5	27.8	27.2	26.7	26.1	25.5	24.9	24.3	23.7	...	...	...	...	...	...
S17700 [Note (15)]	31.6	31.0	30.4	29.5	28.8	28.2	27.6	27.0	26.4	25.8	25.1	24.5	...	...	...	...	...	...
S66286 [Note (16)]	31.0	30.6	30.2	29.2	28.5	27.9	27.3	26.7	26.1	25.5	24.9	24.2	...	...	...	...	...	...

Figure 31 Carbon and Stainless Steel Modulus of Elasticity

Table TM-4
Moduli of Elasticity E of High Nickel Alloys for Given Temperatures

	Modulus of Elasticity E = Value Given $\times 10^6$ psi, for Temperature, °F, of																	
Material	-325	-200	-100	70	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
N06230	32.8	32.0	31.5	30.6	29.9	29.5	29.0	28.6	28.2	27.7	27.2	26.7	26.1	25.5	24.9	24.2	23.6	22.8
N06455	32.0	31.2	30.7	29.8	29.2	28.7	28.3	27.9	27.4	27.0	26.5	26.0	25.5	24.9	24.3	23.6	22.9	22.2
N06600	33.3	32.5	31.9	31.0	30.3	29.9	29.4	29.0	28.6	28.1	27.6	27.1	26.5	25.9	25.3	24.6	23.9	23.1
N06617	...	...	...	29.2	28.4	28.0	27.7	27.4	27.0	26.5	26.0	25.5	24.9	24.3	23.8	23.2	22.5	21.8
N06625	32.2	31.4	30.9	30.0	29.4	28.9	28.5	28.1	27.6	27.2	26.7	26.2	25.7	25.1	24.5	23.8	23.1	22.4
N06686	32.7	31.9	31.3	30.5	29.9	29.4	29.0	28.5	28.1	27.6	27.1	26.6	26.0	25.4	24.8	24.1	23.4	22.8
N06690	32.6	31.8	31.2	30.3	29.6	29.2	28.8	28.3	27.9	27.5	27.0	26.5	25.9	25.3	24.7	24.0	23.3	22.6
N07718	31.0	30.5	29.9	28.9	28.3	27.9	27.5	27.2	26.8	26.3	25.8	25.2	24.7	24.2	...	...	...	...
N07750	33.2	32.6	31.9	30.9	30.3	29.8	29.4	29.1	28.6	28.2	27.6	27.0	26.4	25.8	25.3	...	...	...
N08020	30.0	29.3	28.8	28.0	27.4	27.0	26.6	26.2	25.8	25.4	24.9	24.4	23.9	23.4	22.8	22.2	21.6	20.9
N08031	30.7	30.1	29.5	28.7	28.1	27.7	27.2	26.8	26.4	26.0	25.5	25.0	24.5	24.0	23.4	22.8	22.1	21.4
N08330	30.0	29.3	28.8	28.0	27.4	27.0	26.6	26.2	25.8	25.4	24.9	24.4	23.9	23.4	22.8	22.2	21.6	20.9

Figure 32 Inconel 625 and 718 Modulus of Elasticity

Table PRD
Poisson's Ratio and Density of Materials

Material	Poisson's Ratio	Density, lb/in. ³	Material	Poisson's Ratio	Density, lb/in. ³
Ferrous Materials			Ferrous Materials (Cont'd)		
Carbon steels	0.30	0.280	High alloy steels (duplex/austenitic-ferritic)	0.31	0.282
Cast irons	0.29	0.260	PH stainless: S66286	0.31	0.286
Low alloy steels			Cast high alloy steels	0.30	0.283
C-Mn steels	0.30	0.280	Nonferrous Materials		
$\frac{1}{2}$ Cr to $1\frac{1}{4}$ Cr steels	0.30	0.280	Aluminum Base		
$1\frac{3}{4}$ Cr to 3Cr steels	0.30	0.280	Alclad 3003	0.33	0.098
5Cr to 9Cr steels	0.30	0.280	Alclad 3004	0.33	0.098
Mn, Mn-Mo, and Si steels	0.30	0.280	Alclad 6061	0.33	0.098
Ni steels	0.30	0.280	A02040	0.33	0.101
PH stainless: S15500, S17400, S17700	0.31	0.280	A03560	0.33	0.097
High alloy steels (200 series)	0.31	0.282	A24430	0.33	0.097
High alloy steels (300 series)	0.31	0.290	A91060	0.33	0.098
High-Si stainless: S30600, S30601, S32615, and S38815	0.31	0.275	A91100	0.33	0.098
5-7% Mo stainless: S32050, S31254, S31266, S31277, and S32654	0.31	0.293	A92014	0.33	0.101
S32202	0.31	0.280	A92024	0.33	0.100
High alloy steels (400 series)	0.31	0.280	A93003	0.33	0.099
			A93004	0.33	0.098
			A95052	0.33	0.097

Figure 33 Carbon and Stainless Steel Poisson's Ratio and Density

Table PRD
Poisson's Ratio and Density of Materials (Cont'd)

Material	Poisson's Ratio	Density, lb/in. ³	Material	Poisson's Ratio	Density, lb/in. ³
Nonferrous Materials (Cont'd)			Nonferrous Materials (Cont'd)		
Aluminum Base (Cont'd)			Nickel Base (Cont'd)		
A95083	0.33	0.096	N04400 and N04405	0.31	0.320
A95086	0.33	0.096	N05500	0.31	0.300
A95154	0.33	0.096	N06002	0.31	0.300
A95254	0.33	0.096	N06022	0.31	0.314
A95454	0.33	0.097	N06030	0.31	0.297
A95456	0.33	0.096	N06045	0.31	0.289
A95652	0.33	0.096	N06059	0.31	0.311
A96061	0.33	0.098	N06200	0.31	0.307
A96063	0.33	0.097	N06230	0.31	0.324
Chromium Base			N06455	0.31	0.312
R20033	0.31	0.285	N06600	0.31	0.300
Cobalt Base			N06601	0.31	0.291
R30556	0.31	0.297	N06617	0.31	0.302
R31233	0.31	0.306	N06625	0.31	0.305
Copper Base			N06686	0.31	0.315
C10200, C10400, C10500, and C10700	0.33	0.323	N06690	0.31	0.293
C11000	0.33	0.321	N06975	0.31	0.295
C12000, C12200, C12300, and C14200	0.33	0.323	N06985	0.31	0.300
C19200	0.33	0.320	N07718	0.31	0.297
C19400	0.33	0.322	N07750	0.31	0.298
C23000	0.33	0.316	N08020	0.31	0.291
C28000	0.33	0.303	N08024	0.31	0.293
C36500	0.33	0.304	N08026	0.31	0.294
C37700	0.33	0.305	N08028	0.31	0.289
C44300, C44400, and C44500	0.33	0.308	N08031	0.31	0.293
C46400 and C46500	0.33	0.304	N08330	0.31	0.290
C60800	0.33	0.295	N08367 and J94651	0.31	0.291
C61400	0.33	0.285	N08800, N08810, and N08811	0.31	0.290
C63000	0.33	0.274	N08825	0.31	0.294
C64200	0.33	0.278	N08904	0.31	0.291
C65100	0.33	0.316	N08925	0.31	0.294
C65500 and C66100	0.33	0.308	N08926	0.31	0.291
C68700	0.33	0.301	N10001	0.31	0.331
C70400, C70600, C70620,	0.33	0.323	N10003	0.31	0.320
			N10242	0.31	0.327
			N10276	0.31	0.320
			N10629	0.31	0.332
			N10665 and N10675	0.31	0.333
			N12160	0.31	0.292

Figure 34 6061, Inconel 625 and 718 Poisson's Ratio and Density

Table TE-1
Thermal Expansion for Ferrous Materials

Temperature, °F	Coefficients for Carbon and Low Alloy Steels (Group 1) [Note (1)]			Coefficients for Other Alloy Steels (Group 2) [Note (2)]			Coefficients for 5Cr-1Mo and 29Cr-7Ni-2Mo-N Steels		
	A	B	C	A	B	C	A	B	C
70	6.4	6.4	0	7.0	7.0	0	6.4	6.4	0
100	6.6	6.5	0.23	7.1	7.1	0.26	6.6	6.5	0.23
150	6.8	6.6	0.63	7.3	7.2	0.69	6.8	6.6	0.63
200	7.0	6.7	1.0	7.5	7.3	1.1	7.0	6.7	1.0
250	7.2	6.8	1.5	7.6	7.3	1.6	7.1	6.8	1.5

Figure 35 Carbon Steel CTE

Table TE-1
Thermal Expansion for Ferrous Materials (Cont'd)

Temperature, °F	Coefficients for 27Cr Steels			Coefficients for Austenitic Stainless Steels (Group 3) [Note (3)]			Coefficients for Other Austenitic Stainless Steels (Group 4) [Note (4)]		
	A	B	C	A	B	C	A	B	C
70	5.0	5.0	0	8.5	8.5	0	8.2	8.2	0
100	5.1	5.1	0.18	8.7	8.6	0.31	8.3	8.2	0.30
150	5.2	5.1	0.49	9.0	8.8	0.84	8.6	8.4	0.81
200	5.3	5.2	0.81	9.4	8.9	1.4	8.8	8.5	1.3
250	5.3	5.2	1.1	9.6	9.1	2.0	9.0	8.6	1.9

Figure 36 Stainless Steel 316 CTE

Table TE-4
Thermal Expansion for Nickel Alloys (Cont'd)

Temperature, °F	Coefficients for N06455			Coefficients for N06600			Coefficients for N06625		
	A	B	C	A	B	C	A	B	C
70	5.8	5.8	0	6.8	6.8	0	6.7	6.7	0
100	6.0	5.9	0.21	7.0	6.9	0.25	6.9	6.8	0.24
150	6.2	6.0	0.58	7.2	7.0	0.67	7.2	7.0	0.67
200	6.5	6.2	0.97	7.4	7.1	1.1	7.4	7.1	1.1
250	6.8	6.3	1.4	7.6	7.2	1.6	7.4	7.2	1.6

Figure 37 Inconel 625 CTE

Table TE-4
Thermal Expansion for Nickel Alloys (Cont'd)

Temperature, °F	Coefficients for N06690			Coefficients for N07718			Coefficients for N07750		
	A	B	C	A	B	C	A	B	C
70	7.7	7.7	0	7.1	7.1	0	6.7	6.7	0
100	7.8	7.8	0.28	7.1	7.1	0.26	6.8	6.8	0.24
150	7.9	7.8	0.75	7.2	7.2	0.69	7.1	6.9	0.66
200	8.0	7.9	1.2	7.4	7.2	1.1	7.3	7.0	1.1
250	8.0	7.9	1.7	7.5	7.3	1.6	7.5	7.1	1.5

Figure 38 Inconel 718 CTE

Table TE-2
Thermal Expansion for Aluminum Alloys

Temperature, °F	Coefficients for Aluminum Alloys		
	A	B	C
70	12.1	12.1	0
100	12.6	12.4	0.45
150	13.2	12.7	1.2
200	13.5	13.0	2.0
250	13.7	13.1	2.8
300	14.0	13.3	3.7
350	14.3	13.4	4.5
400	14.7	13.6	5.4
450	15.1	13.8	6.3
500	15.3	13.9	7.2
550	15.4	14.1	8.1
600	15.2	14.2	9.0

GENERAL NOTES:

- (a) Aluminum alloys represented by these thermal expansion coefficients include:

A03560	A93003	A95254
A24430	A93004	A95454
A91060	A95052	A95456
A91100	A95083	A95652
A92014	A95086	A96061
A92024	A95154	A96063

- (b) Coefficient A is the instantaneous coefficient of thermal expansion $\times 10^{-6}$ (in./in./°F). Coefficient B is the mean coefficient of thermal expansion $\times 10^{-6}$ (in./in./°F) in going from 70°F to indicated temperature. Coefficient C is the linear thermal expansion (in./100 ft) in going from 70°F to indicated temperature.

Figure 39 Aluminum 6061 CTE

Table 5A
Section VIII, Division 2
Maximum Allowable Stress Values, S, for Ferrous Materials

Line No.	Nominal Composition	Product Form	Spec. No.	Type/Grade	Alloy Desig./UNS No.	Class/Condition/Temp	Size/Thickness, in.	P-No.	Group No.
13	Carbon steel	Plate, bar, shapes	SA-36	...	K02600	...	...	1	1
40	16Cr-12Ni-2Mo	Forgings	SA-182	F316L	S31603	...	$t \leq 5$	8	1
41	16Cr-12Ni-2Mo	Smls. tube	SA-213	TP316L	S31603	...	...	8	1
42	16Cr-12Ni-2Mo	Plate	SA-240	316L	S31603	...	...	8	1
43	16Cr-12Ni-2Mo	Wld. tube	SA-249	TP316L	S31603	...	...	8	1

Table 5A
Section VIII, Division 2
Maximum Allowable Stress Values, S, for Ferrous Materials

Line No.	Min. Tensile Strength, ksi	Min. Yield Strength, ksi	Maximum Use Temperature, °F	External Pressure Chart No.	Notes
13	58	36	650	CS-2	G13
40	70	25	850	HA-4	G2
41	70	25	850	HA-4	G2
42	70	25	850	HA-4	G2
43	70	25	850	HA-4	G2, G6

Table 5A (Cont'd)
Section VIII, Division 2
Maximum Allowable Stress Values, S, for Ferrous Materials

Maximum Allowable Stress, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding																	
Line No.	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900
13	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	...	...	...	...	...
40	16.7	16.7	16.7	16.7	16.7	16.4	15.7	15.2	14.8	14.4	14.0	13.7	13.5	13.2	12.9	12.7	...
41	16.7	16.7	16.7	16.7	16.7	16.4	15.7	15.2	14.8	14.4	14.0	13.7	13.5	13.2	12.9	12.7	...
42	16.7	16.7	16.7	16.7	16.7	16.4	15.7	15.2	14.8	14.4	14.0	13.7	13.5	13.2	12.9	12.7	...
43	14.2	14.2	14.2	14.2	14.2	13.9	13.4	12.9	12.5	12.2	11.9	11.7	11.4	11.2	11.0	10.8	...

Figure 40 Carbon and Stainless Steel Yield and Allowable Stress

Table 2B (Cont'd)
Section III, Division 1, Classes 1, MC, and CS; Section III, Division 3; and Section III, Division 5
Design Stress Intensity Values, S_m , and Section VIII, Division 2, Class 1 Maximum Allowable
Stress Values, S , for Nonferrous Materials

Line No.	Nominal Composition	Product Form	Spec. No.	Type/ Grade	Alloy Desig./UNS No.	Class/Condition/ Temper	Size/ Thickness, in.	P-No.
23	60Ni-22Cr-9Mo-3.5Cb	Bar, rod	SB-446	...	N06625	Annealed	$4 < t \leq 10$	43
24	60Ni-22Cr-9Mo-3.5Cb	Plate, sheet	SB-443	...	N06625	Hot rolled/ann.	≤ 2.75	43
25	60Ni-22Cr-9Mo-3.5Cb	Plate	SB-443	...	N06625	Cold rolled/ann.	≤ 0.375	43
26	60Ni-22Cr-9Mo-3.5Cb	Smls. pipe & tube	SB-444	...	N06625	Annealed	...	43
27	60Ni-22Cr-9Mo-3.5Cb	Bar, rod	SB-446	...	N06625	Annealed	≤ 4	43

Table 2B (Cont'd)
Section III, Division 1, Classes 1, MC, and CS; Section III, Division 3; and Section III, Division 5
Design Stress Intensity Values, S_m , and Section VIII, Division 2, Class 1 Maximum Allowable
Stress Values, S , for Nonferrous Materials

Line No.	Min. Tensile Strength, ksi	Min. Yield Strength, ksi	Applicability and Max. Temperature Limits (NP = Not Permitted) (SPT = Supports Only)		External Pressure Chart No.	Notes
			III	VIII-2		
23	110	50	800	NP	NFN-17	...
24	110	55	800	NP	NFN-17	...
25	110	55	800	NP	NFN-17	...
26	120	60	800	NP	NFN-17	...
27	120	60	800	NP	NFN-17	...

Table 2B (Cont'd)
Section III, Division 1, Classes 1, MC, and CS; Section III, Division 3; and Section III, Division 5
Design Stress Intensity Values, S_m , and Section VIII, Division 2, Class 1 Maximum Allowable
Stress Values, S , for Nonferrous Materials

Line No.	Design Stress Intensity or Maximum Allowable Stress, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding														
	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
23	33.3	...	32.1	...	31.2	...	30.3	...	29.4	...	28.6	28.3	27.9	27.6	27.4
24	36.7	...	35.3	...	34.3	...	33.3	...	32.4	...	31.5	31.1	30.7	30.4	30.1
25	36.7	...	35.3	...	34.3	...	33.3	...	32.4	...	31.5	31.1	30.7	30.4	30.1
26	40.0	...	38.5	...	37.4	...	36.3	...	35.3	...	34.4	33.9	33.5	33.2	32.9
27	40.0	...	38.5	...	37.4	...	36.3	...	35.3	...	34.4	33.9	33.5	33.2	32.9

Figure 41 Inconel 625 Yield and Allowable Strength

Table 2B (Cont'd)
Section III, Division 1, Class 1; Section III, Division 3, Classes TC and SC;
and Section VIII, Division 2, Class 1
Design Stress Intensity Values, S_m , for Nonferrous Materials

Line No.	Nominal Composition	Product Form	Spec. No.	Alloy Desig./UNS No.	Class/Condition/Temper	Size/Thickness, in.	P-No.
1	...	Drawn smls. tube	SB-210	A96061	T4	0.025-0.500	23
2	...	Drawn smls. tube	SB-210	A96061	T6	0.025-0.500	23
3	...	Bar, rod, shapes	SB-221	A96061	T4	...	23
4	...	Bar, rod, shapes	SB-221	A96061	T6	...	23

Table 2B (Cont'd)
Section III, Division 1, Class 1; Section III, Division 3, Classes TC and SC;
and Section VIII, Division 2, Class 1
Design Stress Intensity Values, S_m , for Nonferrous Materials

Line No.	Min. Tensile Strength, ksi	Min. Yield Strength, ksi	Applicability and Max. Temperature Limits (NP = Not Permitted) (SPT = Supports Only)		External Pressure Chart No.	Notes
			III	VIII-2		
1	30	16	NP	300	NFA-13	G8, W3
2	42	35	NP	300	NFA-12,13	G8, W3
3	26	16	NP	300	NFA-13	G2, G8, G9, W3
4	38	35	NP	300	NFA-12,13	G2, G8, G9, W3

Table 2B (Cont'd)
Section III, Division 1, Class 1; Section III, Division 3, Classes TC and SC;
and Section VIII, Division 2, Class 1
Design Stress Intensity Values, S_m , for Nonferrous Materials

Line No.	Design Stress Intensity, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding														
	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
1	10.0	10.0	10.0	8.6	8.1	...	...	...	...	...	...	...	...	...	...
2	14.0	14.0	14.0	13.4	11.3	...	...	...	...	...	...	...	...	...	...
3	8.7	8.7	8.7	8.5	8.0	...	...	...	...	...	...	...	...	...	...
4	12.7	12.7	12.7	12.1	10.2	...	...	...	...	...	...	...	...	...	...

Figure 42 Aluminum 6061 Yield and Allowable Strength

Table 4 Material Properties Summary

Material @70F	Density (lbm/in ³)	CTE (1/F)	E (psi)	Poisson	Yield (ksi)
316 (S31603)	0.29	8.50E-06	28300000	0.31	25
A36 (K02600)	0.28	6.40E-06	29700000	0.3	36
718 (N07718)	0.297	7.10E-06	28900000	0.31	150
625 (N06625)	0.305	6.70E-06	30000000	0.31	50
6061 (A96061)	.098	12.1E-06	10000000	.33	35

Properties of Outline Row 7: 316 Cyclic

	A	B	C
1	Property	Value	Unit
2	Density	0.282	lb in ⁻³
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	8.5E-06	F ⁻¹
5	Isotropic Elasticity	Tabular	
15	Bilinear Isotropic Hardening		
16	Tangent Modulus Type	Plastic	
17	Yield Strength	25000	psi
18	Tangent Modulus	0	psi
19	S-N Curve	Tabular	
23	Tensile Yield Strength	25000	psi
24	Tensile Ultimate Strength	70000	psi

Table of Properties Row 5: Isotropic Elasticity

	A	B	C	D	E
1	Temperature (F)	Young's Modulus (psi)	Poisson's Ratio	Bulk Modulus (Pa)	Shear Modulus (Pa)
2	70	2.83E+07	0.31	1.7116E+11	7.4474E+10
3	200	2.75E+07	0.31	1.6632E+11	7.2369E+10
4	300	2.7E+07	0.31	1.633E+11	7.1053E+10
*					

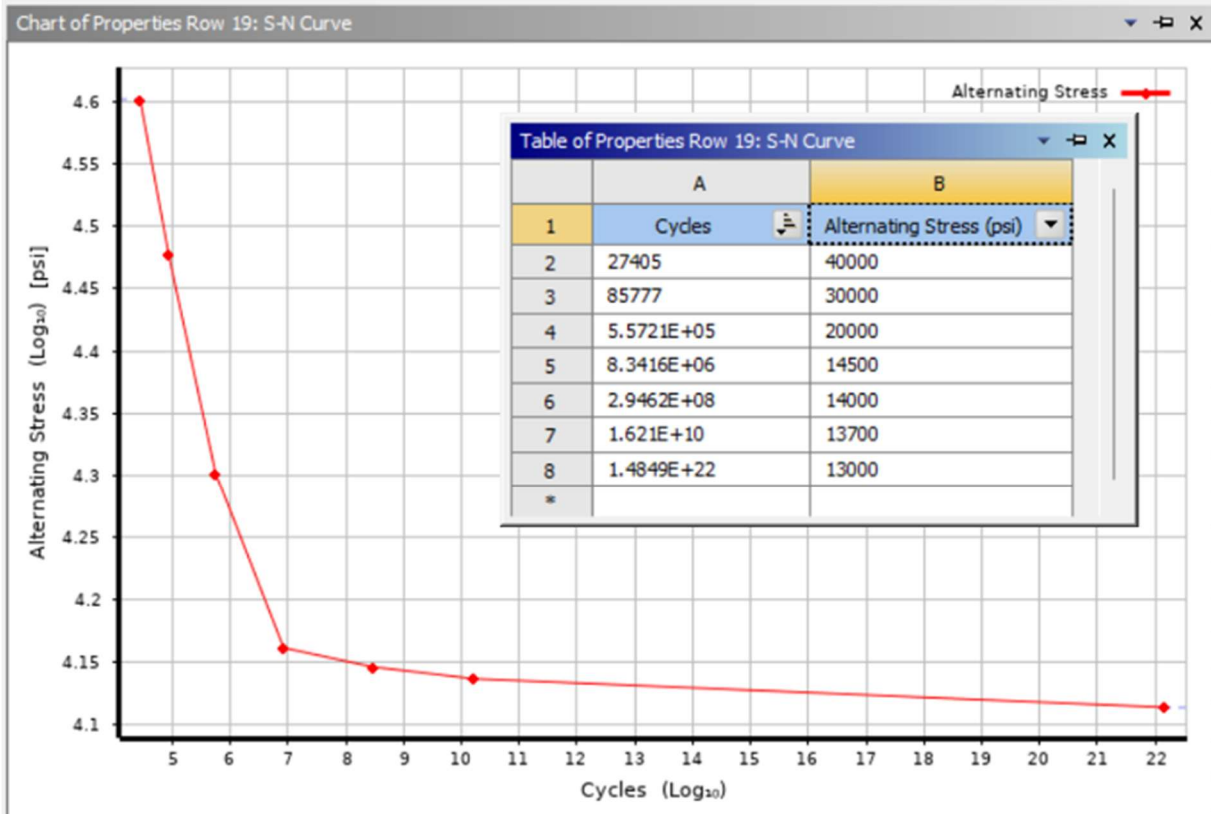


Figure 43 316L Cyclic and Perfectly Plastic Model

	A	B	C
1	Property	Value	Unit
2	Density	0.282	lb in ⁻³
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	Tabular	
5	Scale	1	
6	Offset	0	F ⁻¹
7	Zero-Thermal-Strain Reference Temperature	70	F
8	Isotropic Elasticity	Tabular	
9	Derive from	Young's Modulus ...	
10	Young's Modulus: Scale	1	
11	Young's Modulus: Offset	0	psi
12	Poisson's Ratio: Scale	1	
13	Poisson's Ratio: Offset	0	
14	Bulk Modulus: Scale	1	
15	Bulk Modulus: Offset	0	Pa
16	Shear Modulus: Scale	1	
17	Shear Modulus: Offset	0	Pa
18	Multilinear Kinematic Hardening	Tabular	
19	Scale	1	
20	Offset	0	psi
21	Tensile Yield Strength	25000	psi
22	Tensile Ultimate Strength	70000	psi

	A	B	C	D	E
1	Temperature (F)	Young's Modulus (psi)	Poisson's Ratio	Bulk Modulus (Pa)	Shear Modulus (Pa)
2	70	2.83E+07	0.31	1.7116E+11	7.4474E+10
3	200	2.75E+07	0.31	1.6632E+11	7.2369E+10
4	300	2.7E+07	0.31	1.633E+11	7.1053E+10
*					

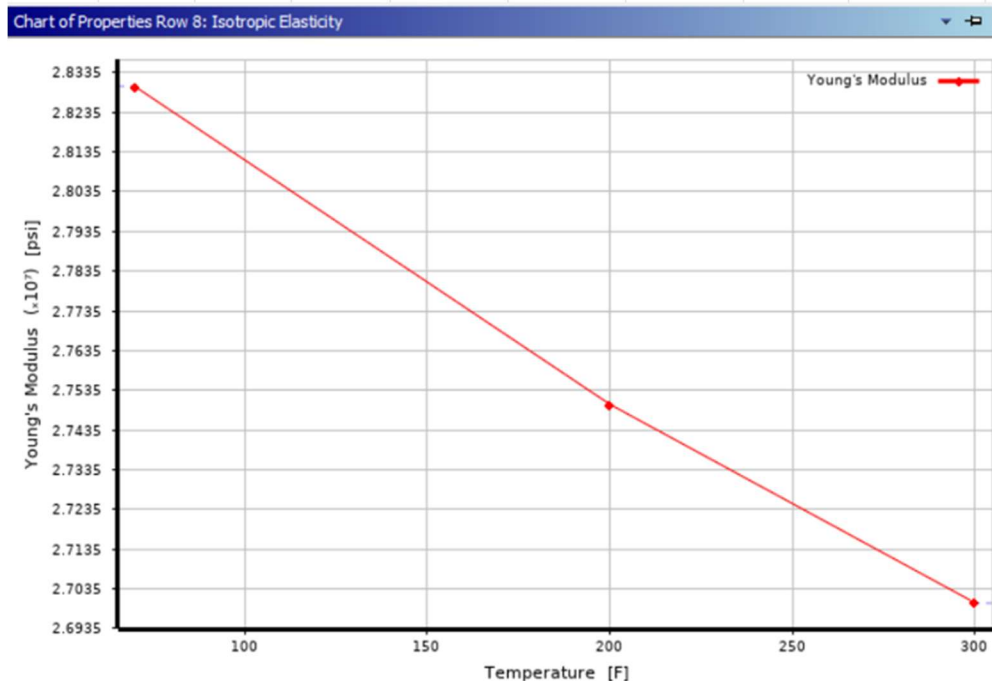


Figure 44 316L Elastic Plastic Model

A		B		C
1	Temperature (F)	1	Plastic Strain (in in ⁻¹)	Stress (psi)
2	70	2	0	25000
3	200	3	0.0048019	30000
4	300	4	0.019379	35000
*		5	0.044873	40000
		6	0.06721	45000
		7	0.086436	50000
		8	0.10624	55000
		9	0.12774	60000
		10	0.15119	65000
		11	0.17664	70000
		12	0.2041	75000
		13	0.23359	80000
		14	0.26512	85000
		15	0.29869	90000
		16	0.33431	95000
		17	0.372	1E+05
		18	0.41176	1.05E+05
		19	0.48295	1.1337E+05
		*		

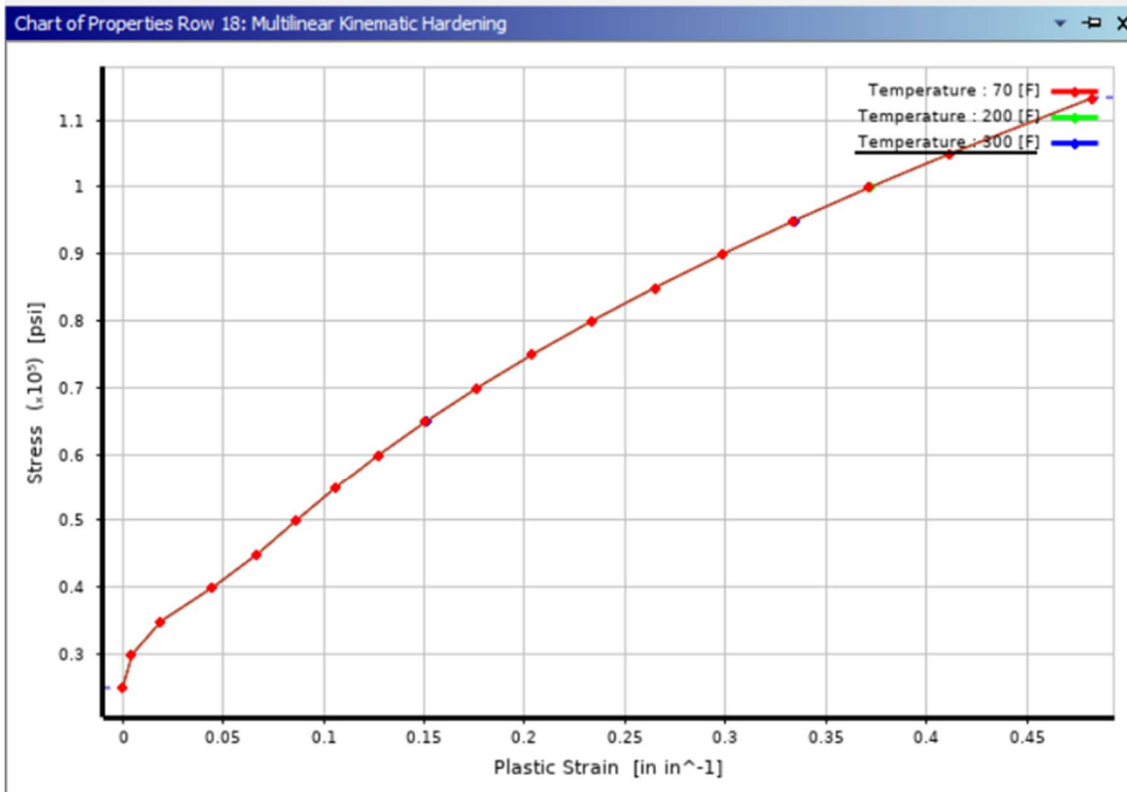


Figure 45 316L Elastic Plastic Model

Properties of Outline Row 21: Carbon Steel			
	A	B	C
1	Property	Value	Unit
2	Density	0.28	lb in ⁻³
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	6.4E-06	F ⁻¹
5	Isotropic Elasticity		
6	Derive from	Young's Modulus ...	
7	Young's Modulus	2.94E+07	psi
8	Poisson's Ratio	0.3	
9	Bulk Modulus	1.6892E+11	Pa
10	Shear Modulus	7.7964E+10	Pa
11	Bilinear Isotropic Hardening		
12	Tangent Modulus Type	Plastic	
13	Yield Strength	36000	psi
14	Tangent Modulus	0	psi
15	S-N Curve	Tabular	
16	Interpolation	Log-Log	
17	Scale	1	
18	Offset	0	psi

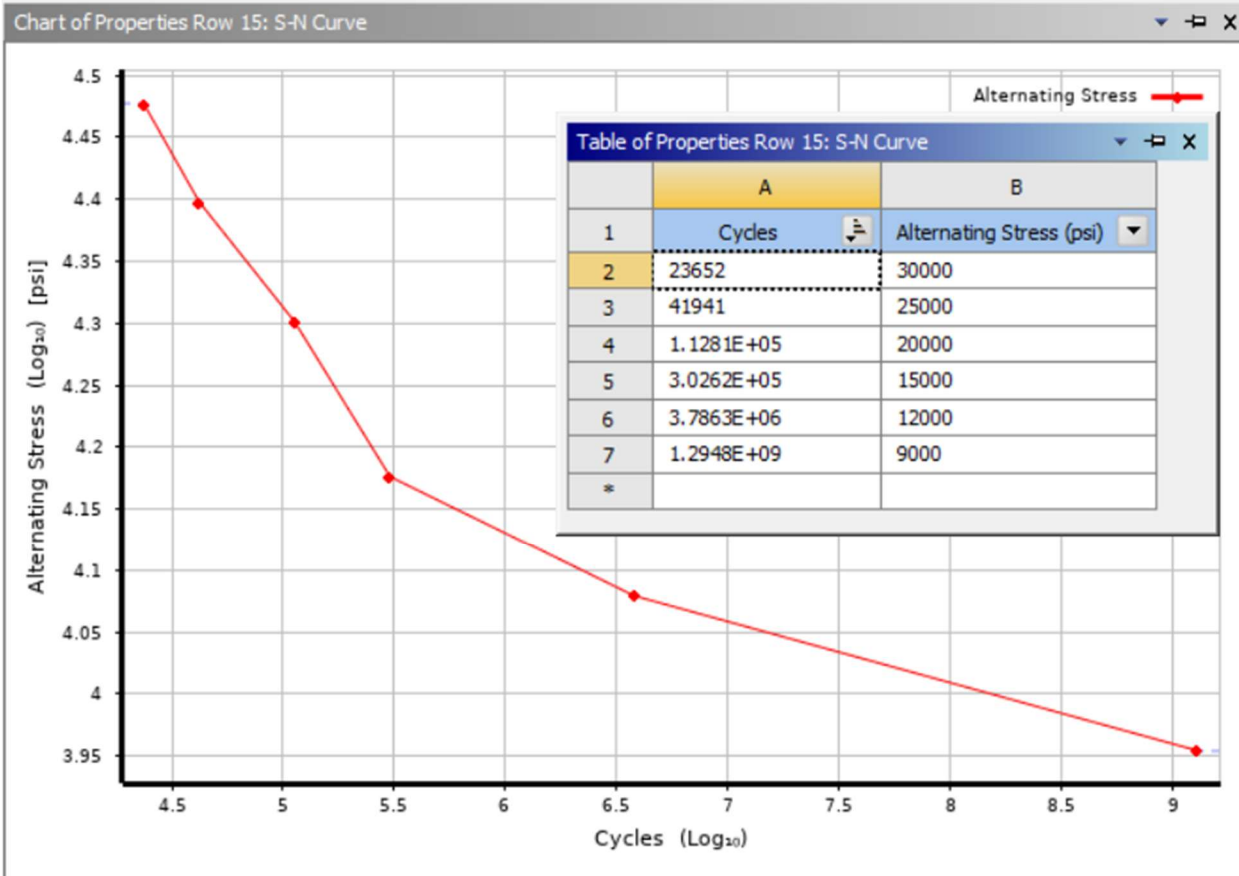


Figure 46 Carbon Steel (A36) Cyclic and Perfectly Plastic Model

Properties of Outline Row 22: Carbon Steel Plastic			
	A	B	C
1	Property	Value	Unit
2	Density	0.28	lb in ⁻³
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	6.4E-06	F ⁻¹
5	Isotropic Elasticity		
6	Derive from	Young's Modulus ...	
7	Young's Modulus	2.94E+07	psi
8	Poisson's Ratio	0.3	
9	Bulk Modulus	1.6892E+11	Pa
10	Shear Modulus	7.7964E+10	Pa
11	Multilinear Kinematic Hardening	Tabular	
12	Scale	1	
13	Offset	0	psi

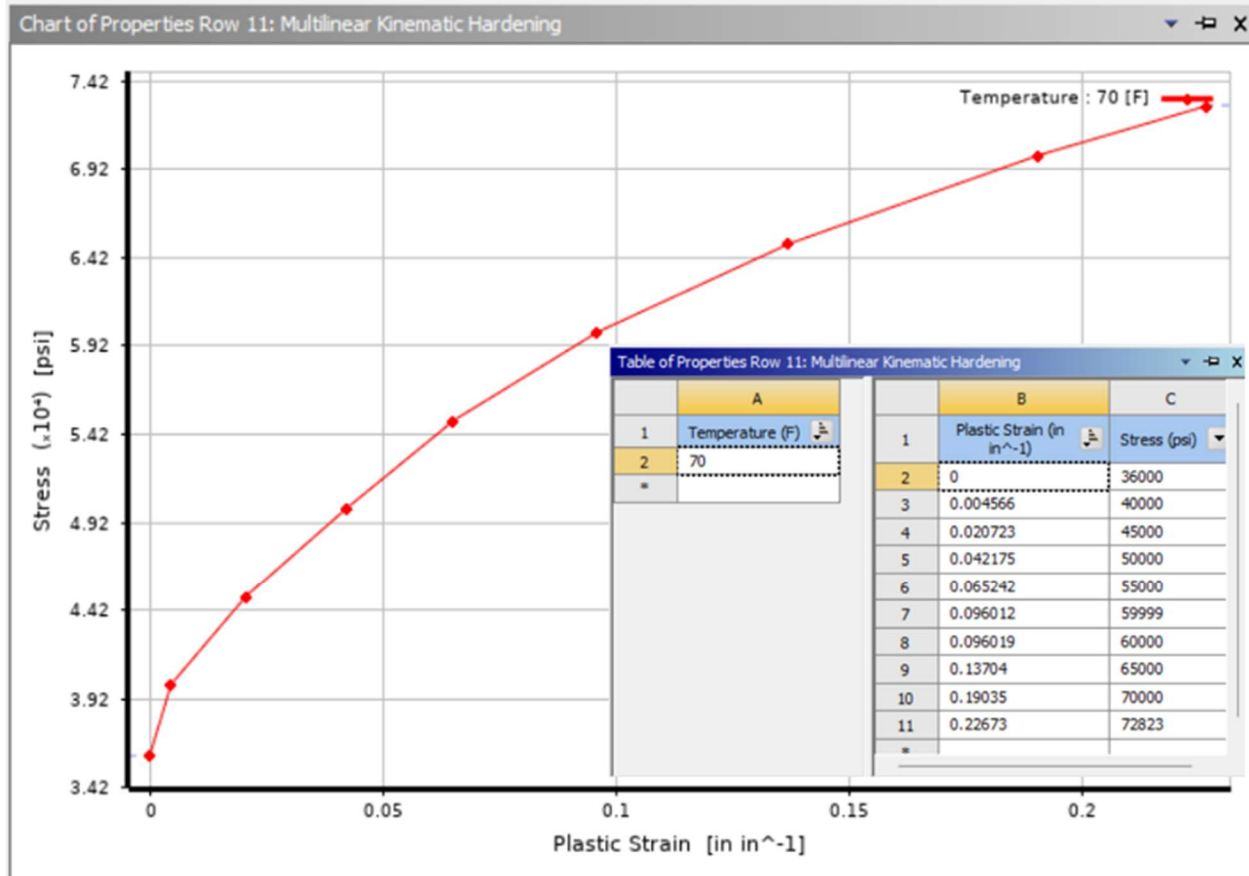


Figure 47 Carbon Steel (A36) Elastic Plastic Model

Properties of Outline Row 17: 625 Cyclic			
	A	B	C
1	Property	Value	Unit
2	Density	0.305	lb in ⁻³
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	6.7E-06	F ⁻¹
5	Isotropic Elasticity		
6	Derive from	Young's Modulus ...	
7	Young's Modulus	3E+07	psi
8	Poisson's Ratio	0.31	
9	Bulk Modulus	1.8144E+11	Pa
10	Shear Modulus	7.8948E+10	Pa
11	Bilinear Isotropic Hardening		
12	Tangent Modulus Type	Plastic	
13	Yield Strength	50000	psi
14	Tangent Modulus	0	psi
15	S-N Curve	Tabular	
16	Interpolation	Log-Log	
17	Scale	1	
18	Offset	0	psi
19	Tensile Yield Strength	50000	psi
20	Tensile Ultimate Strength	1.1E+05	psi

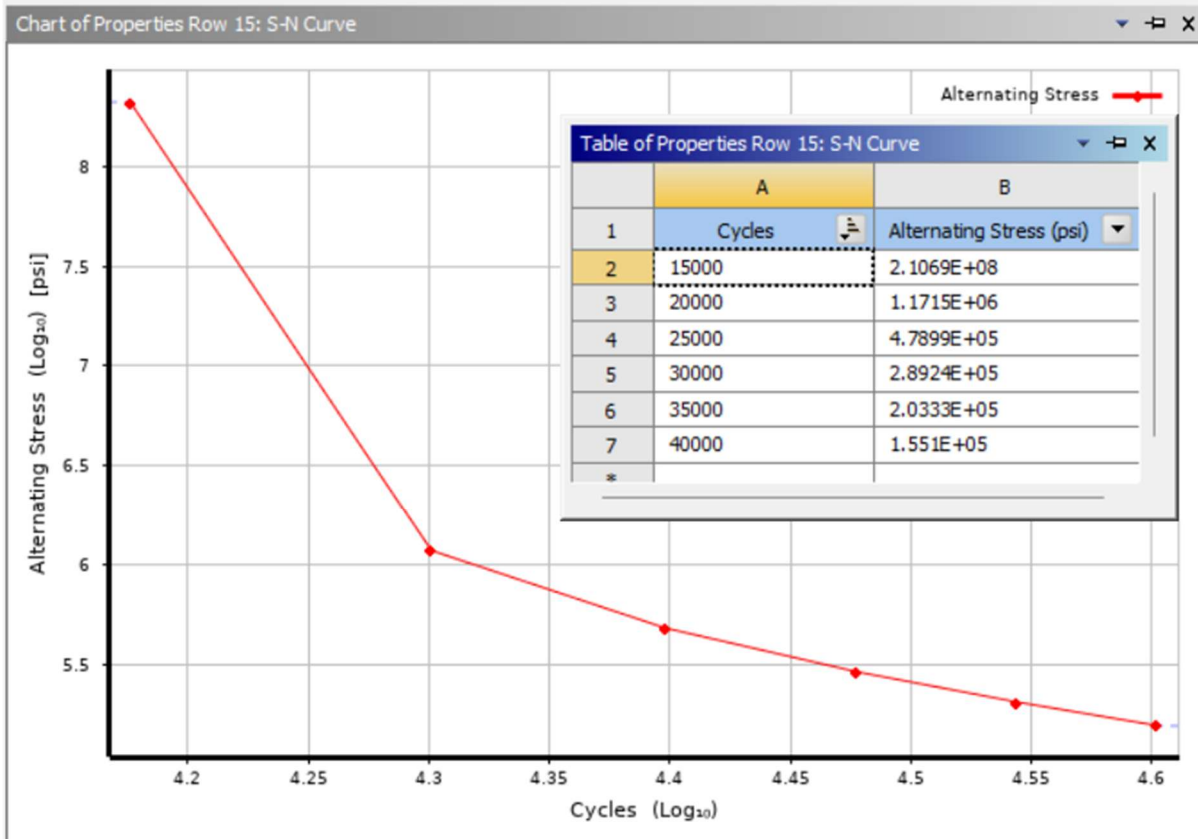
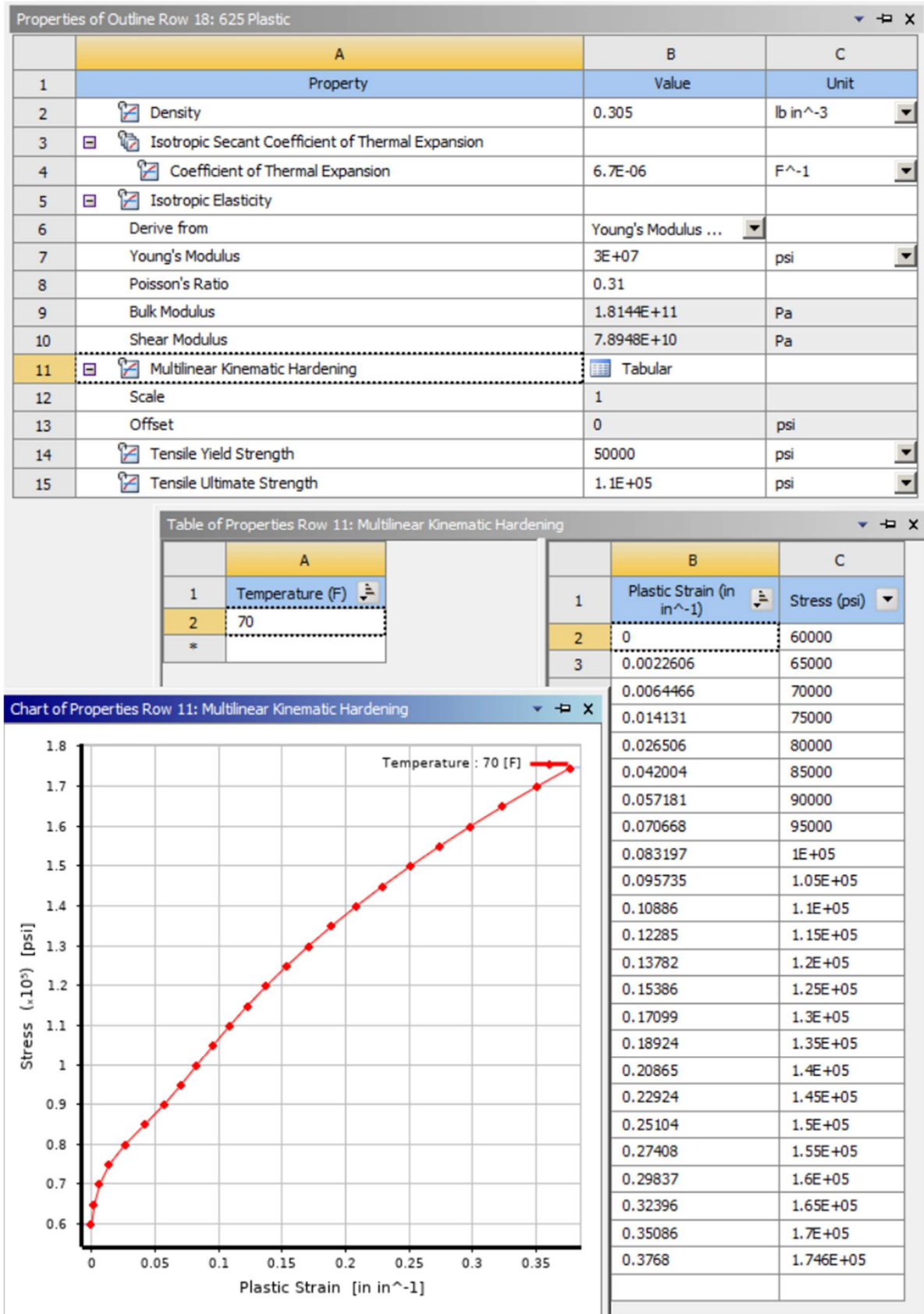


Figure 48 625 Cyclic and Perfectly Plastic Model



Properties of Outline Row 21: 6061			
	A	B	C
1	Property	Value	Unit
2	 Density	0.098	lb in ⁻³
3	 Isotropic Secant Coefficient of Thermal Expansion		
4	 Coefficient of Thermal Expansion	1.21E-05	F ⁻¹
5	 Isotropic Elasticity		
6	Derive from	Young's Modulus and Poisson's Ratio	
7	Young's Modulus	1E+07	psi
8	Poisson's Ratio	0.33	
9	Bulk Modulus	6.7596E+10	Pa
10	Shear Modulus	2.592E+10	Pa

Figure 50 6061 T6 Model

3.3 REQUIREMENTS AND LOADS

3.3.1 Load Parameters

Load cases used in this analysis are based on the system requirements. The Target Assembly has four Requirements documents covering the main assembly, shaft, segment, and drive system [8][9][10][11]. There are additional parameters needed for the load cases that come from Interface Sheets, these documents are referenced from the Requirements documents. The first requirements covered are code based.

Table 5 Code Based Requirements

Component	Number	Description
Target Assembly	3006 - Design Loads and Acceptance Criteria	Target assembly shall be designed so that limit states (structural integrity) are maintained under all load combinations (including seismic). Loads and limit states defined by listed codes/criteria (ASME / ASCE 7 / RCSC / NASA / judgement / datasheets) for multiple failure modes.
Target Shaft	1687 - Design Loads and Acceptance Criteria	Shaft shall be designed so that limit states are maintained under all load combinations (including seismic); evaluated per ASME/ ASCE 7/ RCSC/ NASA/ judgement/ datasheets (table).
Target Segment	1600 - Design Loads and Acceptance Criteria	Segment shall be designed so that limit states are maintained under all load combinations (including seismic); evaluated per ASME / ASCE7/ RCSC/ NASA/ judgement/ datasheets (table).

The ASME code is the source for all the design and operating loads with ACSE 7 providing the seismic criteria. Using the results from the design and operating loads, RCSC and NASA provide fastener acceptance criteria. The ASME code used in this analysis is BPVC Section VIII Div 2, note that the Target Assembly is not a pressure vessel however, the loads and allowable properties are construed so they are applicable to the Target analysis. Table 5 shows the Load Combination Parameters used in the Load Cases.

Table 6 Section VIII Div 2 Parameters

Table 5.2 Load Combination Parameters		
Design Load Parameter	Operating Load Parameter [Note (1)]	Description
P	P_o	Internal and external specified design or operating pressure
P_s	P_{so}	Design or operating static head from liquid or bulk materials (e.g., catalyst)
P_T	...	Selected hydrostatic or pneumatic test pressure [see 8.2.1(d) or 8.3.1]. Used only in the pressure test load combinations.
D	D_o	Deadweight of the vessel, contents, and appurtenances at the location of interest, including the following: • weight of vessel including internals, supports (e.g., skirts, lugs, saddles, and legs), and appurtenances (e.g., platforms, ladders, etc.) • weight of vessel contents design, operating, and test conditions • refractory linings, insulation • static reactions from the weight of attached equipment, such as motors, machinery, other vessels, and piping • transportation loads (the static forces obtained as equivalent to the dynamic loads experienced during normal operation of a transport vessel [see 1.2.1.3(b)])
L	L_o	• Appurtenance live loading • Effects of fluid momentum, steady state, and transient • Loads resulting from wave action
E	Same as design parameter	Earthquake loads (see 5.1.3.2)
W		Wind loads (see 5.1.3.2)
W_{pt}		The pressure test wind load case. The design wind speed for this case shall be specified by the Owner-User. Used only in the pressure test load combinations.
S_s		Snow loads
T	T_o	The self-restraining load case (i.e., thermal loads, applied displacements). This load case does not typically affect the collapse load, but should be considered in cases where elastic follow-up causes stresses that do not relax sufficiently to redistribute the load without excessive deformation.

NOTE:
(1) The operating load parameters do not necessarily represent single quantities, but rather each operating load parameter may represent multiple operating conditions as specified in the User's Design Specification [see 2.2.1.1(e) and 2.2.1.1(f)].

The parameters used in this analysis are Pressure, Deadload, Live load, Earthquake and Temperature. Starting with Pressure loads, these values are obtained from the Remote Handling Interface Sheet [12] and the Process Systems Interface Sheet [13]. In Remote Handling operations the cooling lines will be purged with air, so no head is included with this pressure. The Process Systems Interface Sheet shows the water pressure, this would require the static head included. Table 6 shows the air pressure value bounding the water pressure so for simplicity only the relief pressure of 125psi is used for the P value.

Table 7 Pressure Loads

Component	Source	Parameter	Value	Fluid
Target Assembly	IS - Target Assembly - Target Process Systems	MAWP	75 PSIA	Water
Target Assembly	IS - Target Assembly - Remote Handling	Relief Pressure / Operating Pressure	125 PSI / 100 PSI	N2 or Dry Air

The Deadload Parameter is covered in the material properties in the Finite Element model, the correct density is assigned to each component and the gravity load captures this parameter. The Target Assembly has two Live loads, there is a rotational velocity and a rotational acceleration. There are several requirements covering these parameters shown in Table 7.

Table 8 Live Load Requirements

Component	Number	Description
Target Drive	1666 - Drive Spurious Stop	Drive components shall not undergo permanent deformation after a sudden stop (deceleration from full speed using peak motor torque).
Target Shaft	1694 - Shaft Spurious Stop	Shaft shall have FOS > 1 during a Spurious Stop Event.
Target Shaft	1693 - Drive Segment Connection Spurious Stop Survival	Connection between the segment and the drive shall survive a spurious stop event without plastic deformation.
Target Segment	1605 - Segment Spurious Stop	Segment shall not undergo permanent deformation after a sudden stop (deceleration from full speed using peak motor torque).
Target Assembly	1543 - Spurious Stop Survival	The segments shall not undergo permanent deformation after a sudden stop, where a stop is defined as a deceleration from full speed using the peak torque of the motor.
Target Assembly	3597 - Start up time	The target assembly shall have torque and power to achieve 45 rpm within 10 minutes from rest.

Requirement 3597 gives the rotational velocity, the rest cover the rotational acceleration due to an sudden stop. To determine what value is needed for the rotational acceleration the peak torque of the motor is needed. Using the part number from the model [1], Table 8 shows the torque values for this class of motor. Also taken from the model is the inertia of the system, shown in Figure 37.

Table 9 Motor Torque Values [2]

KBM(S) Frames	Outside Diameter	Through Bore	Continuous Stall Torque	Peak Stall Torque	Continuous Output KW
"Torquer" Form Factor					
KBM(S)-43	159.78 mm (6.29 in)	76.28 mm (3.00 in)	6.11 - 44.2 Nm	18.0 - 153 Nm	1.23 - 2.875 KW
KBM(S)-57	202.90 mm (7.99 in)	104.17 mm (4.10 in)	18.8 - 109 Nm	60 - 441 Nm	2.31 - 3.00 KW
KBM(S)-60	229.85 mm (9.05 in)	105.05 mm (4.14 in)	29.4 - 154 Nm	69.1 - 393 Nm	2.96 - 8.42 KW
KBM(S)-79	259.63 mm (10.22 in)	152.43 mm (6.00 in)	43.5 - 222 Nm	152 - 1075 Nm	2.585 - 3.75 KW
KBM(S)-88	331.46 mm (13.05 in)	155.01 mm (6.10 in)	102 - 545 Nm	197 - 1200 Nm	3.87 - 16.0 KW
KBM(S)-118	361.11 mm (14.22 in)	225.04 mm (8.86 in)	172 - 672 Nm	498 - 2400 Nm	7.78 - 19.85 KW
KBM(S)-163	605.0 mm (23.82 in)	315.50 mm (12.42 in)	764 - 1329 Nm	1966 - 3932 Nm	17.3 - 20.1 KW
KBM(S)-260	850.0 mm (33.46 in)	557.85 mm (21.96 in)	1932 - 3445 Nm	6494 - 12812 Nm	13.7 - 18.5 KW

INERTIA at CENTER OF GRAVITY with respect to _0000004343 coordinate frame: (KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 5.9572260e+10 6.6759063e+06 -1.2032063e+05
 Iyx Iyy Iyz 6.6759063e+06 1.5603880e+09 1.8810493e+07
 Izx Izy Izz -1.2032063e+05 1.8810493e+07 5.9571133e+10

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 1.5603812e+09 5.9571127e+10 5.9572273e+10

Figure 51 Target Assembly Inertia

Some quick math shows what the acceleration on the system is for a 2400Nm torque and an inertia value of I1 and the time to decelerate from 45rpms.

$$T := 2400 \cdot N \cdot m$$

$$I := 1560381200 \cdot kg \cdot mm^2$$

$$a := \frac{T}{I} = 1.538 \frac{1}{s^2}$$

$$v := 45 \cdot rpm$$

$$t := \frac{v}{a} = 3.1 \text{ s}$$

Figure 52 Sudden Stop Deceleration

For conservatism a sudden stop of 1 second will be used as the design load L and a gradual stop of 10 seconds will be used as the operation live load L_o . Velocity will be the same for both design and operating load parameters.

$$v := 45 \cdot rpm$$

$$t_1 := 1 \text{ s} \quad t_{10} := 10 \text{ s}$$

$$a_1 := \frac{v}{t_1} = 4.71 \frac{1}{s^2}$$

$$a_{10} := \frac{v}{t_{10}} = 0.47 \frac{1}{s^2}$$

Figure 53 Live Load Values

The next parameter to define is the Earthquake load, this is defined by ACSE 7 [1]. Using the ASCE 7 Hazard Tool the parameters for the seismic loads are found for the Second Target Station site.

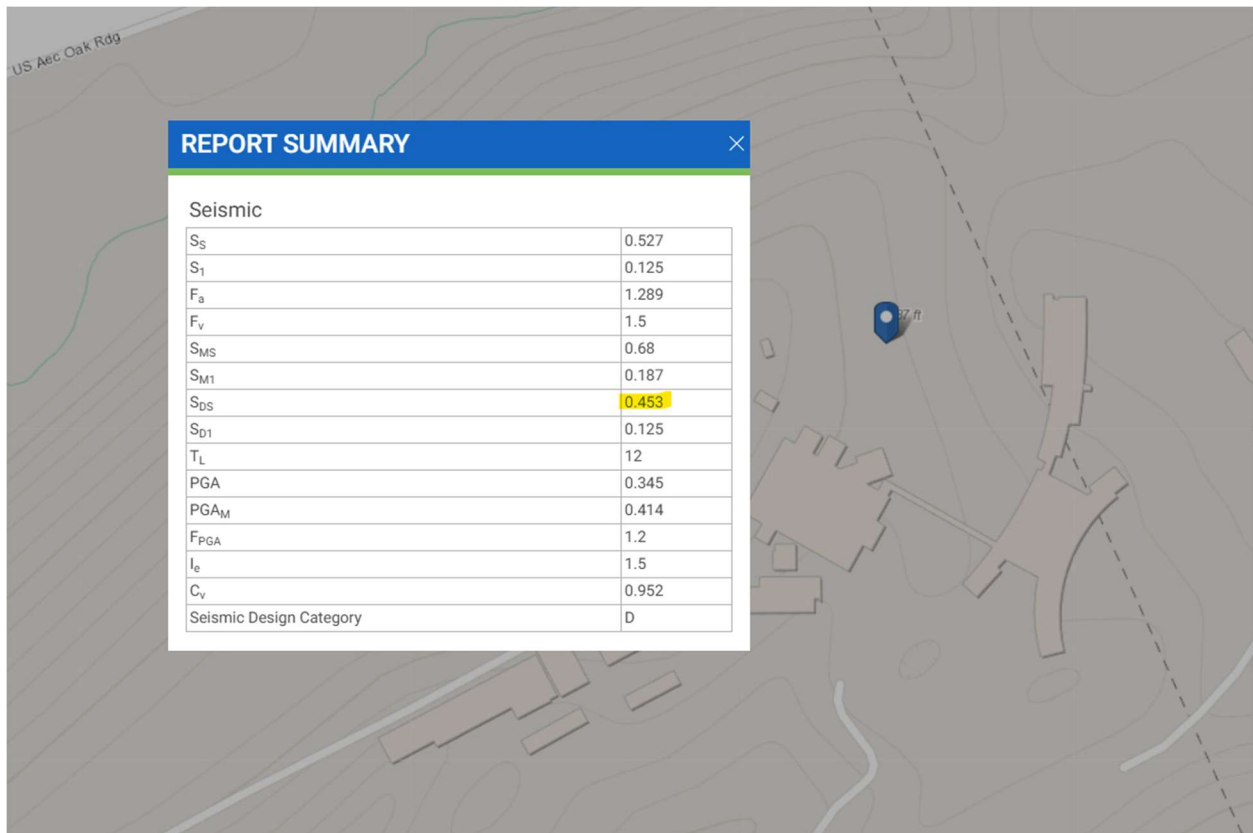


Figure 54 ASCE 7 Hazard Tool Results for STS

Per DOE-STD-1020 [2] and STS-NPH-BOD [3] the design shall use SDC 2 and limit state C for Importance Factor and Response Modification.

13.3 SEISMIC DEMANDS ON NONSTRUCTURAL COMPONENTS

13.3.1 Seismic Design Force

13.3.1.1 Horizontal Force. The horizontal seismic design force (F_p) shall be applied at the component's center of gravity and distributed relative to the component's mass distribution and shall be determined in accordance with Eq. (13.3-1):

$$F_p = \frac{0.4a_p S_{DS} W_p}{\left(\frac{R_p}{I_p}\right)} \left(1 + 2\frac{z}{h}\right) \quad (13.3-1)$$

F_p is not required to be taken as greater than

$$F_p = 1.6 S_{DS} I_p W_p \quad (13.3-2)$$

and F_p shall not be taken as less than

$$F_p = 0.3 S_{DS} I_p W_p \quad (13.3-3)$$

where

- F_p = seismic design force;
- S_{DS} = spectral acceleration, short period, as determined from Section 11.4.5;
- a_p = component amplification factor that varies from 1.00 to 2.50 (select appropriate value from Table 13.5-1 or 13.6-1);
- I_p = component Importance Factor that varies from 1.00 to 1.50 (see Section 13.1.3);
- W_p = component operating weight;
- R_p = component response modification factor that varies from 1.00 to 12 (select appropriate value from Table 13.5-1 or 13.6-1);
- z = height in structure of point of attachment of component with respect to the base. For items at or below the base, z shall be taken as 0. The value of z/h need not exceed 1.0; and
- h = average roof height of structure with respect to the base.

Figure 55 Method for Seismic Load

$S_{DS} := .453$	Hazard Tool
$a_p := 1.0$	Rigid Attachment
$W_p := 42000 \text{ lbf}$	Model Properties
$I_p := 1.5$	Nuclear Safety Based
$R_p := 1.25$	Response Modification
$z := 1$	Height factors set to 1.0, the component is attached at the top of the roof (CV).
$h := 1$	
$F_p := \frac{.4 \cdot a_p \cdot S_{DS}}{\left(\frac{R_p}{I_p}\right)} \cdot \left(1 + 2 \cdot \frac{z}{h}\right) = 0.65$	

Figure 56 Seismic Coefficient Calculation

The seismic parameter E is defined as 0.65g.

The final parameter to define is temperature, the temperature data comes from a separate analysis [2] where the thermal data is imported to the finite element model as external data that is mapped onto the assembly. Note that the temperature parameter is the same for design and operating loads.

With the load parameters defined the remaining requirements can be detailed, Table 9 shows the lifespan requirements for the components listed.

Table 10 Cyclic Requirements

Component	Number	Description
Target Assembly	1447 – Operational Lifetime	The system shall be capable of use for at least 40 years.

Target Shaft	1677 - Shaft Lifetime	The system shall be capable of use for at least 40 years.
Target Segment	1574 - Segment Lifetime	Segment Fatigue margin shall be >1 for a 10-year operational life for structural materials with the following load combinations:
Target Assembly	Interface Sheet – Target Systems	The Target Systems design shall allow for greater than 5000 hours of proton beam on target per year

Section VIII Div 2 covers lifespan analysis and with the motor speed, hours per year and number of years the total number of cycles can be calculated for S-N curves. The calculations are shown here in Figure 40.

Cycles:

$$t_{year} := 5000 \cdot hr$$

$$v_{rpm} := 45 \cdot rpm = (2.7 \cdot 10^3) \frac{rev}{hr}$$

$$years_{segment} := 10 \quad years_{LoF} := 40$$

$$Segment := (t_{year} \cdot years_{segment}) \cdot v_{rpm} = 8.5 \cdot 10^8$$

$$LoF := (t_{year} \cdot years_{LoF}) \cdot v_{rpm} = 3.4 \cdot 10^9$$

Figure 57 Required Cycle Count

In addition to live load cycles there is a cycle count for a thermal load, beam trips are a cooling down cycle from the steady state operating temperature. The cycle count for beam trips is 10^5 [5]

Deflection in the system is also a requirement; the Target should not make contact with neighboring components during any of the load cases. Only elastic load cases are used for this check. The requirements are shown in Table 10.

Table 11 Deflection Requirements

Component	Number	Description
Target Assembly	3297 - Deflections & Errors	Target assembly boundary shall not deviate more than 10 mm horizontally or 5 mm vertically from the ideal outline defined in [7] under any load combinations (ASME BPVC/ASCE 7-16), tolerances, or accumulated errors.
Target Segment	2085 - Segment Rotary Deflection	Deflection due to rotation (centripetal forces) shall not exceed 2.5 mm.
Target Assembly	2840 – Seismic Deflection	Deflection of the target assembly at any location shall not exceed 8mm when subjected to seismic design loads set forth in ASCE 7-16, Chapter 13.
Target Assembly	1539 – Imbalance Deflection	The deflection due to rotation with an unbalanced target shall be less than 0.25mm.

With all the load parameters defined, the load combinations can be defined. The Design by Analysis section of Section VIII Div 2 has Elastic and Elastic Plastic load combinations, in this analysis, both are used. These load combinations are used to satisfy several failure modes, these include; Local Failure, Plastic Collapse, Plastic Ratcheting, Cyclic Fatigue, and Buckling. The Target Assembly is primarily suspended and the only components that experience compression are the bearing housings, which are short, thick-walled cylinders. Therefore, Buckling is ignored in this analysis. Table 11 shows Elastic Analysis load combinations.

Table 12 Elastic Load Combinations

Table 5.3 Load Case Combinations and Allowable Stresses for an Elastic Analysis					
Load Combinations [Note (1)]	Stress Assessment and Allowable Stress [Note (2)]				
	General Primary Membrane	Local Primary Membrane	Local Primary Membrane Plus Bending	Range of Primary Plus Secondary	Range of Primary Plus Secondary Plus Peak
	P_m	P_L	$P_L + P_b$	$P_L + P_b + Q$	$P_L + P_b + Q + F$
Design					
(1) $P + P_s + D$	S	S_{PL}	S_{PL}	Not applicable	
(2) $P + P_s + D + L$					
(3) $P + P_s + D + L + T$					
(4) $P + P_s + D + S_s$					
(5) $0.6D + (0.6W \text{ or } 0.7E)$ [Note (3)]					
(6) $\Omega_p P + P_s + D + (0.6W \text{ or } 0.7E)$ [Note (4)]					
(7) $\Omega_p P + P_s + D + 0.75(L + T) + 0.75S_s$ [Note (4)]					
(8) $\Omega_p P + P_s + D + 0.75(0.6W \text{ or } 0.7E) + 0.75L + 0.75S_s$ [Note (4)]					
(9) Other design load combinations as defined in the User's Design Specification					
Operating					
(10) $P_o + P_{So} + D_o$	Not applicable		S_{PS}	$2S_a$ (see 5.5.1.4)	
(11) $P_o + P_{So} + D_o + L_o$					
(12) $P_o + P_{So} + D_o + L_o + T_o$					
(13) $P_o + P_{So} + D_o + S_s$					
(14) $P_o + P_{So} + D_o + (0.6W \text{ or } 0.7E)$					
(15) $P_o + P_{So} + D_o + 0.75(L_o + T_o) + 0.75S_s$					
(16) $P_o + P_{So} + D_o + 0.75(0.6W \text{ or } 0.7E) + 0.75L_o + 0.75S_s$					
(17) Other operating load combinations as defined in the User's Design Specification					
Pressure Test					
(18) $P_T + P_S + D + 0.6W_{pt}$	See 5.2.2.5	Not applicable	See 5.2.2.5	Not applicable	
GENERAL NOTE: Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered. NOTES: (1) The parameters used in the Load Combinations column are defined in Table 5.2. (2) See Figure 5.1 for additional guidance on stress categories and limits on equivalent stress. (3) This load combination addresses an overturning condition for foundation design. It does not apply to design of anchorage (if any) to the foundation. Refer to ASCE/SEI 7-10, 2.4.1, Exception 2 for an additional reduction to W that may be applicable. (4) The product of $\Omega_p P$ is used in lieu of the design pressure, P, for evaluation of P_m, P_L, and $P_L + P_b$ stress assessments since it is unlikely the occasional loads would occur at the same time as the maximum design pressure, P.					

Note that there are no Wind or Snow loads, this excludes combinations number 4, 5, 7, 13, and 15. Combination 18 can also be ignored due to the pressure parameter is set to the relief pressure requirement, so the max pressure is already being analyzed. Looking at the Design combinations, numbers 1, 2, 3, 6, and 8 remain, some simplification is used to reduce this down to combinations 3, 6, and 8. Under the remaining Operating combinations, only 12 is used, this is a cyclic analysis so it does not include seismic

loads, only operating live loads, pressure and temperature. The elastic load combinations are used for validating the deflection requirements in Table 10, the elastic loads are also used for obtaining fastener loads. Finally the Elastic loads are used to satisfy the Plastic Ratcheting criteria. The elastic stress strain curves are set to be Perfectly Plastic at the material's yield point. To show there is no Plastic Ratcheting the Elastic analysis will show there is no plastic strain in the model.

Table 13 Elastic Plastic Load Combinations

Table 5.5 Load Case Combinations and Load Factors for an Elastic-Plastic Analysis	
Criteria	Required Factored Load Combinations
	Design Conditions
Global	(1) $\beta(P + P_s + D)$ (2) $0.88\beta(P + P_s + D + T) + 1.13\beta L + 0.36\beta S_s$ (3) $0.88\beta(P + P_s + D) + 1.13\beta S_s + 0.71\beta L$ or $0.36\beta W$ (4) $0.88\beta(P + P_s + D) + 0.71\beta W + 0.71\beta L + 0.36\beta S_s$ (5) $0.88\beta(P + P_s + D) + 0.71\beta E + 0.71\beta L + 0.14\beta S_s$
Local	$1.7(P + P_s + D)$
Serviceability	Per User's Design Specification, if applicable; see 5.2.4.3(b)
	Test Condition
Global	$\frac{\beta}{1.5} \times \frac{1}{\beta_T} (P_T + P_S + D + 0.6W_{pt})$
Serviceability	Per User's Design Specification, if applicable
GENERAL NOTES: (a) The parameters used in the Design Load Combination column are defined in Table 5.2. (b) See 5.2.4.3 for descriptions of global and serviceability criteria. (c) S is the allowable membrane stress at the design temperature. (d) S_T is the allowable membrane stress at the pressure test temperature. (e) Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.	

Table 12 provides the Elastic Plastic load combinations, similar to the Elastic loads, the wind and snow loads can be removed. Combinations 1, 2, and 5 are used, combination 1 is meant to be a primary operating case, for the Target Assembly that would include the live loads and temperature loads within the factored parameters. Combination 2 and 5 offer a higher factored Live load and a seismic load. The Local combo is bound by combo 1 and pressure loads are set to the relief pressure so Test pressures are ignored. These loads are used to satisfy the Plastic Collapse and Local Failure criteria. The requirements for Plastic Collapse are for the analysis to converge, this indicates the component is stable under the applied loads.

The criteria for Local Failure is to determine the limiting triaxial strain and compare that the plastic strain is less than or equal to that value. If the components had any cold working that would be a contributing factor but the components in this analysis are not cold worked. The expression for triaxial strain is shown in Figure 42.

$$\epsilon_L = \epsilon_{Lu} \cdot \exp \left[- \left(\frac{\alpha_{sl}}{1 + m_2} \right) \left(\left\{ \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3\sigma_e} \right\} - \frac{1}{3} \right) \right]$$

Figure 58 Triaxial Strain Limit

The full calculations for this strain limit are shown in the Appendix calculations, but most of these parameters are outputs in ANSYS, the principal stresses and equivalent stress are pulled from the analysis results and entered into a User Defined result that plots the strain comparison.

Table 14 Analysis Load Cases

Model	Type	Combination	Requirement	Failure Criteria
Target Assembly	Elastic	(3) P+D+L+T	3006, 3297, 2085	Deflection
Target Assembly	Elastic	(6) P+D+0.7E	3006, 3297,	Deflection
Target Assembly	Elastic	(8) P+D+0.53E+0.75L	3006, 3297,	Deflection
Segment/Bolt	Elastic	(3) P+D+L+T	1574, 1600, 2085, 1605	Plastic Ratchet, Fastener, Cyclic, Deflection
Segment/Bolt	Elastic	(6) P+D+0.7E	1600	Plastic Ratchet, Fastener, Deflection
Segment/Bolt	Elastic	(8) P+D+0.53E+0.75L	1600	Plastic Ratchet, Fastener, Deflection
Segment	EP	(1) 2.4(P+D+L+T)	1600	Plastic Collapse, Local Failure
Segment	EP	(2) 2.1(P+D+T)+2.7(L)	1600	Plastic Collapse, Local Failure
Segment	EP	(5) 2.1(P+D+T)+1.7(E)+1.7(L)	1600	Plastic Collapse, Local Failure
Shaft/Tie Rods	Elastic	(3) P+D+L+T	1677, 1693, 1687	Plastic Ratchet, Fastener, Cyclic, Deflection
Shaft/Tie Rods	Elastic	(6) P+D+0.7E	1687	Plastic Ratchet, Fastener, Deflection
Shaft/Tie Rods	Elastic	(8) P+D+0.53E+0.75L	1687	Plastic Ratchet, Fastener, Deflection
Shaft	EP	(1) 2.4(P+D+L+T)	1687	Plastic Collapse, Local Failure
Shaft	EP	(2) 2.1(P+D+T)+2.7(L)	1687	Plastic Collapse, Local Failure
Shaft	EP	(5) 2.1(P+D+T)+1.7(E)+1.7(L)	1687	Plastic Collapse, Local Failure
Drive/Fasteners	Elastic	(3) P+D+L+T	1666, 3006	Plastic Ratchet, Fastener, Cyclic, Deflection
Drive/Fasteners	Elastic	(6) P+D+0.7E	3006	Plastic Ratchet, Fastener, Deflection
Drive/Fasteners	Elastic	(8) P+D+0.53E+0.75L	3006	Plastic Ratchet, Fastener, Deflection

Drive	EP	(1) $2.4(P+D+L+T)$	3006	Plastic Collapse, Local Failure
Drive	EP	(2) $2.1(P+D+T)+2.7(L)$	3006	Plastic Collapse, Local Failure
Drive	EP	(5) $2.1(P+D+T)+1.7(E)+1.7(L)$	3006	Plastic Collapse, Local Failure

3.3.2 Weld Strength

Weld design allowable strength come from AWS D1.6 [1], the welds in this analysis are all complete joint thickness. Fatigue lifespan uses the same SN curve as the parent material as all welds are machined and inspected per Section VIII Div 2, 5.5.5.1 [2].

Table 15 AWS D1.6 Allowable Weld Stress

Table 4.1
Allowable Stresses in Welds (see 4.3.2)

Stress in Weld	Allowable Stress ^{a,b,c,d,e}
<i>CJP Groove Welds</i>	
Tension normal to the effective area	The lesser of values for base metal or filler metal
Compression normal to the effective area	The lesser of values for base metal (<u>specified minimum yield strength</u>) or for filler metal
Tension or compression parallel to the axis of the weld	Same as for base metal (<u>specified minimum yield strength</u>)
Shear on the effective area	$0.30 \times$ nominal tensile strength of filler metal, except shear stress on base metal shall not exceed $0.40 \times$ <u>specified minimum yield strength</u> of base metal

In the examples of prequalified welds there is a commonality between the CJP welds, that is if the root of the weld cannot be back gouged a backing strip is required. The welded joints on the Target shaft and segment are designed with an alignment feature that acts like a backing strip. The figure below shows an example of the typical design used in the welded joints.

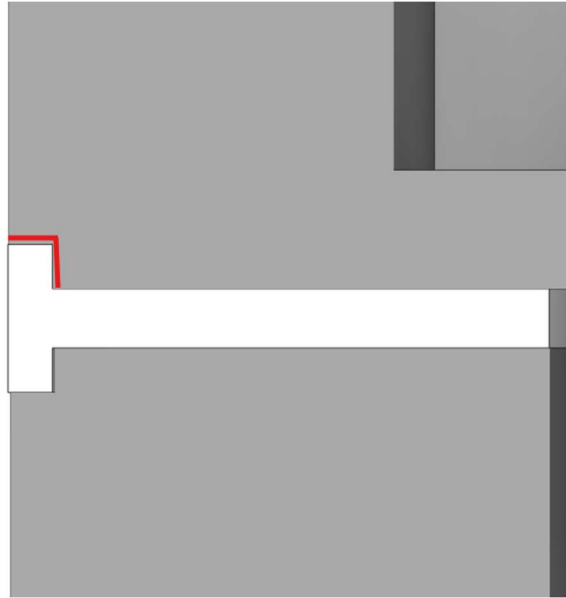
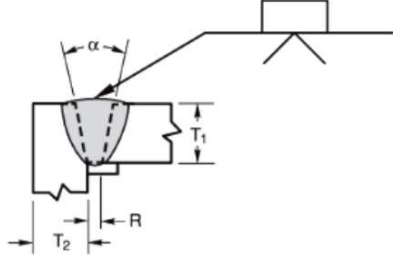


Figure 59 Typical Welded Joint Design

The next figure shows a prequalified CJP corner joint, note the callout for a backing strip.

See Notes on Page 37

Single-V-groove weld (2) Corner joint (C)		Tolerances	
		As Detailed (see 5.11.2)	As Fit-Up (see 5.11.2)
		$R = +1/16, -0$	$+1/4, -1/16$
		$\alpha = +10^\circ, -0^\circ$	$+10^\circ, -5^\circ$

Welding Process	Joint Designation	Base Metal Thickness (U = Unlimited)		Groove Preparation		Allowed Welding Positions	Notes
		T_1	T_2	Root Opening	Groove Angle		
SMAW	C-U2a	U	U	$R = 1/4$	$\alpha = 45^\circ$	All	I, o
GTAW	C-L2a	1 max.	U	$R = 3/8$	$\alpha = 30^\circ$	All	I, o
				$R = 1/2$	$\alpha = 20^\circ$	All	I, o
GMAW FCAW	C-U2a-GF	U	U	$R = 3/16$	$\alpha = 45^\circ$	All	a, o
				$R = 1/4$	$\alpha = 45^\circ$	All	a, I, o
				$R = 3/8$	$\alpha = 30^\circ$	All	a, I, o
SAW	C-L2a-S	2 max.	U	$R = 1/4$	$\alpha = 30^\circ$	F	I
SAW	C-U2-S	U	U	$R = 5/8$	$\alpha = 20^\circ$	F	I

Figure 60 AWS D1.6 CJP Weld Example

Finally, an example comparing the prequalified CJP joint to the joint design of the segment foot pin. Therefore, it is safe to assume that because the welds have a backing strip for the filler metal to bond with and not an unshielded open root with crack forming potential, they can use allowable strength criteria for CJP welds. The weld as modeled in the FEA model would take on the thickness of the T_1 dimension.

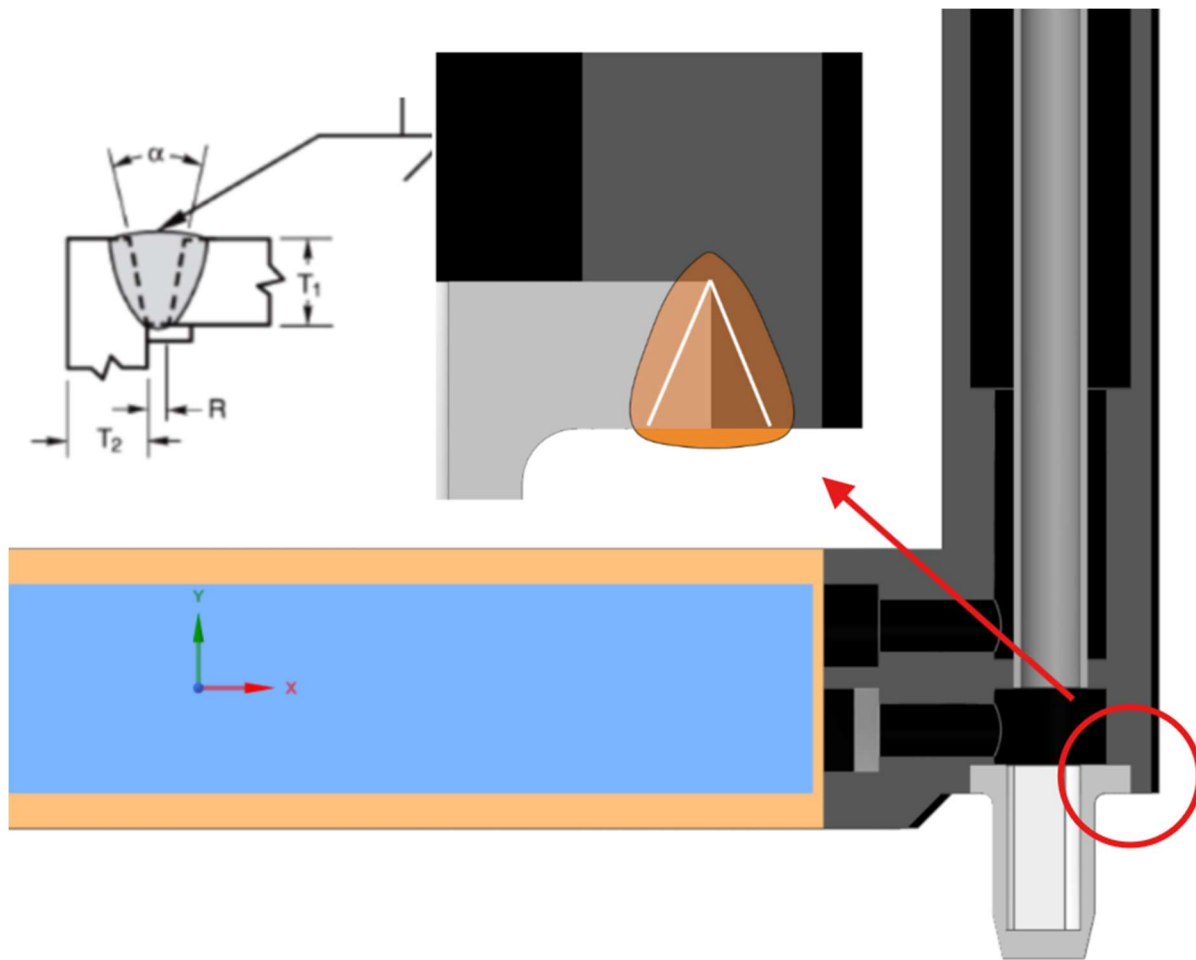


Figure 61 Segment Weld Compared to CJP Weld

3.3.3 Fastener Calculations

See section [5.1.4.3](#) for details on the fasteners, method and results.

3.3.4 Fatigue Analysis

The fatigue analysis loosely follows the elastic method in Section VIII Div 2 5.5.4 [9], using equation 5.48, the analysis simply compares allowable cycles to required cycles. Instead of ‘damage’ reported that the code uses, a safety factor plot is shown. The allowable cycles for each material comes from Annex 3-F.1 [9], shown in Figure 60. An example calculation is shown here for 316 SS, the remaining material calculations can be found in the Appendix.

(b) Series 3XX High Alloy Steels, Nickel–Chromium–Iron Alloy, Nickel–Iron–Chromium Alloy, and Nickel–Copper Alloy for temperatures not exceeding 427°C (800°F) (see Figures 3-F.3M and 3-F.3) and for 93.7 MPa (13.6 ksi) ≤ S_a ≤ 6 000 MPa (870 ksi)

ASME BPVC.VIII.2-2019

$$Y = \log \left[28.3 E3 \left(\frac{S_a}{E_T} \right) \right] \quad (3-F.6)$$

$$X = \frac{17.0181 - 19.8713Y + 4.21366Y^2}{1 - 0.1720606Y - 0.633592Y^2} \quad \text{for } 10^Y \geq 14.4 \quad (3-F.7)$$

$$X = \frac{1}{-0.331096 + \frac{4.3261 \ln(Y)}{Y^2}} \quad \text{for } 10^Y < 14.4 \quad (3-F.8)$$

3-F.1.3

The design number of design cycles, N , can be computed from eq. (3-F.21) based on the parameter X calculated for the applicable material.

$$N = 10^X \quad (3-F.21)$$

Figure 62 Fatigue Calculation Method, 300 Series Stainless Steel

A range for the stress amplitude is selected to get a wide range of points for the SN curve. ANSYS will only give results that are within the max and min stress amplitude so it is important to get a good set of data points for the curve.

Stainless Steel 316L

$$S_a := \begin{bmatrix} 13000 \\ 13700 \\ 14000 \\ 14500 \\ 20000 \\ 30000 \\ 40000 \end{bmatrix} \cdot \text{psi} \quad Y_{316} := \log \left(28300 \cdot \left(\frac{S_a}{28300 \cdot \text{ksi}} \right) \right) = \begin{bmatrix} 1.114 \\ 1.137 \\ 1.146 \\ 1.161 \\ 1.301 \\ 1.477 \\ 1.602 \end{bmatrix} \quad Y_x := 10^{Y_{316}} = \begin{bmatrix} 13 \\ 13.7 \\ 14 \\ 14.5 \\ 20 \\ 30 \\ 40 \end{bmatrix}$$

$$X_{SS1} := \frac{17.0181 - 19.8713 \cdot Y_{316} + 4.21366 \cdot Y_{316}^2}{1 - .1720606 \cdot Y_{316} - .633592 \cdot Y_{316}^2} = \begin{bmatrix} 5.025 \\ 8.788 \\ 7.521 \\ 6.921 \\ 5.746 \\ 4.933 \\ 4.438 \end{bmatrix} \quad 10^Y > 14.4$$

$$X_{SS2} := \frac{1}{-.331096 + \frac{4.3261 \cdot \ln(Y_{316})}{Y_{316}^2}} = \begin{bmatrix} 22.172 \\ 10.21 \\ 8.469 \\ 6.724 \\ 2.929 \\ 2.261 \\ 2.159 \end{bmatrix} \quad 10^Y < 14.4$$

$$N_{SS1} := 10^{X_{SS1}} = \begin{bmatrix} 105951 \\ 613323664 \\ 33219094 \\ 8341636 \\ 557213 \\ 85777 \\ 27405 \end{bmatrix} \quad N_{SS2} := 10^{X_{SS2}} = \begin{bmatrix} 14849175495644000000000 \\ 16210324723 \\ 294624164 \\ 5291273 \\ 848 \\ 182 \\ 144 \end{bmatrix}$$

$$N_{SS} := \begin{bmatrix} 1.485^{22} \\ 16210324723 \\ 294624164 \\ 8341636 \\ 557213 \\ 85777 \\ 27405 \end{bmatrix}$$

	A	B
1	Cycles	Alternating Stress (psi)
2	27405	40000
3	85777	30000
4	5.5721E+05	20000
5	8.3416E+06	14500
6	2.9462E+08	14000
7	1.621E+10	13700
8	1.4849E+22	13000

Figure 63 Stainless Steel Example Calculation

3.3.5 Snubber Ring Load

The Snubber Ring analysis is a requirement that the shaft must be able to rest on the Snubber ring for installation or maintenance purposes. The check is simply a force applied to the top of the lower shaft that is equal to the weight of the components above it. The weight of the Target Assembly [2] is 42000lbf.

Target Shaft	7092 - Lower Shaft Load-Bearing Integrity	Allowable forces (load capacity)	Shaft shall be designed to bear its own weight and the weight of 20 target segments on the lowermost surface of the shaft.	Load case defined	This is a defined minimum load-bearing scenario; actual forces depend on segment mass.
--------------	---	----------------------------------	--	-------------------	--

Figure 64 Snubber Requirement

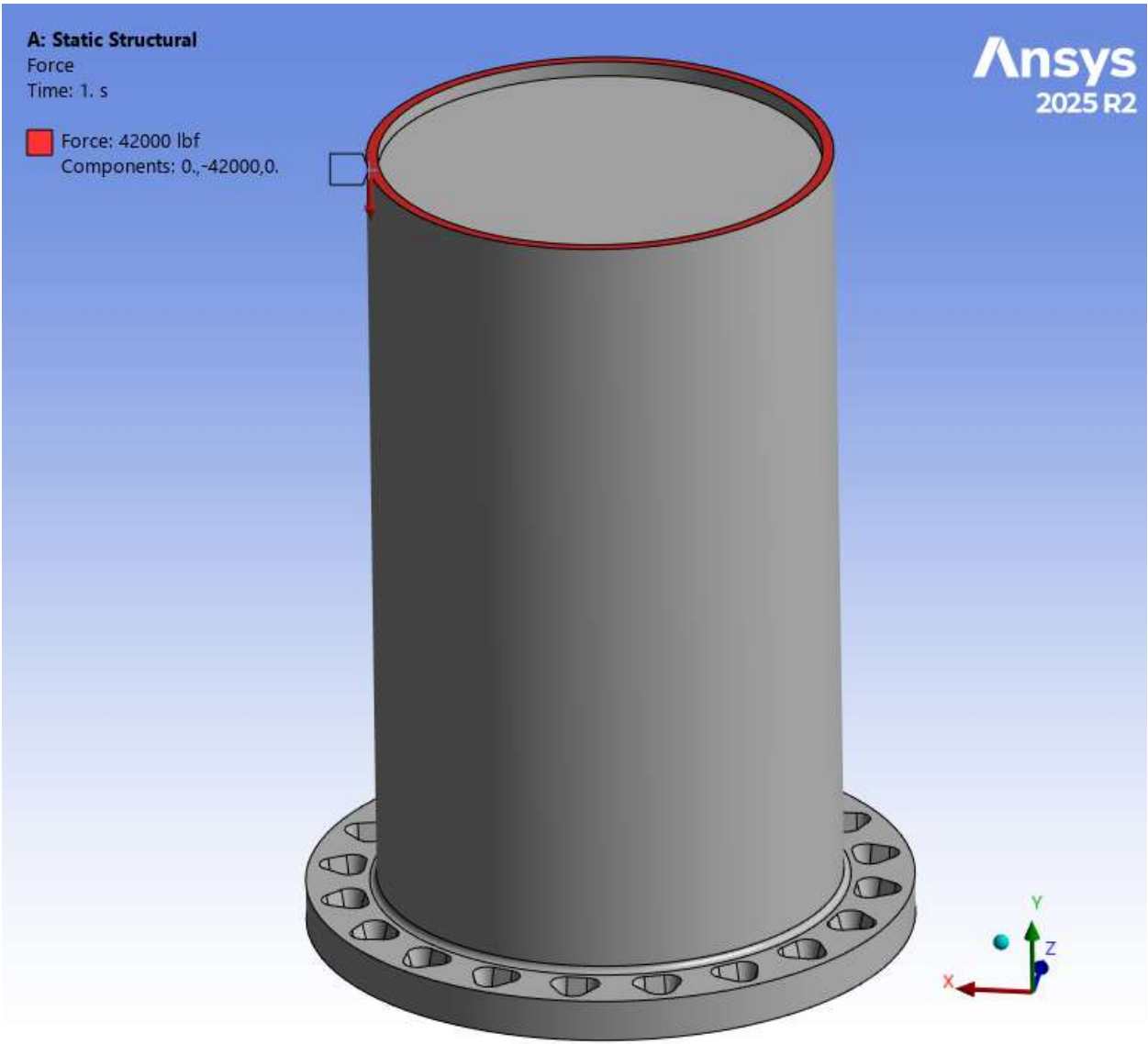


Figure 65 Snubber Force

4. NUMERICAL MODEL OR SIMULATION

4.1 SOFTWARE

ANSYS	○ 2025 R2 ○ Point Releases and Patches installed: ○ Discovery (reduced install) 2025 R2 ○ Core WB Files 2025 R2 ○ Remote Solve Manager Standalone Services 2025 R2 ○ Aqwa 2025 R2 ○ Autodyn 2025 R2 ○ ICEM CFD 2025 R2 ○ Material Calibration App 2025 R2 ○ Mechanical Products 2025 R2 ○ Motion 2025 R2 ○ ACIS Geometry Interface 2025 R2 ○ AutoCAD Geometry Interface 2025 R2 ○ Catia, Version 4 Geometry Interface 2025 R2 ○ Catia, Version 5 Geometry Interface 2025 R2 ○ Catia, Version 6 Geometry Interface 2025 R2 ○ Creo Elements/Direct Modeling Geometry Interface 2025 R2 ○ Creo Parametric Geometry Interface 2025 R2 ○ Inventor Geometry Interface 2025 R2 ○ JTOpen Geometry Interface 2025 R2 ○ NX Geometry Interface 2025 R2 ○ Parasolid Geometry Interface 2025 R2 ○ Solid Edge Geometry Interface 2025 R2 ○ SOLIDWORKS Geometry Interface 2025 R2 ○ Ansys, Inc. License Manager 2025 R2 ○ Granta Selector 2025 R2
Mathcad	Prime 9.0
PC Used:	
○ Device name LAP137768 ○ Full device name LAP137768.ornl.gov ○ Processor 13th Gen Intel(R) Core(TM) i9-13950HX (2.20 GHz) ○ Installed RAM 64.0 GB (63.6 GB usable) ○ Device ID 7696314F-4B34-40AF-8834-B5CC7ED85C2D ○ Product ID 00329-00000-00003-AA423 ○ System type 64-bit operating system, x64-based processor	Edition Windows 11 Enterprise Version 24H2 Installed on 8/7/2025 OS build26100.7462 Experience Windows Feature Experience Pack 1000.26100.275.0

4.2 UNIT SYSTEM

In this analysis the US Customary system in ANSYS is used.



Figure 66 Unit System

4.3 DISCRETIZATION

4.3.1 Target Assembly

The full model of the Target Assembly is a large complex assembly, most of the components are meshed automatically. The Target Assembly model isn't used for detailed stress results like the smaller models but for overall displacement. The pipes are converted to shell elements and the Manifold Shroud is converted to shell elements. The Segment dummy models use 1D beam elements, the remaining parts are 3D solid elements.

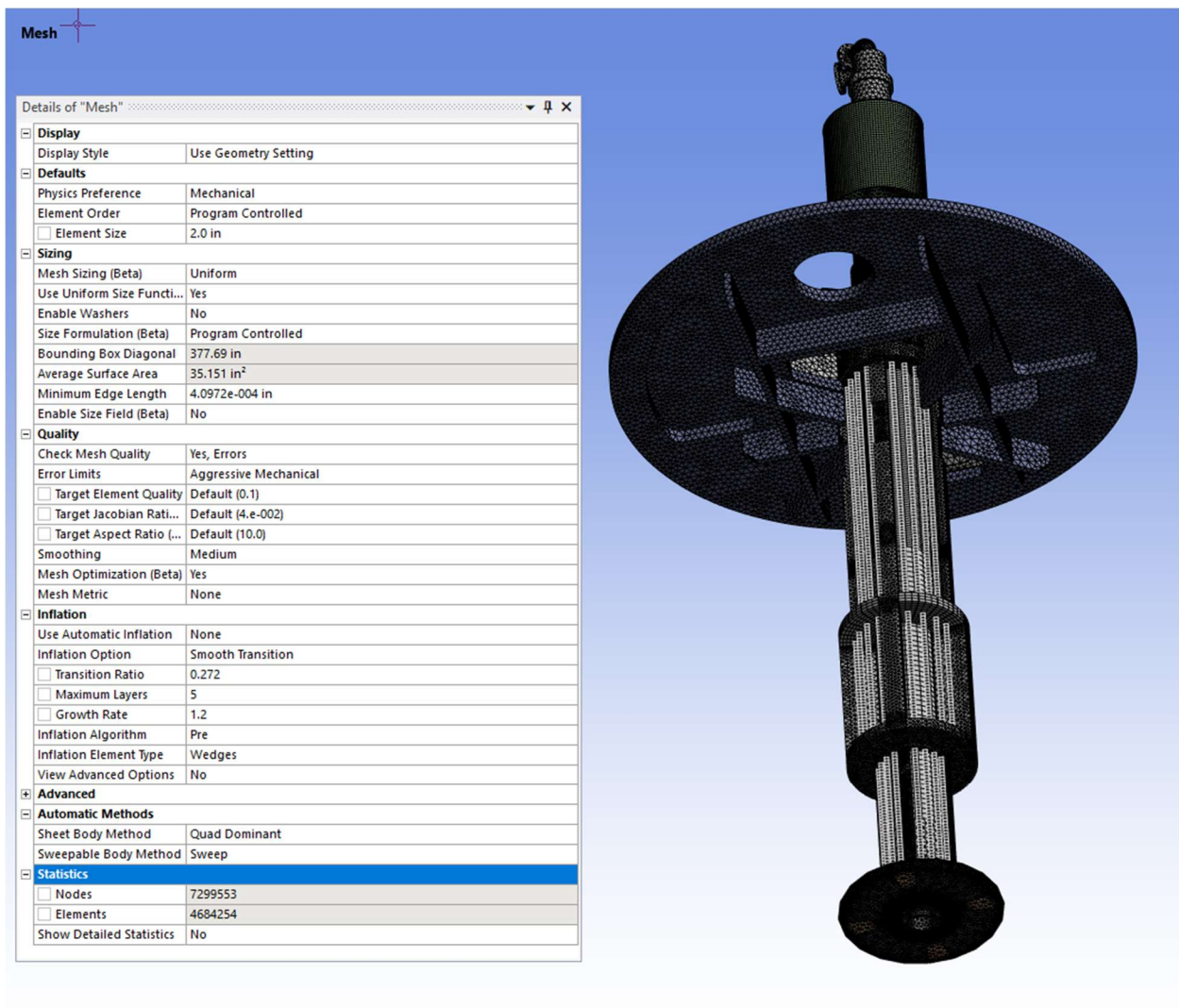


Figure 67 Target Assembly General Mesh Settings

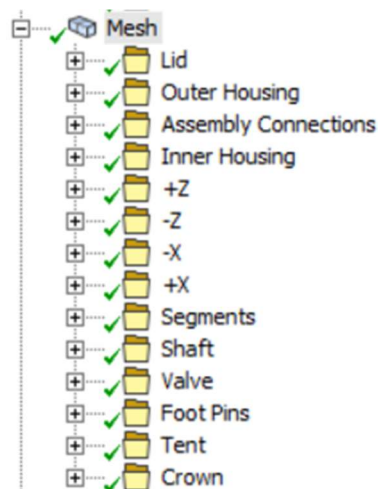


Figure 68 Target Assembly Mesh Sizing and Methods

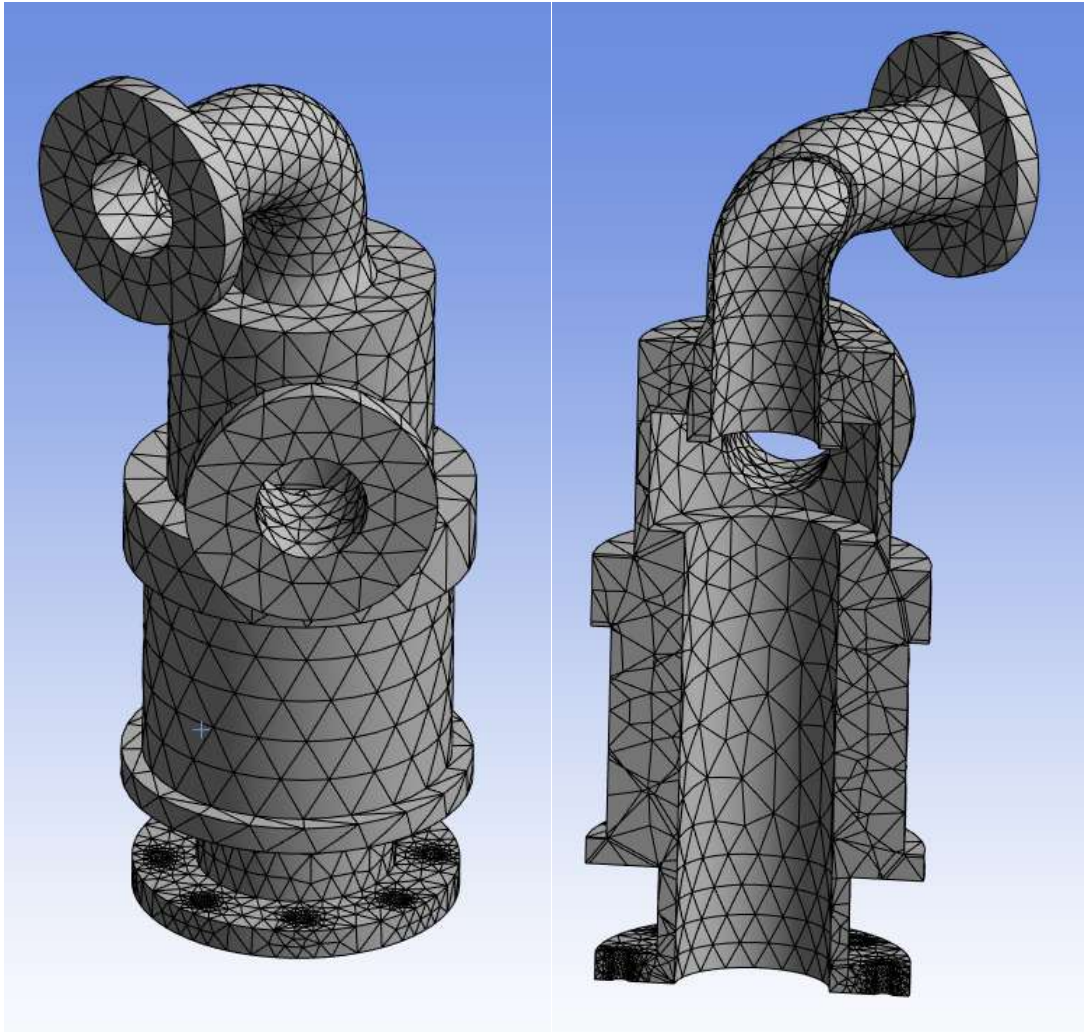


Figure 69 Water Union Mesh

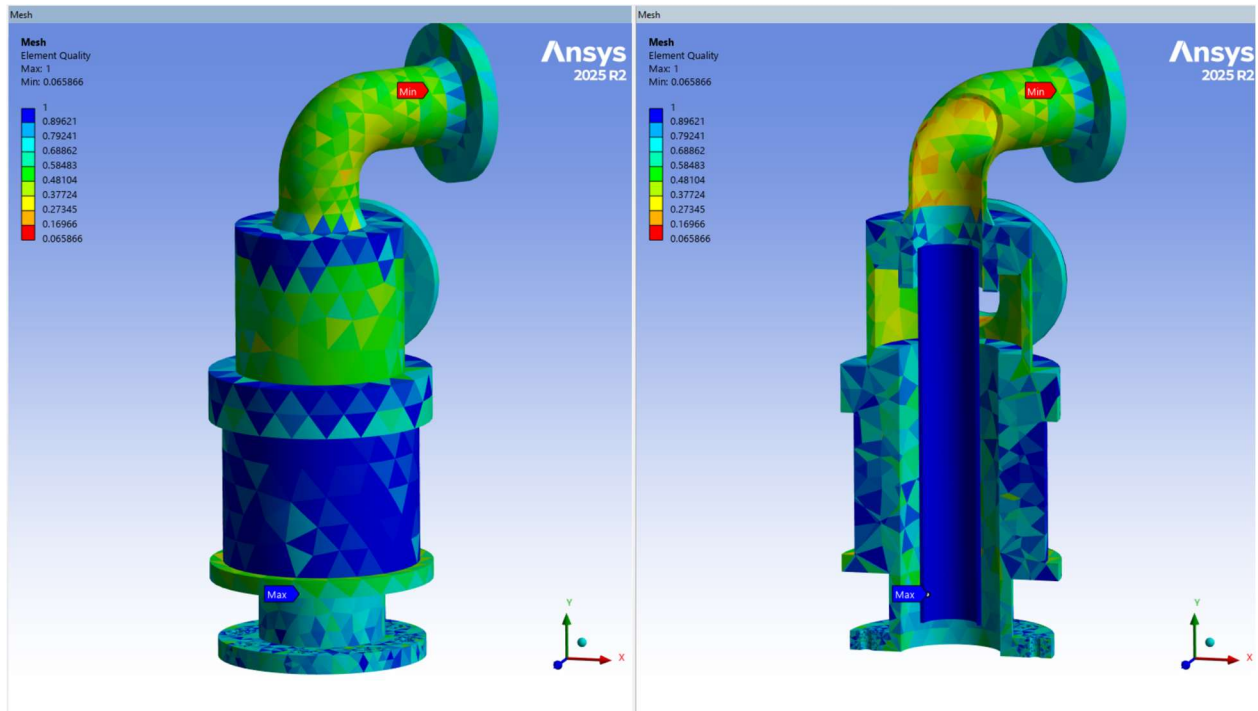


Figure 70 Water Union Mesh Quality

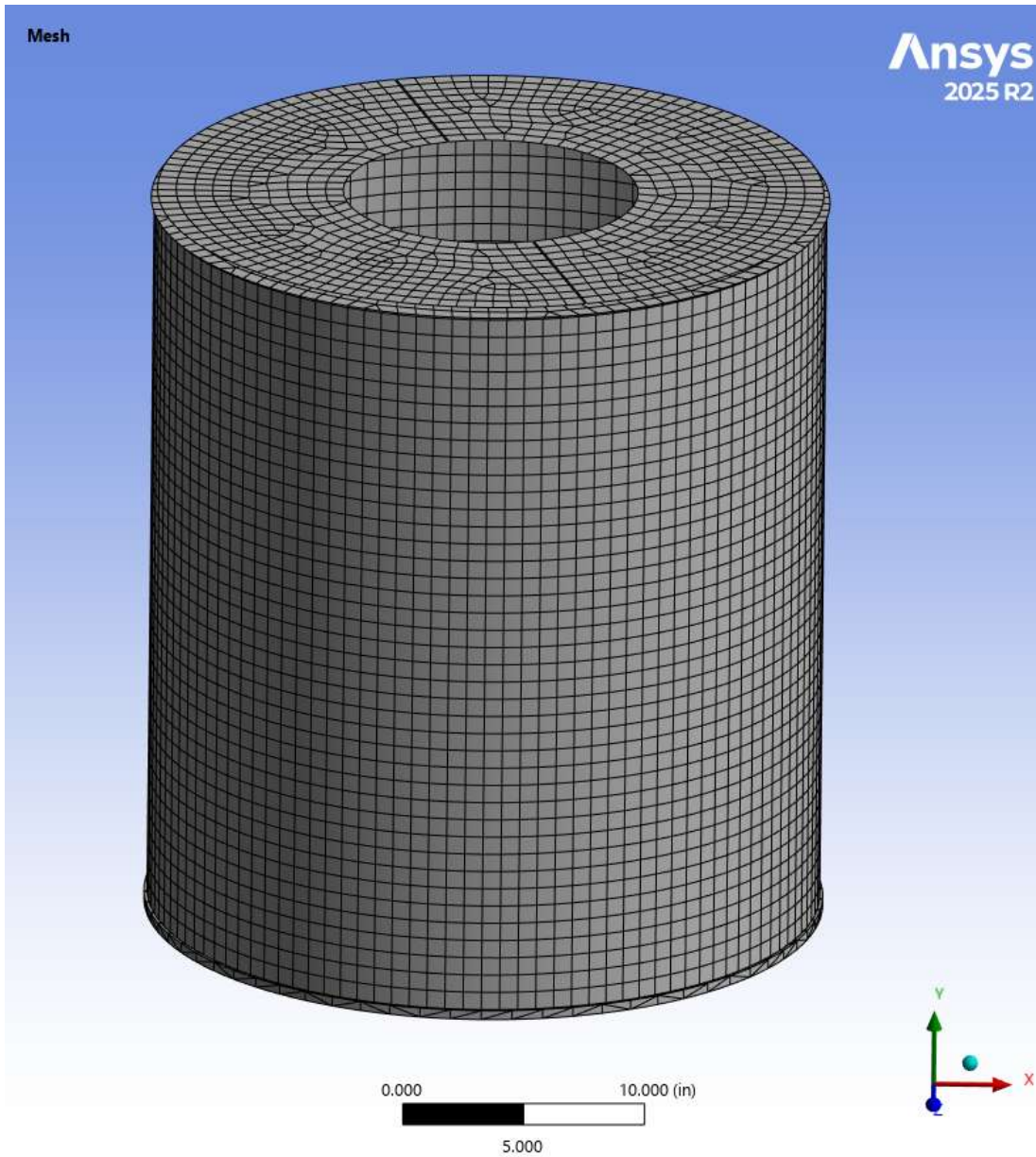


Figure 71 Manifold Shroud Mesh

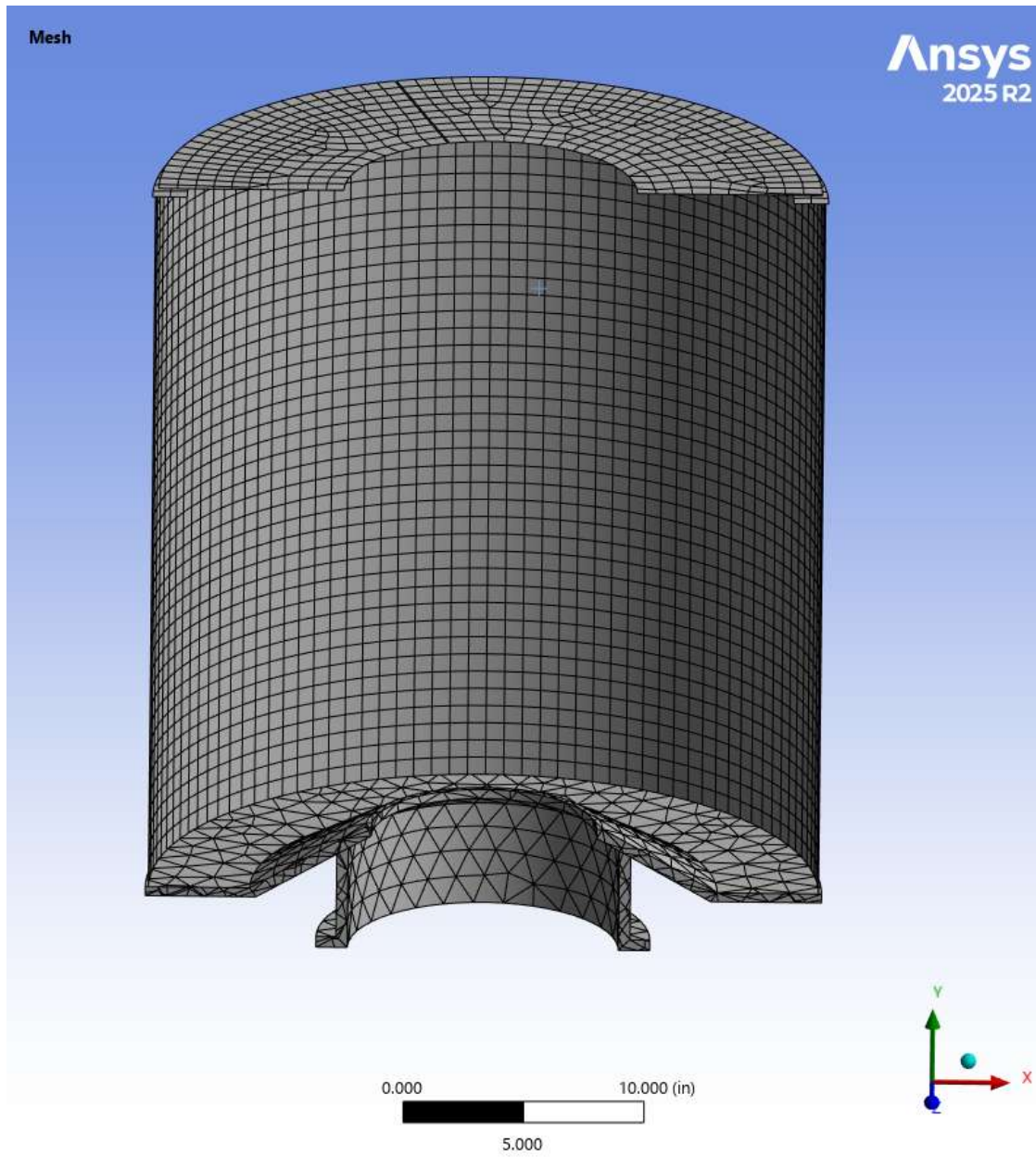


Figure 72 Manifold Shroud Mesh Section

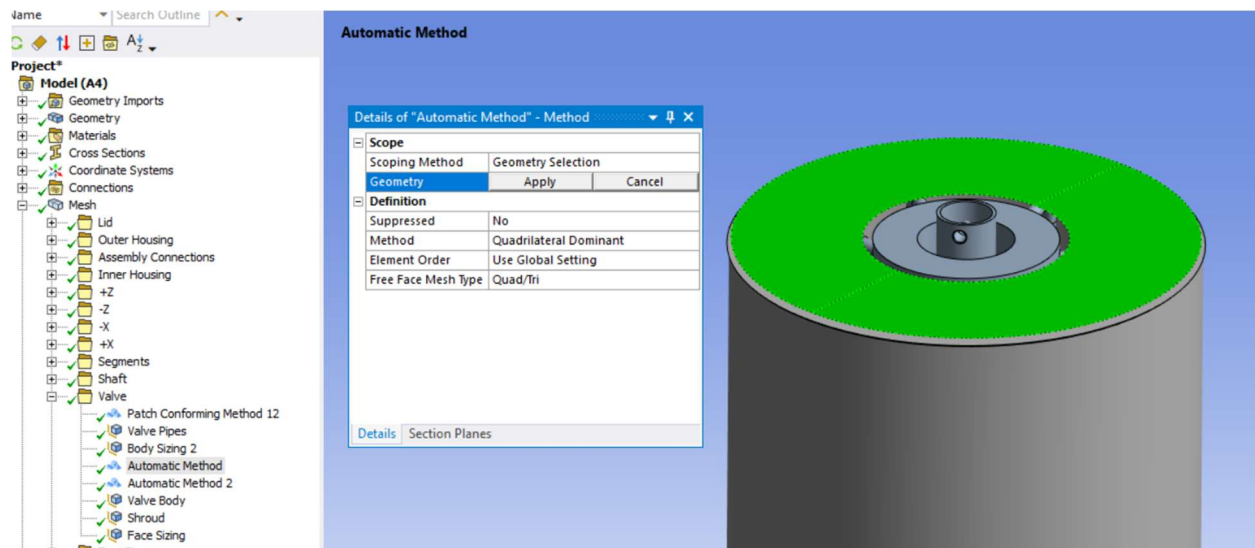


Figure 73 Shroud Mesh Method, 2D Elements

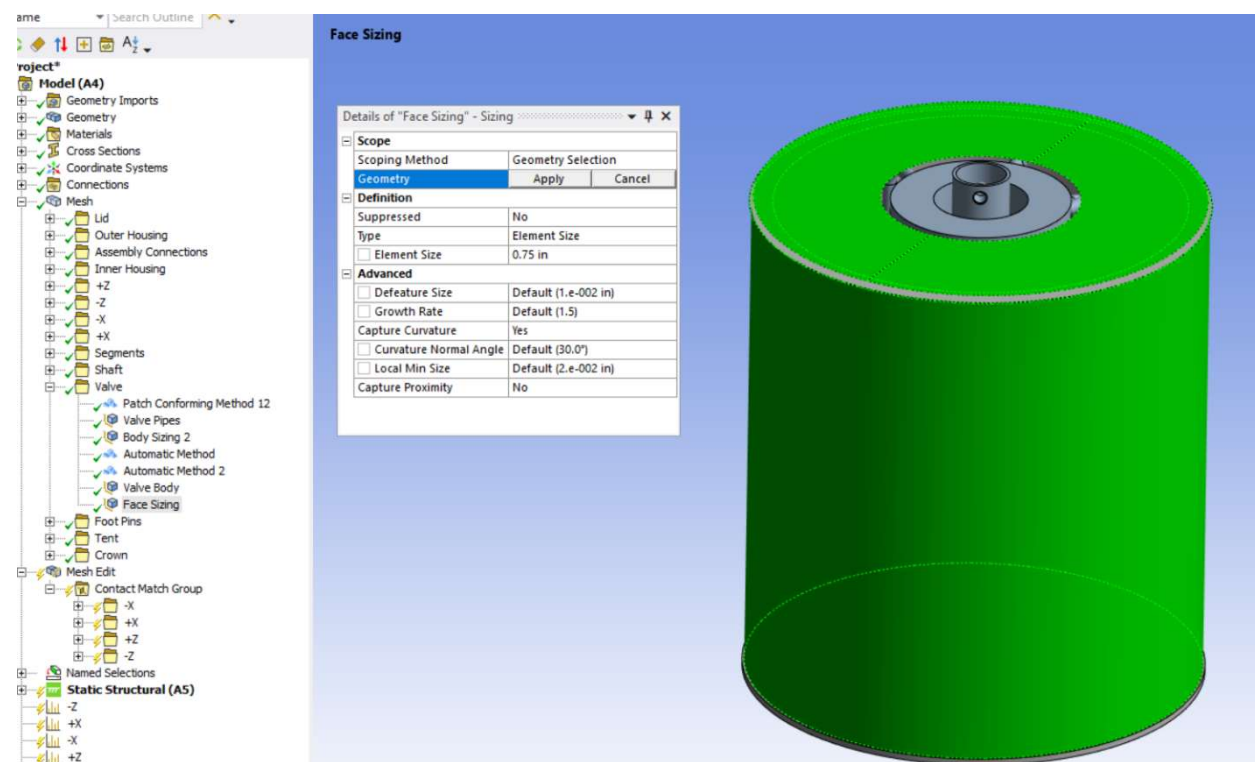


Figure 74 Shroud Mesh Sizing, 2D Elements

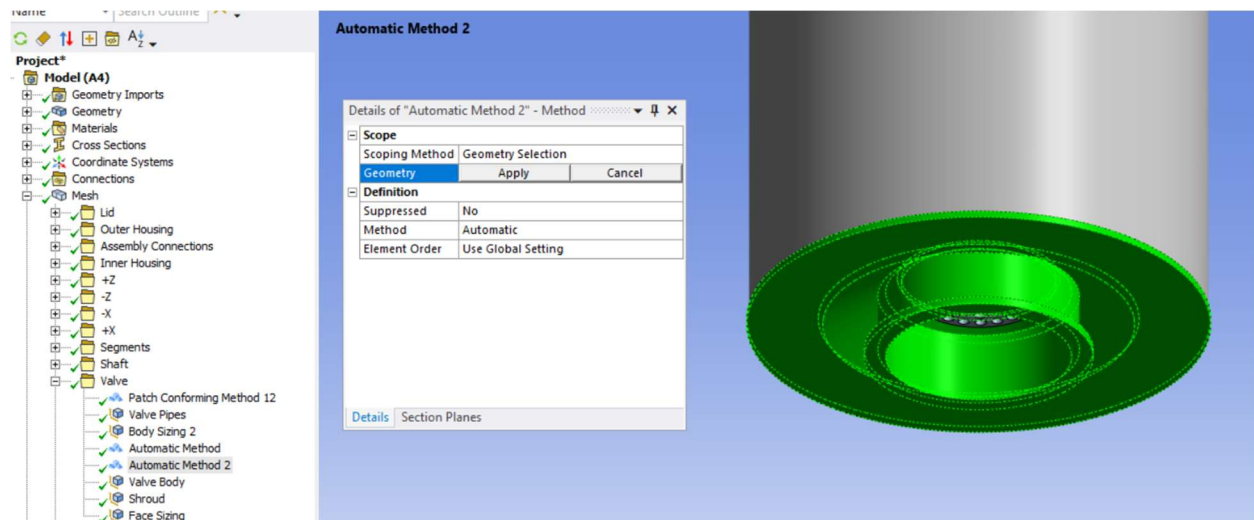


Figure 75 Shroud Mesh Method, 3D Elements

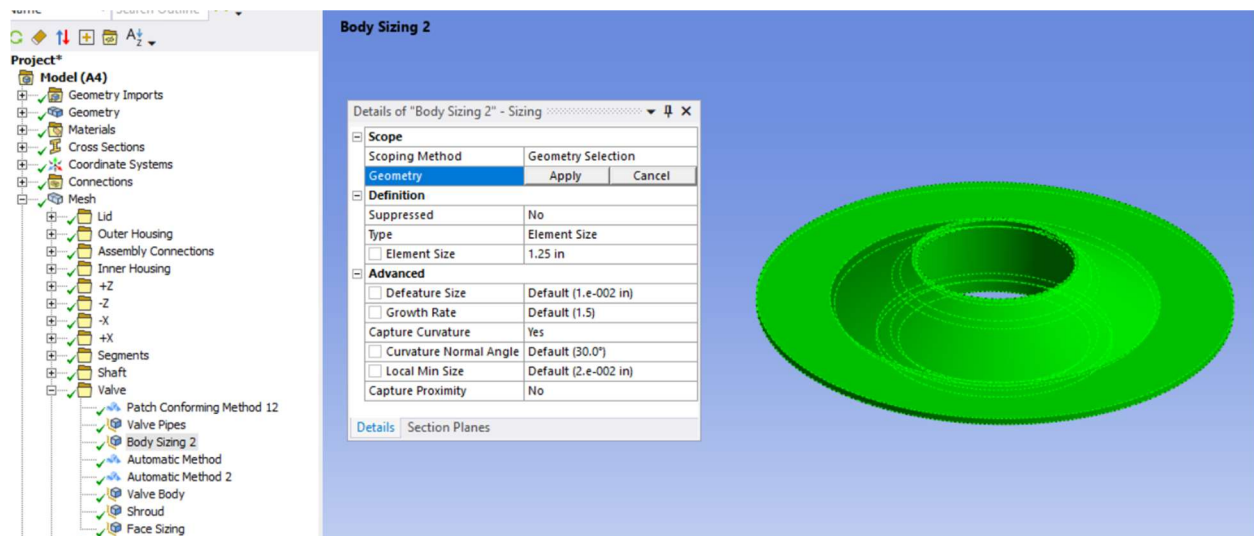


Figure 76 Shroud Mesh Sizing, 3D Elements

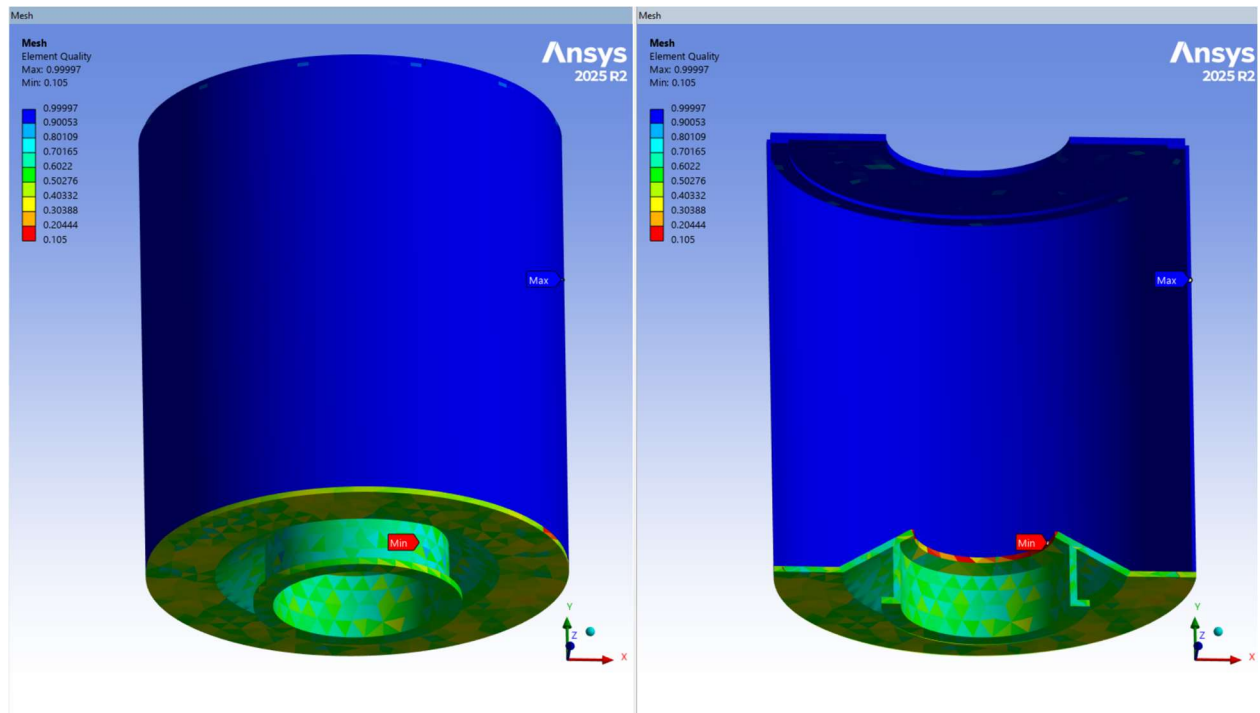


Figure 77 Shroud Mesh Quality

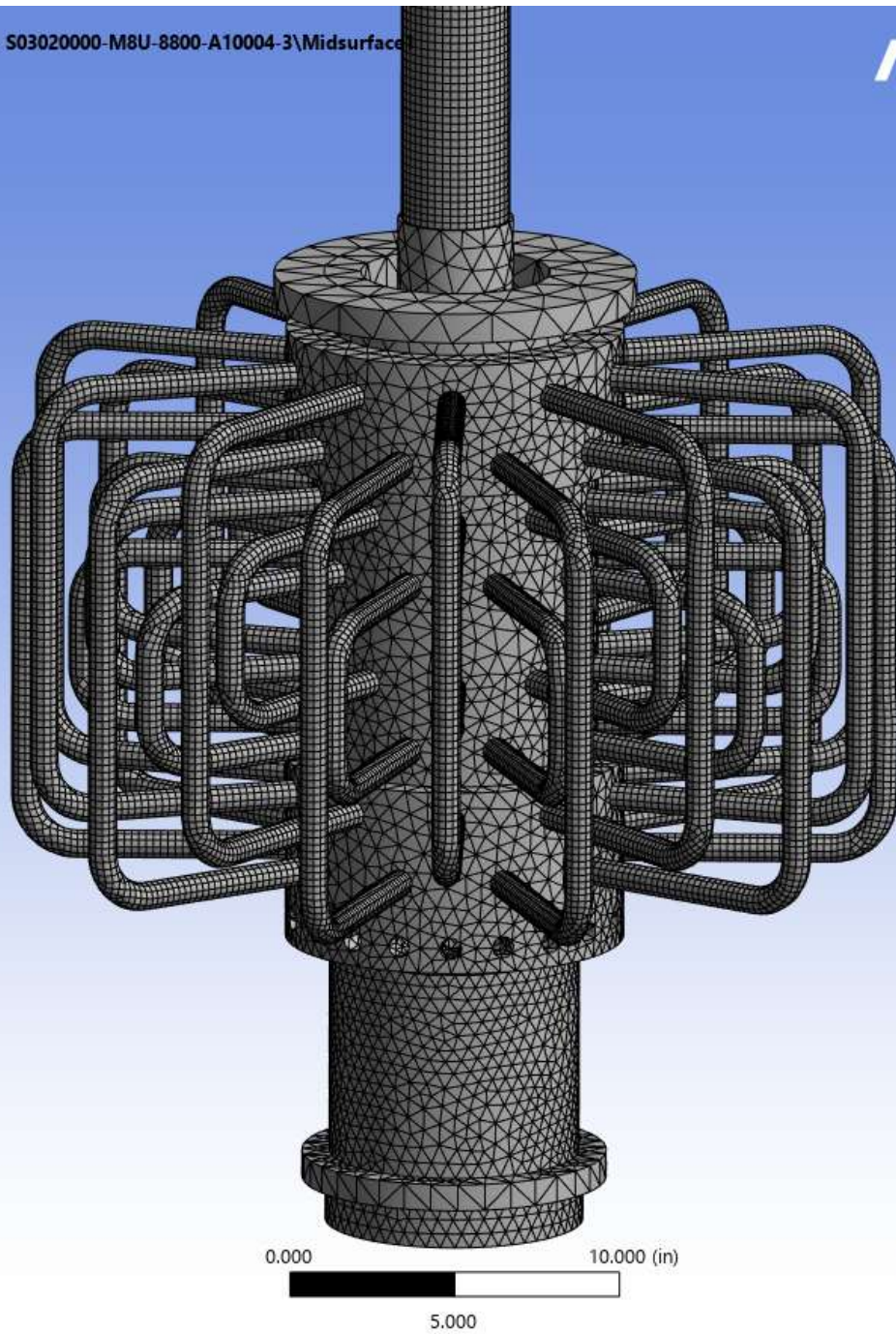


Figure 78 Water Manifold Mesh

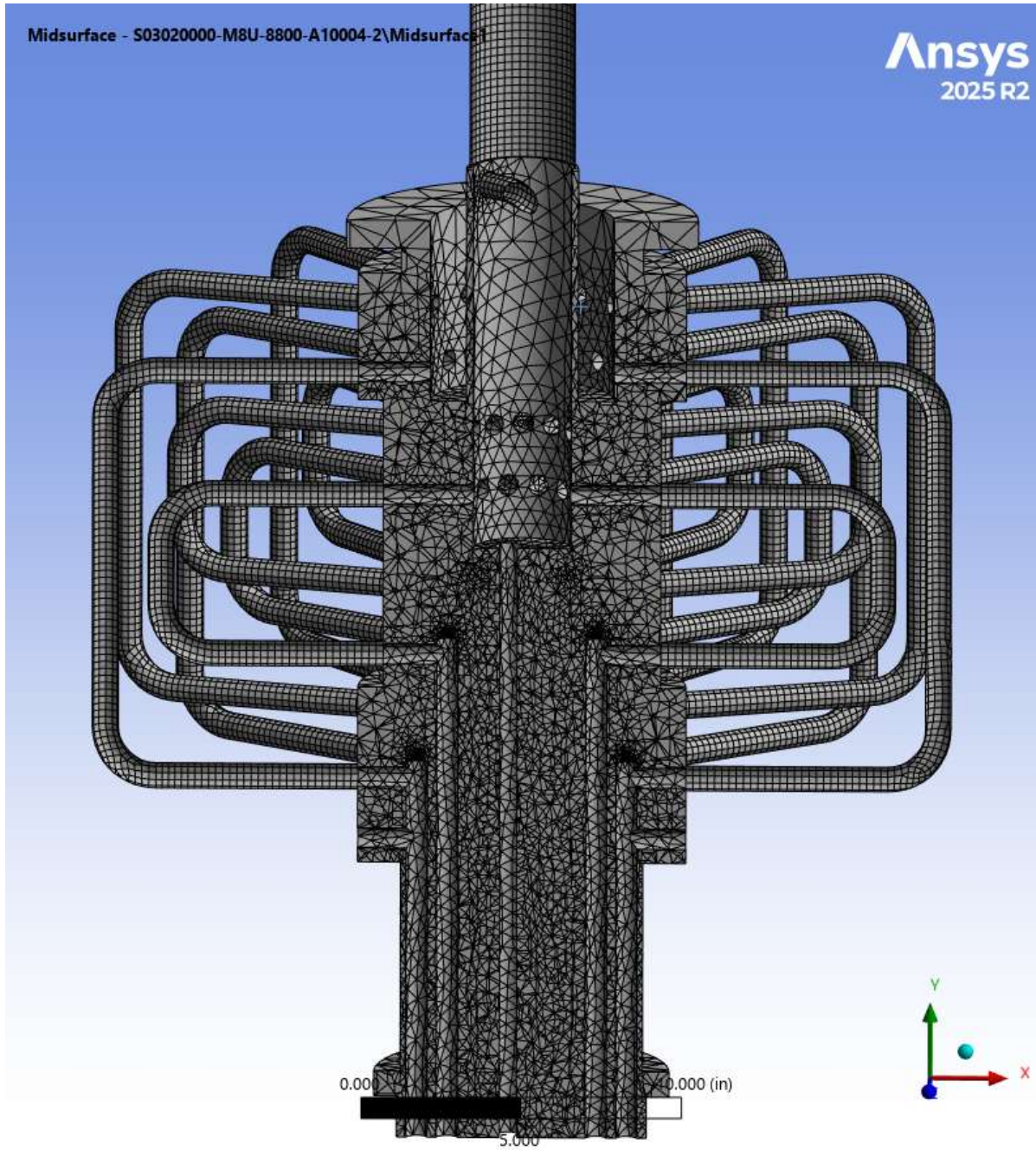


Figure 79 Water Manifold Mesh, Section

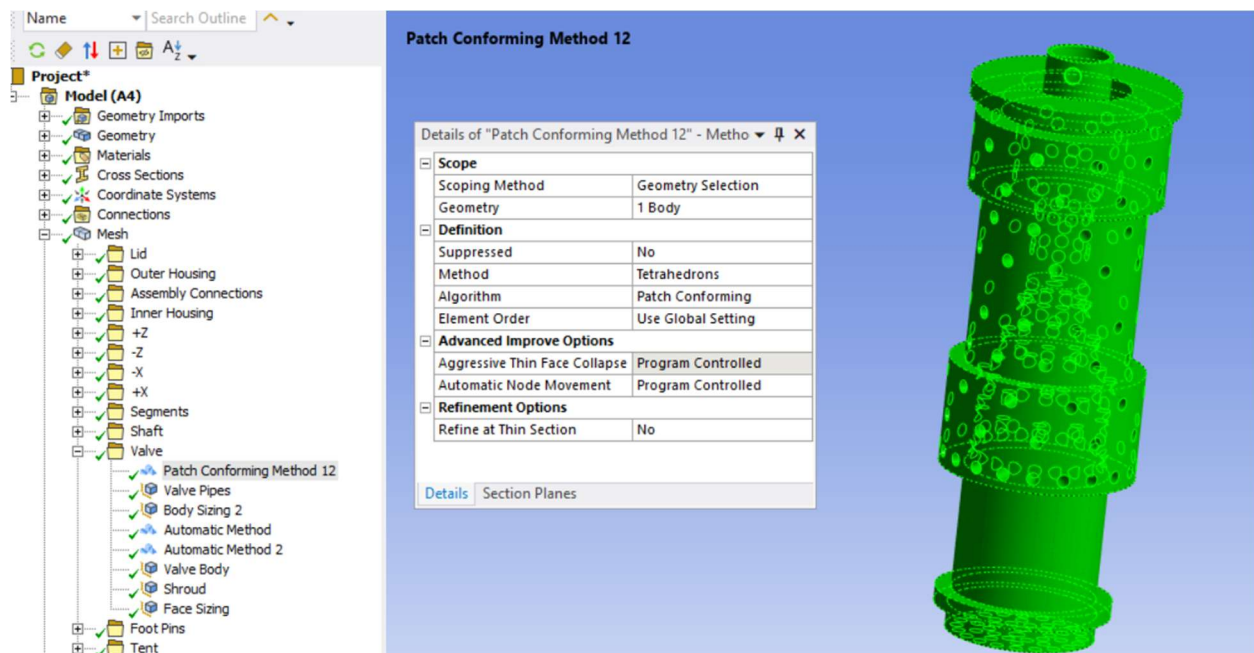


Figure 80 Water Manifold Mesh Method

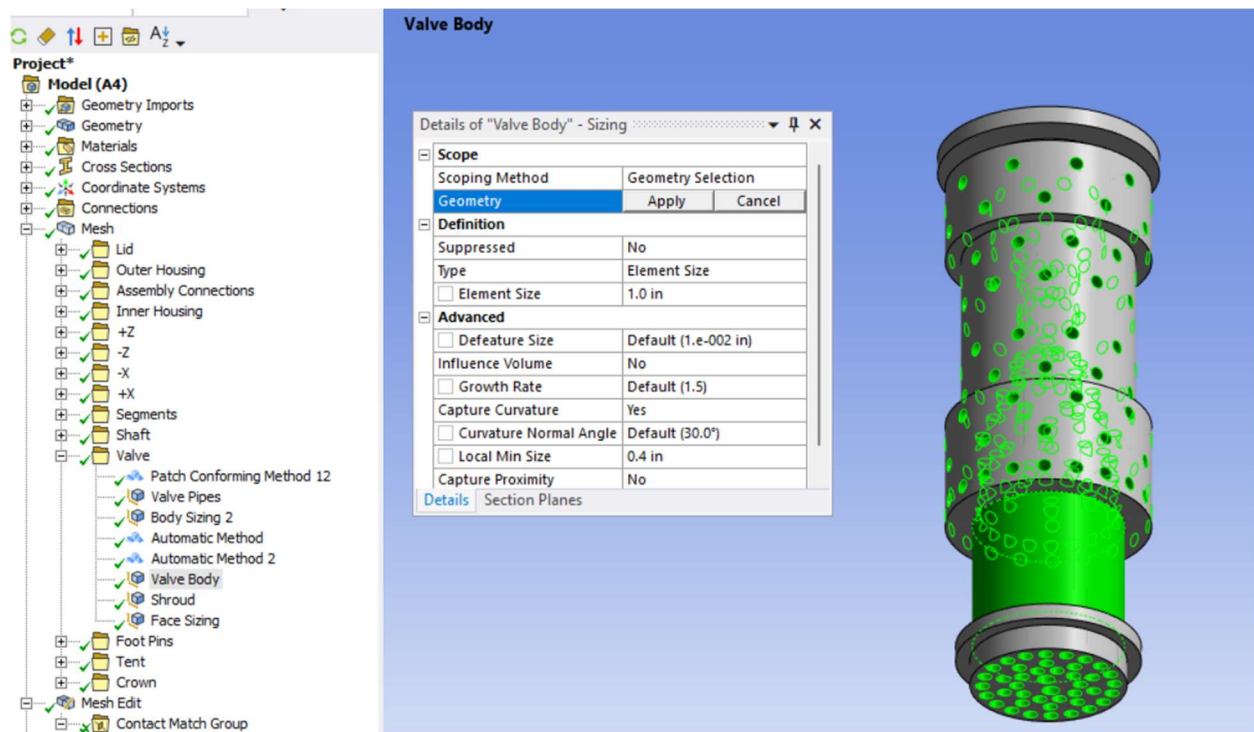


Figure 81 Water Manifold Mesh Sizing, 3D Elements

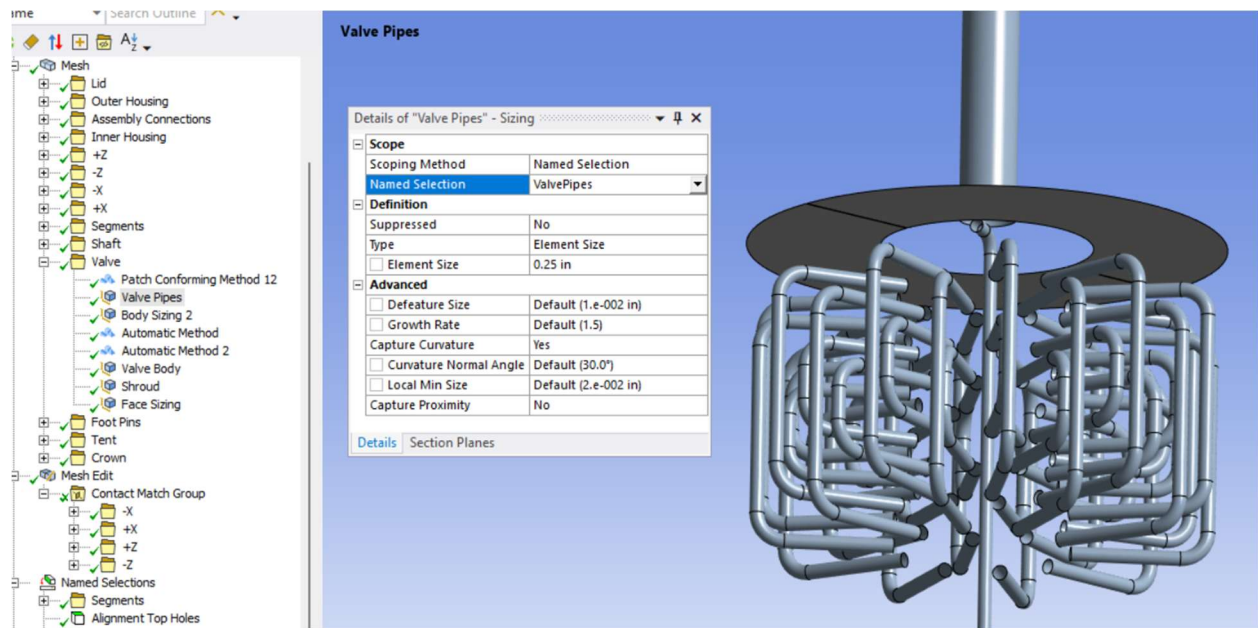


Figure 82 Water Manifold Mesh Sizing, 2D Elements

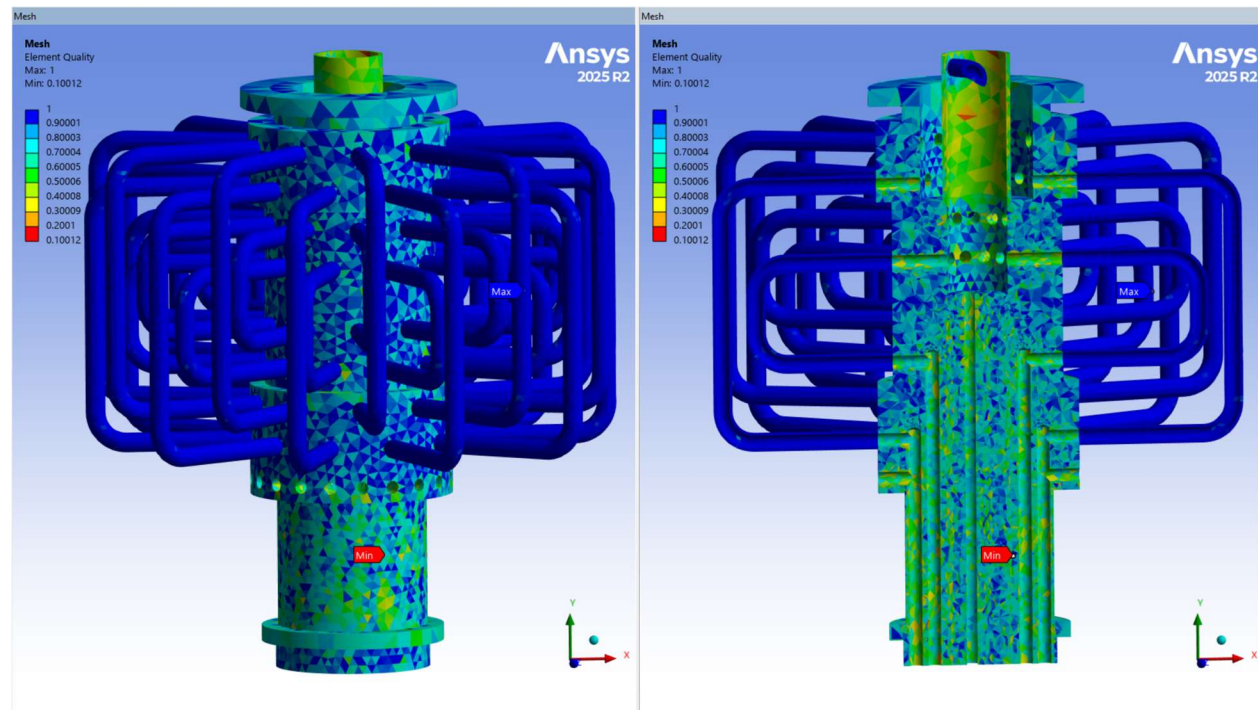


Figure 83 Water Manifold Mesh Quality

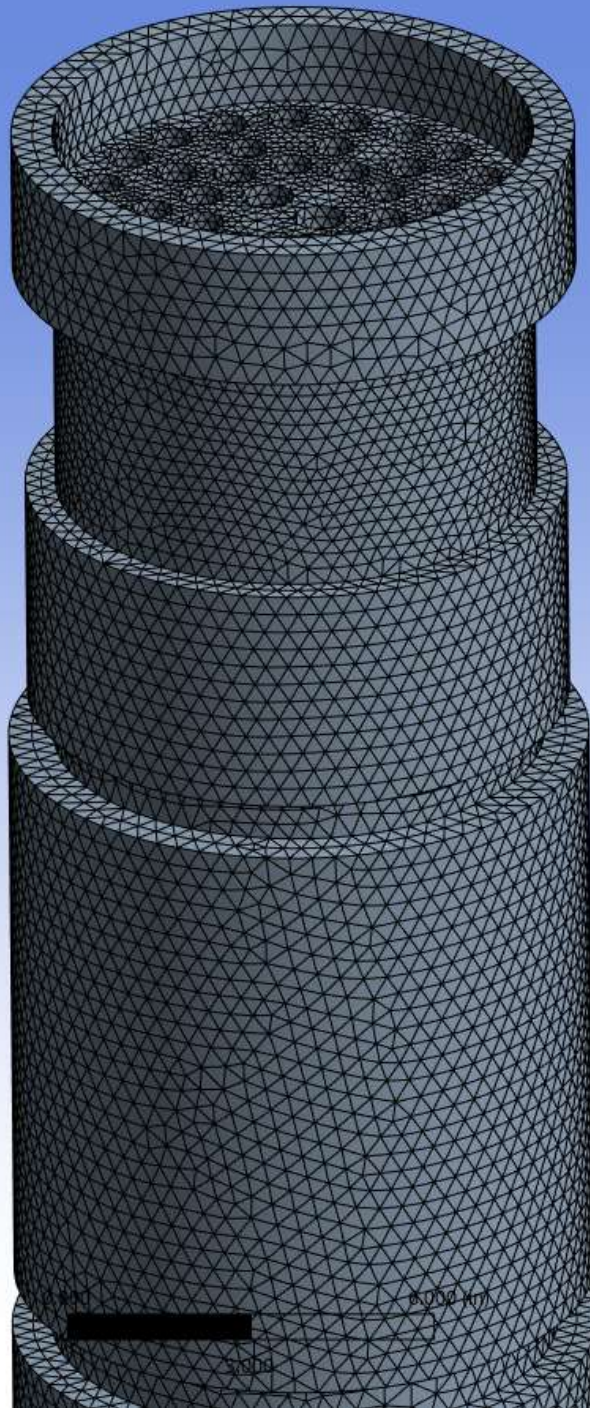


Figure 84 Upper Crown Mesh

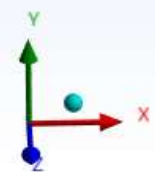


Figure 85 Upper Crown Mesh, Section

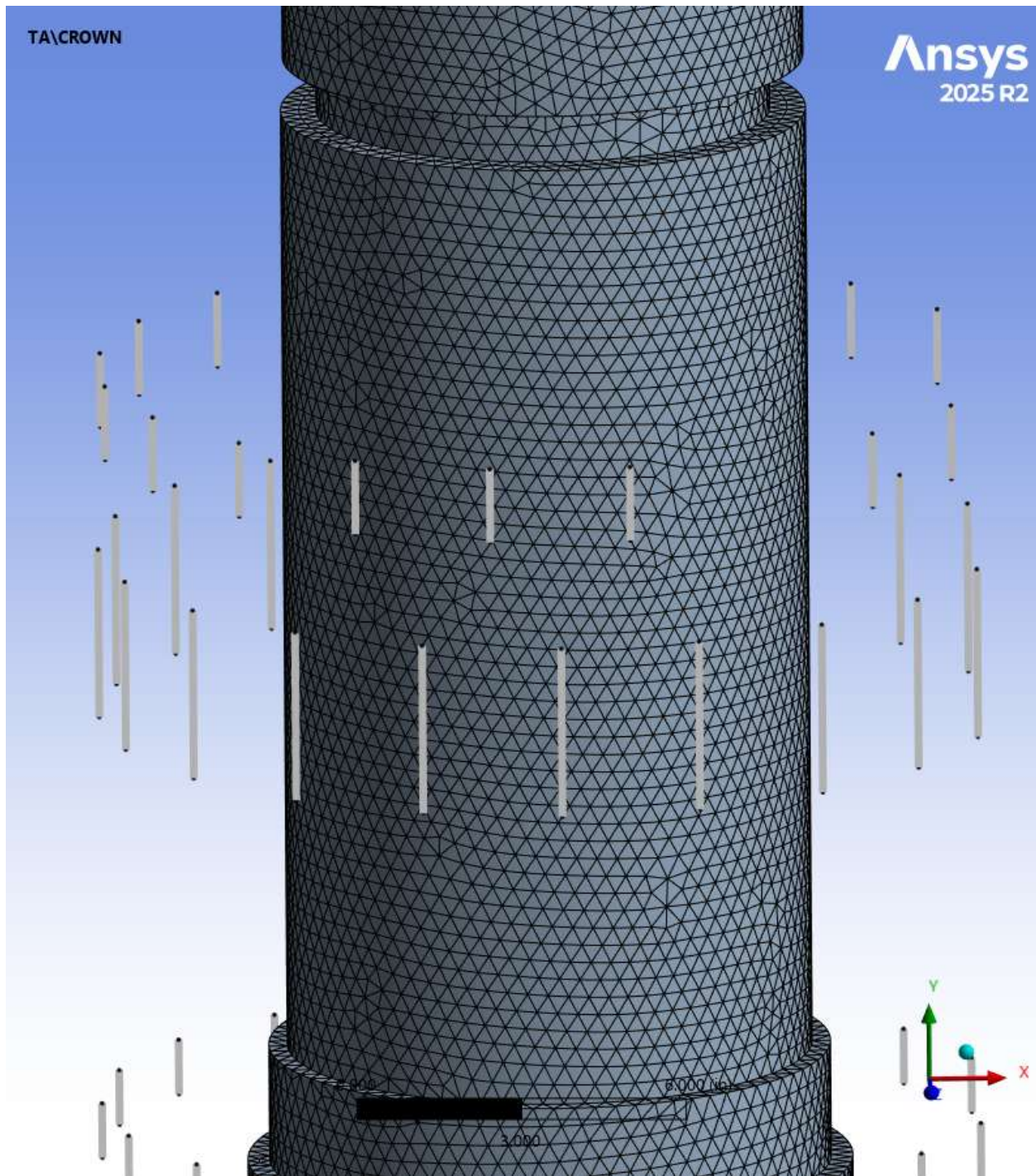


Figure 86 Mid Crown Mesh



Figure 87 Mid Crown Mesh, Section

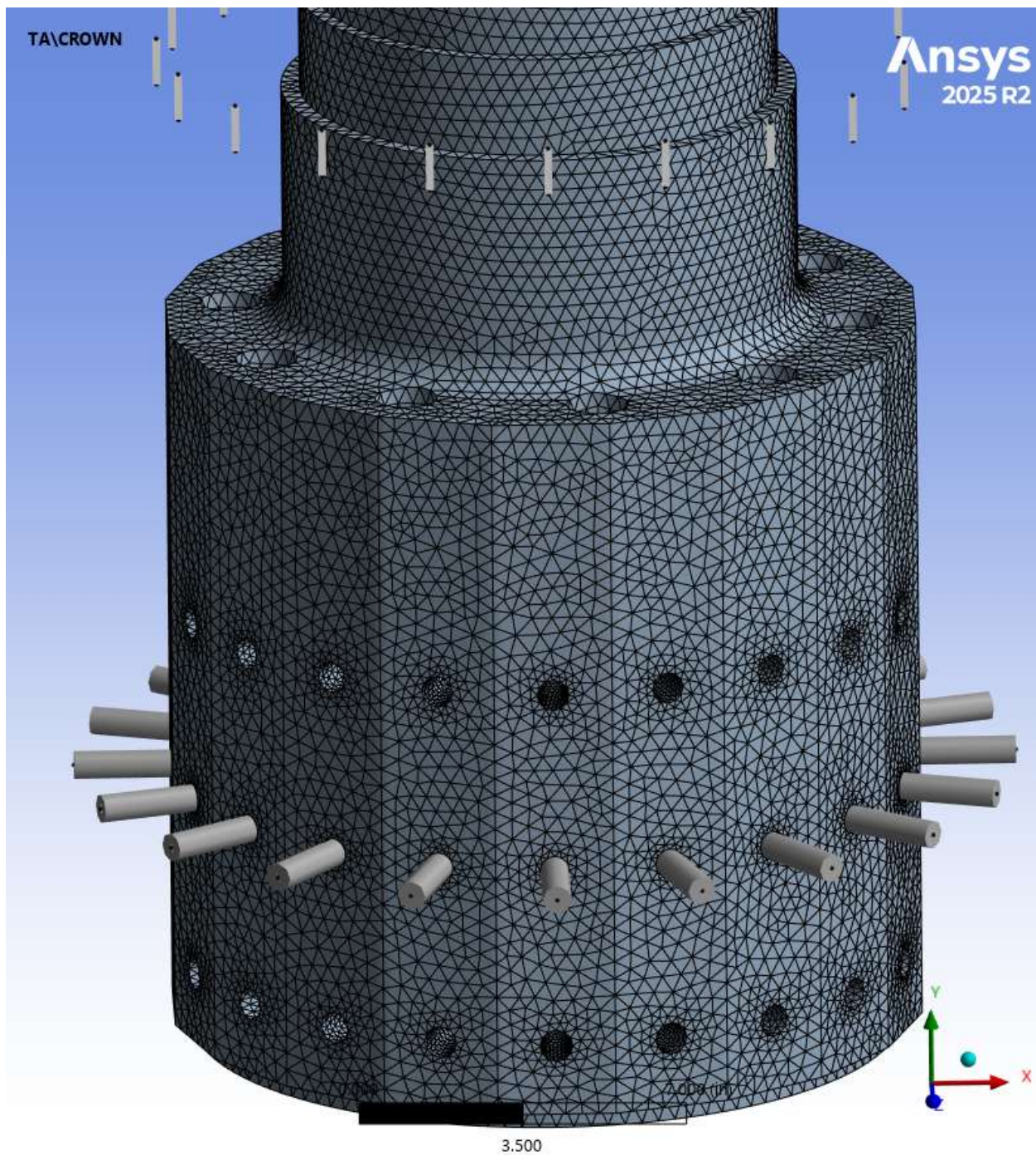


Figure 88 Lower Crown Mesh

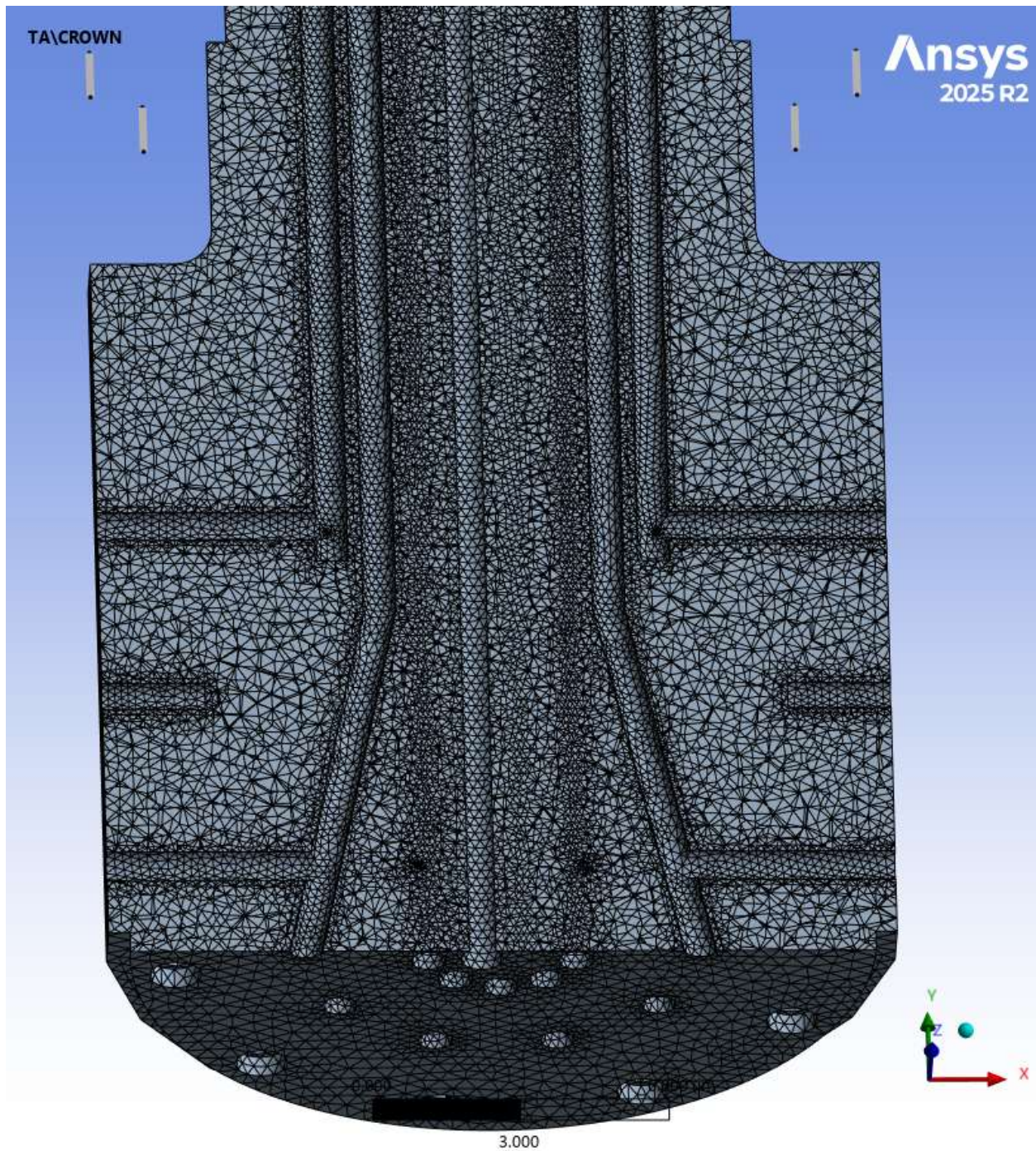


Figure 89 Lower Crown Mesh, Section

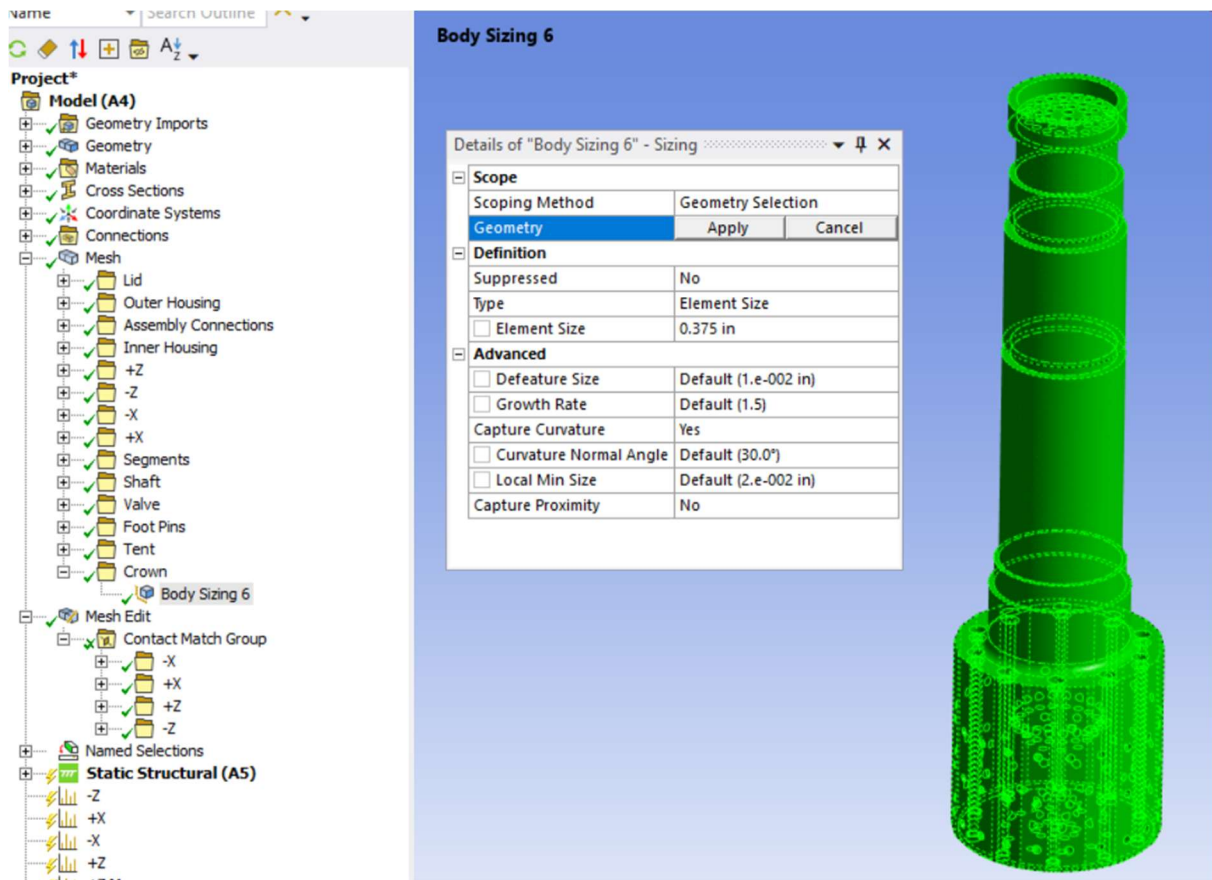


Figure 90 Crown Mesh Sizing

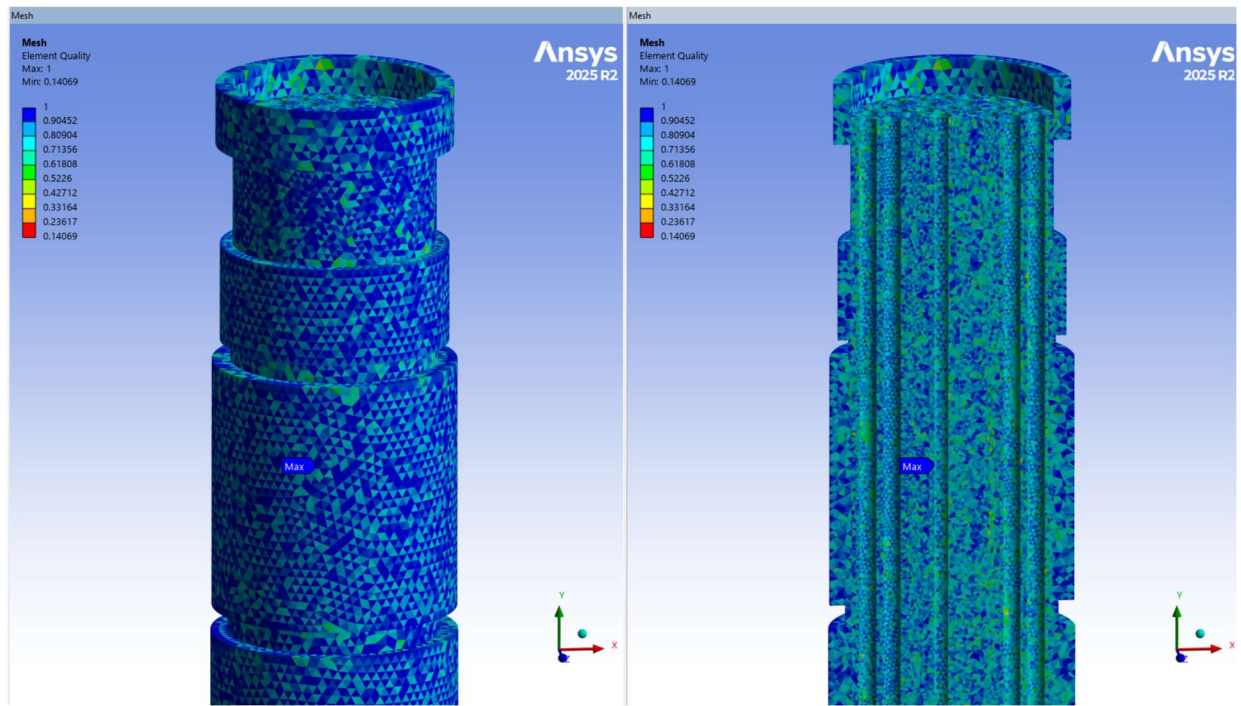


Figure 91 Upper Crown Mesh Quality

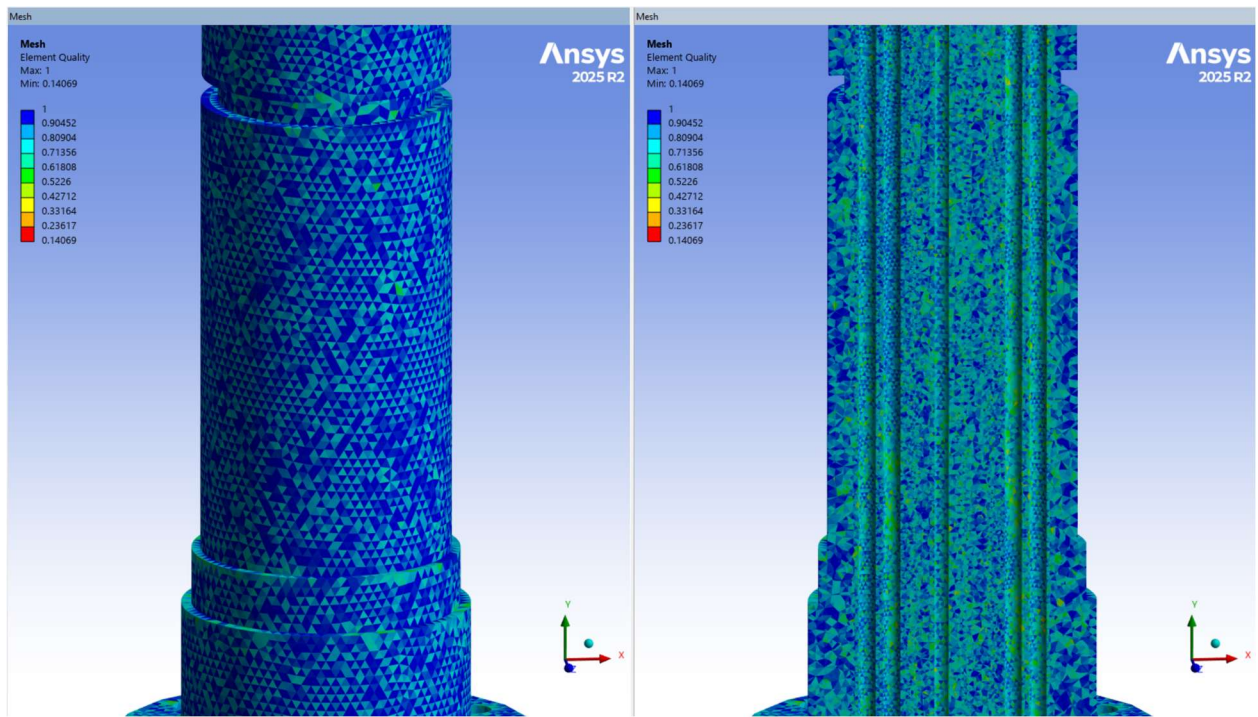


Figure 92 Mid Crown Mesh Quality

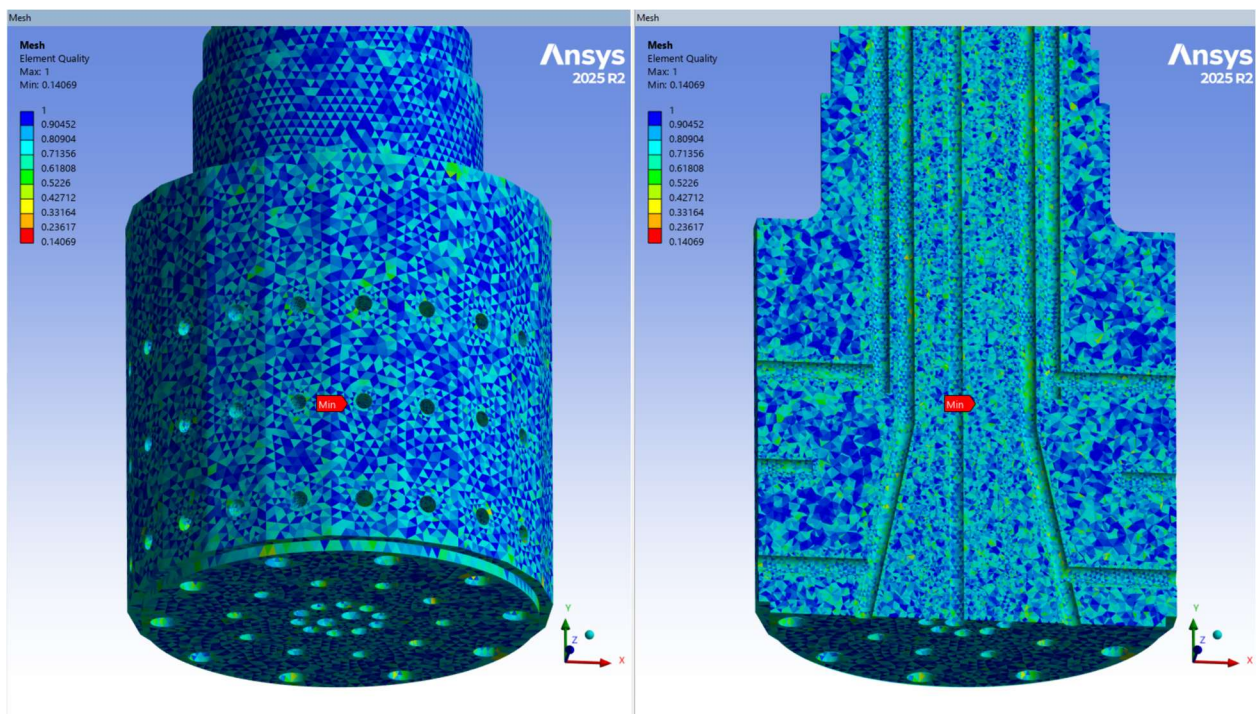


Figure 93 Lower Crown Mesh Quality

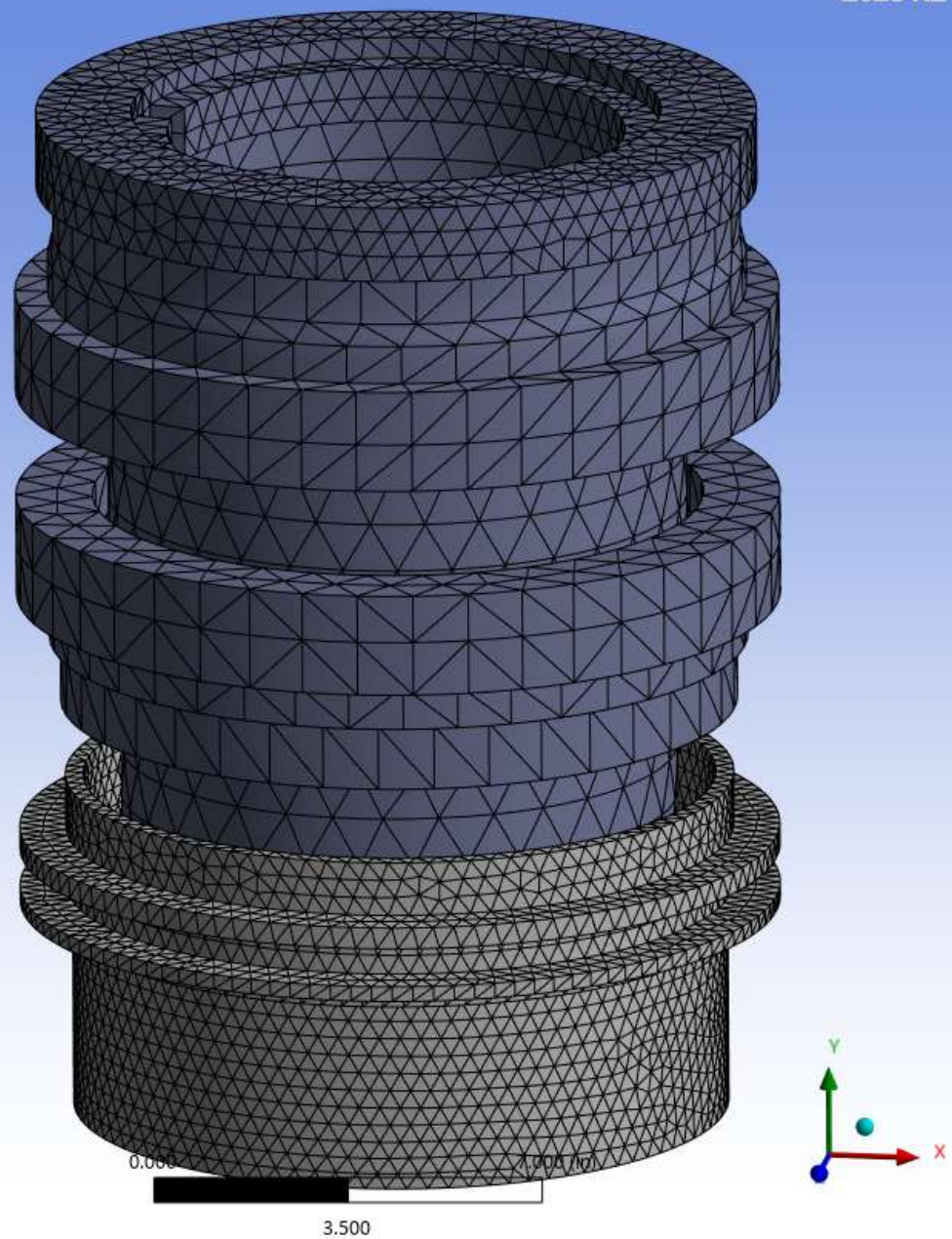
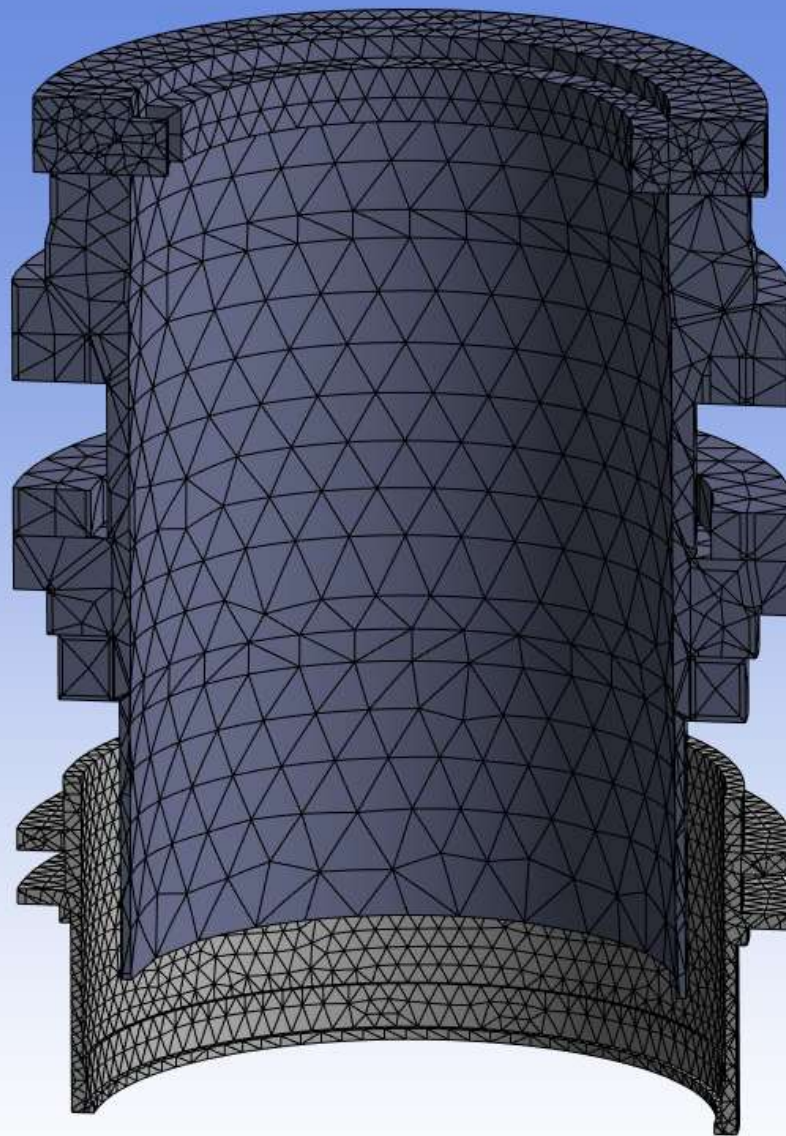


Figure 94 Inner Housing Mesh



0.000 7.000 (in)
3.500



Figure 95 Inner Housing Mesh, Section

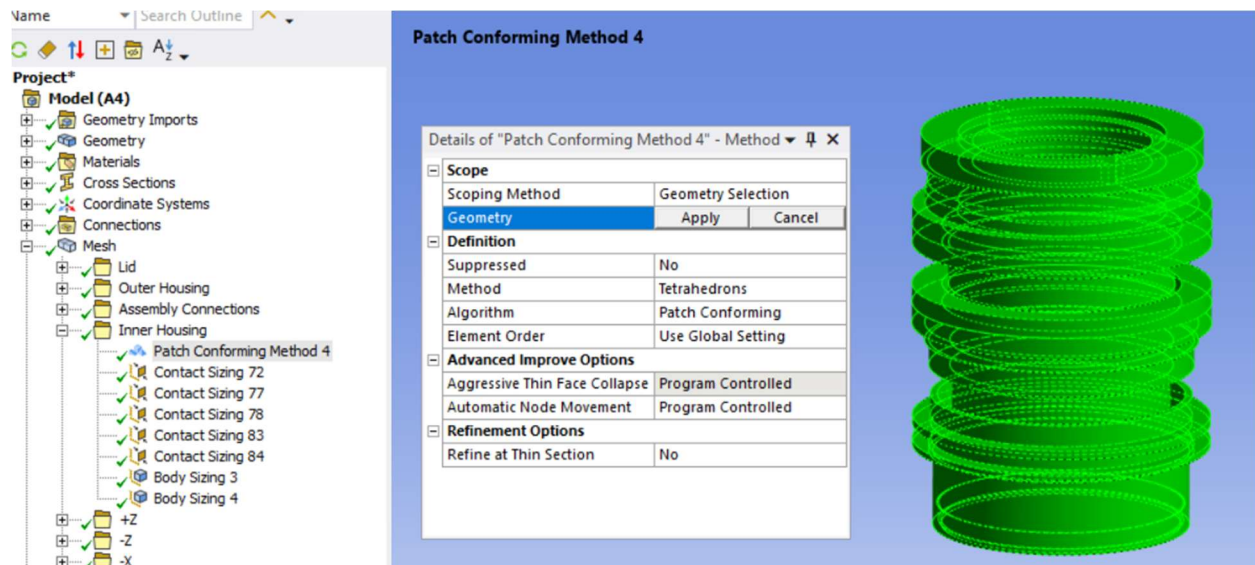


Figure 96 Inner Housing Mesh Method

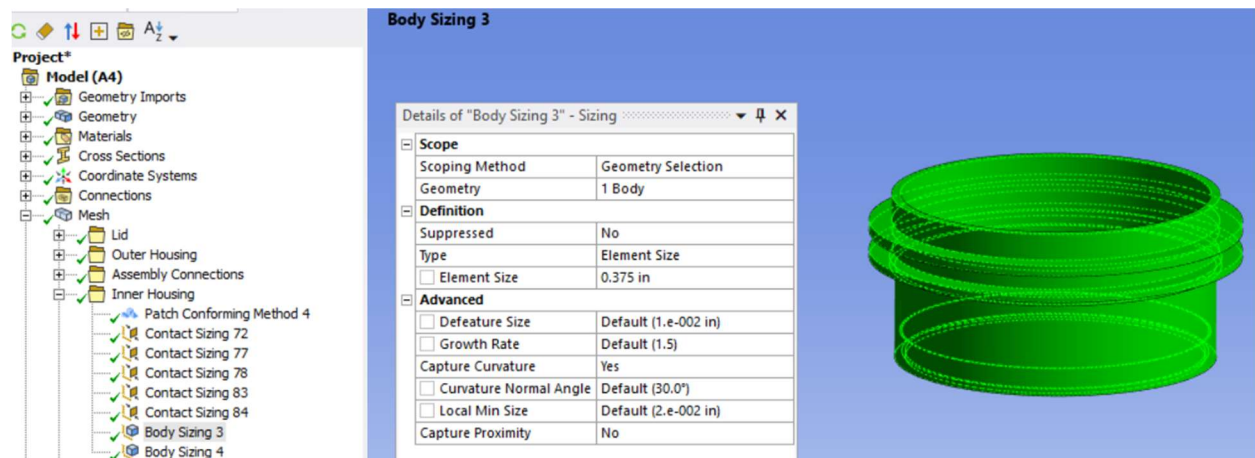


Figure 97 Inner Housing Mesh Sizing

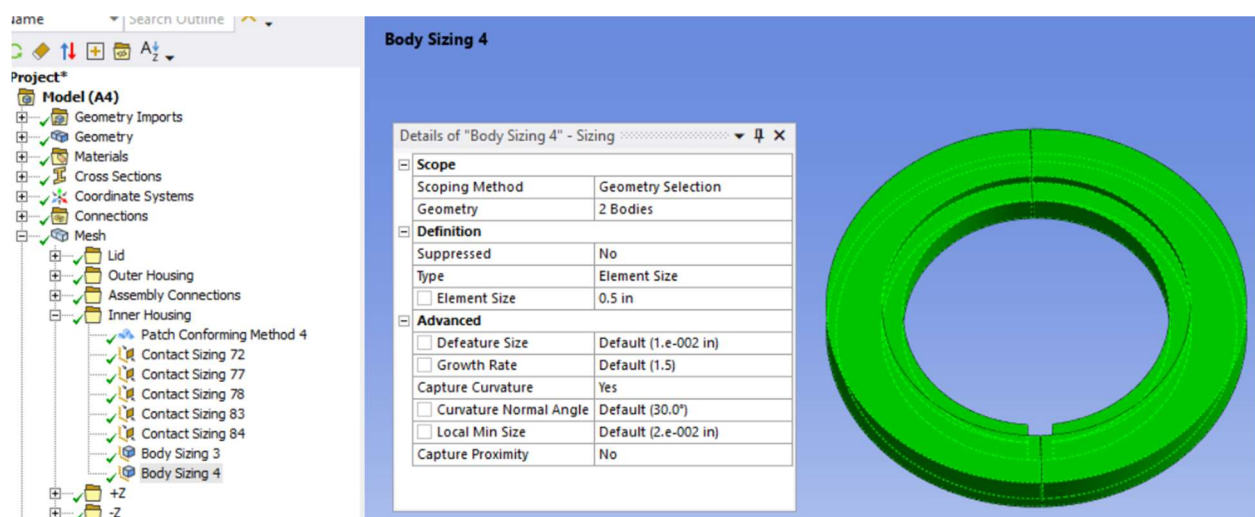


Figure 98 Inner Housing Mesh Sizing

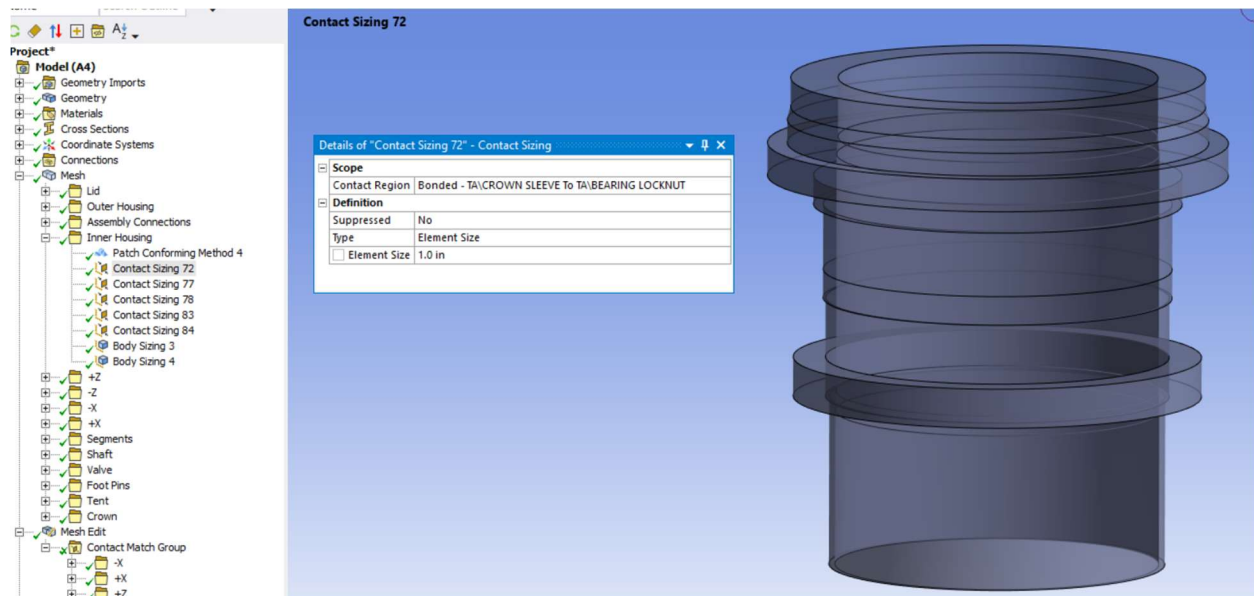


Figure 99 Inner Housing Contact Sizing

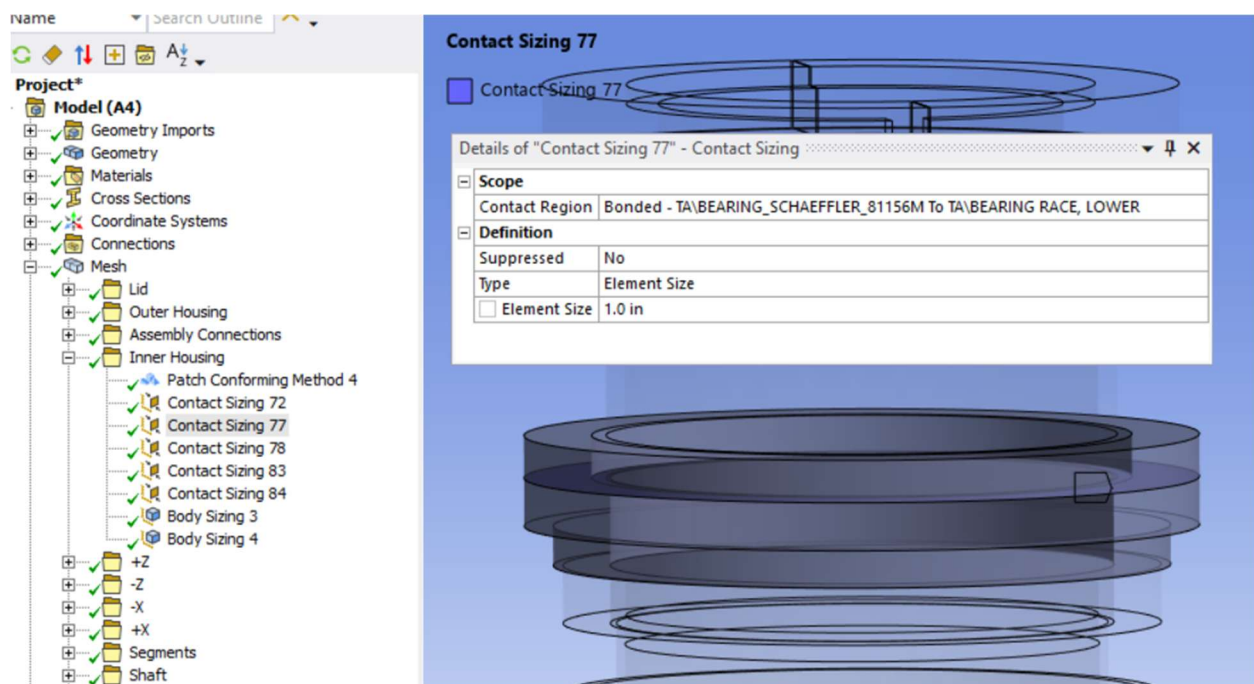


Figure 100 Inner Housing Contact Sizing

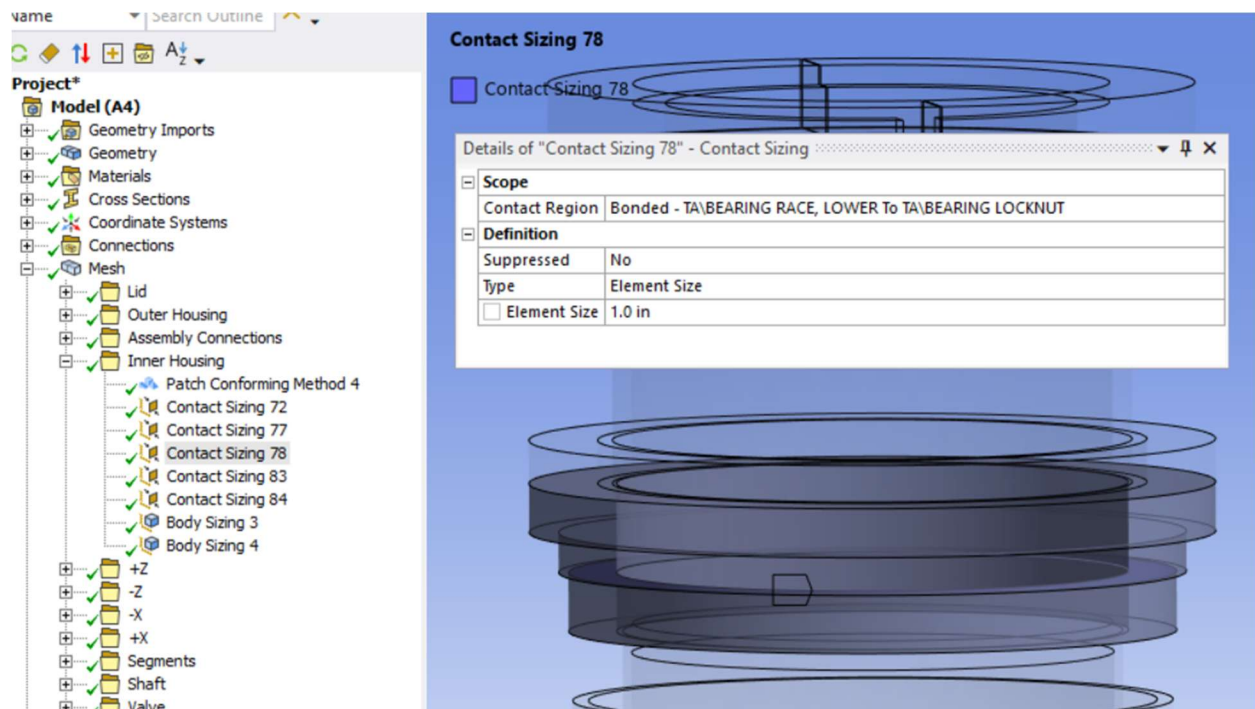


Figure 101 Inner Housing Contact Sizing

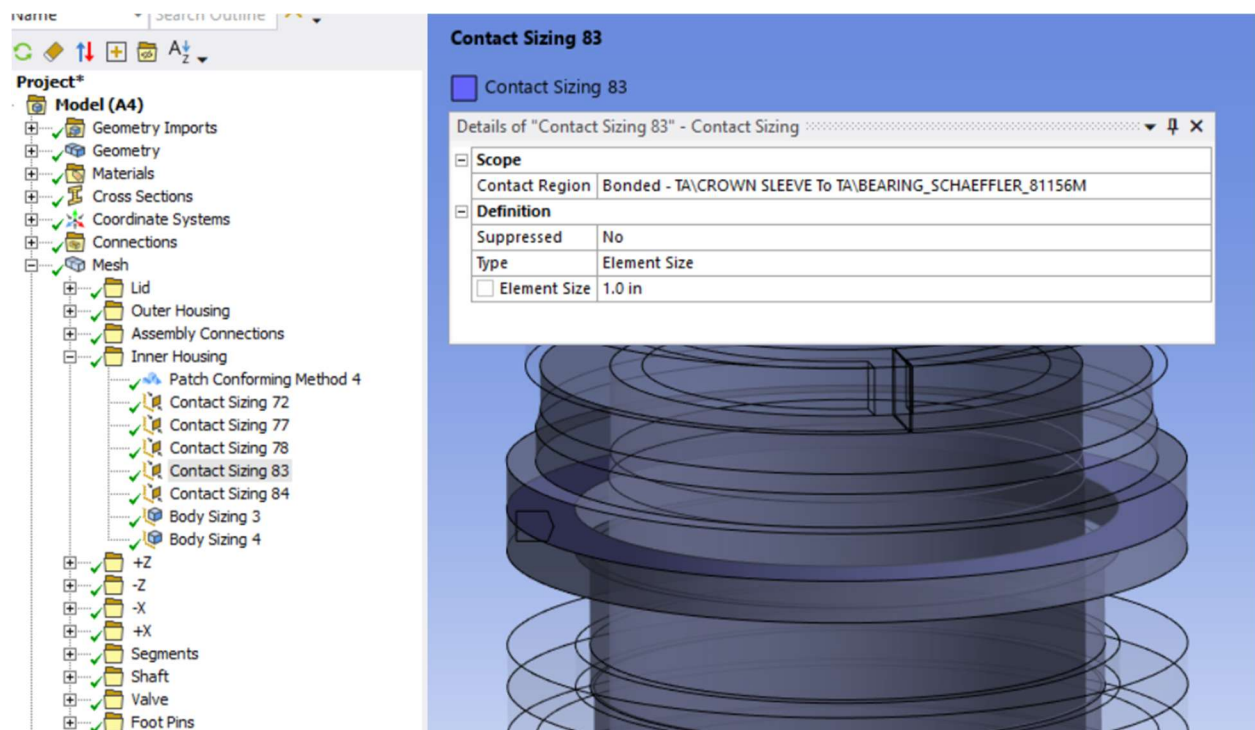


Figure 102 Inner Housing Contact Sizing

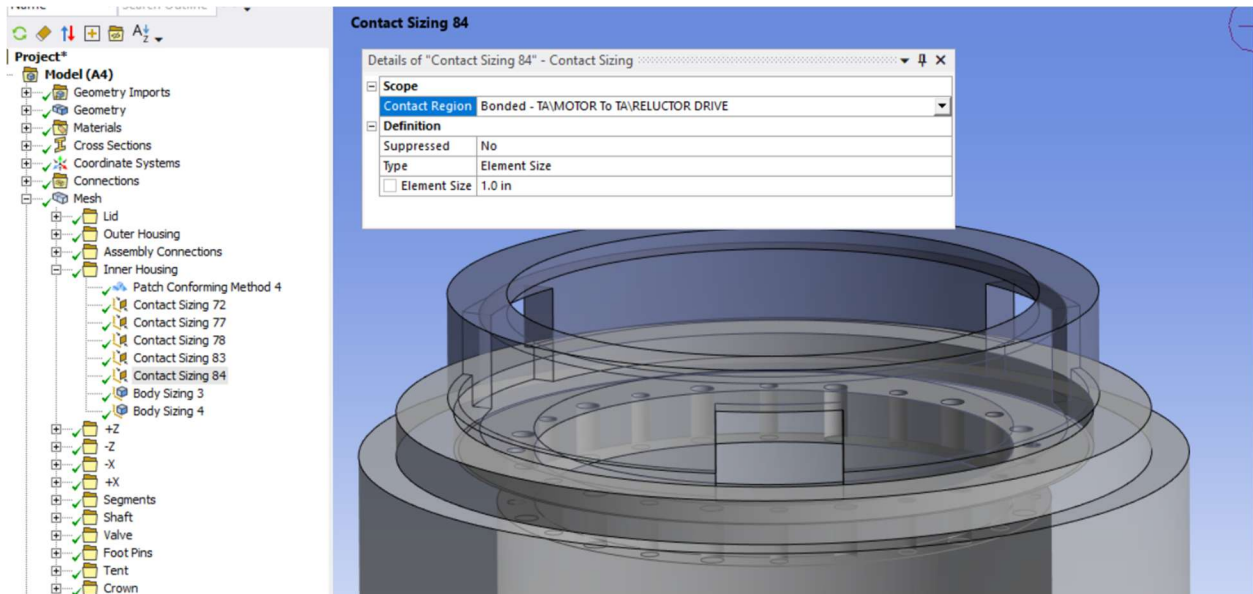


Figure 103 Inner Housing Contact Sizing

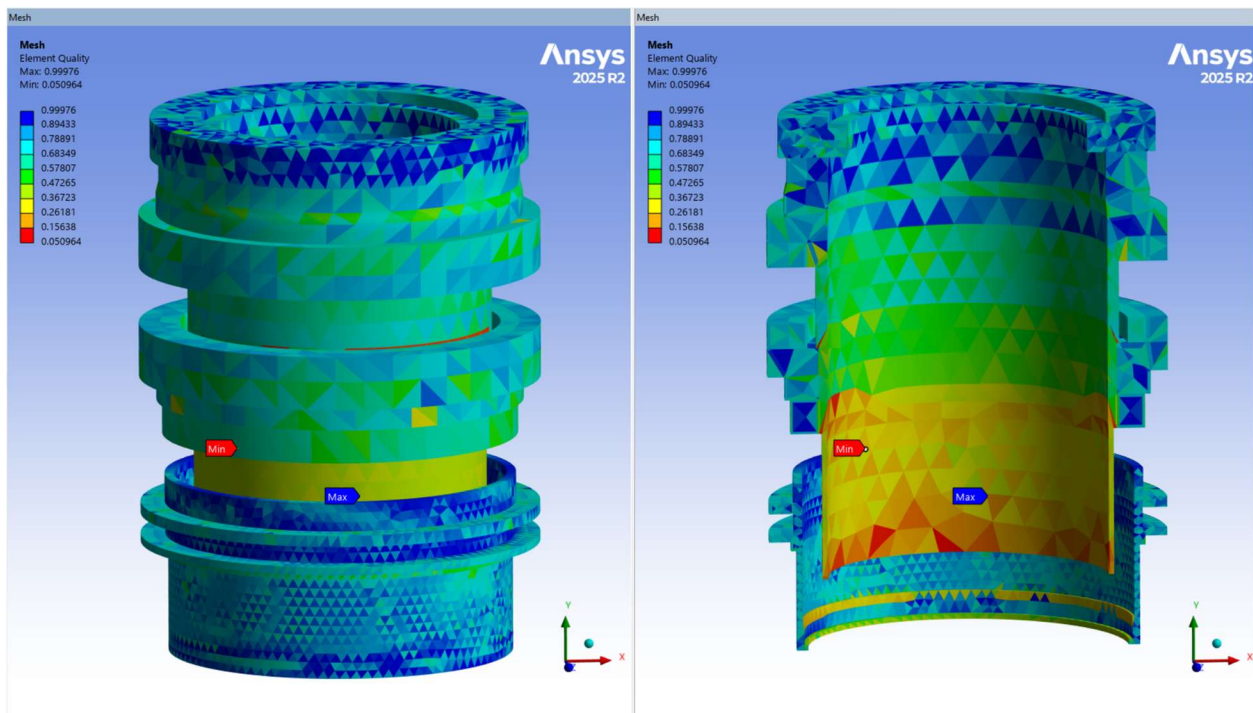


Figure 104 Inner Housing Mesh Quality

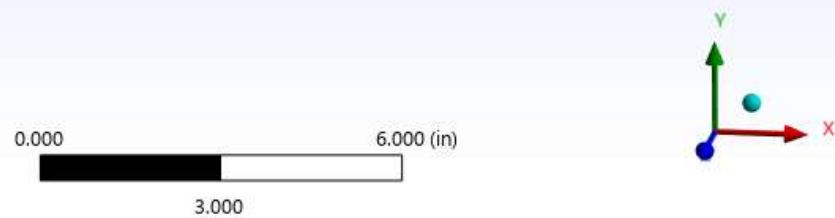
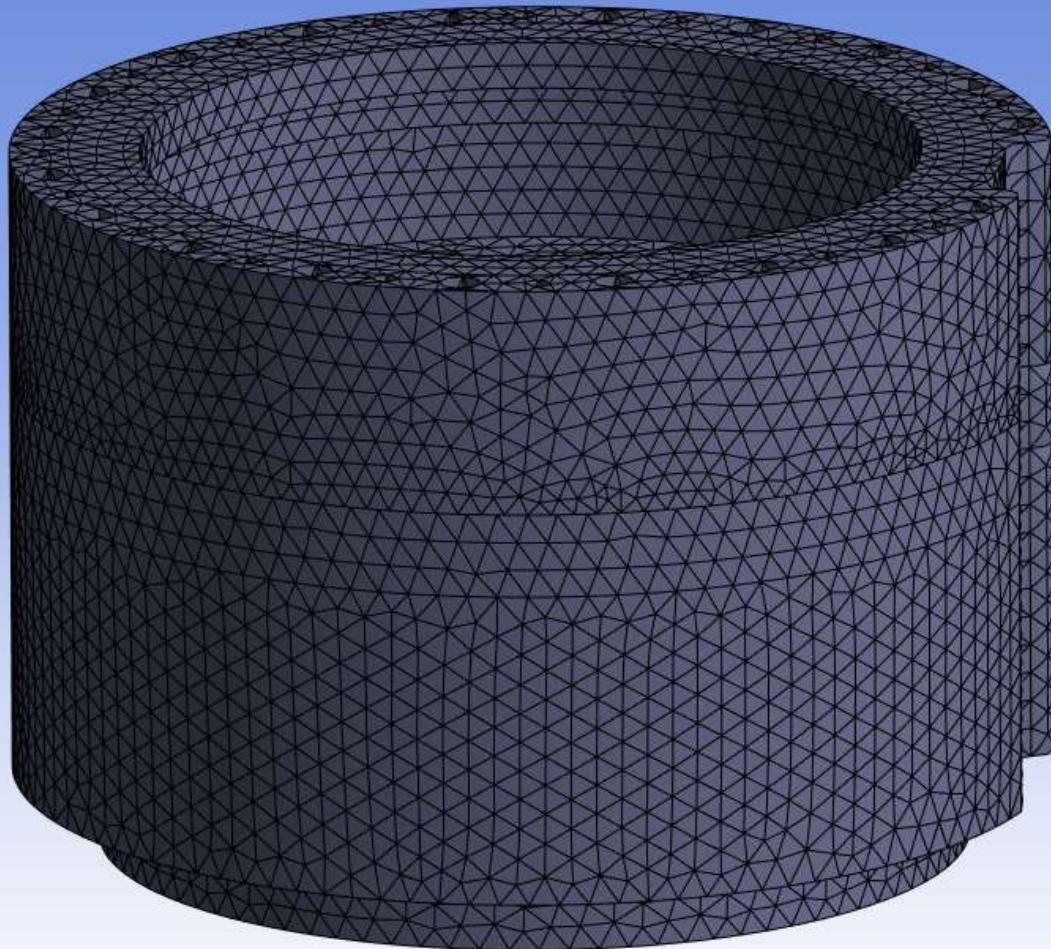
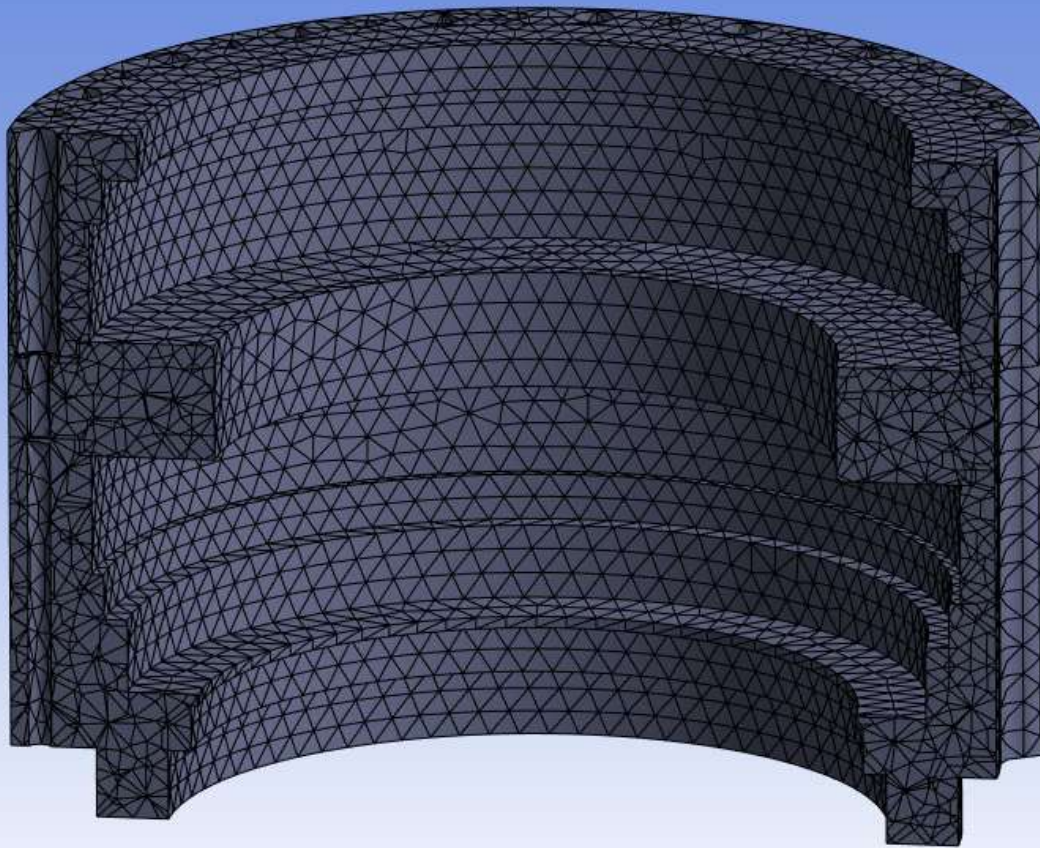


Figure 105 Outer Housing Mesh



0.000 3.000 6.000 (in)



Figure 106 Outer Housing Mesh, Section

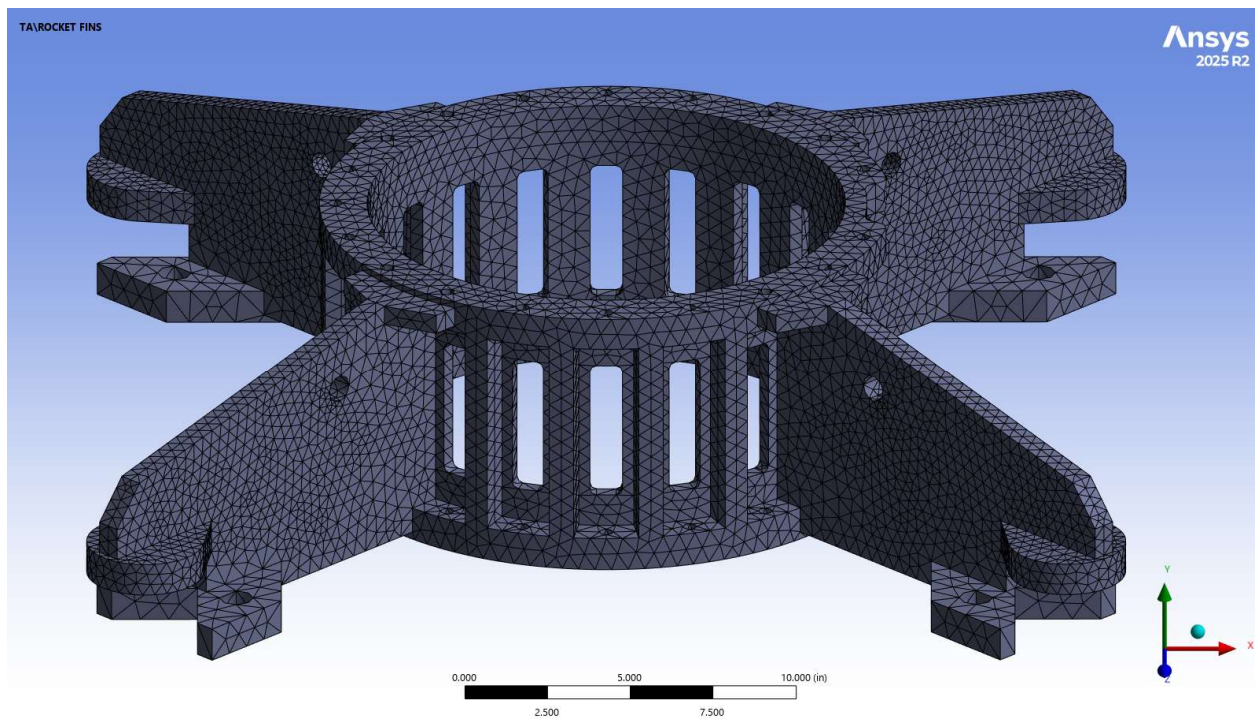


Figure 107 Rocket Fins Mesh

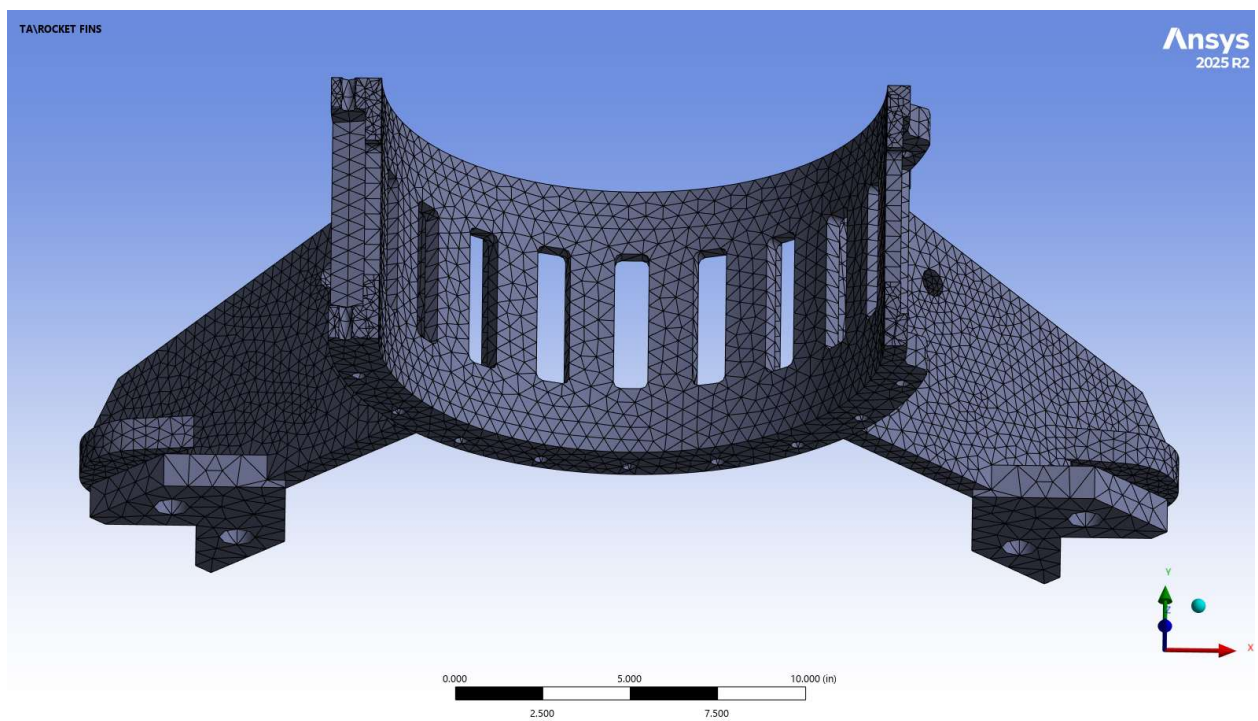
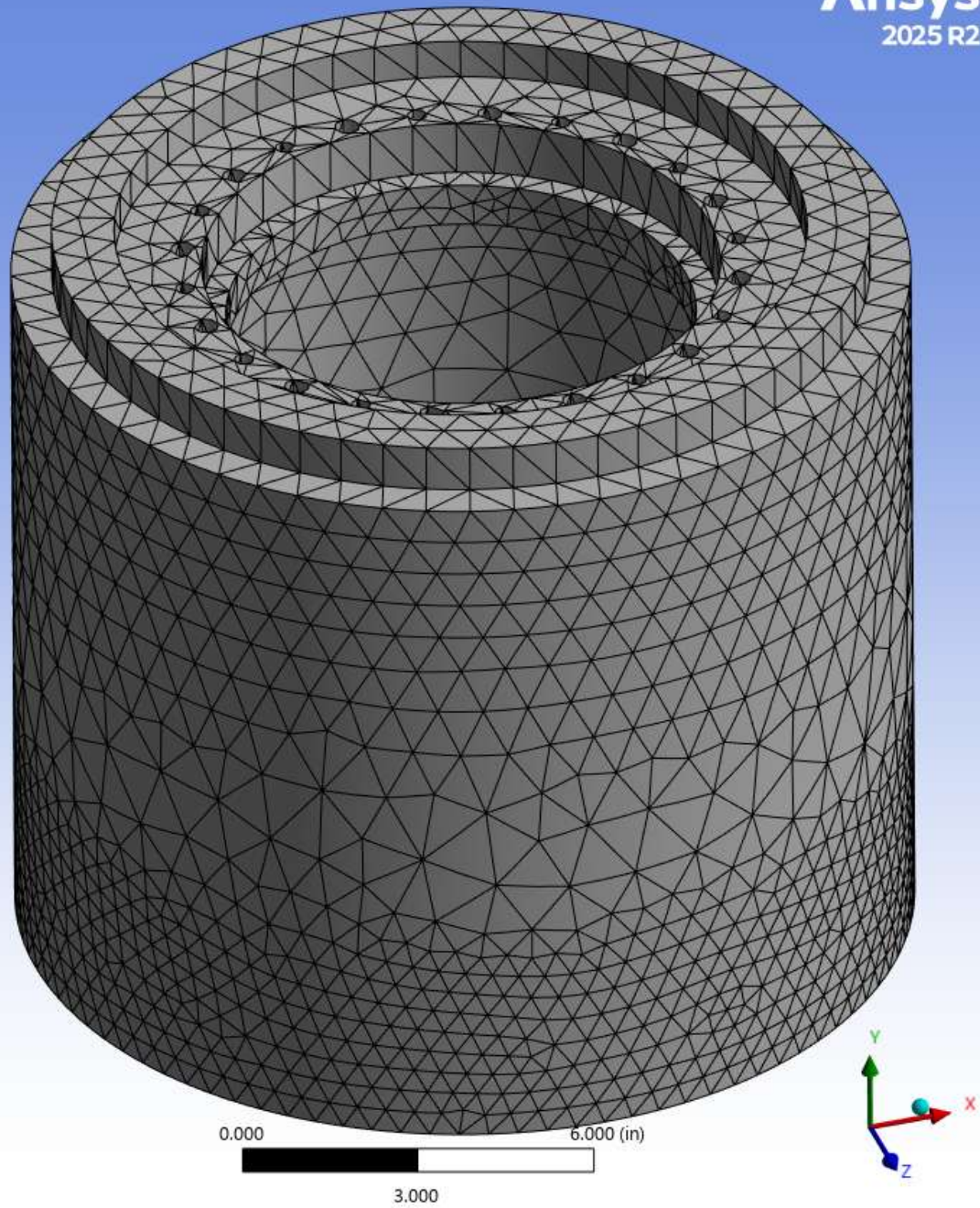
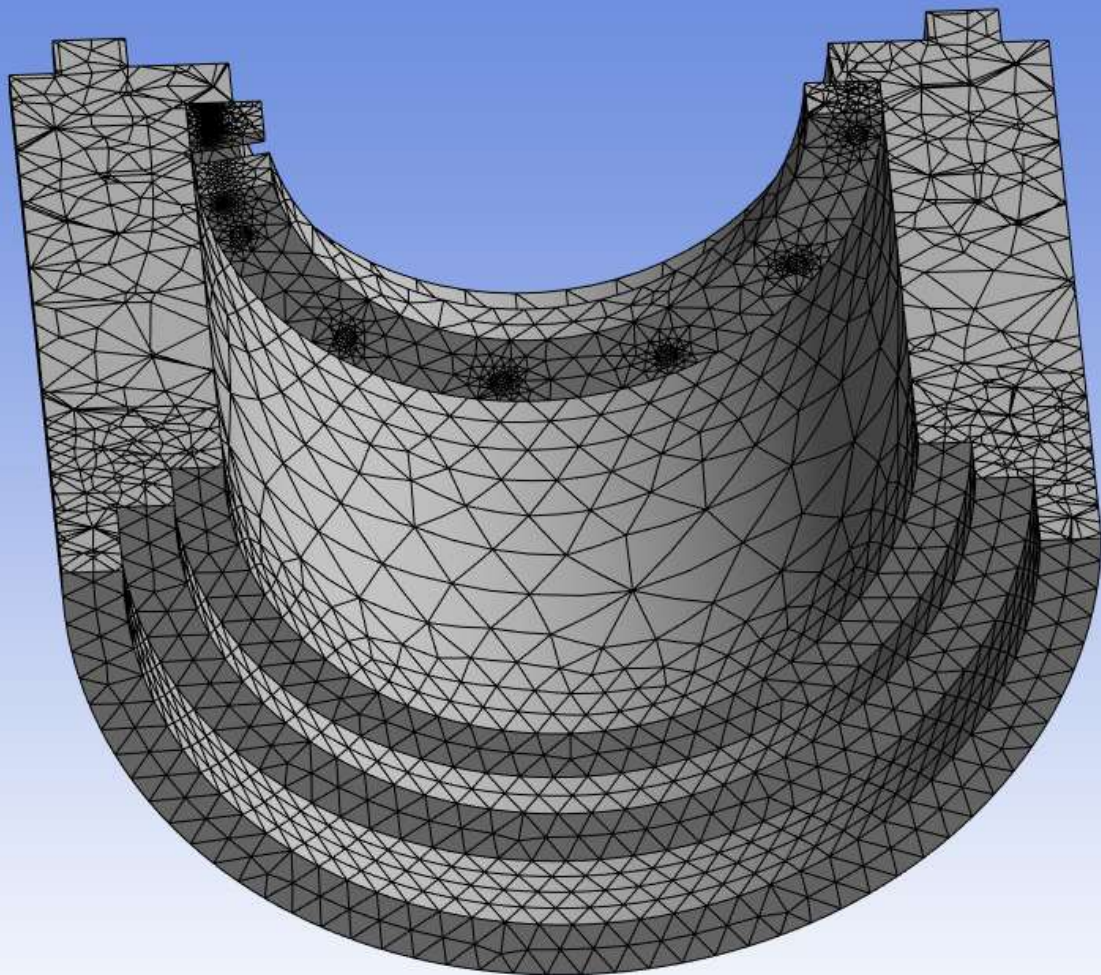


Figure 108 Rocket Fins Mesh, Section

*Figure 109 Motor Mesh*



0.000 6.000 (in)
3.000

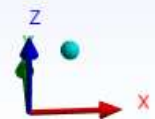


Figure 110 Motor Mesh, Section

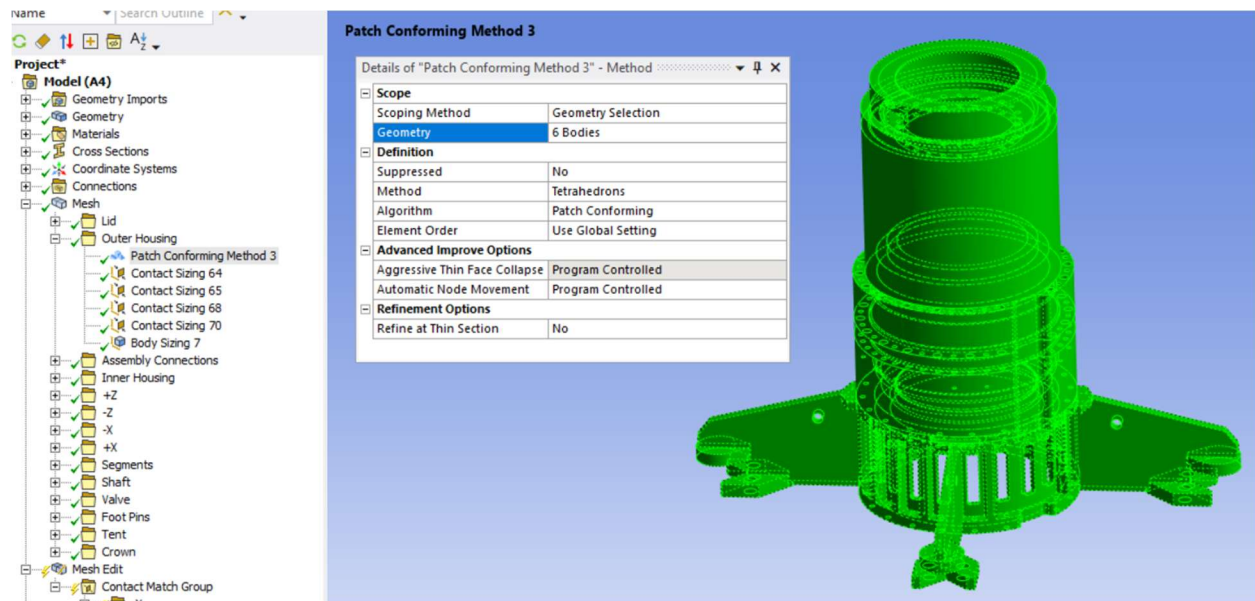


Figure 111 Outer Housing, Motor, Rocket Fins Mesh Method

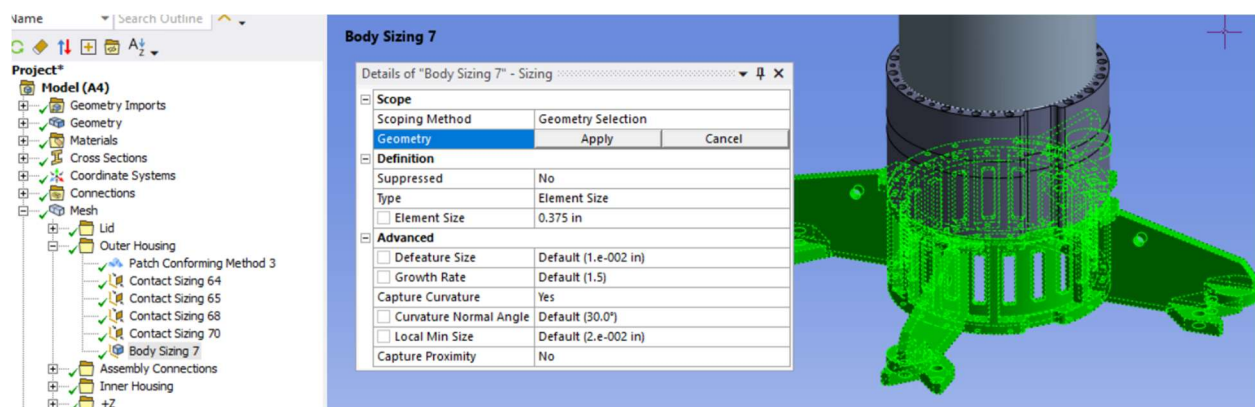


Figure 112 Rocket Fins Mesh Sizing

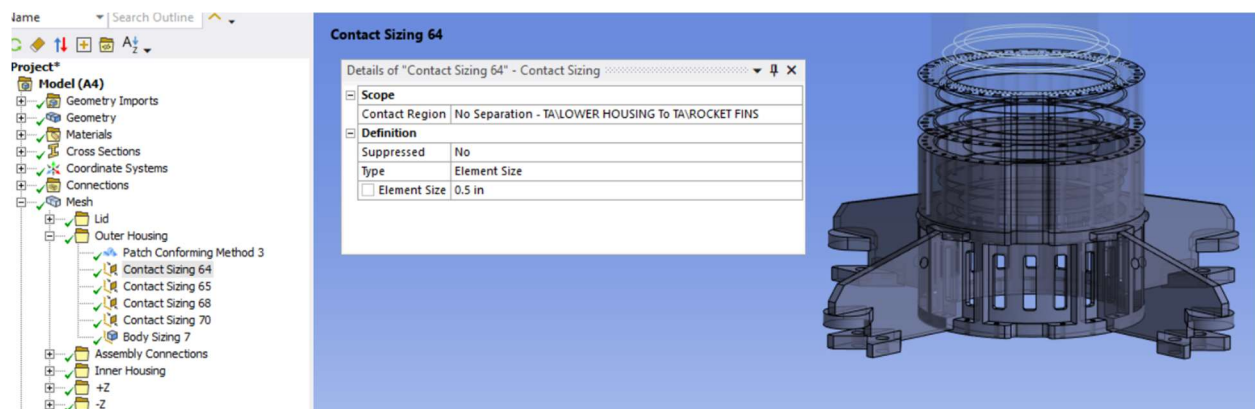


Figure 113 Rocket Fins, Housing Contact Sizing

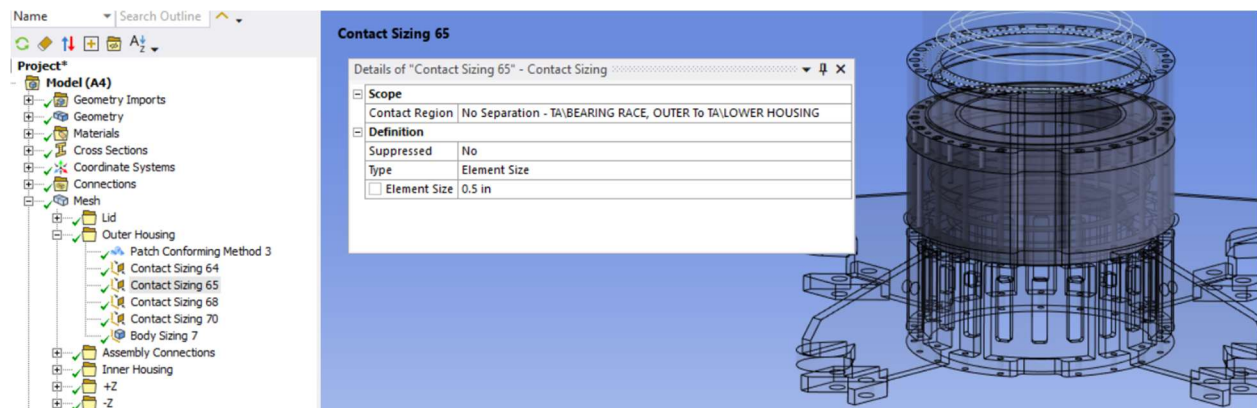


Figure 114 Outer Housing Contact Sizing

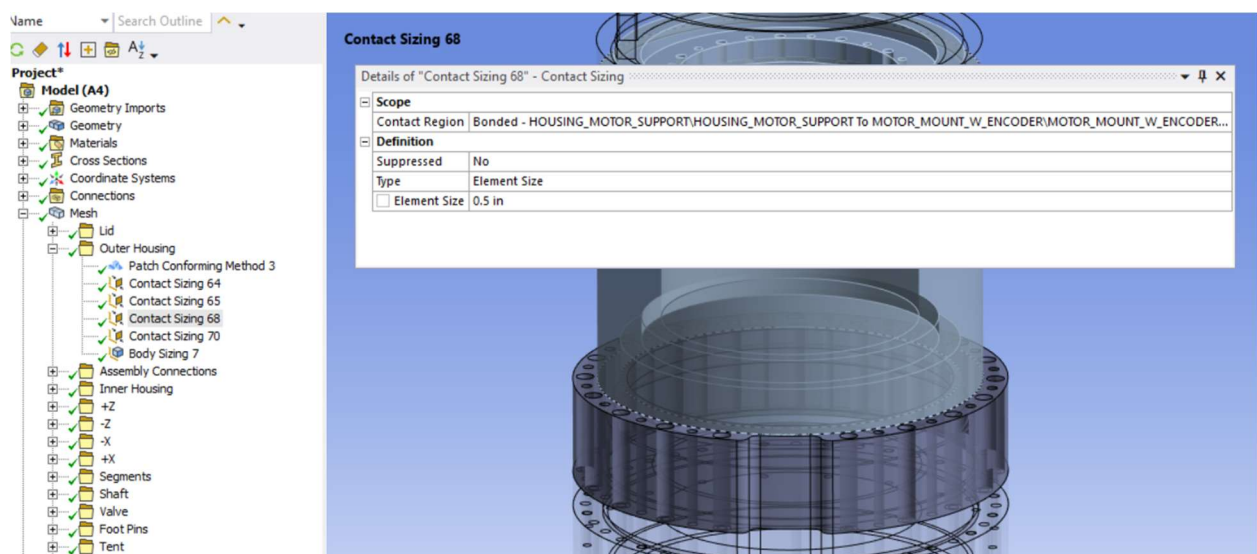


Figure 115 Outer Housing Contact Sizing

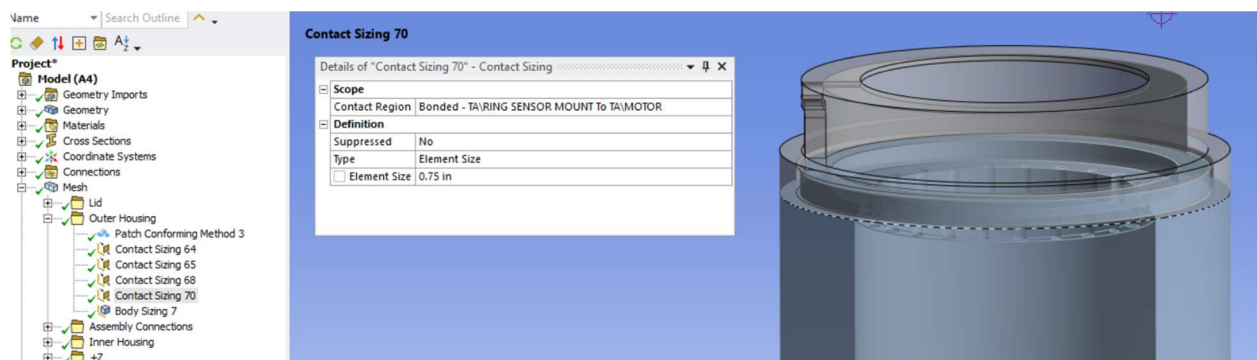


Figure 116 Motor Contact Sizing

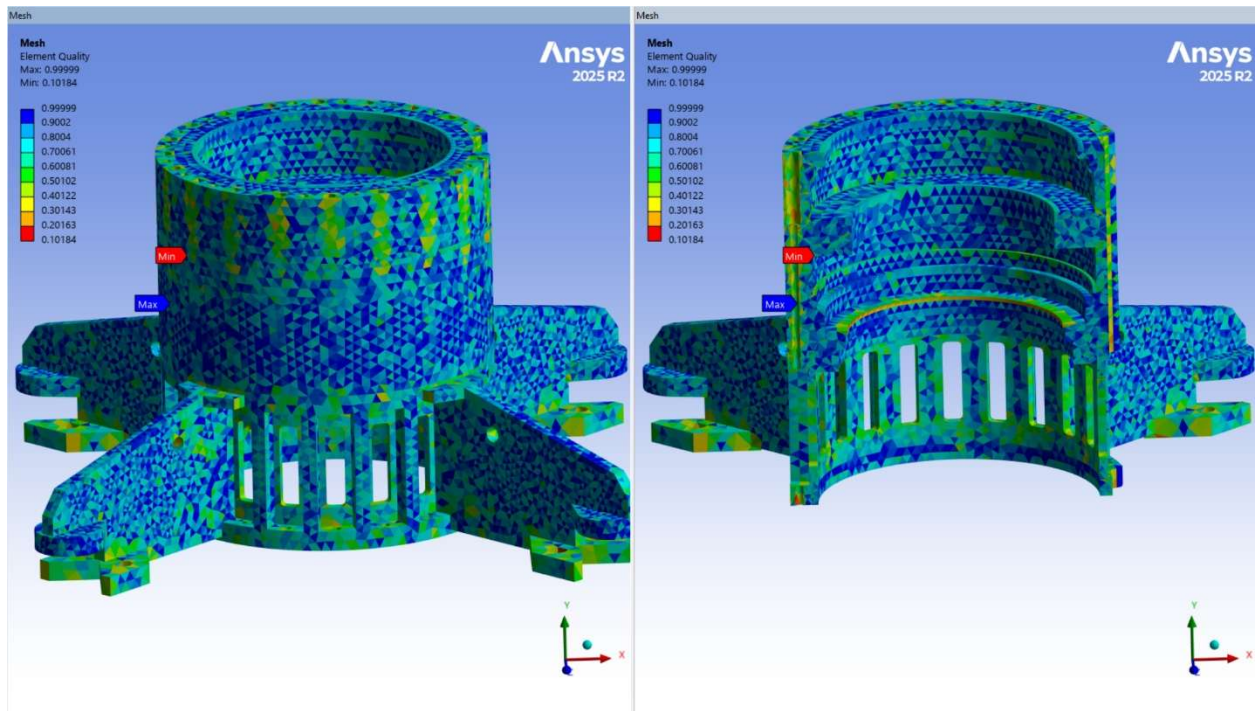


Figure 117 Outer Housing, Rocket Fins Mesh Quality

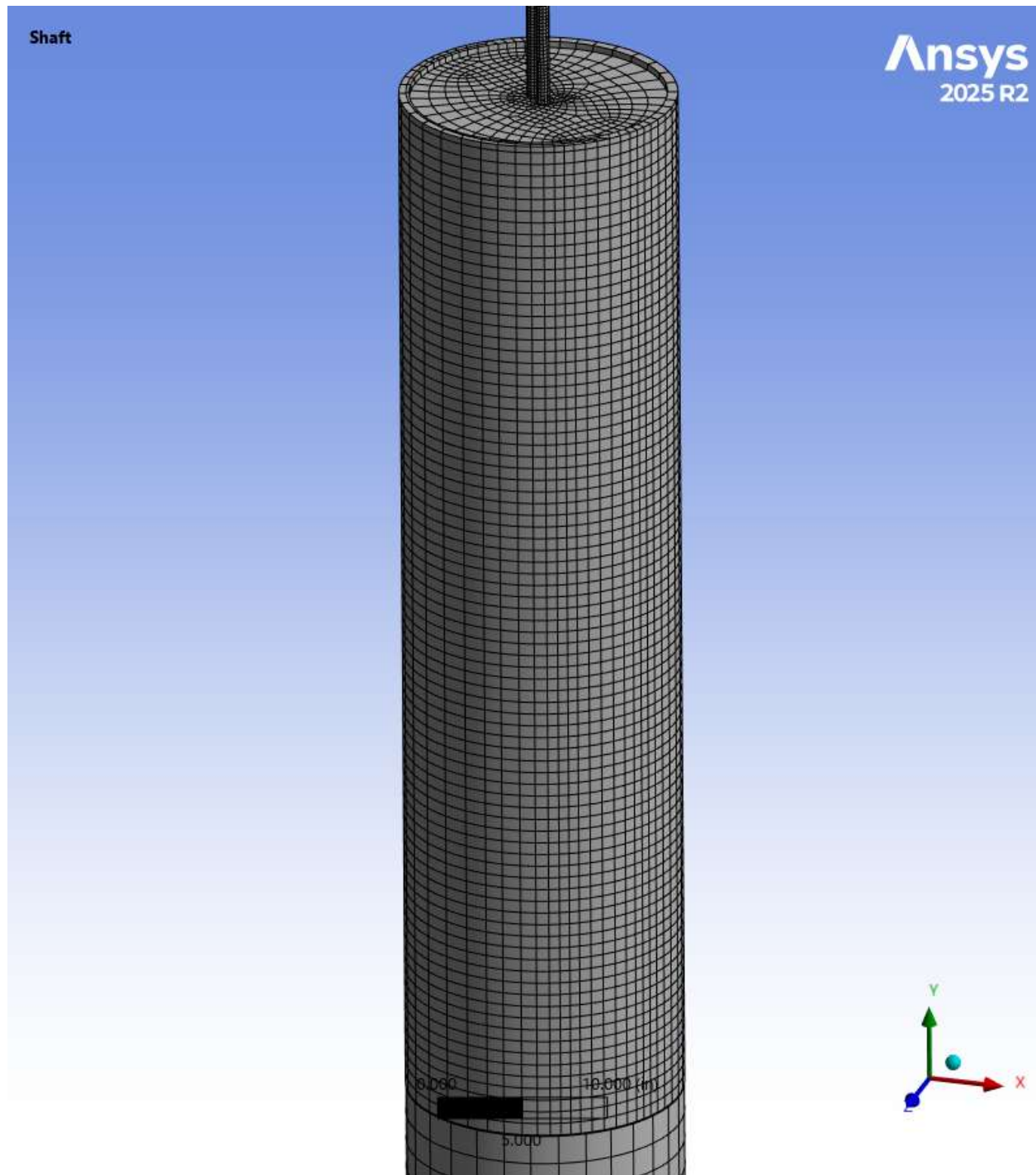


Figure 118 Shaft Mesh

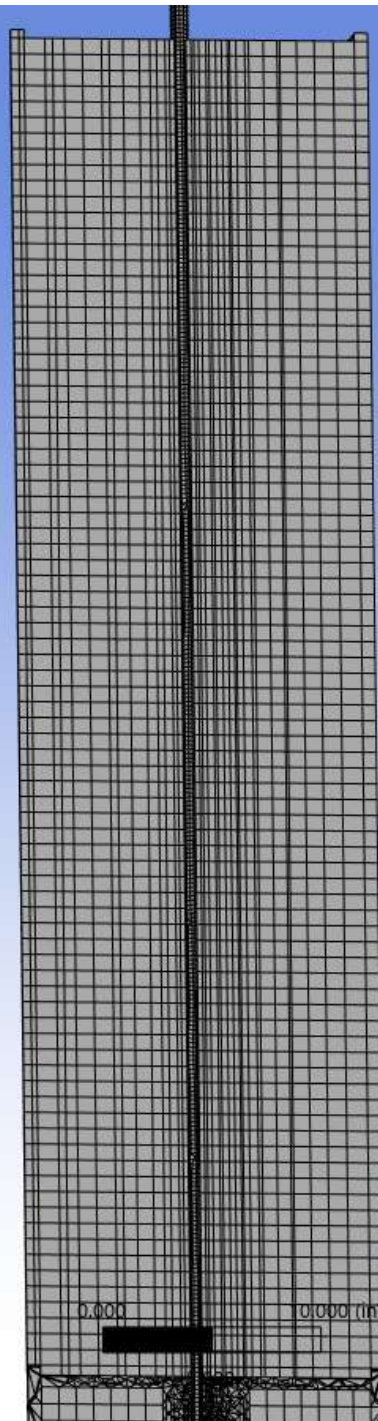


Figure 119 Shaft Mesh

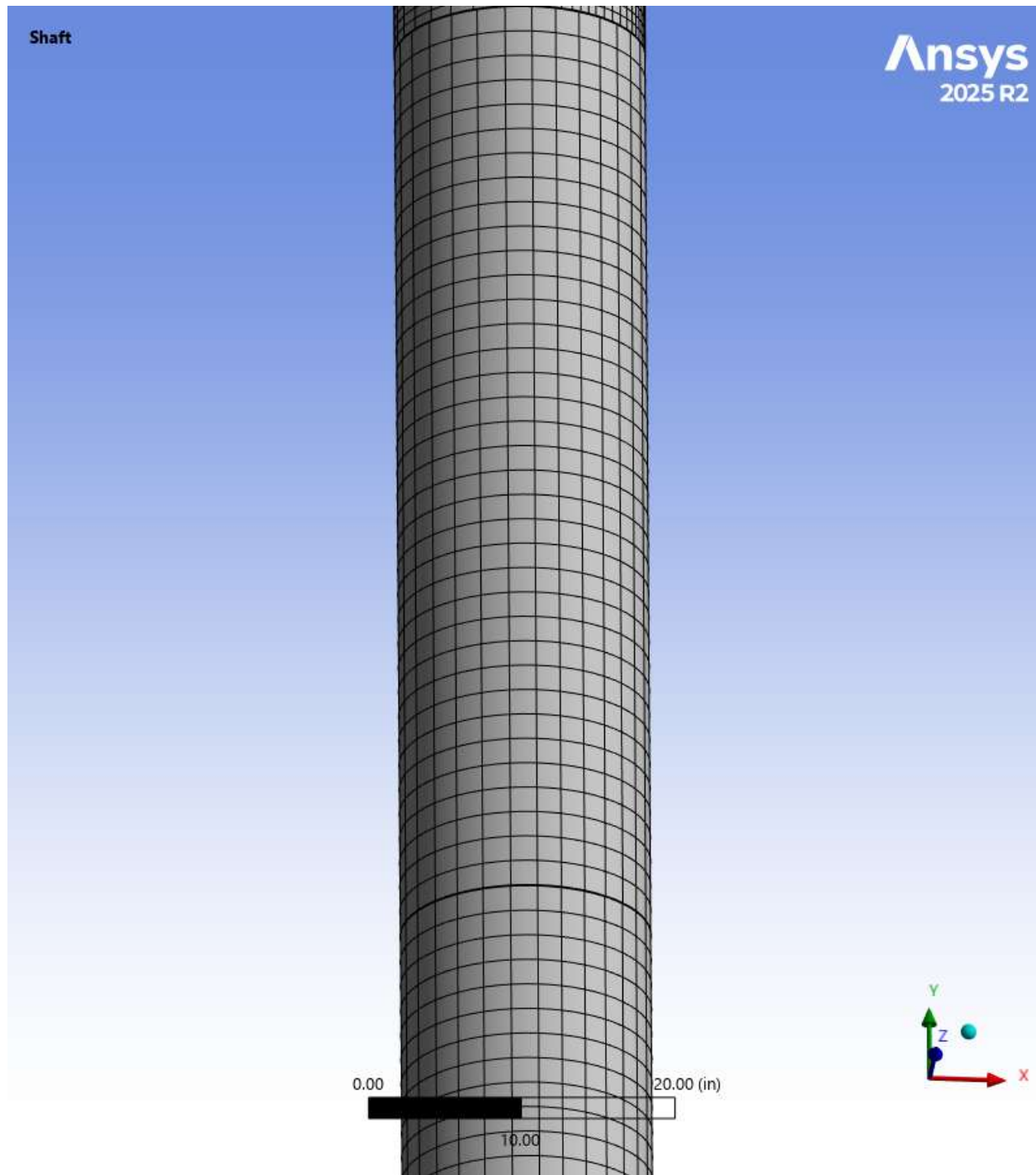


Figure 120 Shaft Mesh

Shaft

Ansys
2025 R2

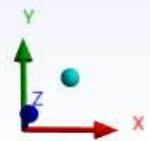
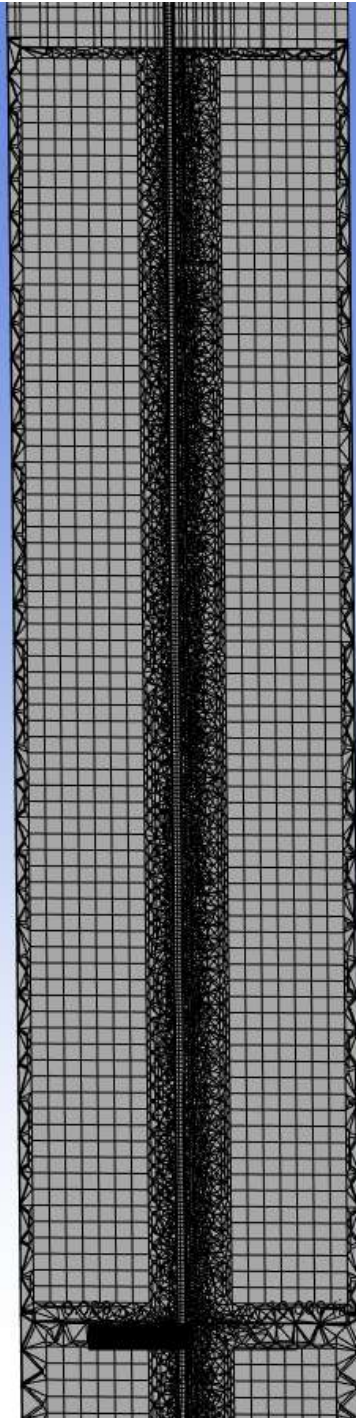


Figure 121 Shaft Mesh, Section

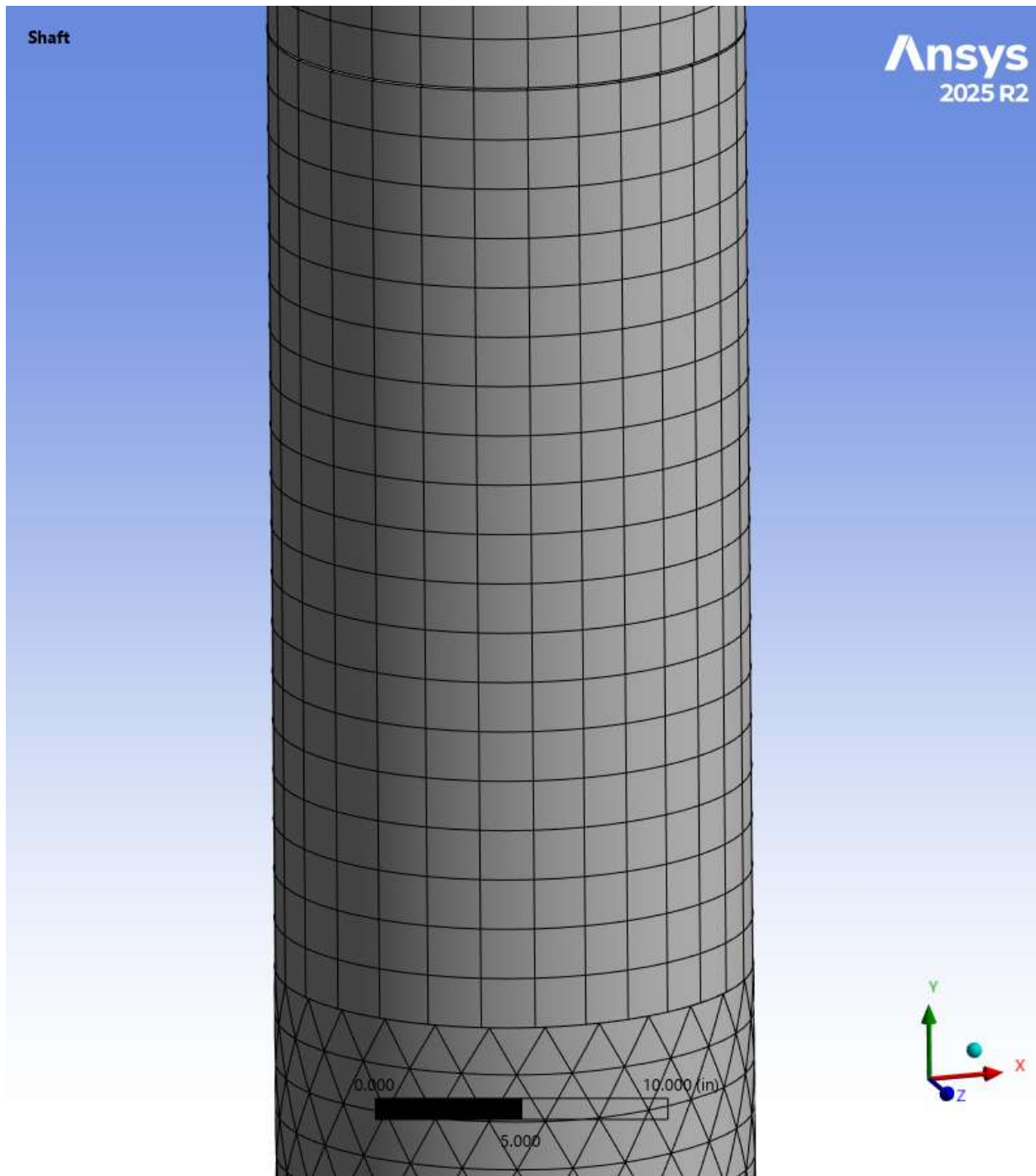
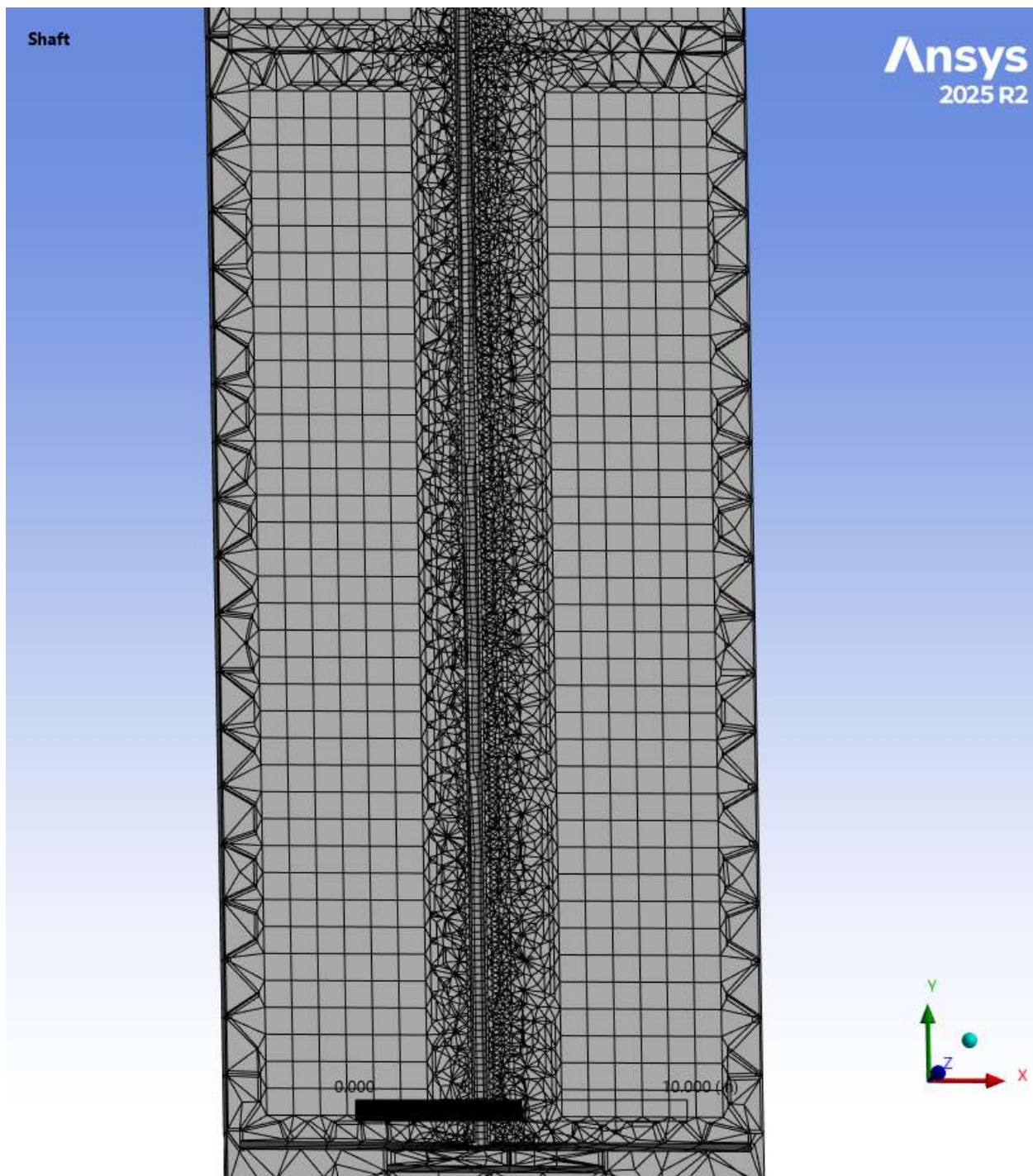


Figure 122 Shaft Mesh



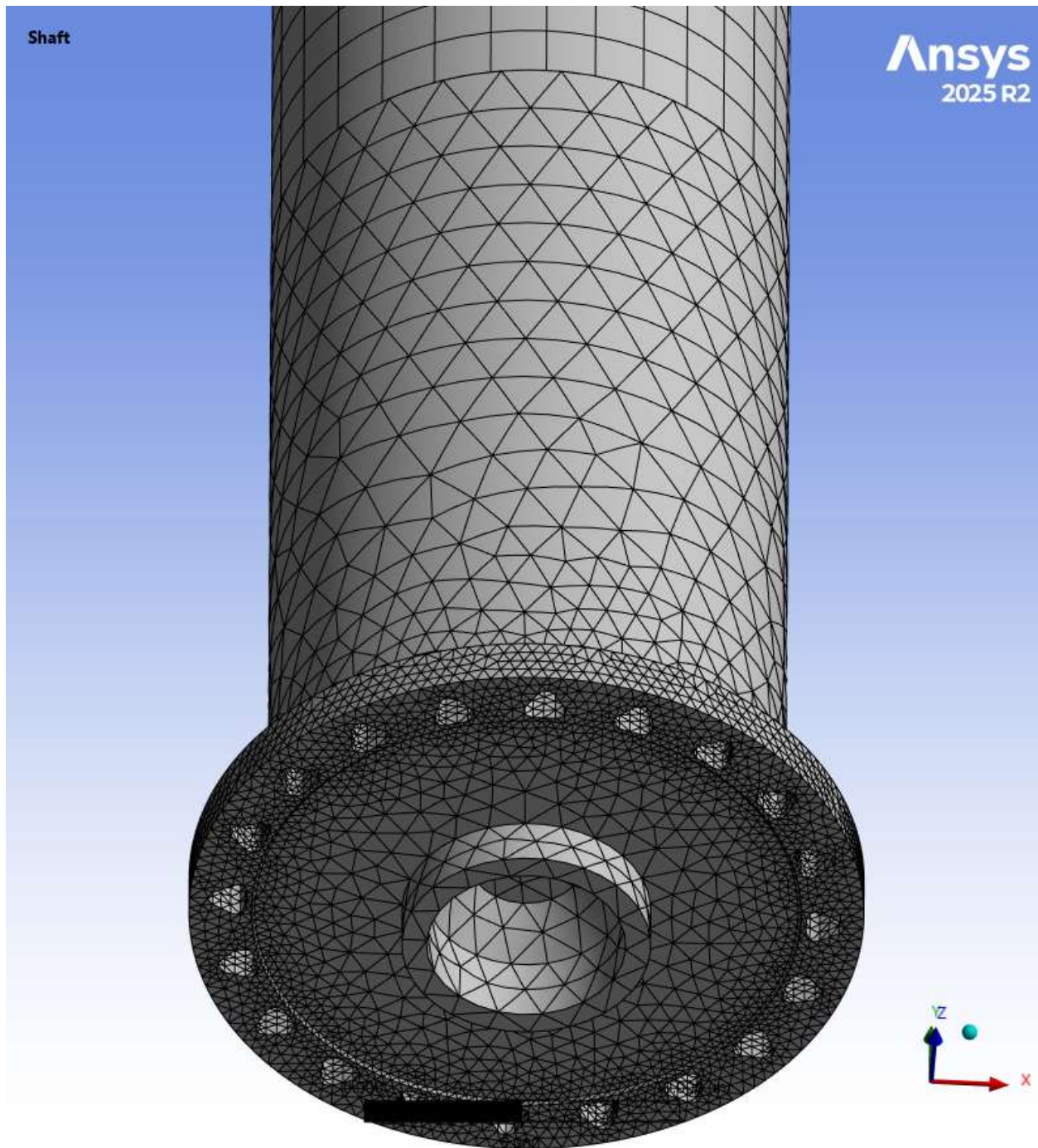


Figure 124 Shaft Mesh

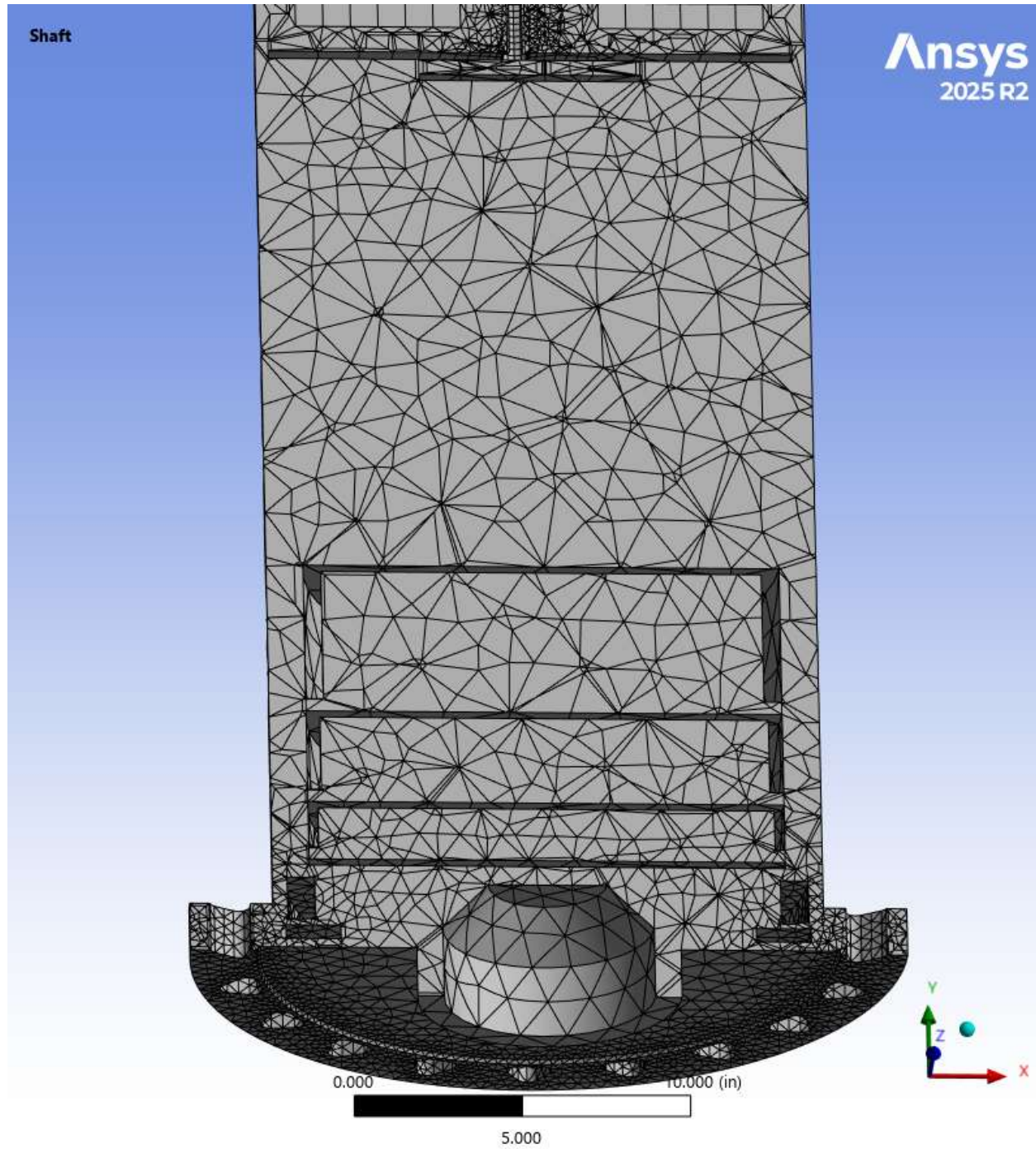


Figure 125 Shaft Mesh, Section



Figure 126 Shaft Mesh Sizing

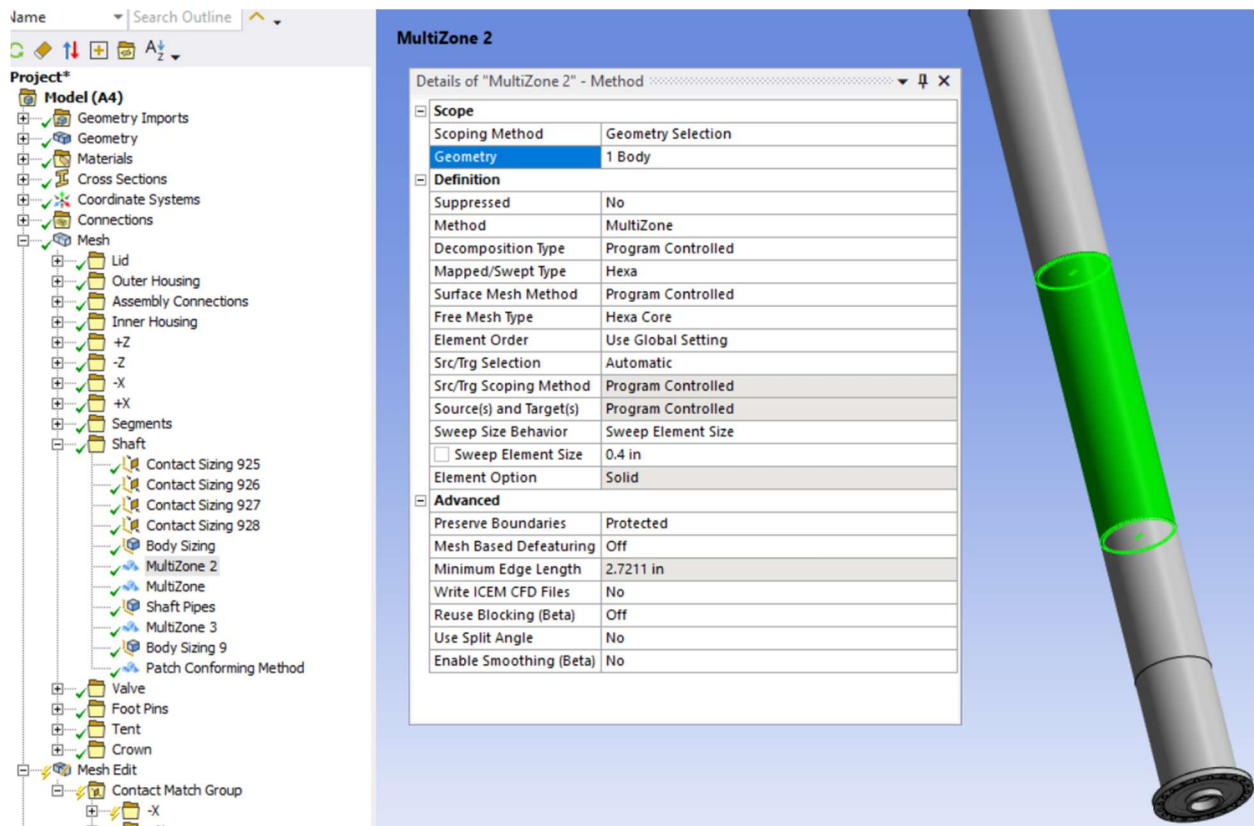


Figure 127 Shaft Mesh Method

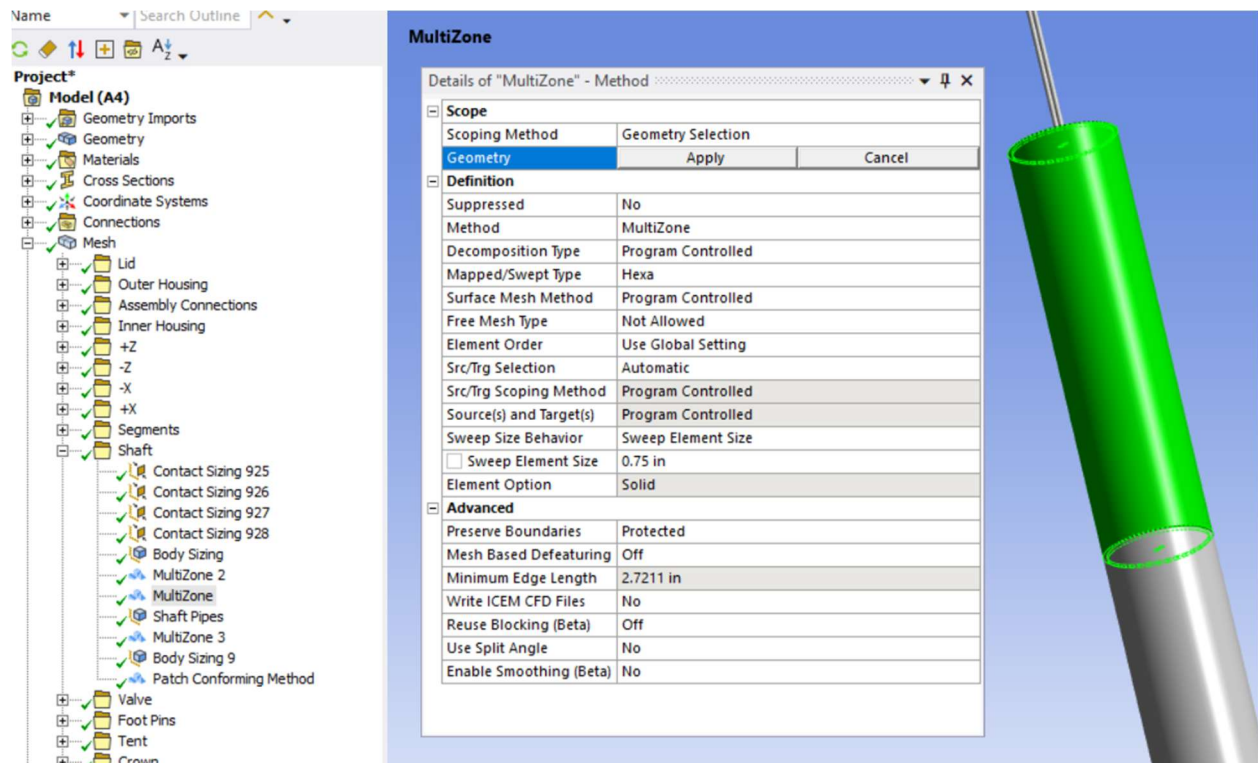


Figure 128 Shaft Mesh Method

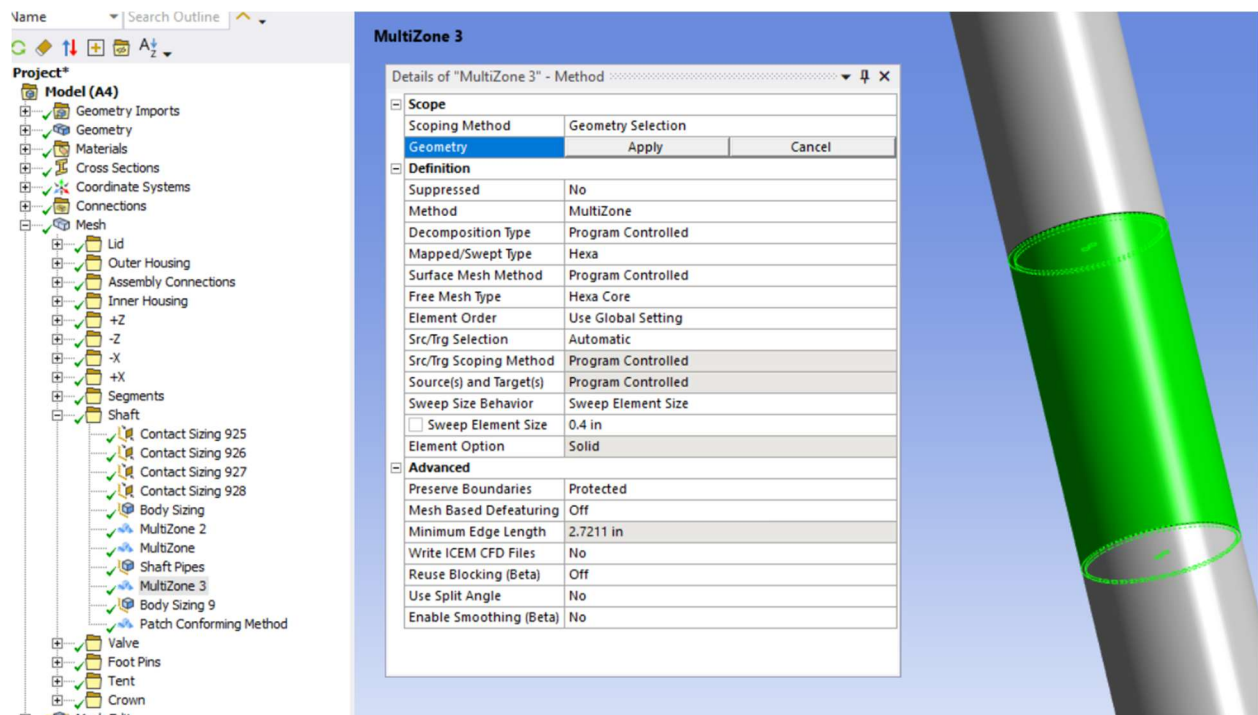


Figure 129 Shaft Mesh Method

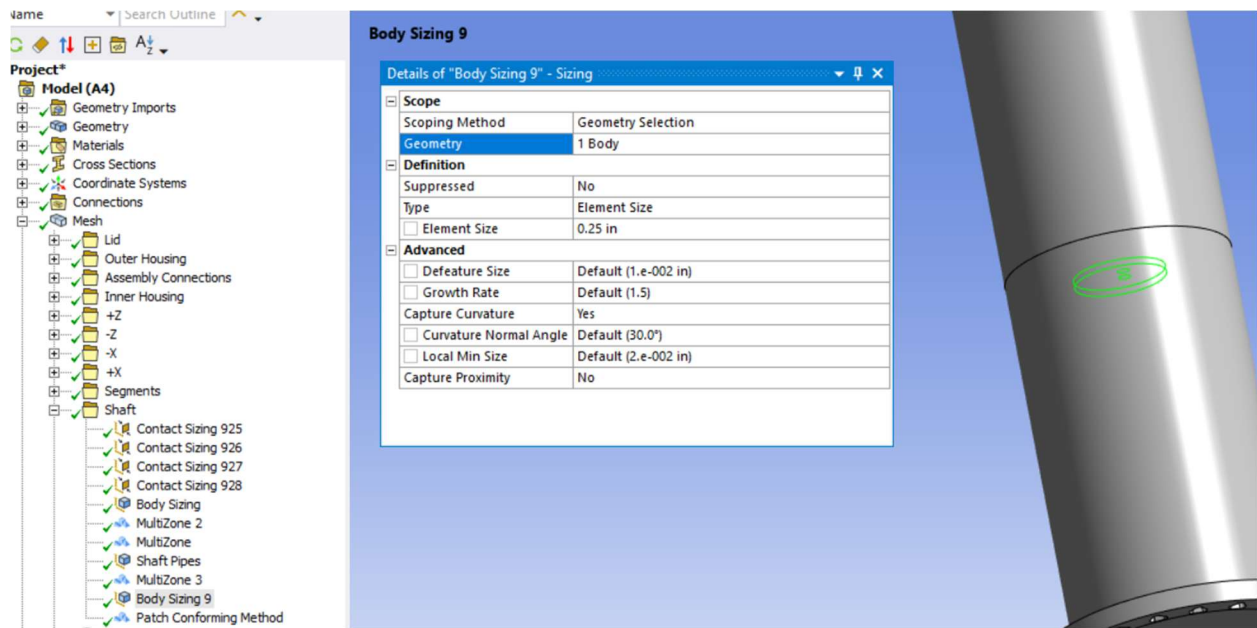


Figure 130 Shaft Mesh Sizing

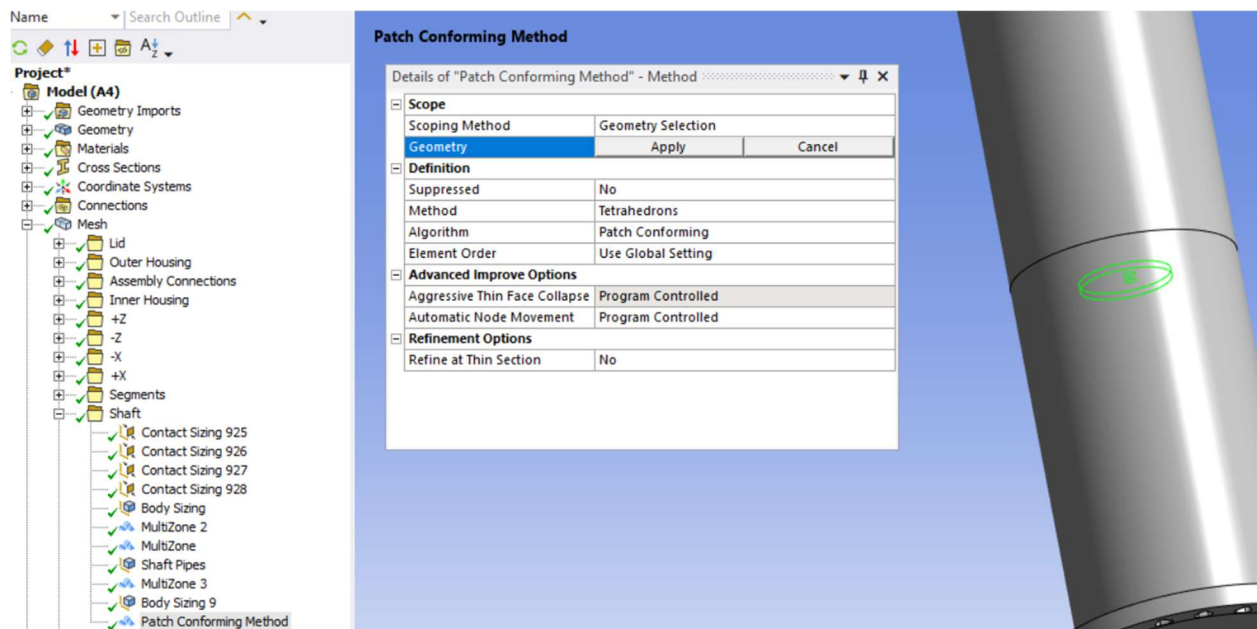


Figure 131 Shaft Mesh Method

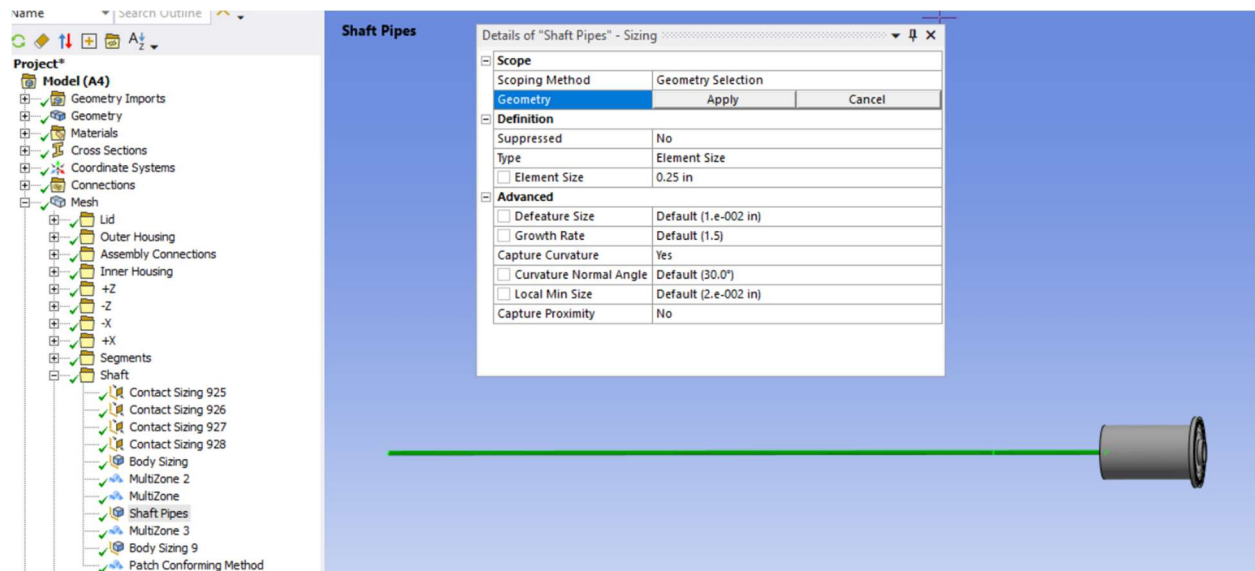


Figure 132 Shaft Piping Mesh Size

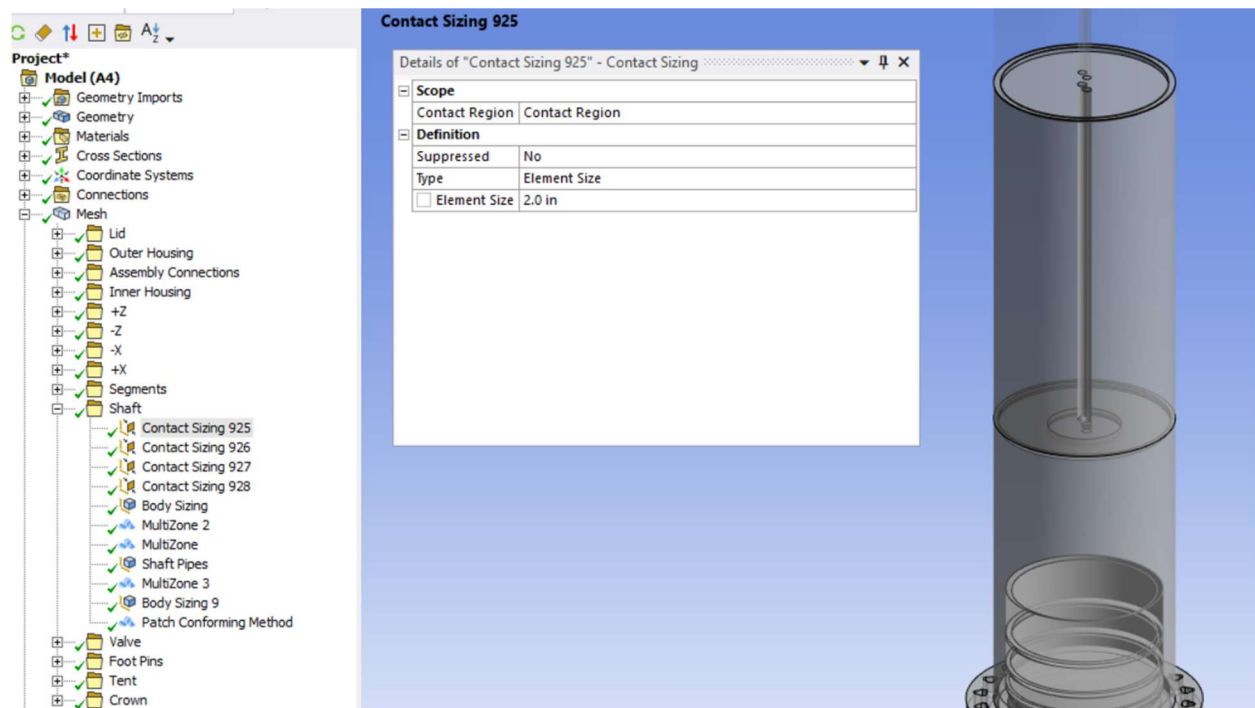


Figure 133 Shaft Contact Sizing

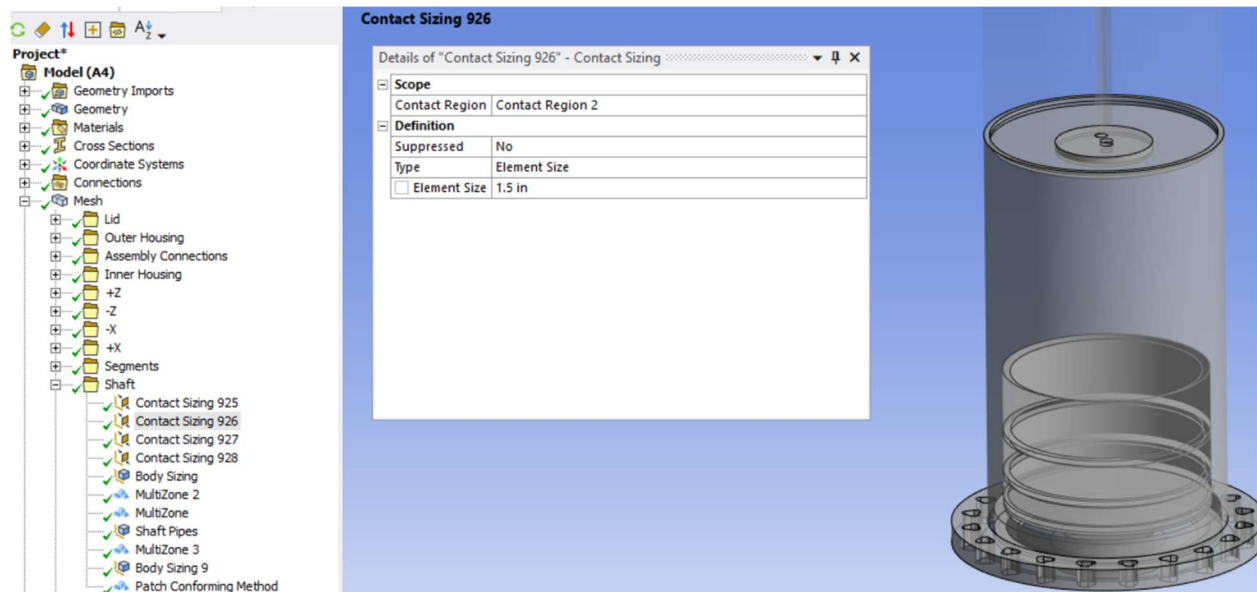


Figure 134 Shaft Contact Sizing

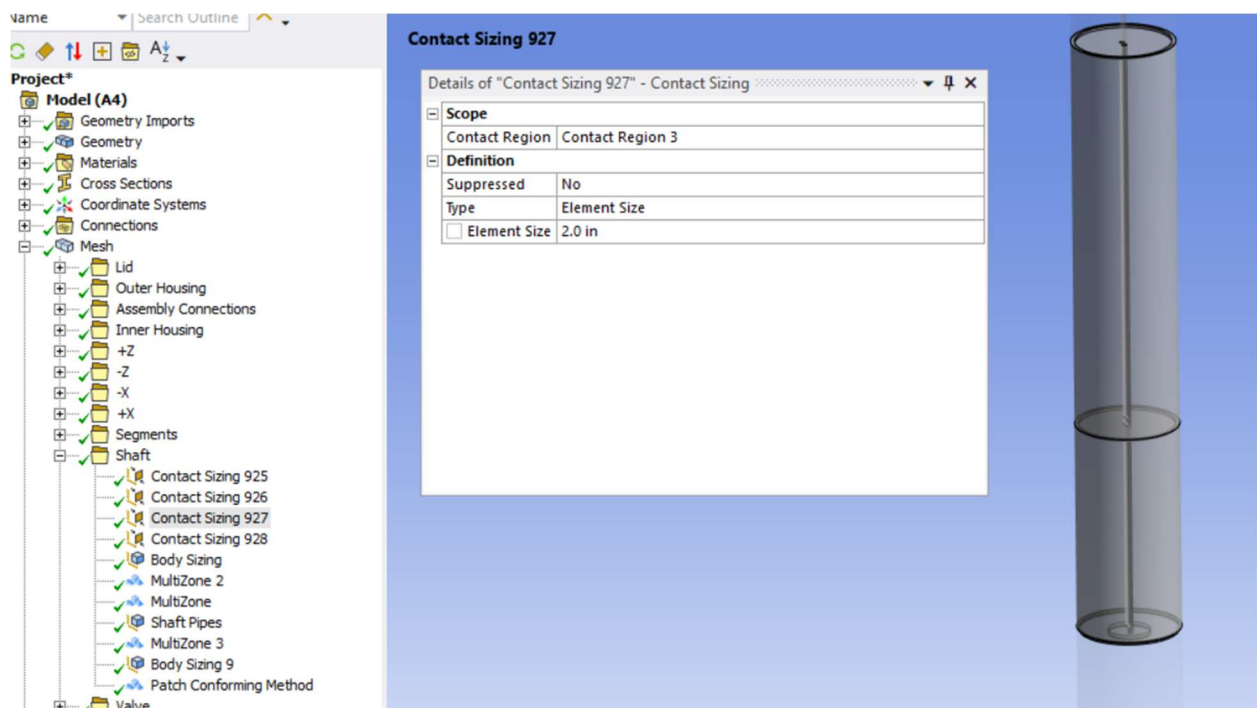


Figure 135 Shaft Contact Sizing

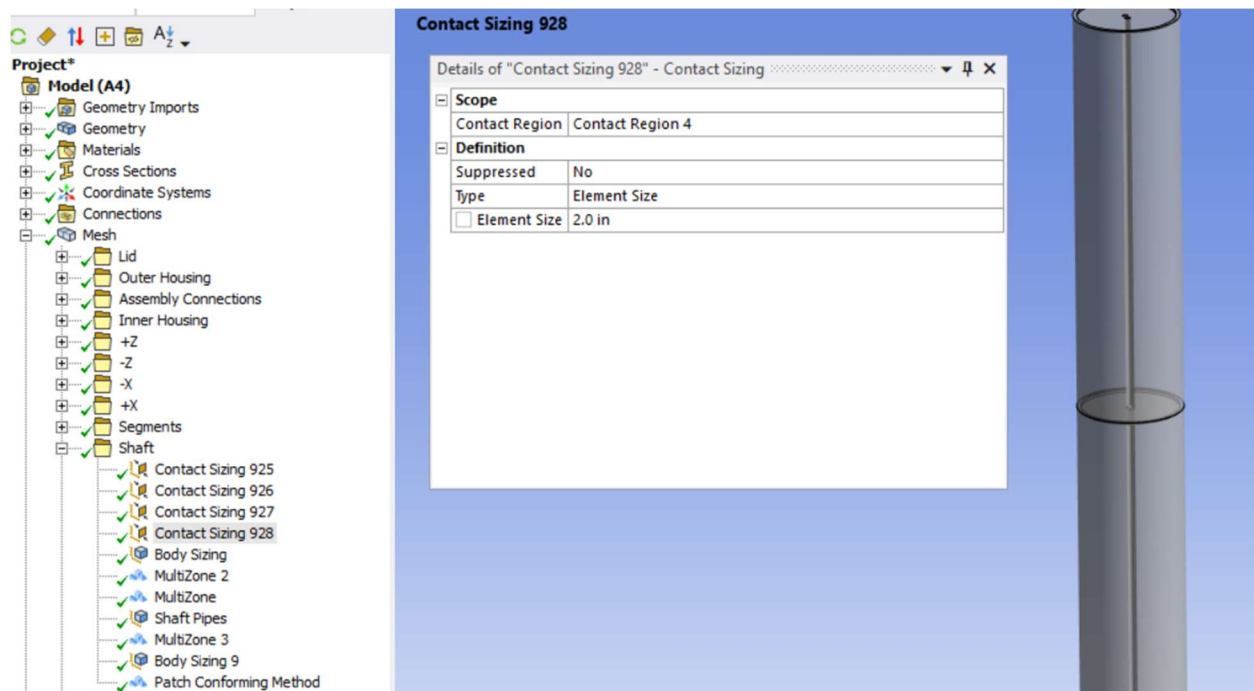


Figure 136 Shaft Contact Sizing

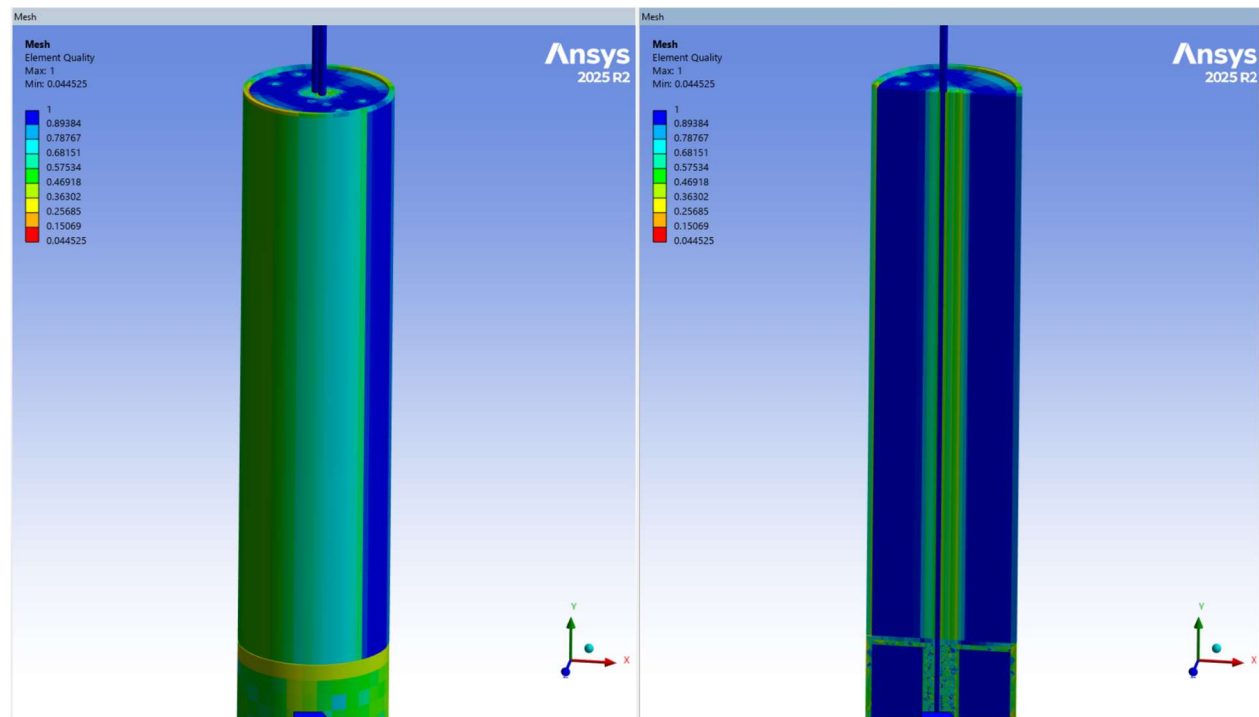


Figure 137 Shaft Mesh Quality

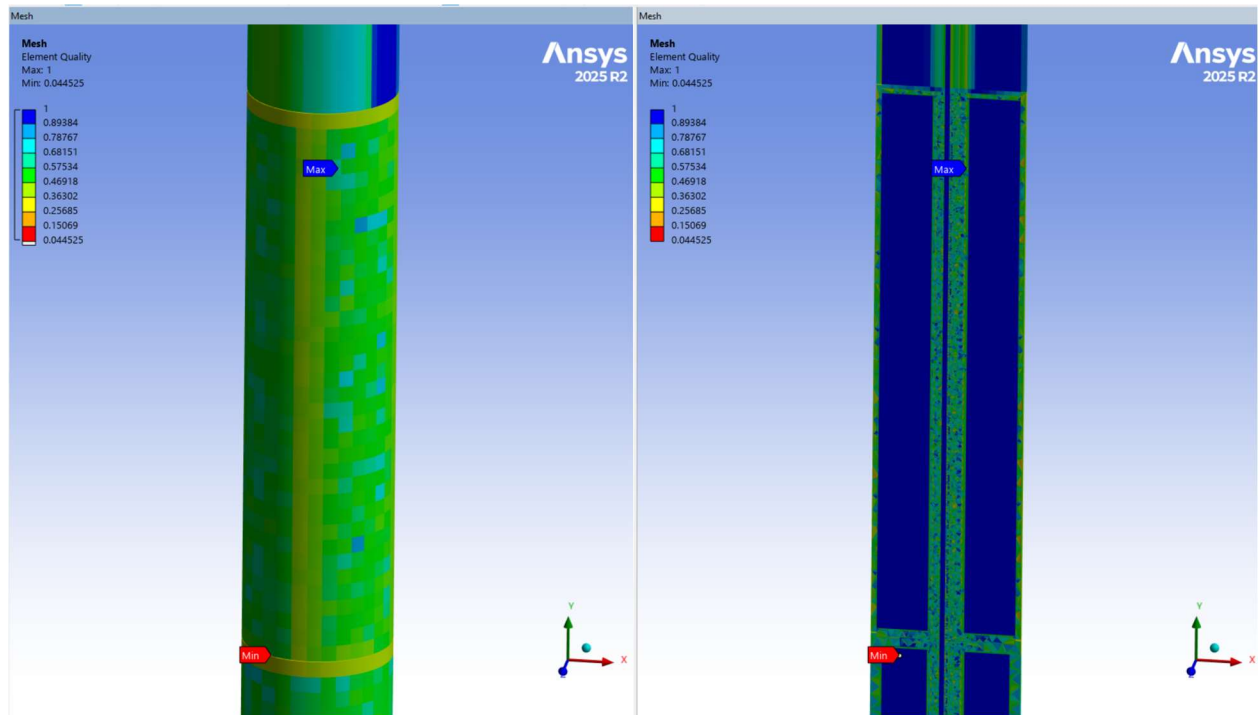


Figure 138 Shaft Mesh Quality

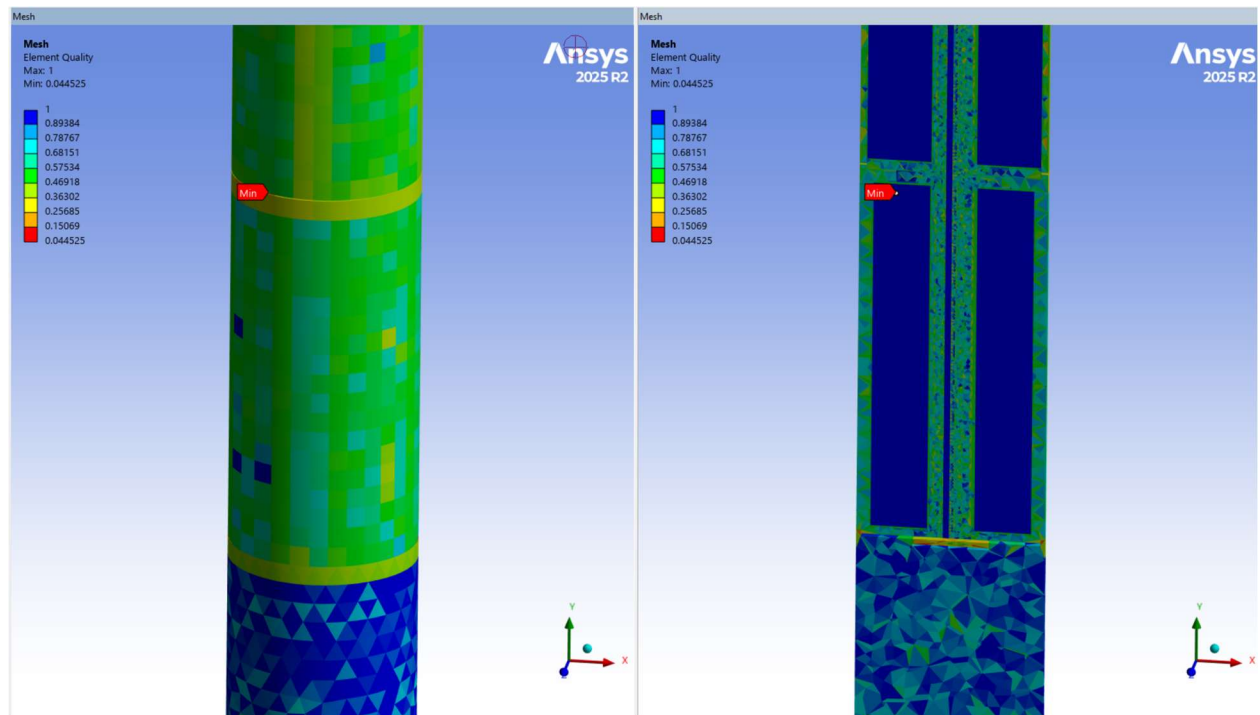


Figure 139 Shaft Mesh Quality

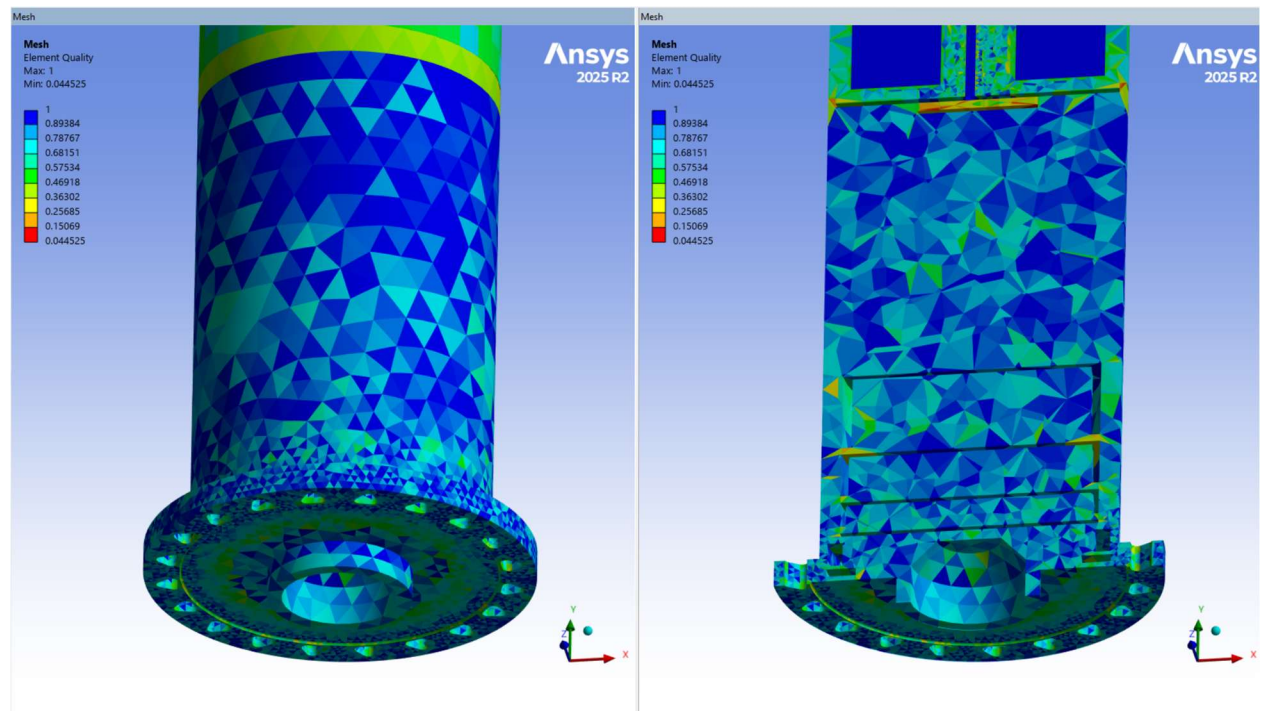


Figure 140 Shaft Mesh Quality

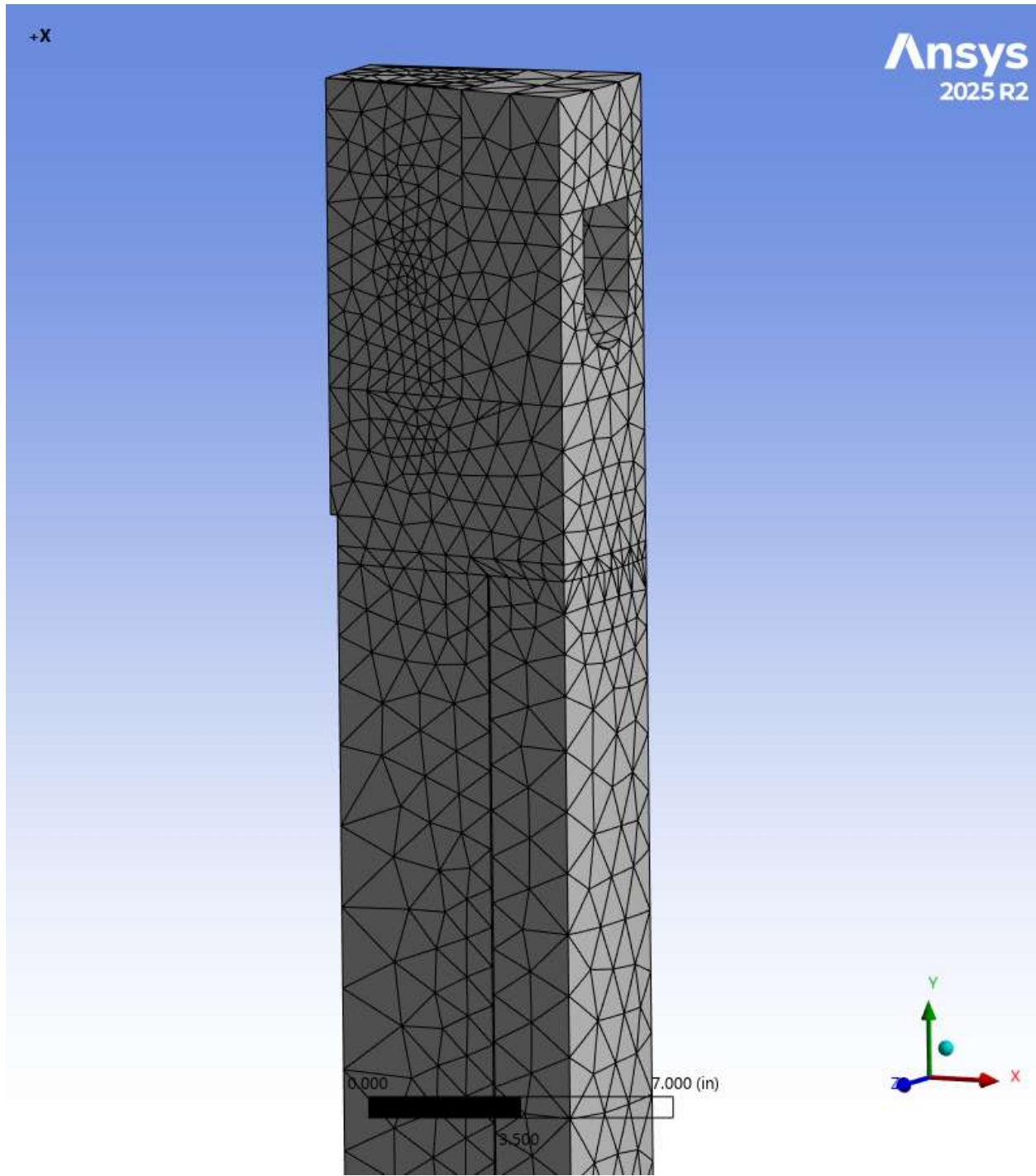


Figure 141 Segment Mesh

+Z

Ansys
2025 R2

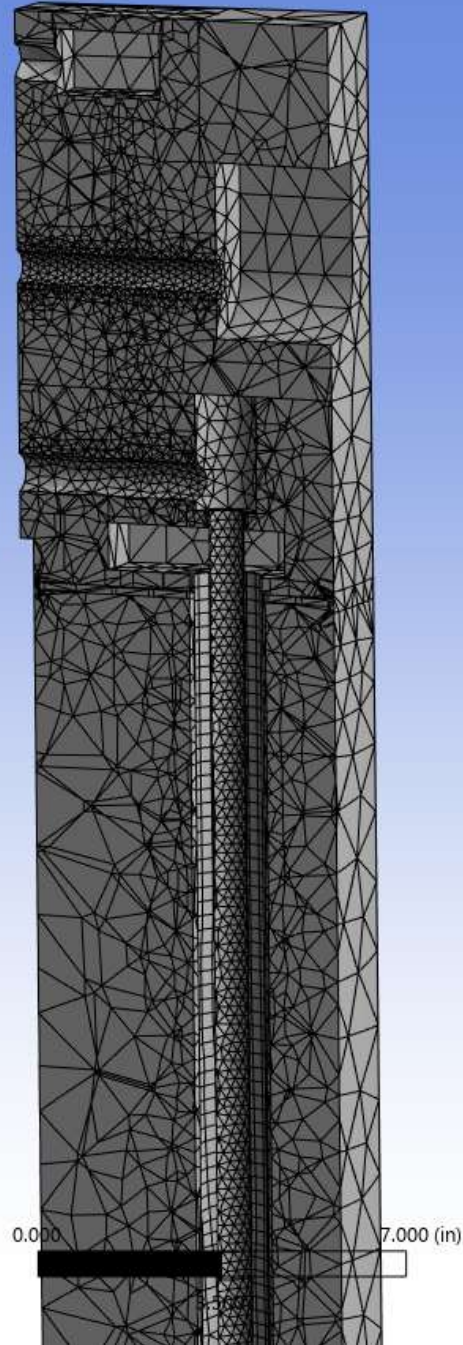


Figure 142 Segment Mesh, Section

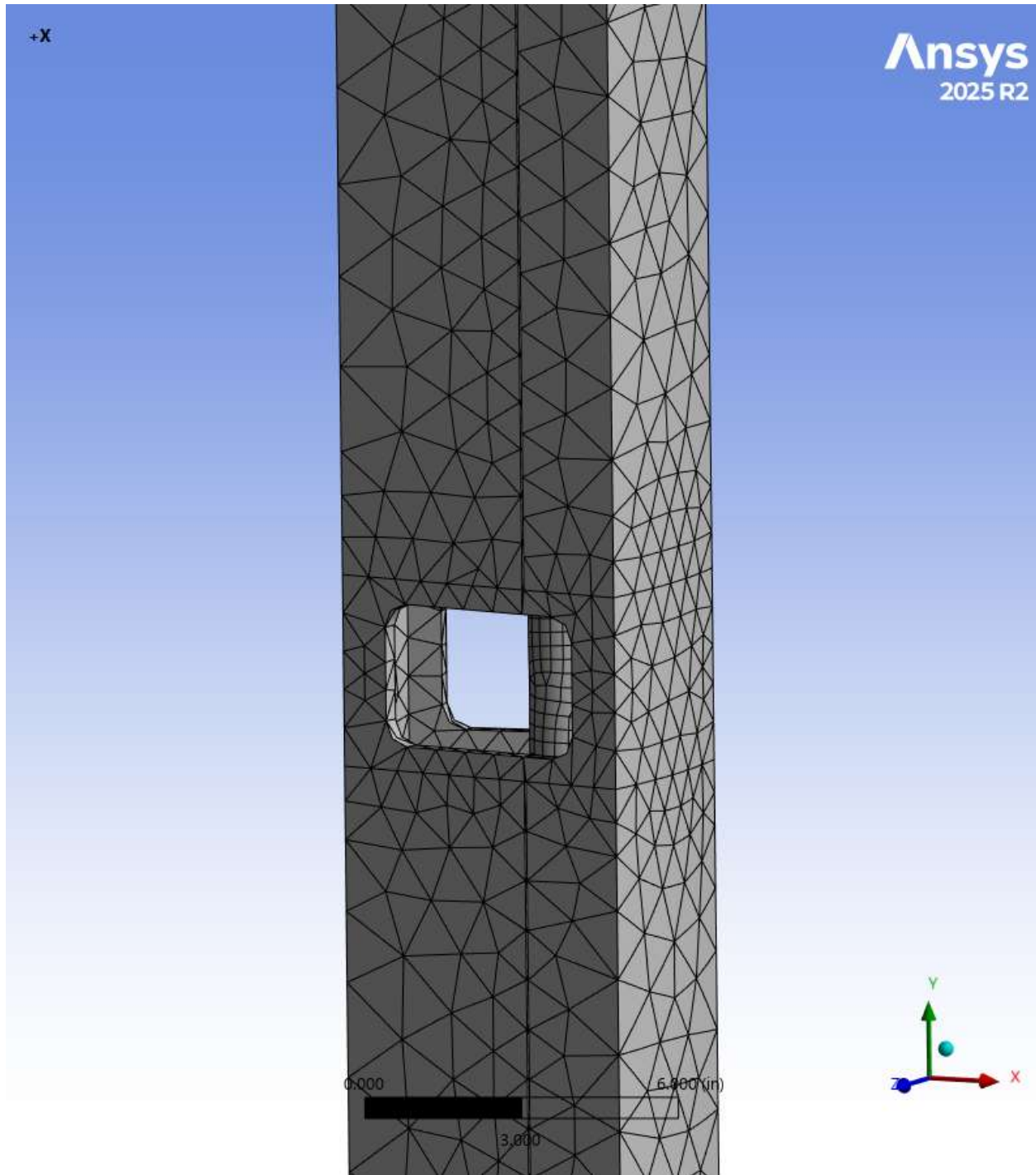


Figure 143 Segment Mesh

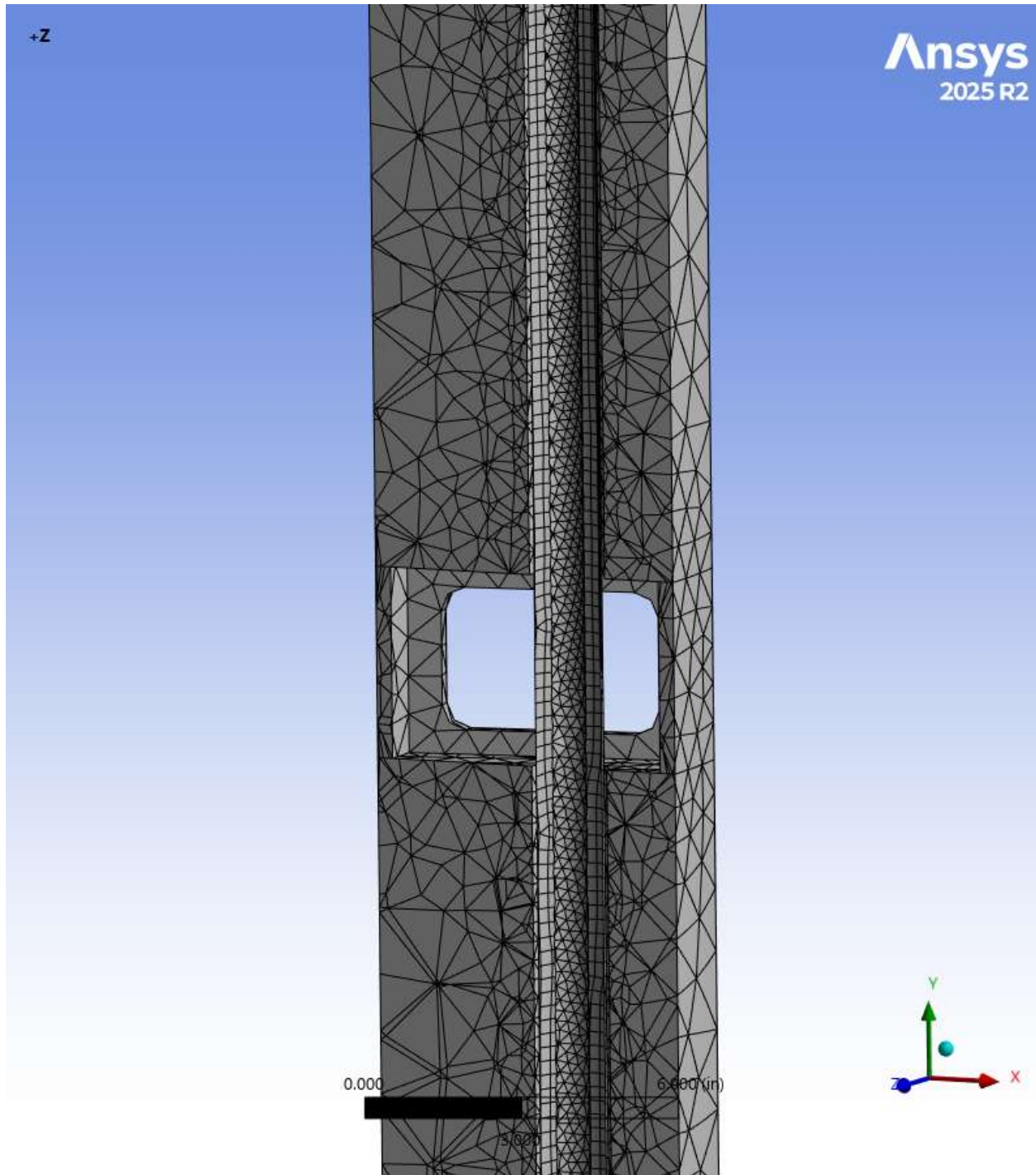


Figure 144 Segment Mesh, Section

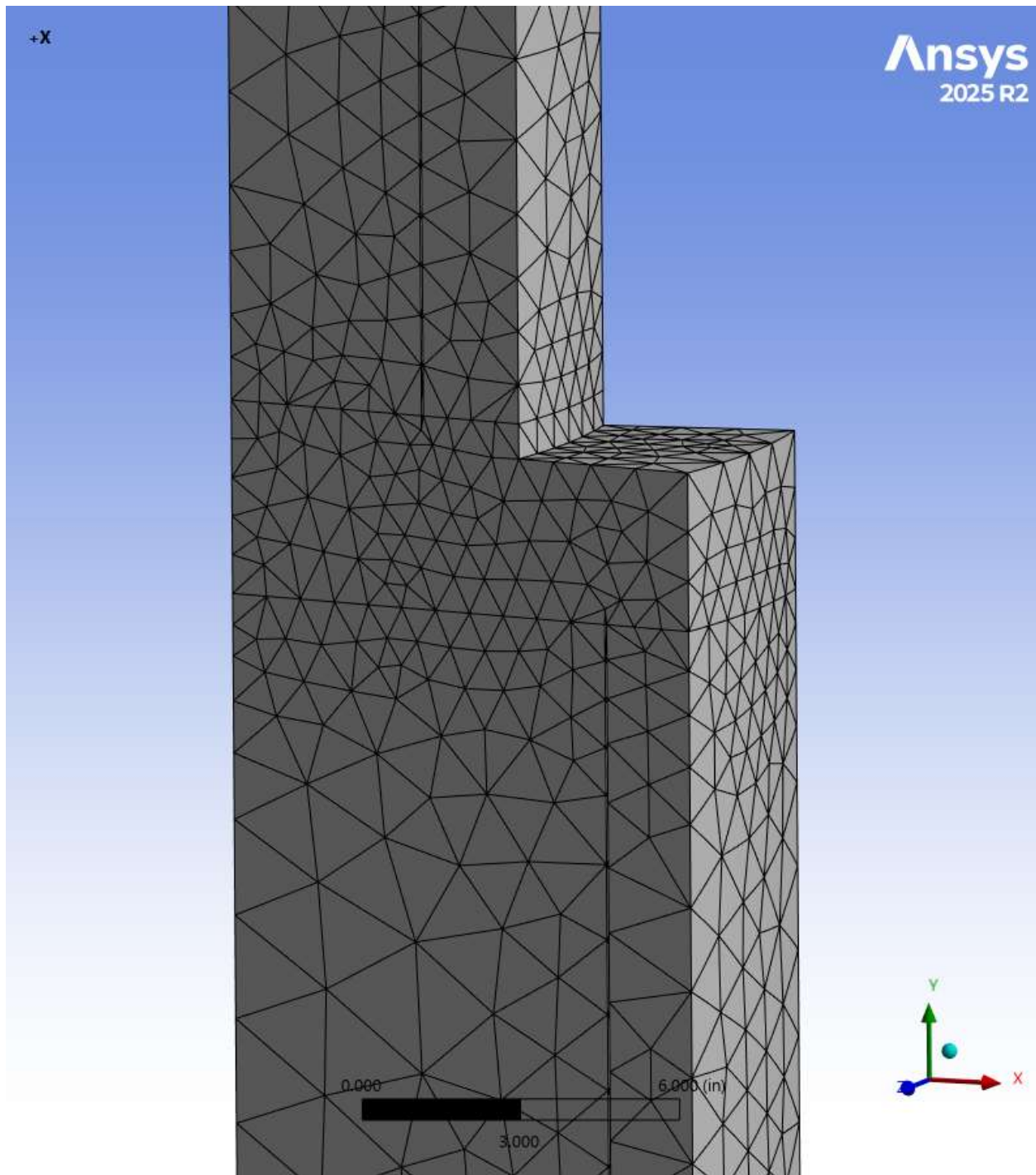


Figure 145 Segment Mesh

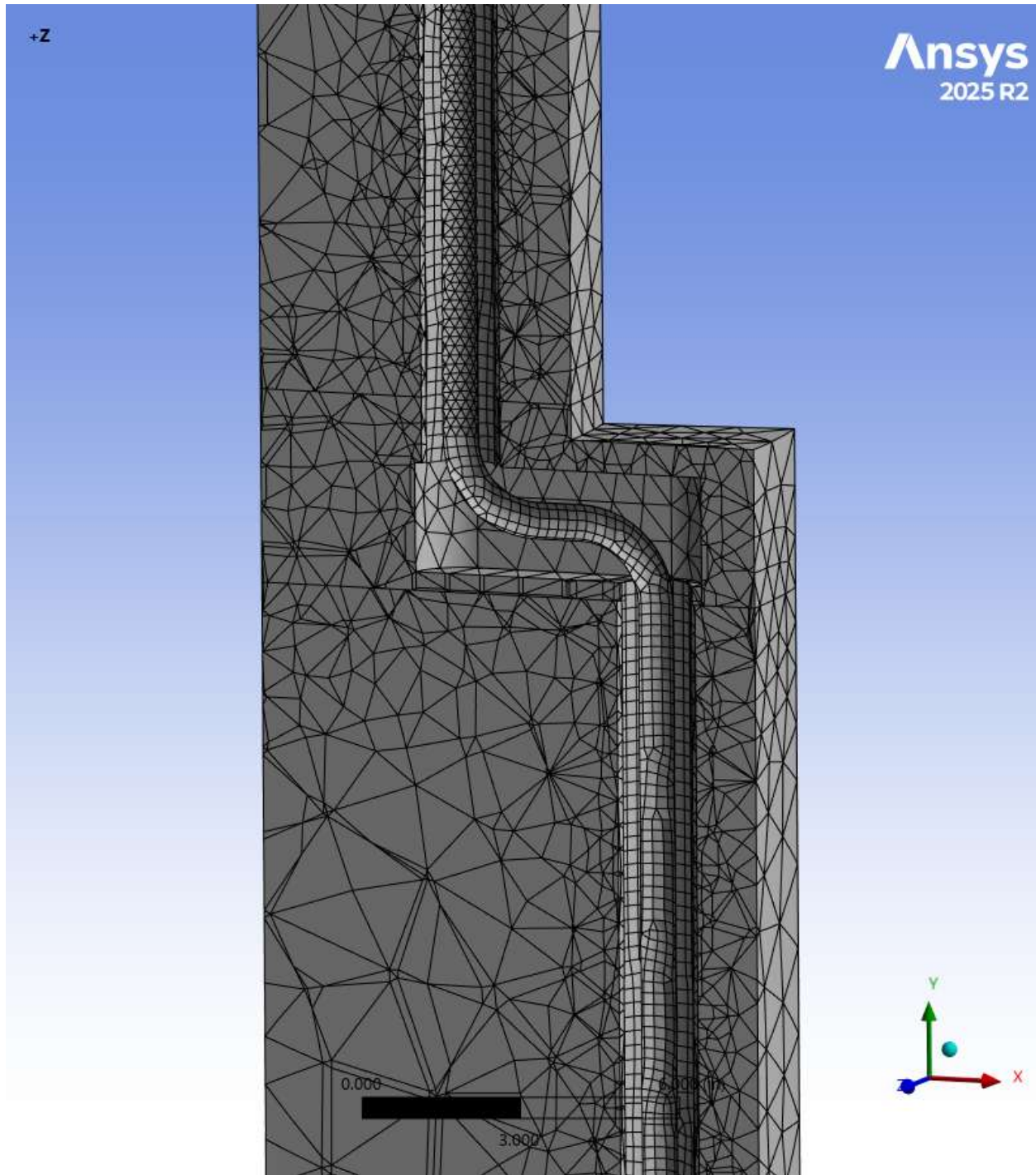


Figure 146 Segment Mesh, Section

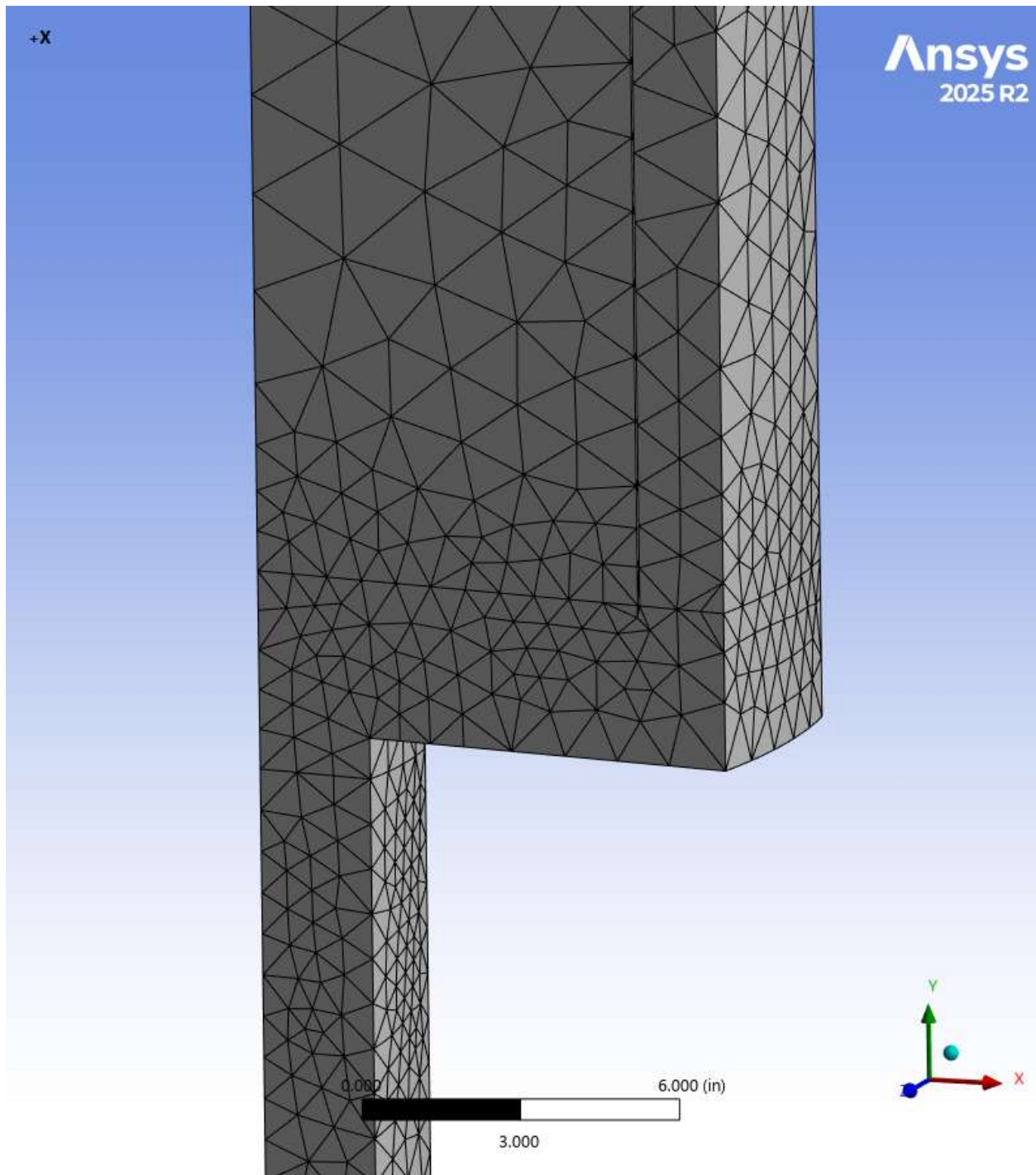


Figure 147 Segment Mesh

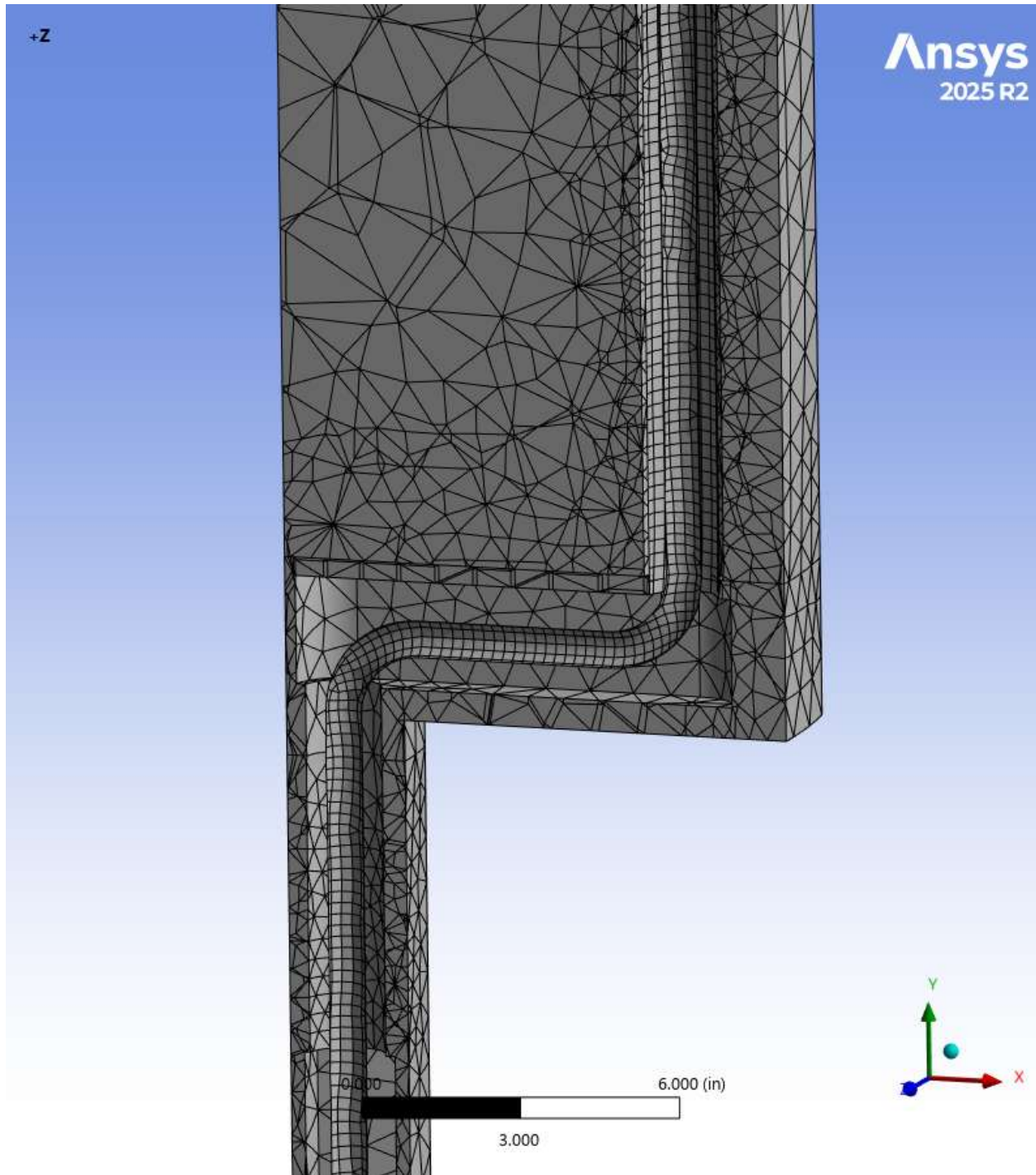


Figure 148 Segment Mesh, Section

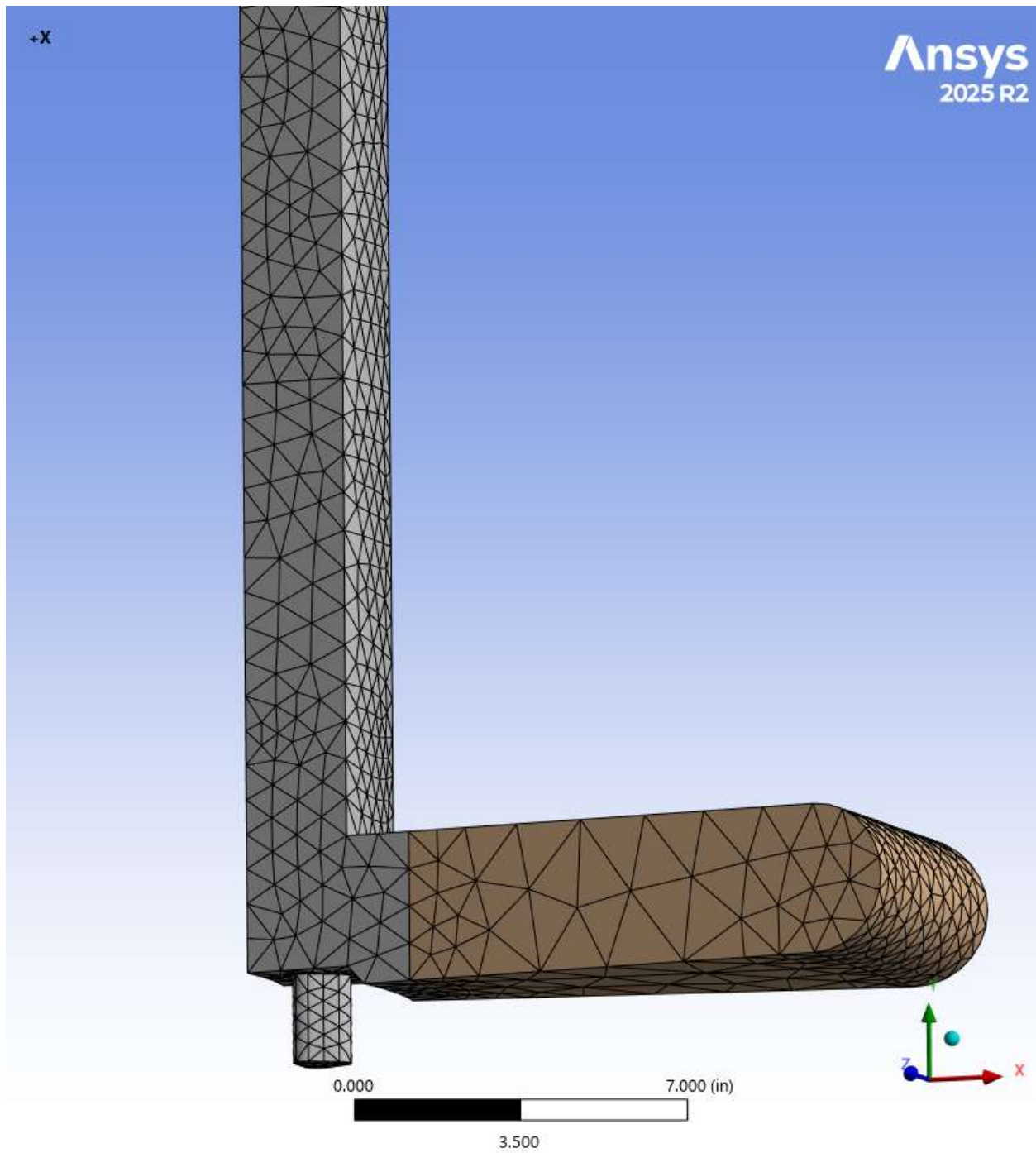


Figure 149 Segment Mesh

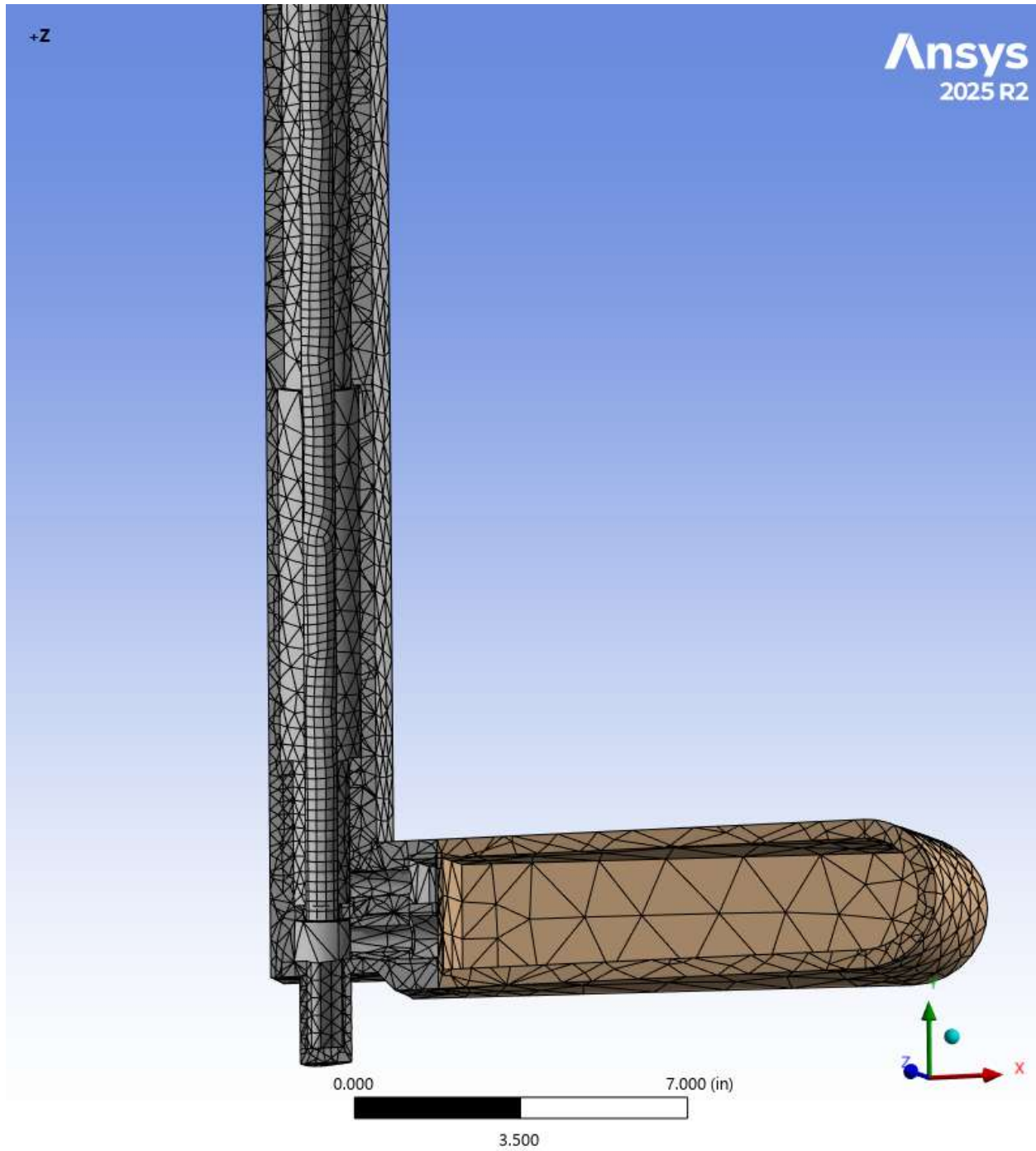


Figure 150 Segment Mesh, Section

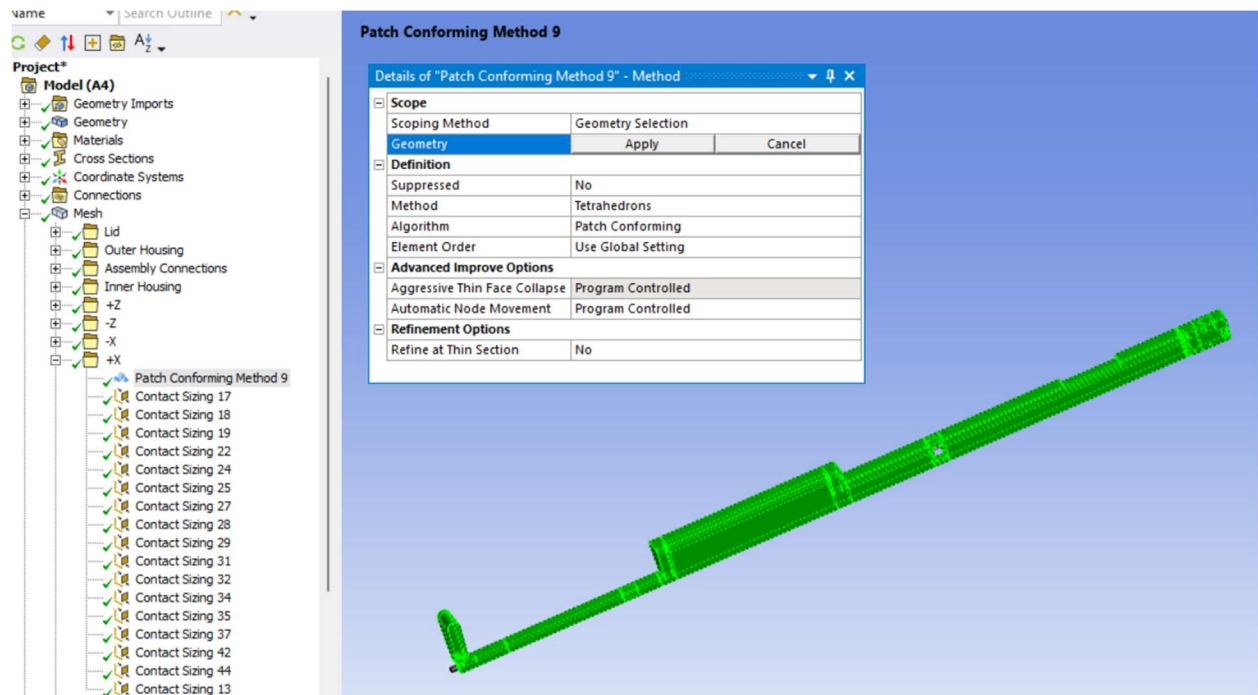


Figure 151 Segment Mesh Method

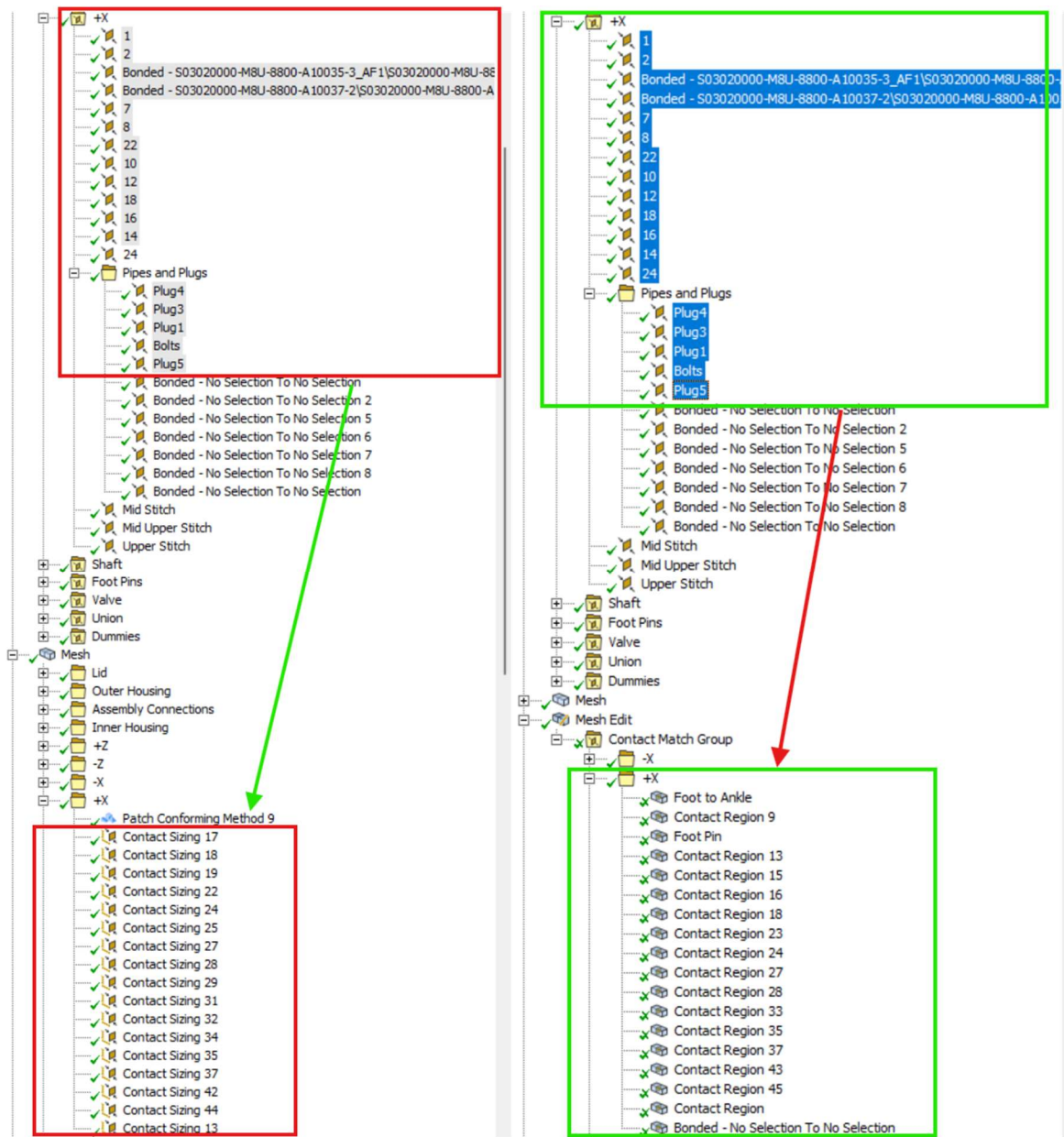


Figure 152 Segment Contacts to Contact Sizing and Contact Matching

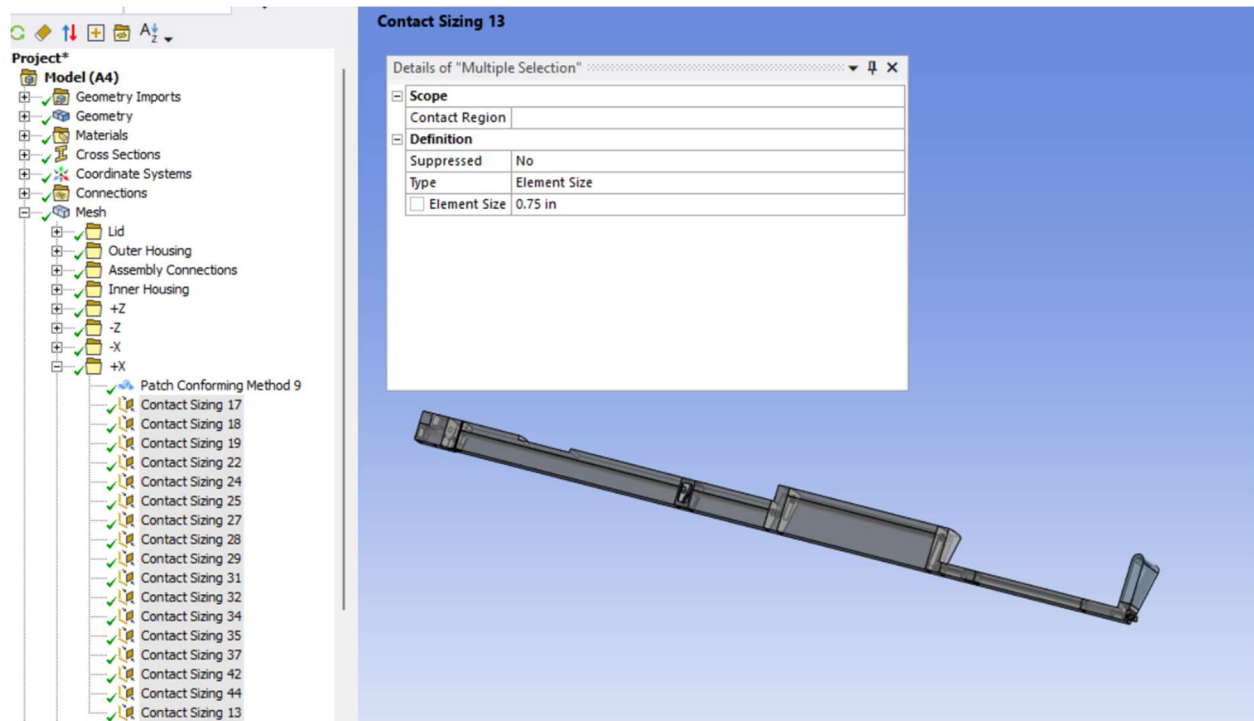


Figure 153 Segment Contact Sizing

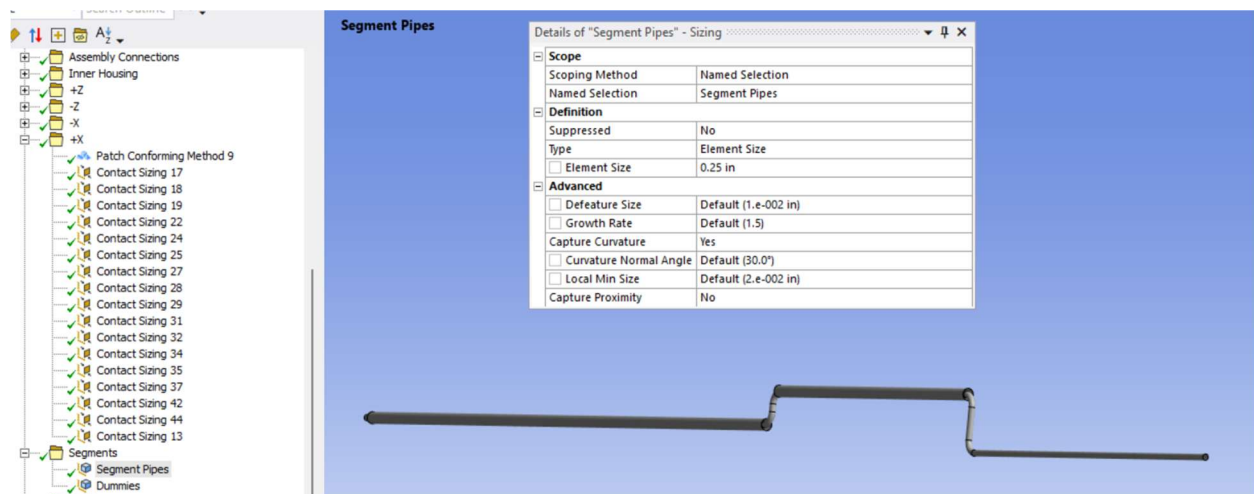


Figure 154 Segment Pipe Mesh Sizing

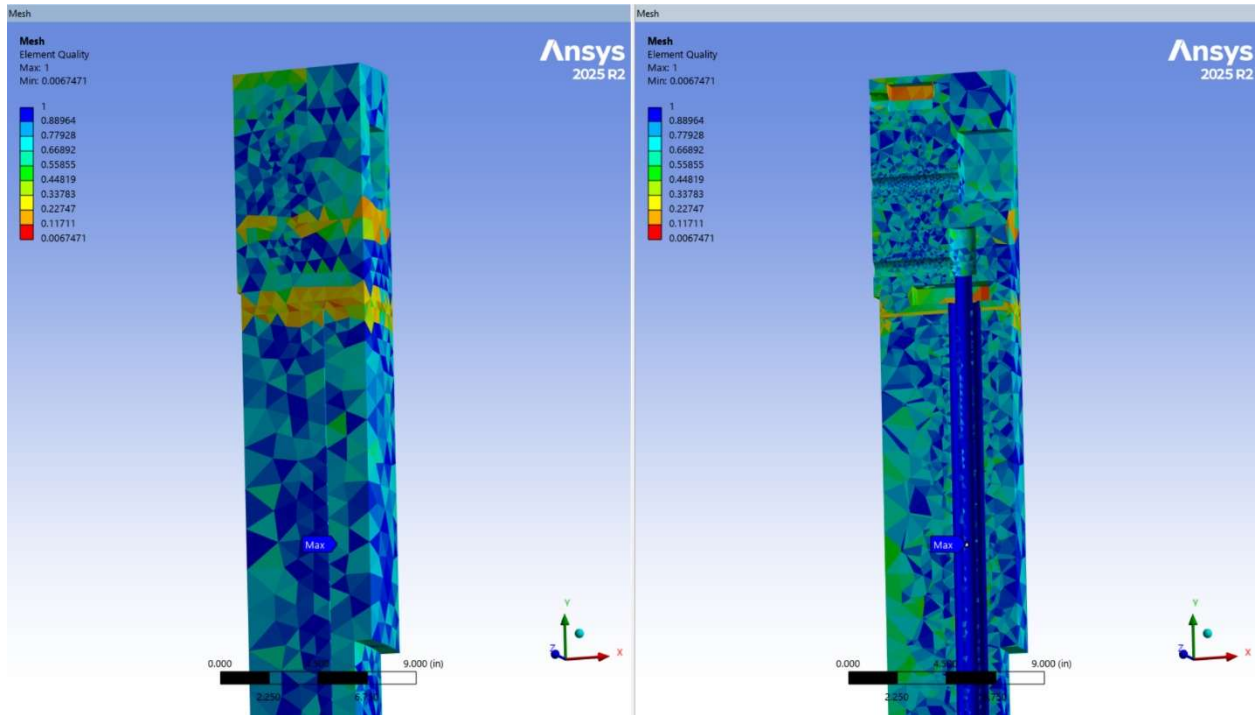


Figure 155 Segment Mesh Quality

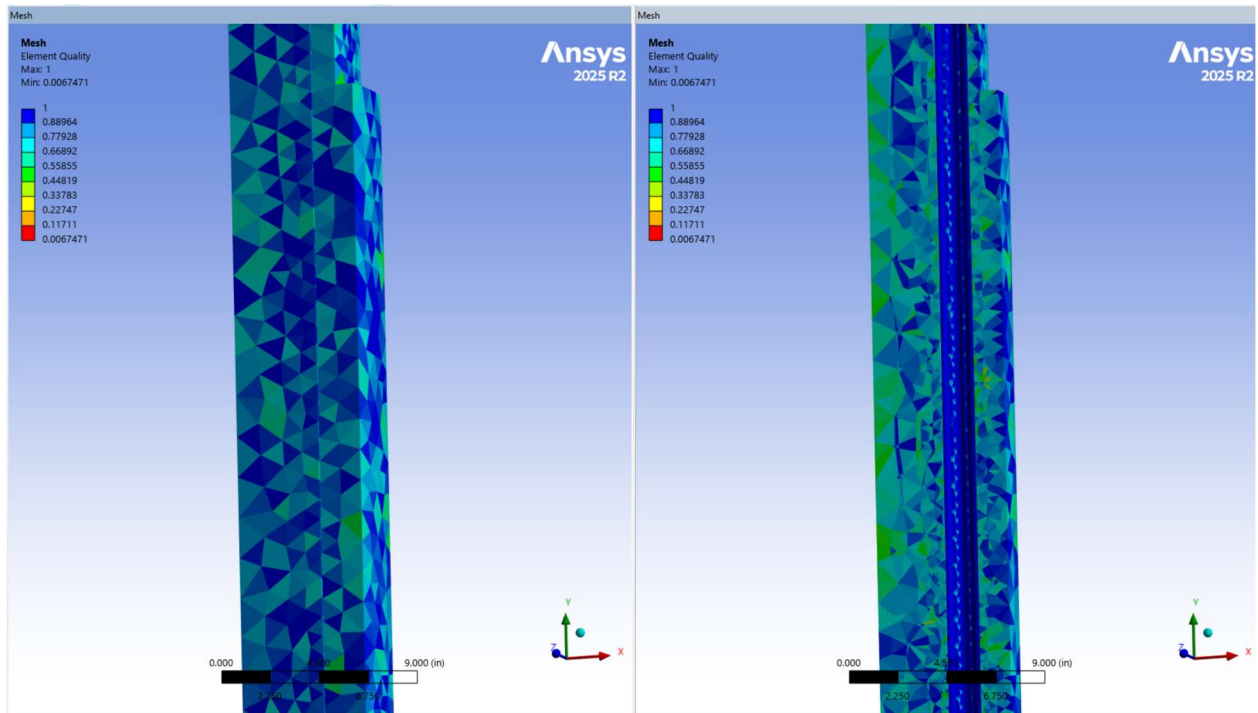


Figure 156 Segment Mesh Quality

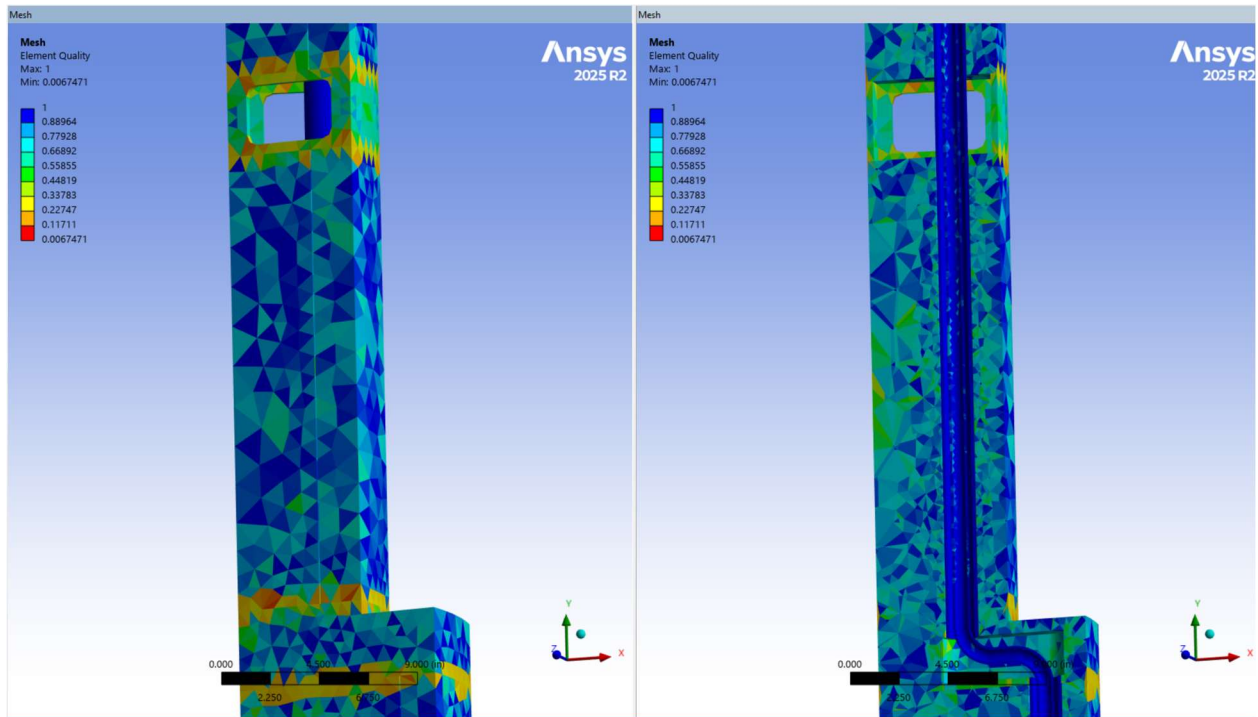


Figure 157 Segment Mesh Quality

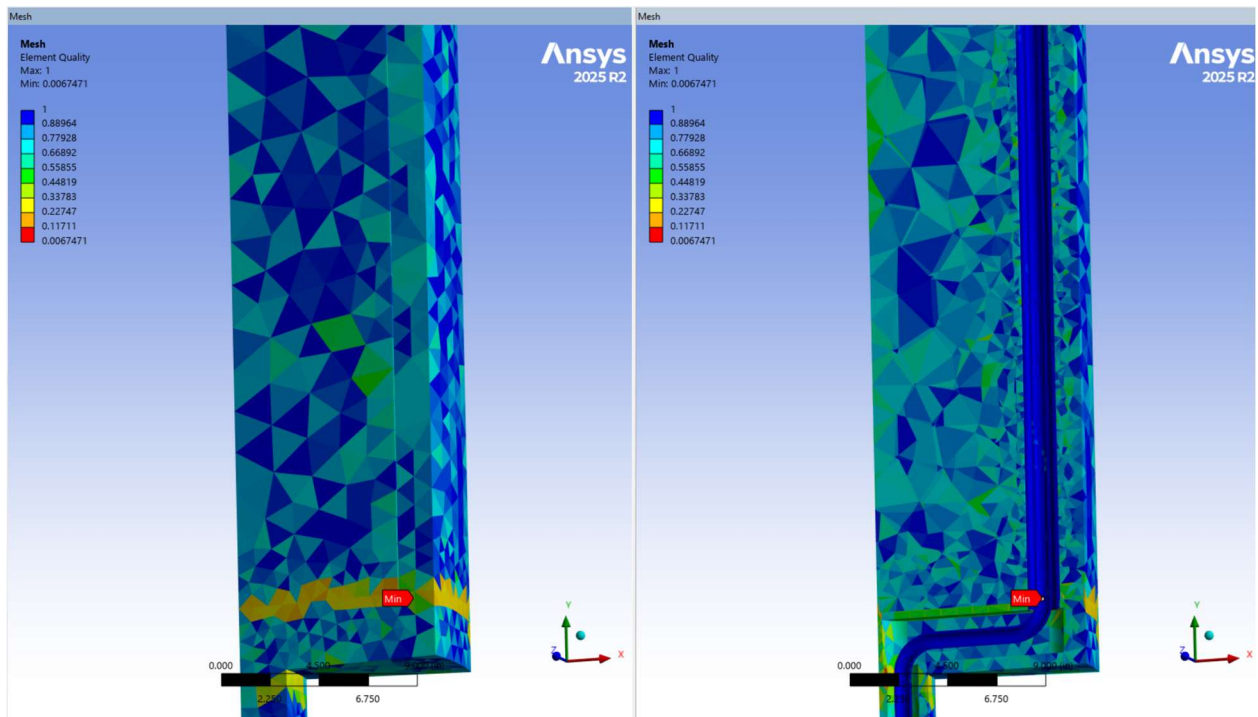


Figure 158 Segment Mesh Quality

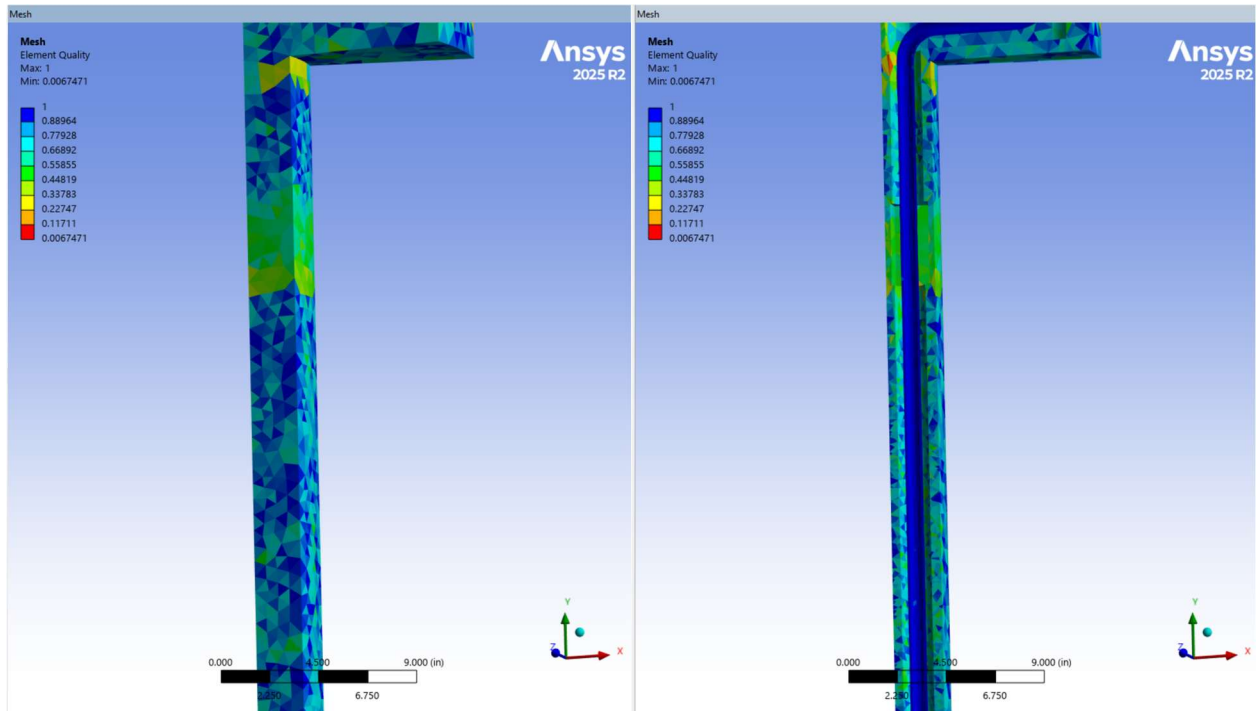


Figure 159 Segment Mesh Quality

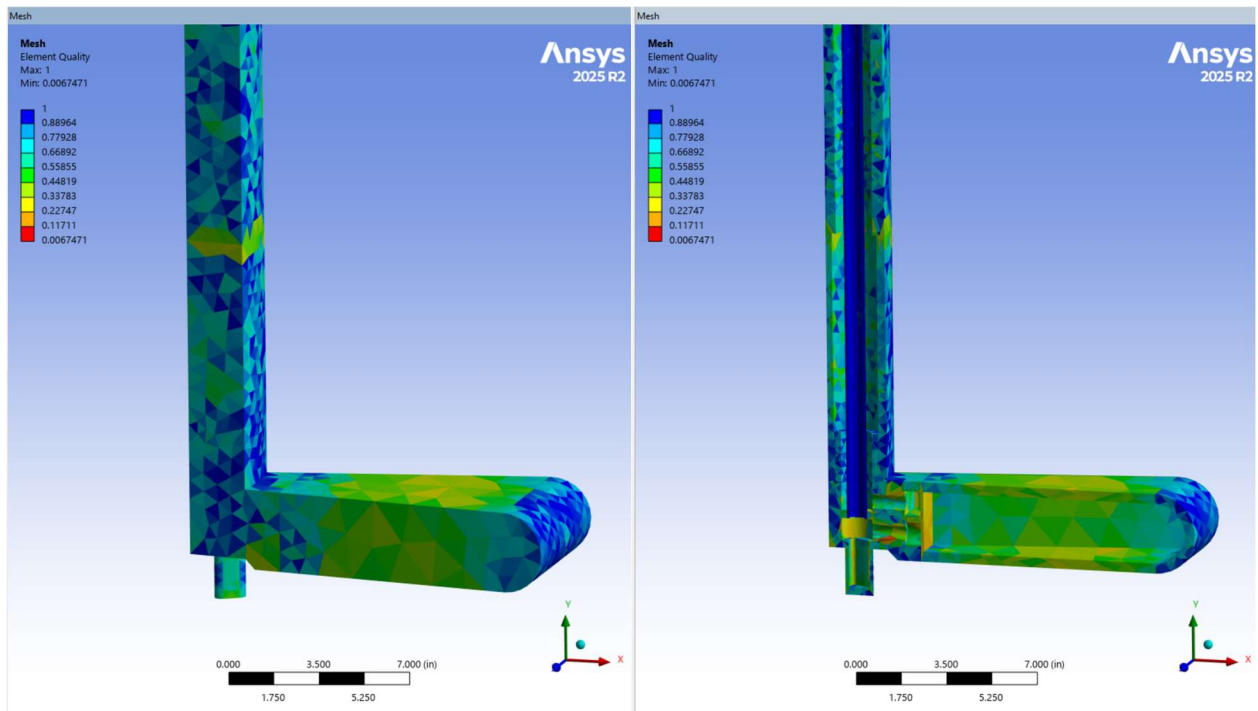


Figure 160 Segment Mesh Quality

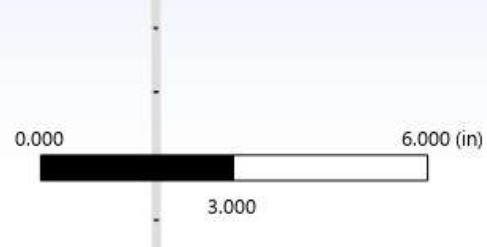
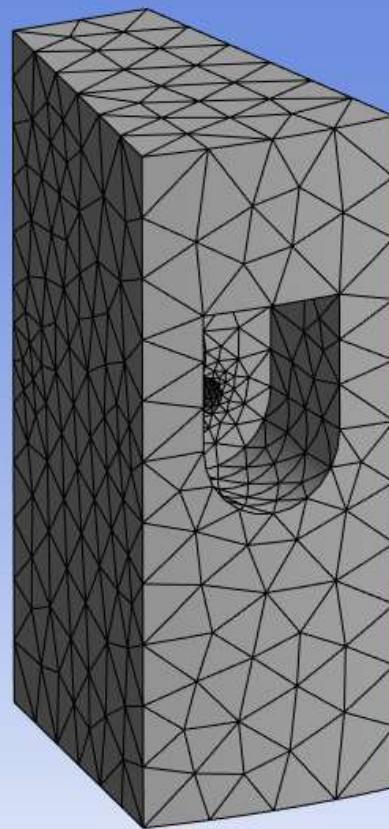


Figure 161 Dummy Segment Mesh

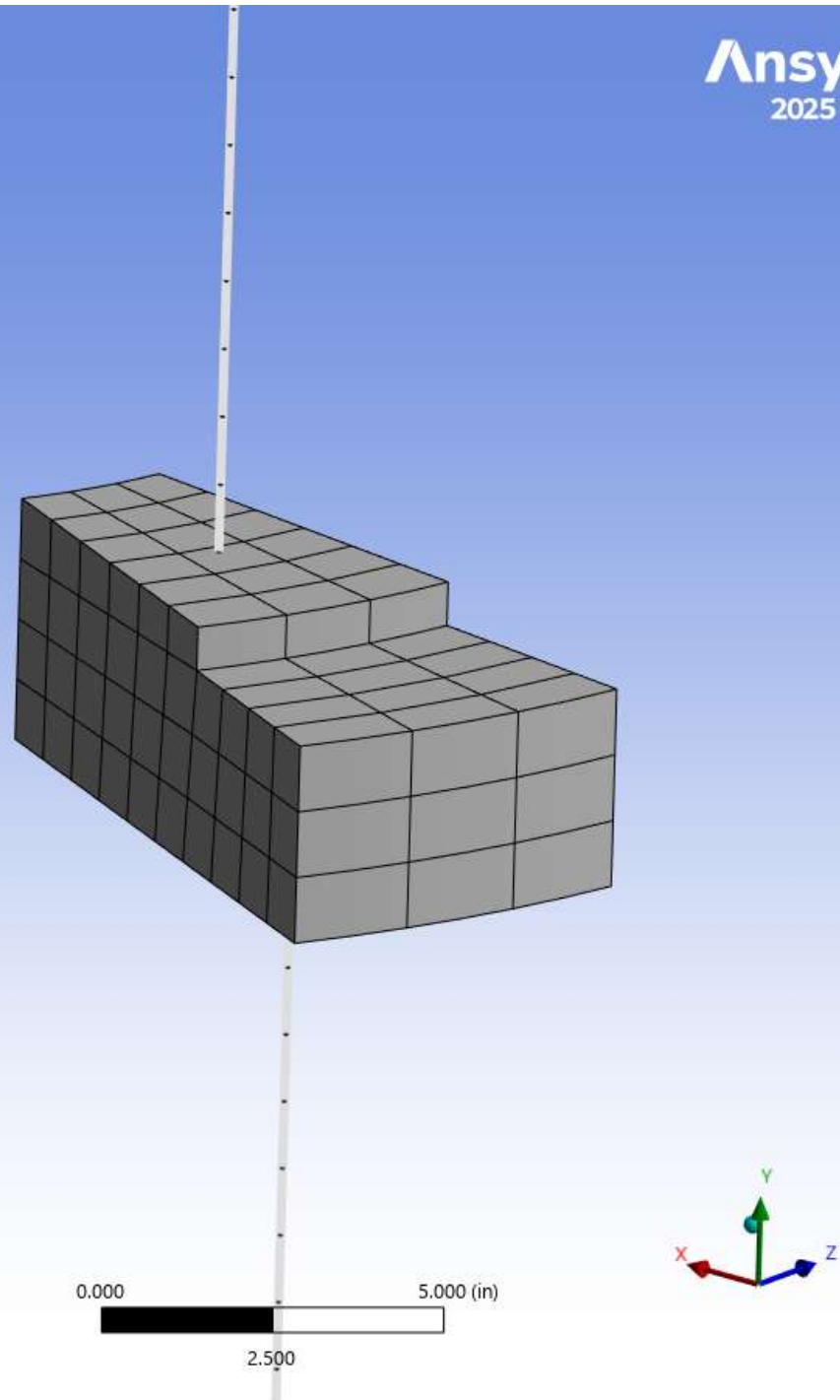


Figure 162 Dummy Segment Mesh

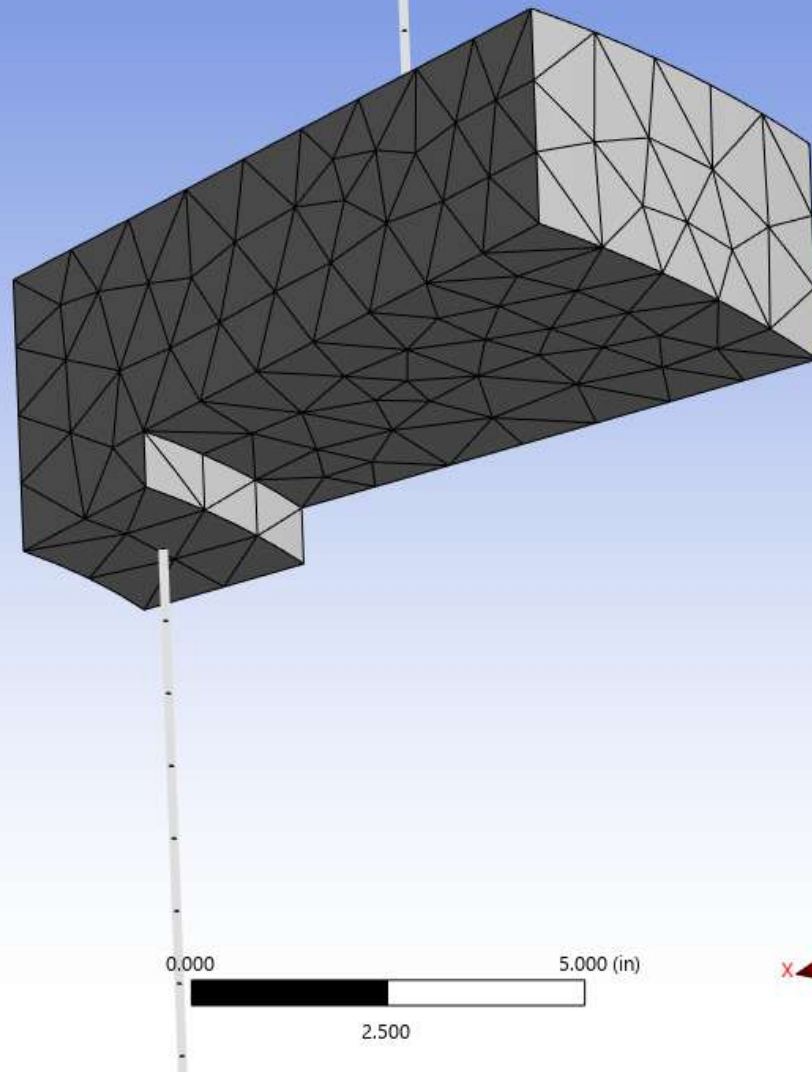


Figure 163 Dummy Segment Mesh

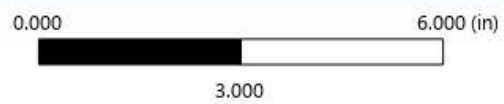
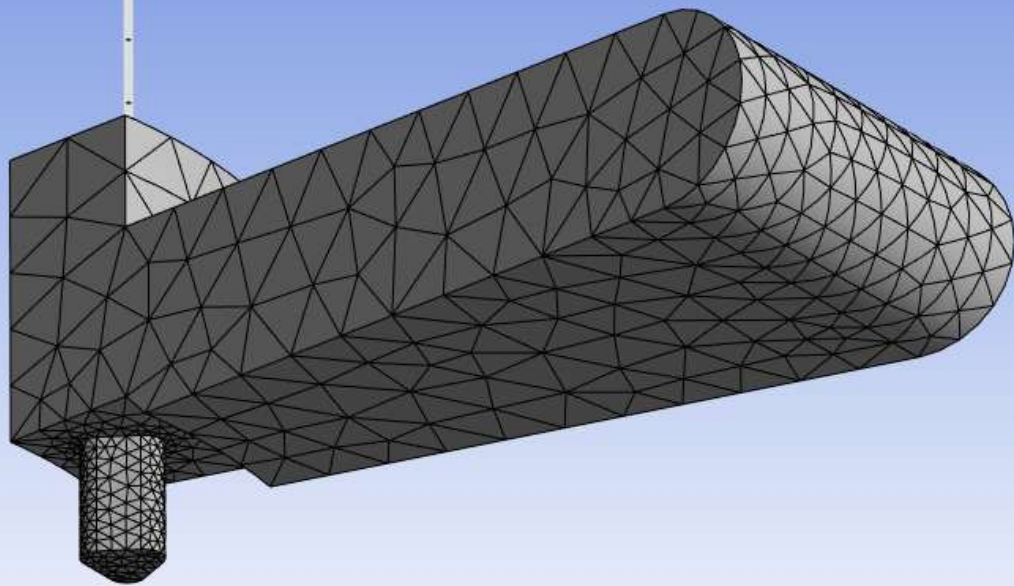


Figure 164 Dummy Segment Mesh

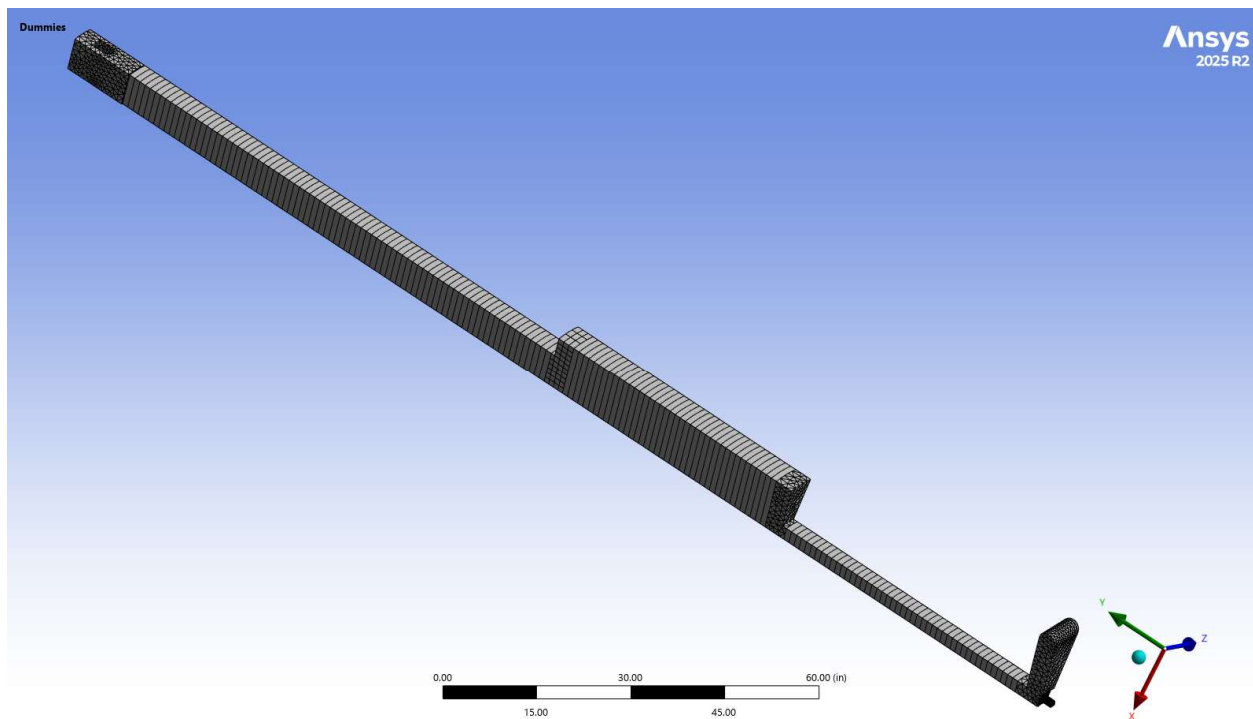


Figure 165 Dummy Segment Mesh

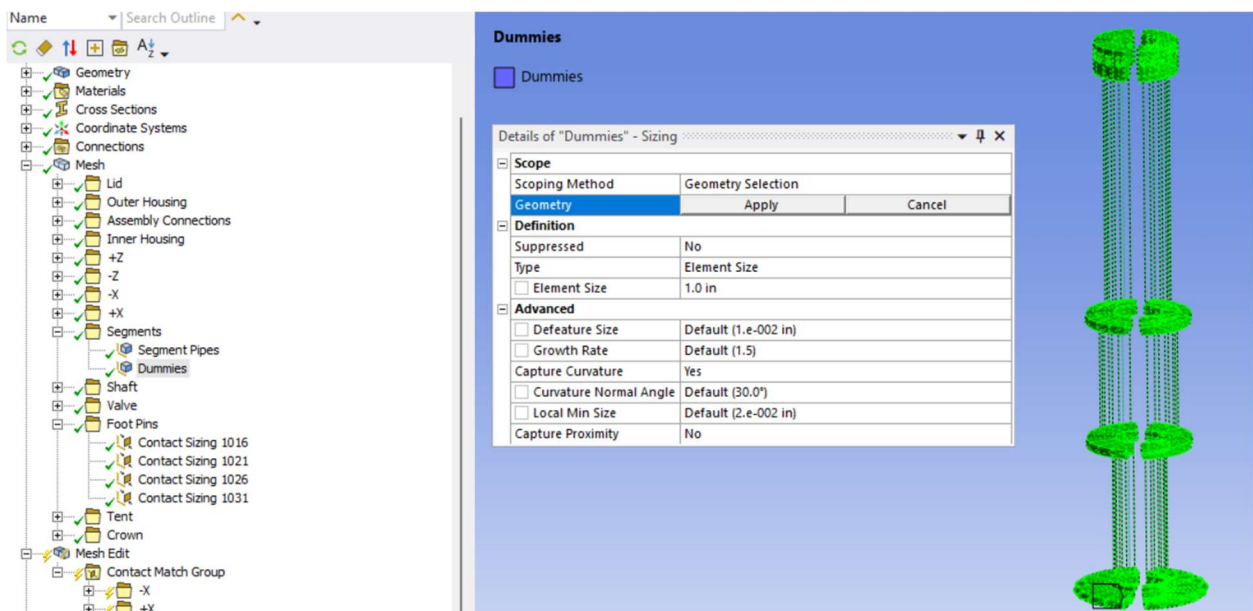


Figure 166 Dummy Segment Mesh Sizing

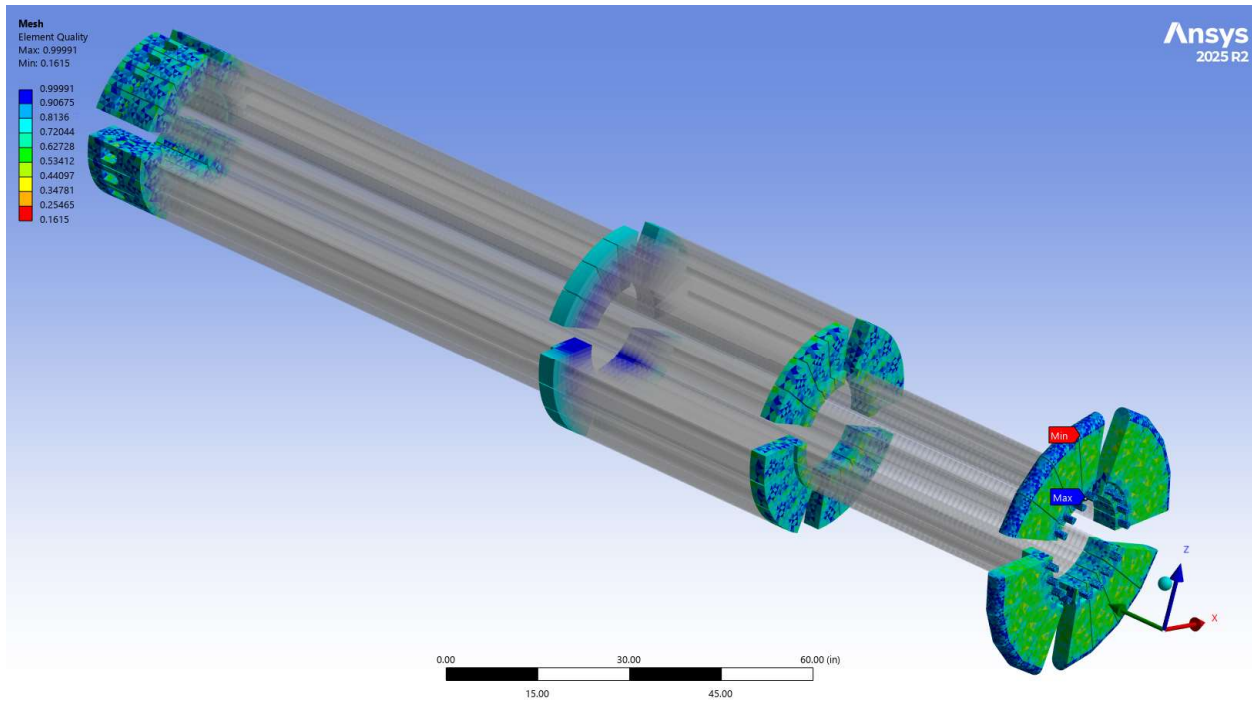


Figure 167 Dummy Segment Mesh Quality

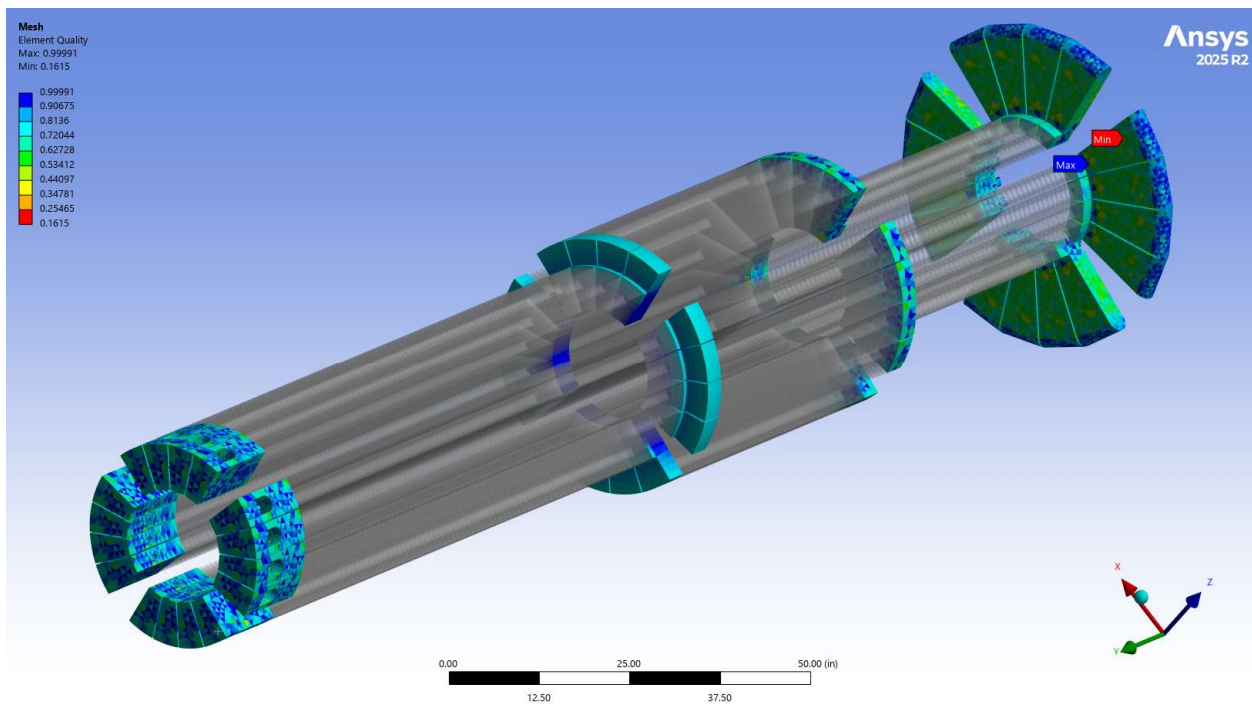


Figure 168 Dummy Segment Mesh Quality

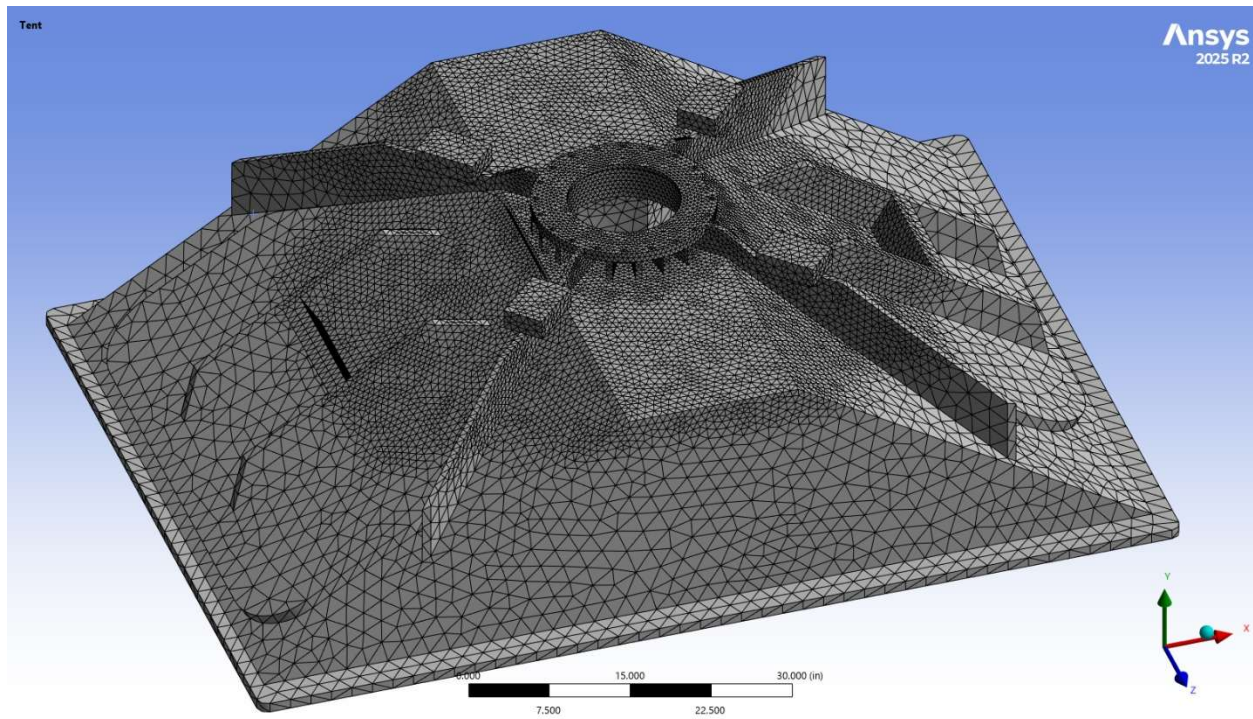


Figure 169 Tent Mesh

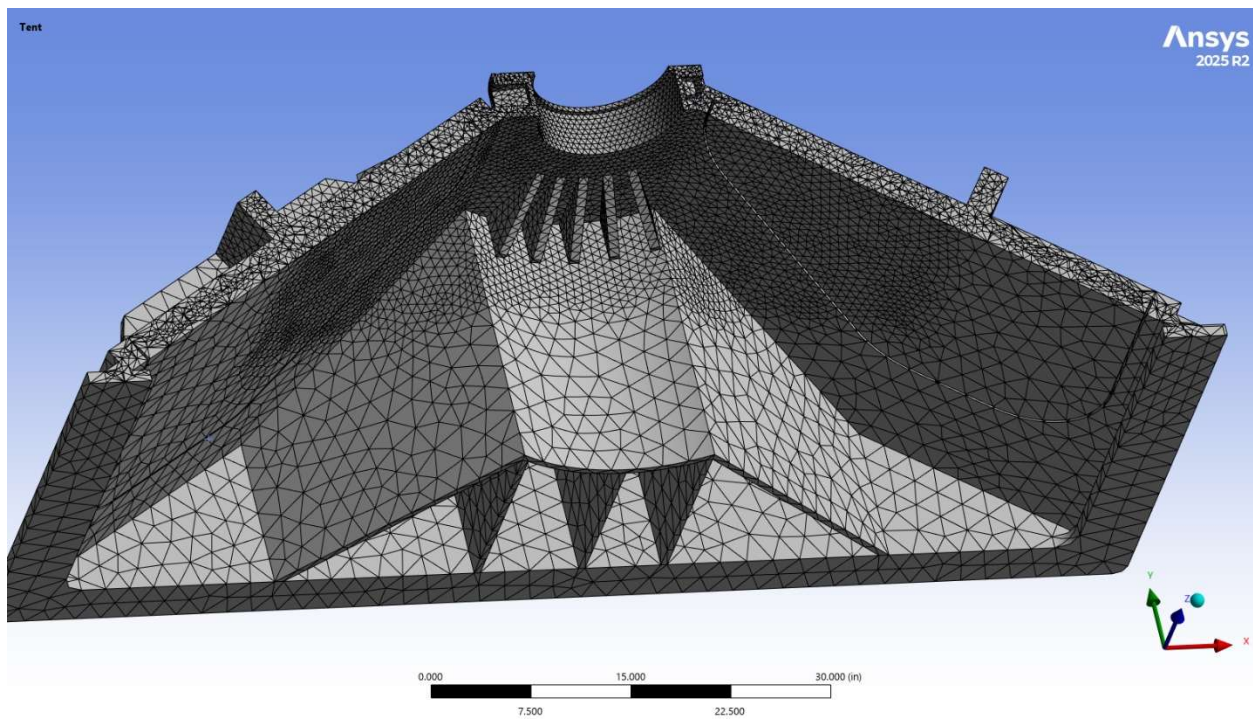


Figure 170 Tent Mesh, Section

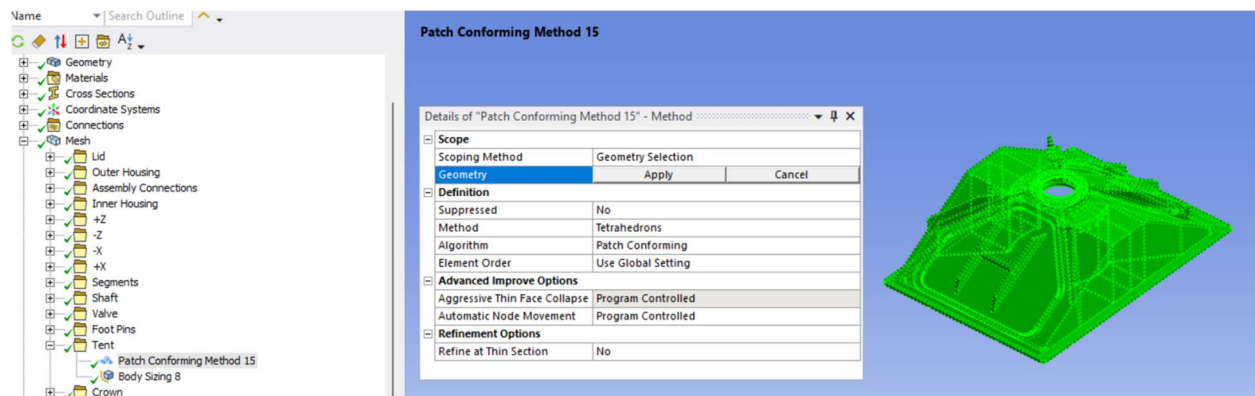


Figure 171 Tent Mesh Method

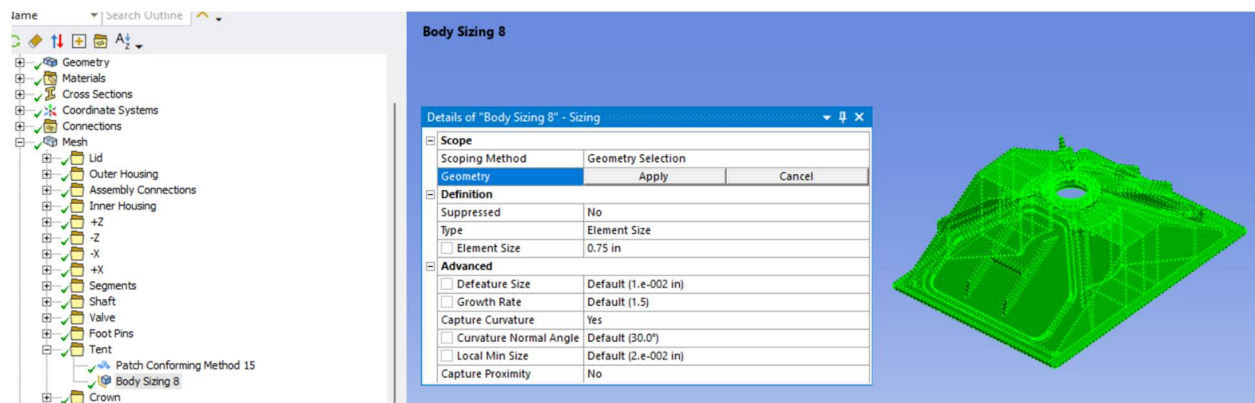


Figure 172 Tent Mesh Sizing

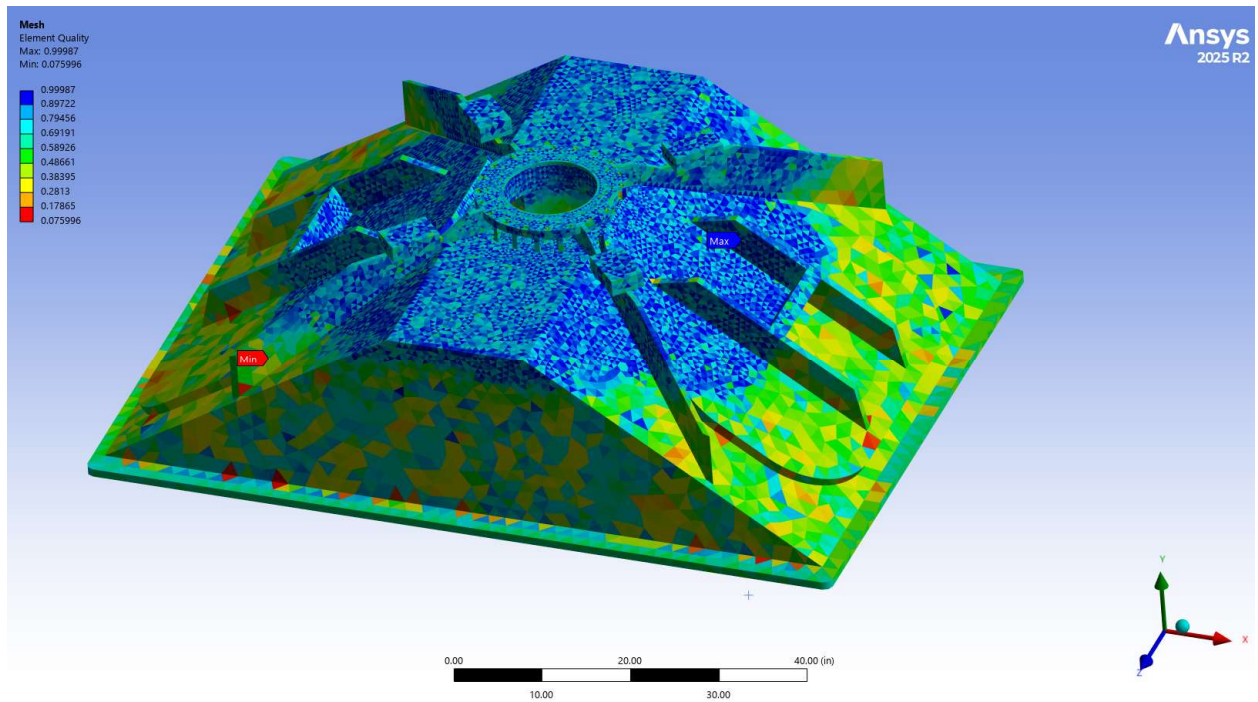
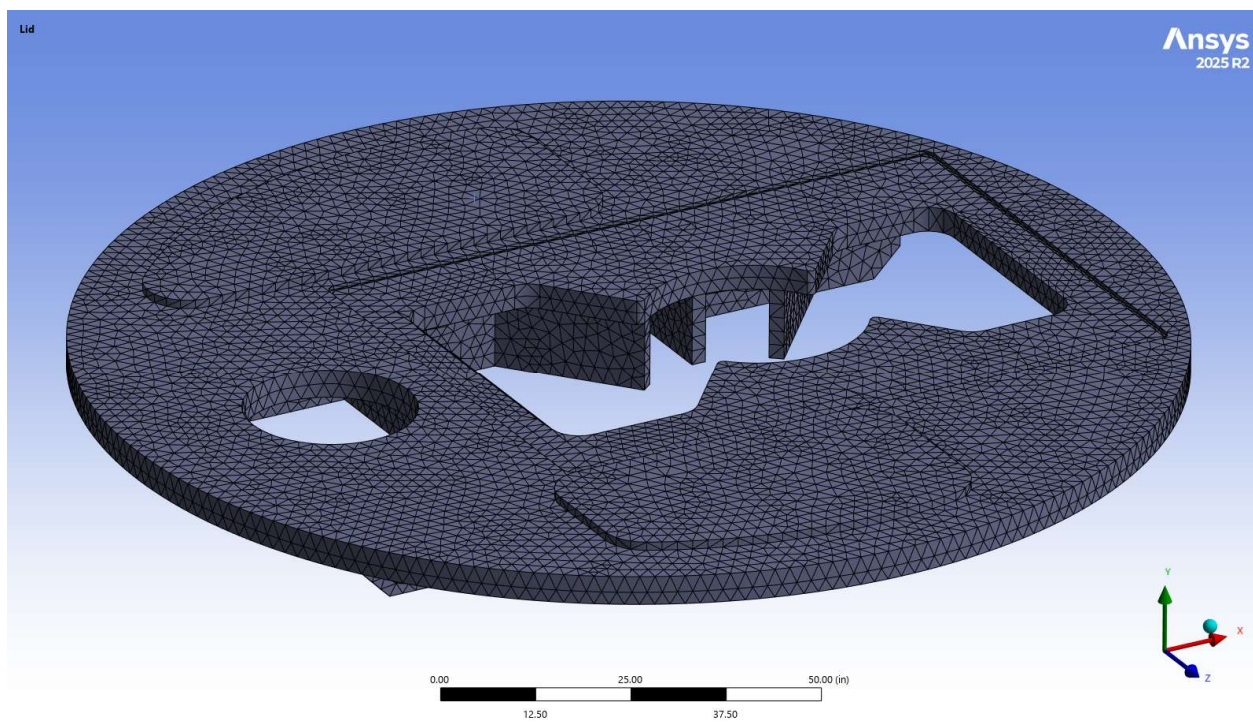
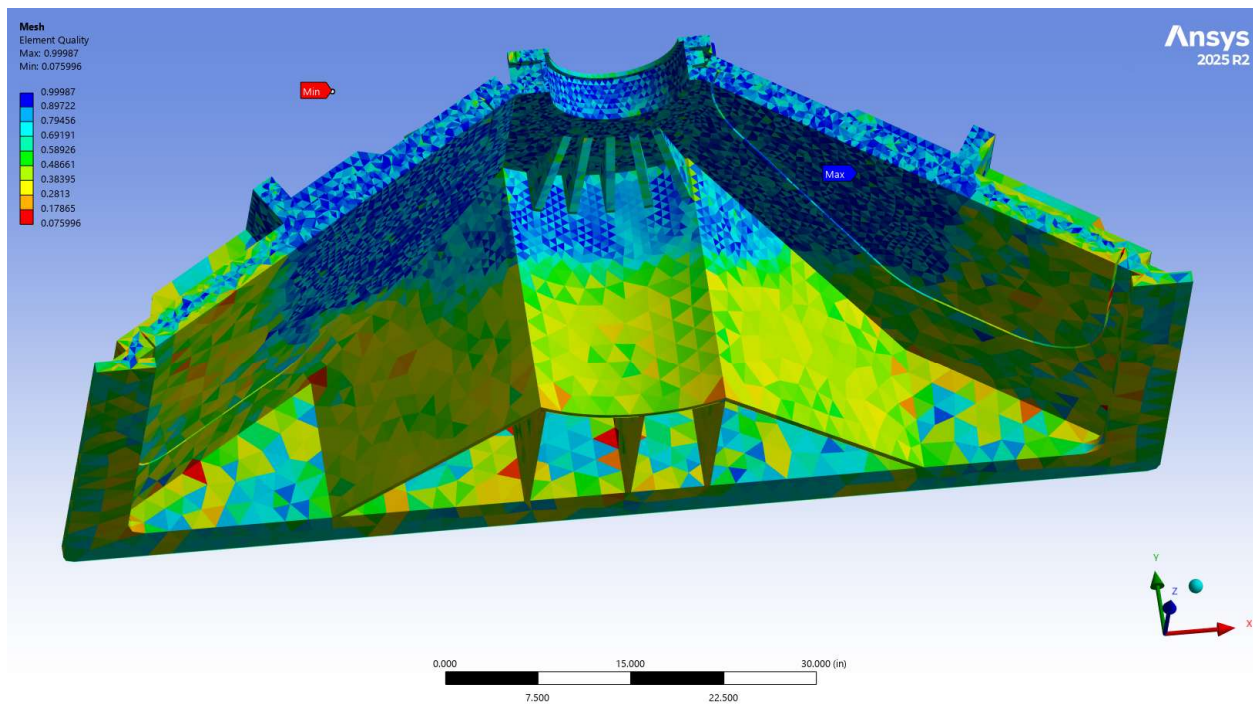


Figure 173 Tent Mesh Quality



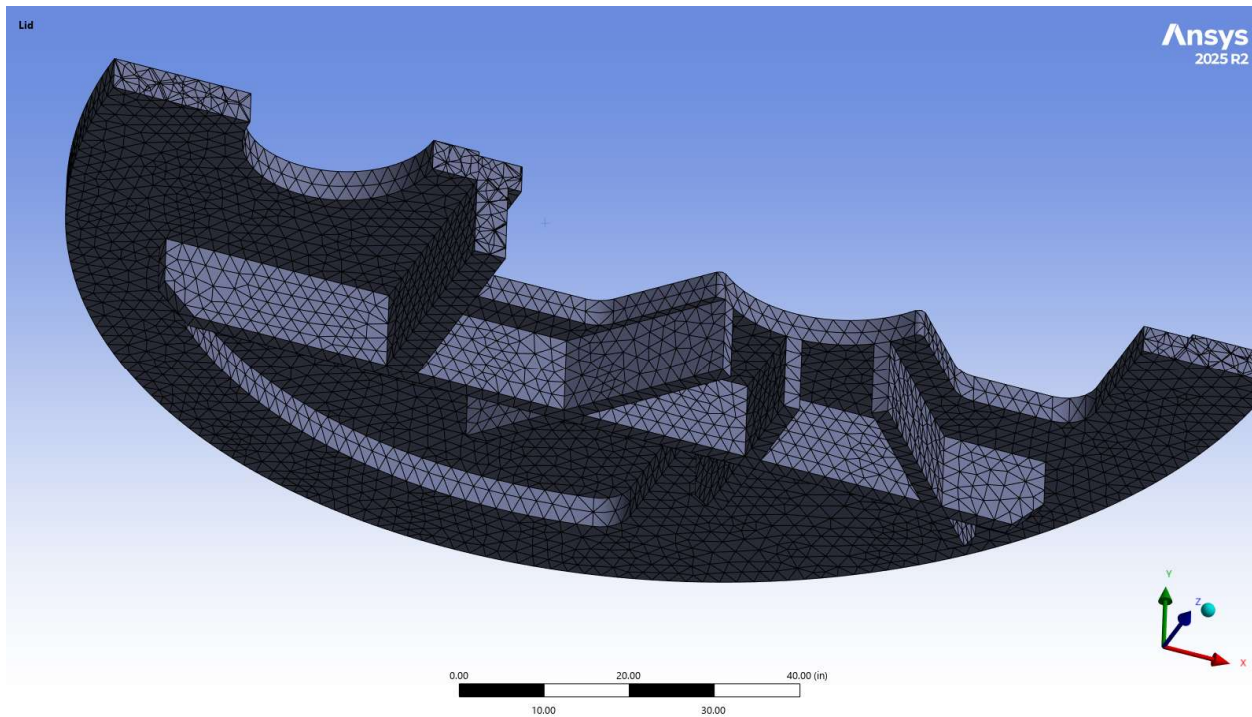


Figure 176 Lid Mesh, Section

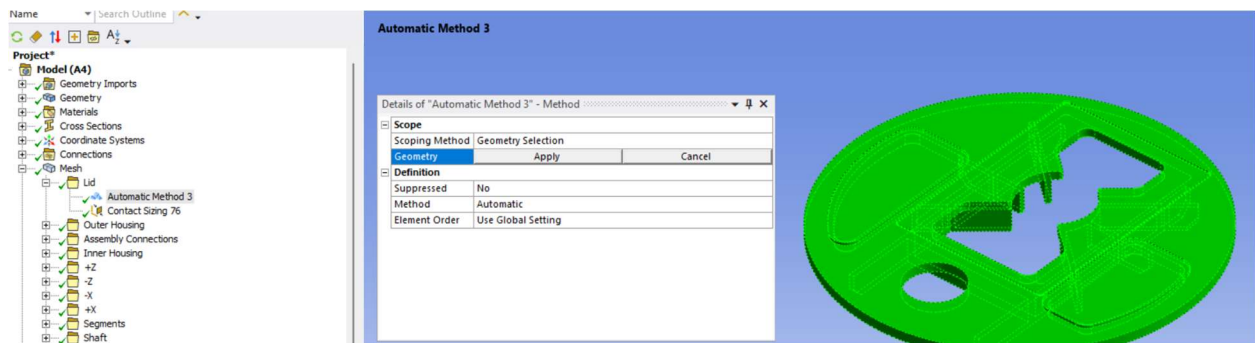
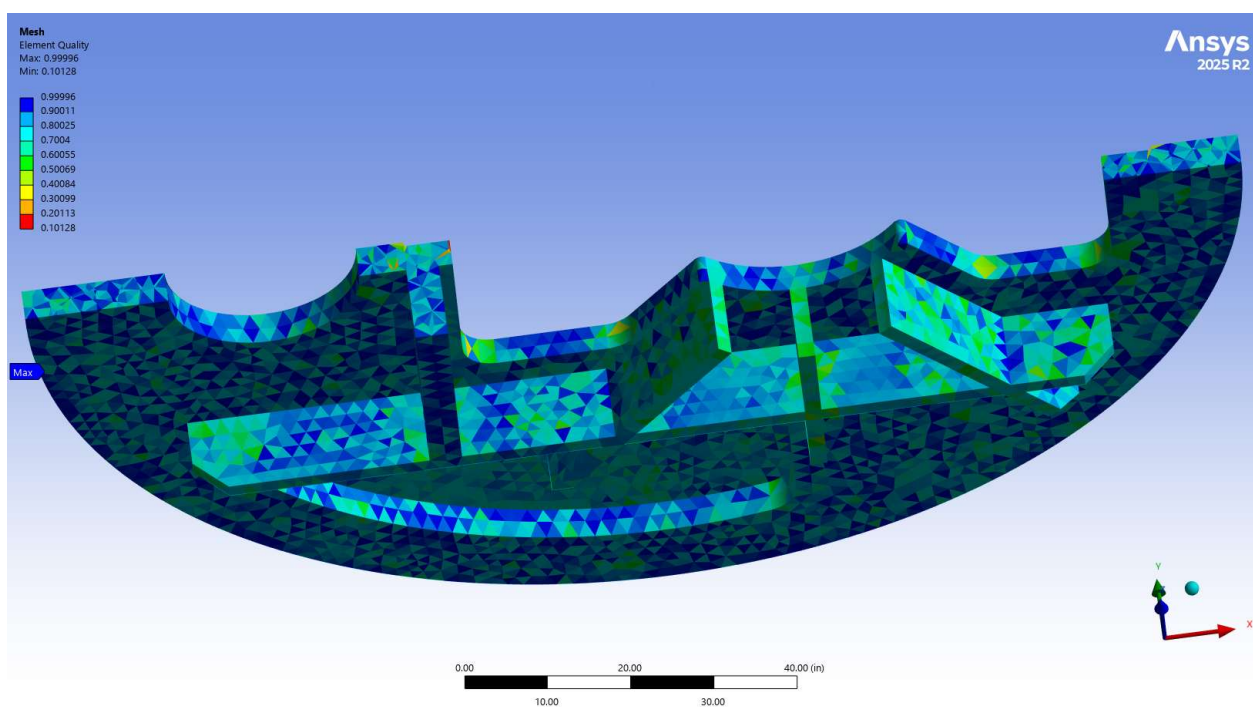
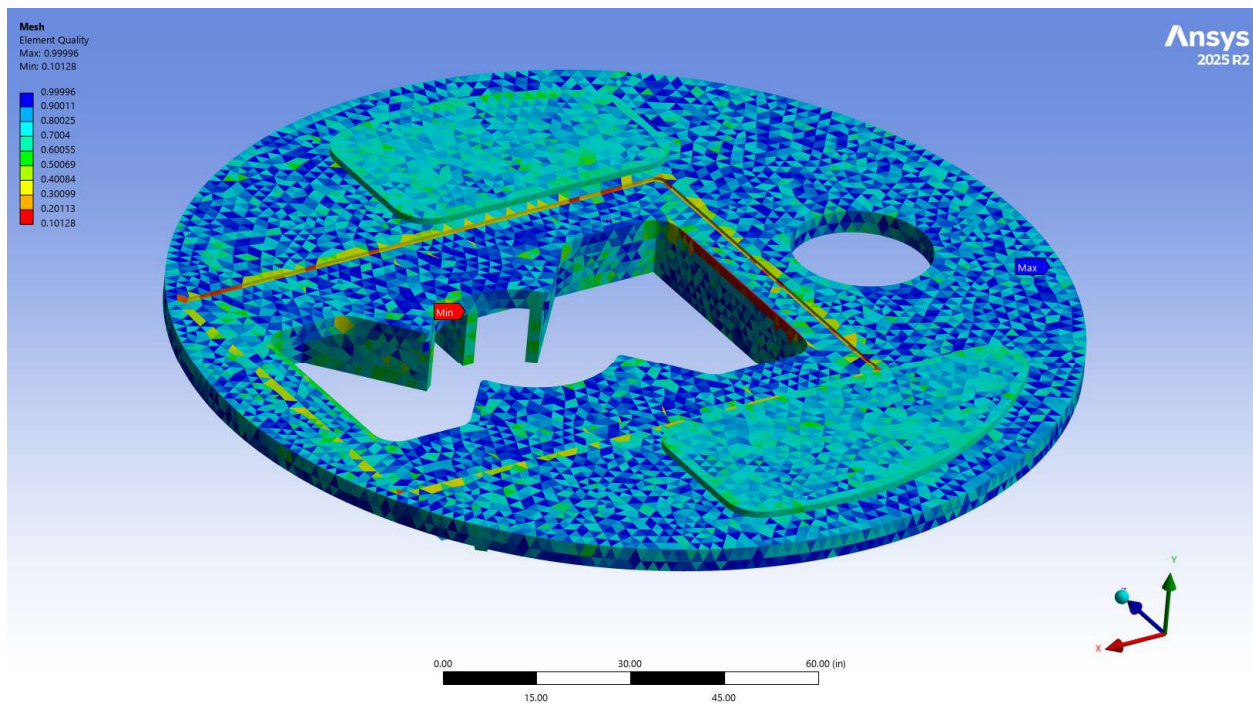


Figure 177 Lid Mesh Method



Figure 178 Lid, Tent Contact Sizing



4.3.2 Target Segment

The Target Segment model is meshed with the intent of obtaining accurate stress values that the full assembly can't provide with its coarser mesh. The top of the model is the segment bolt and water seal interface with the Crown. There is piping that runs through the segment and shell elements are used. The solid bodies of the Segment have complex geometry and mostly high order tetrahedral elements are used. Contact Sizing and a Contact Match Group are used with each weld interface and the water seal interface.

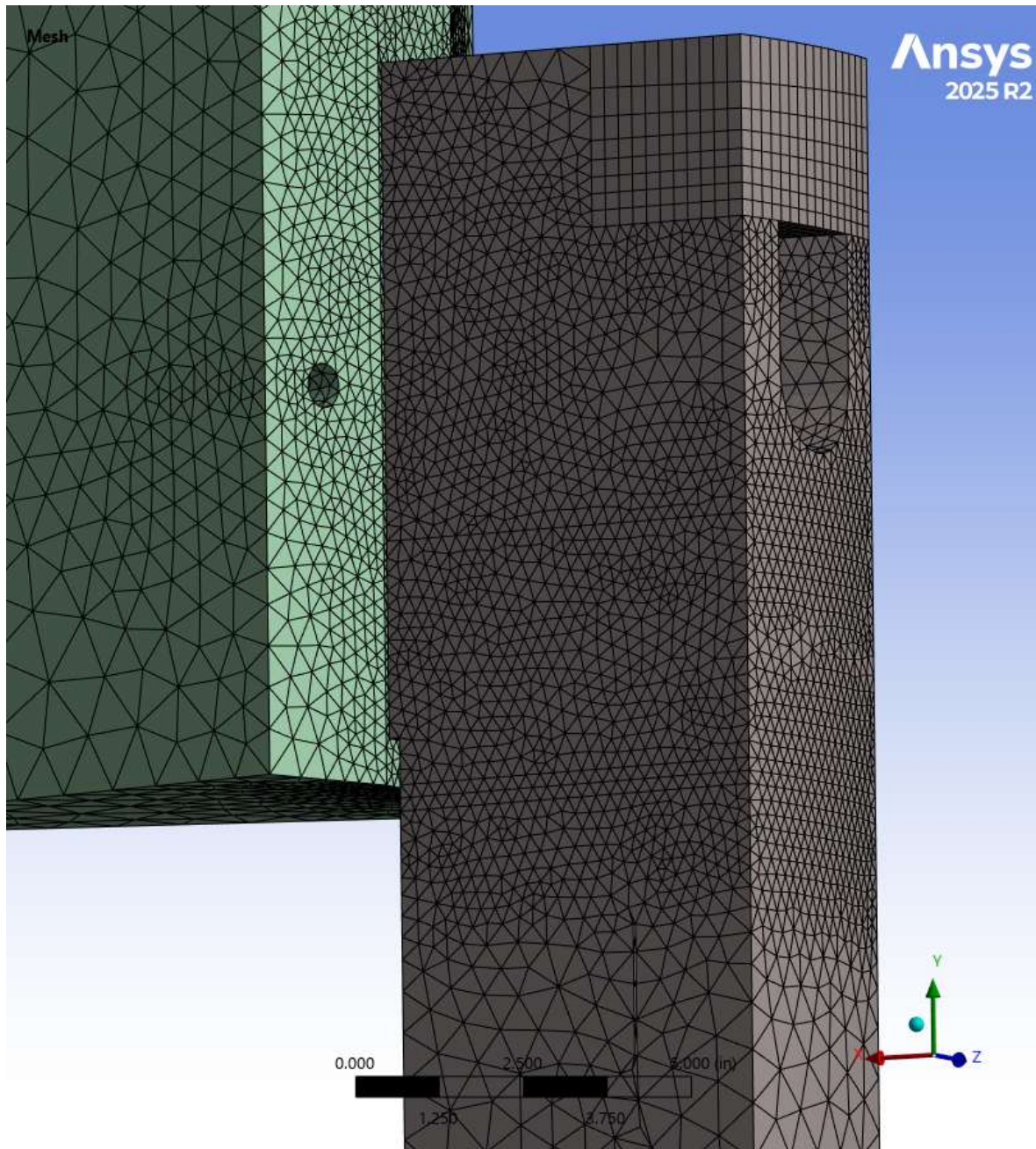


Figure 181 Segment Mesh

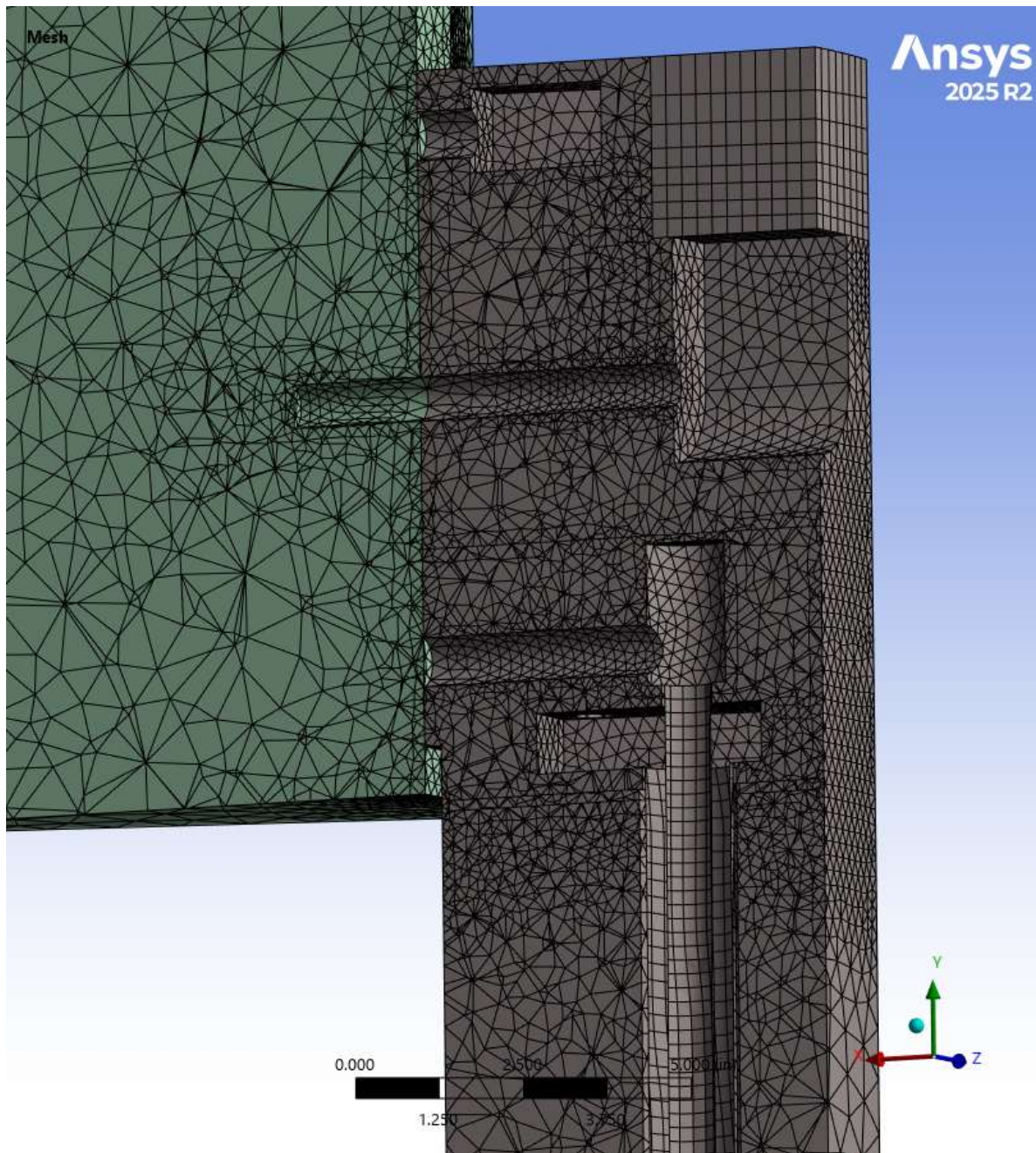


Figure 182 Segment Mesh, Section

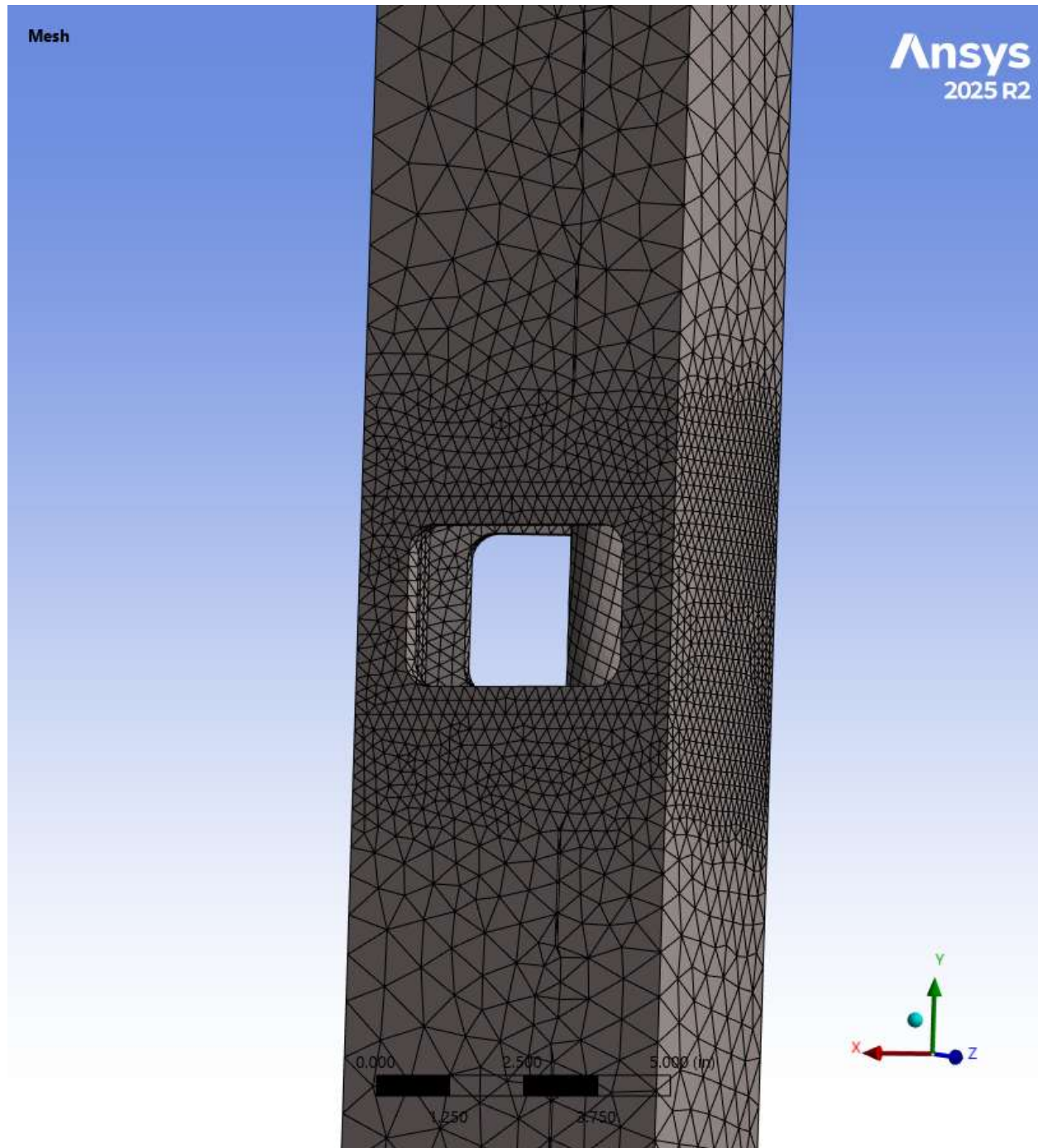


Figure 183 Segment Mesh

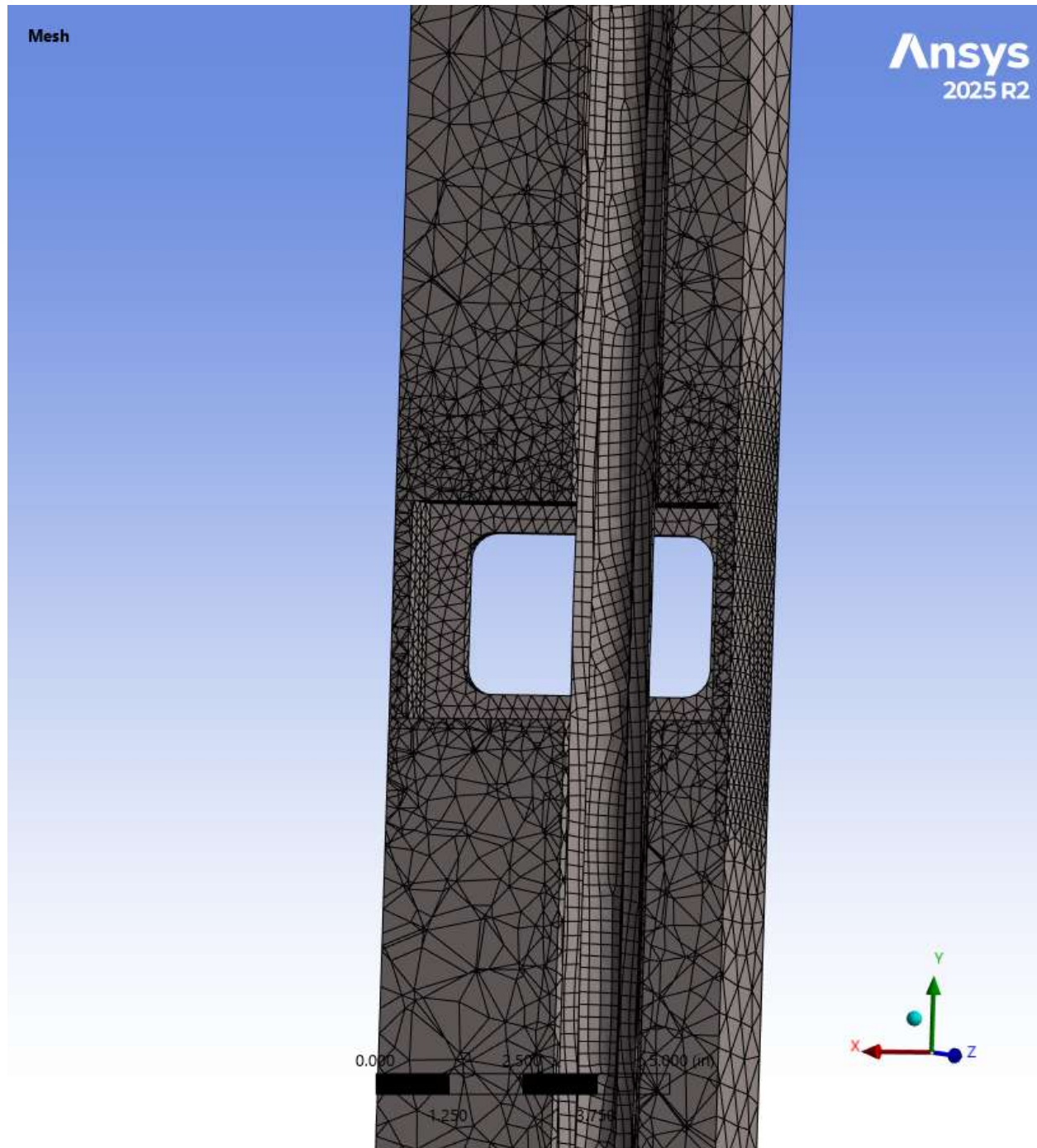


Figure 184 Segment Mesh, Section

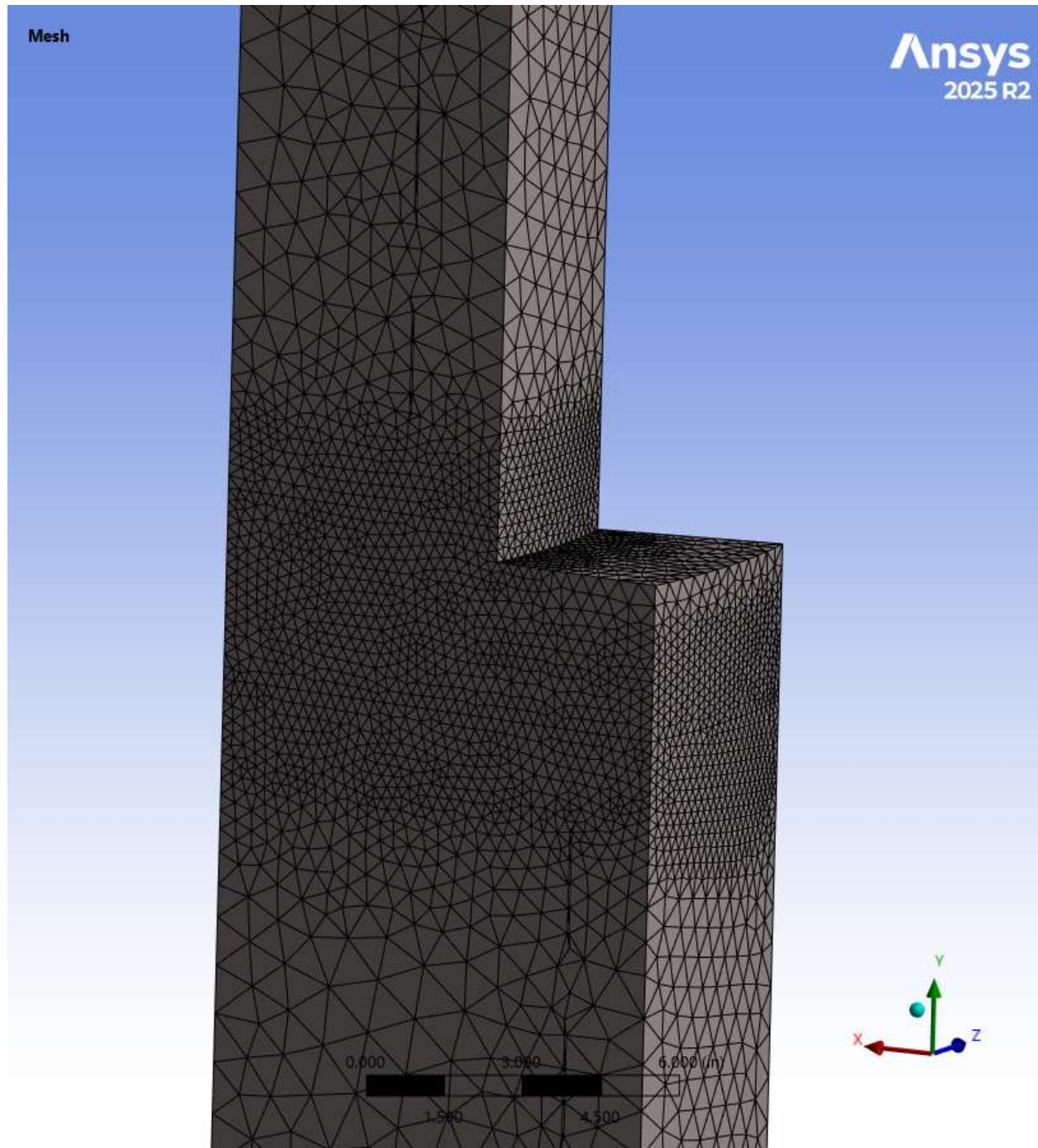


Figure 185 Segment Mesh

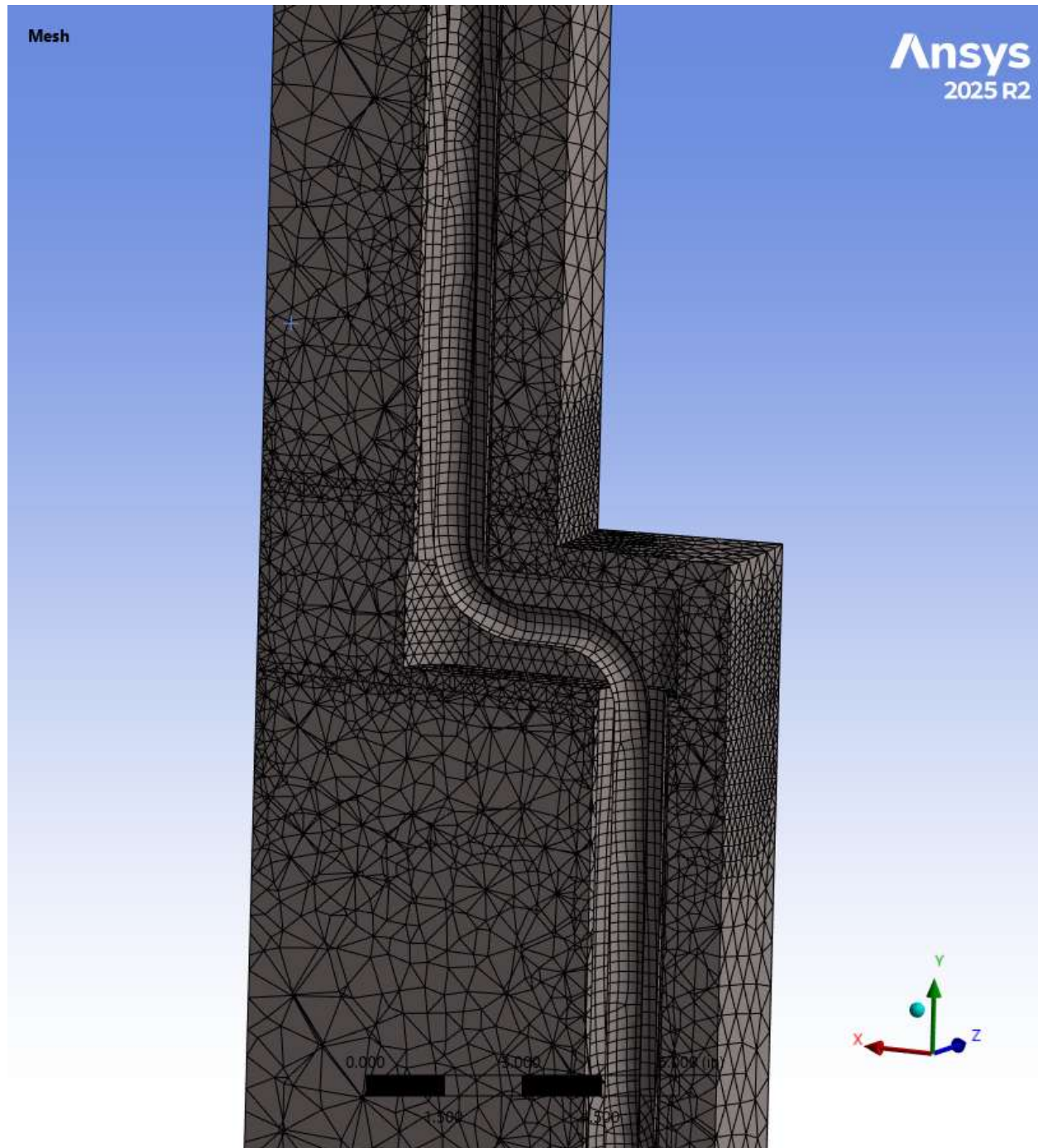


Figure 186 Segment Mesh, Section

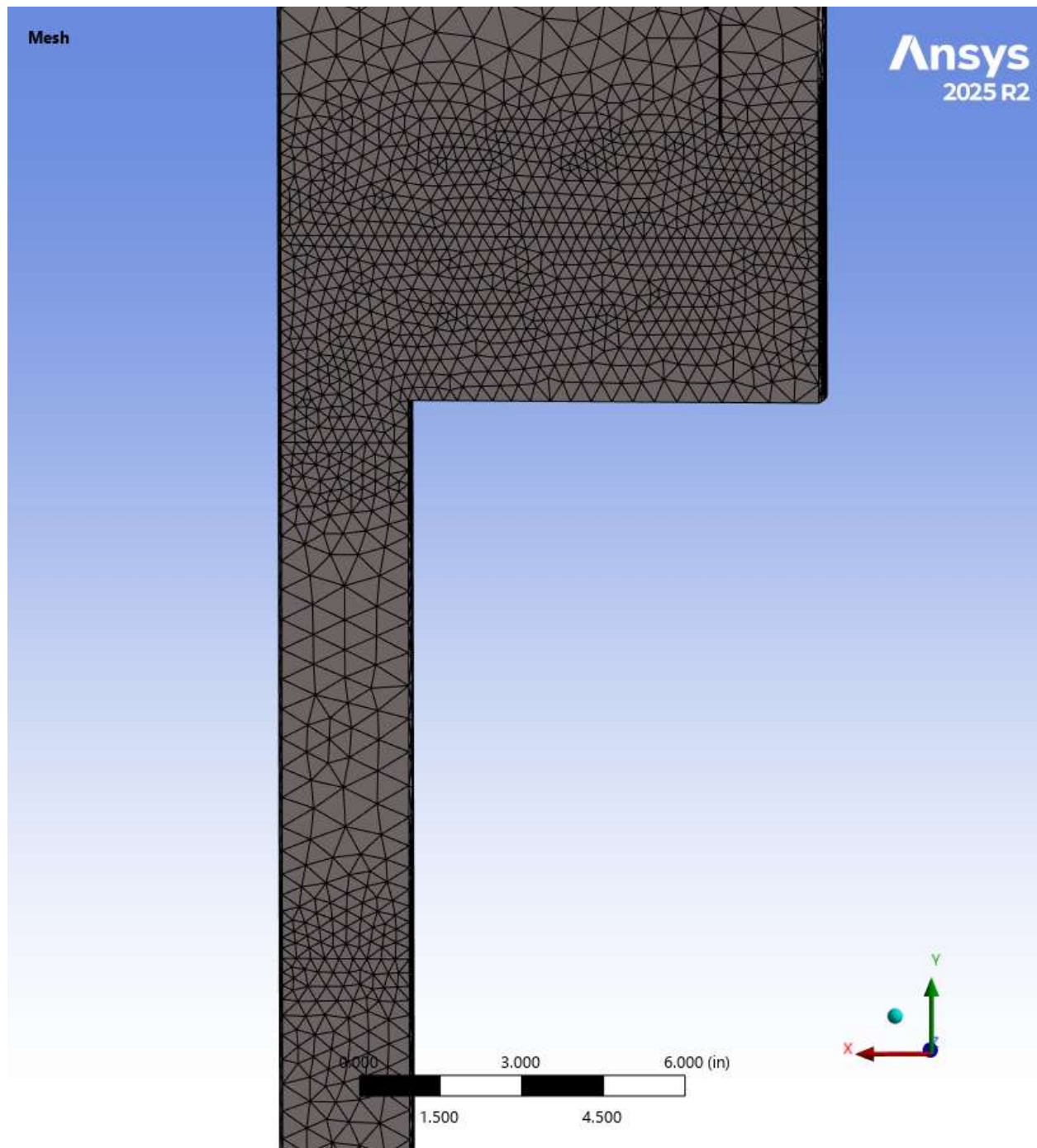


Figure 187 Segment Mesh

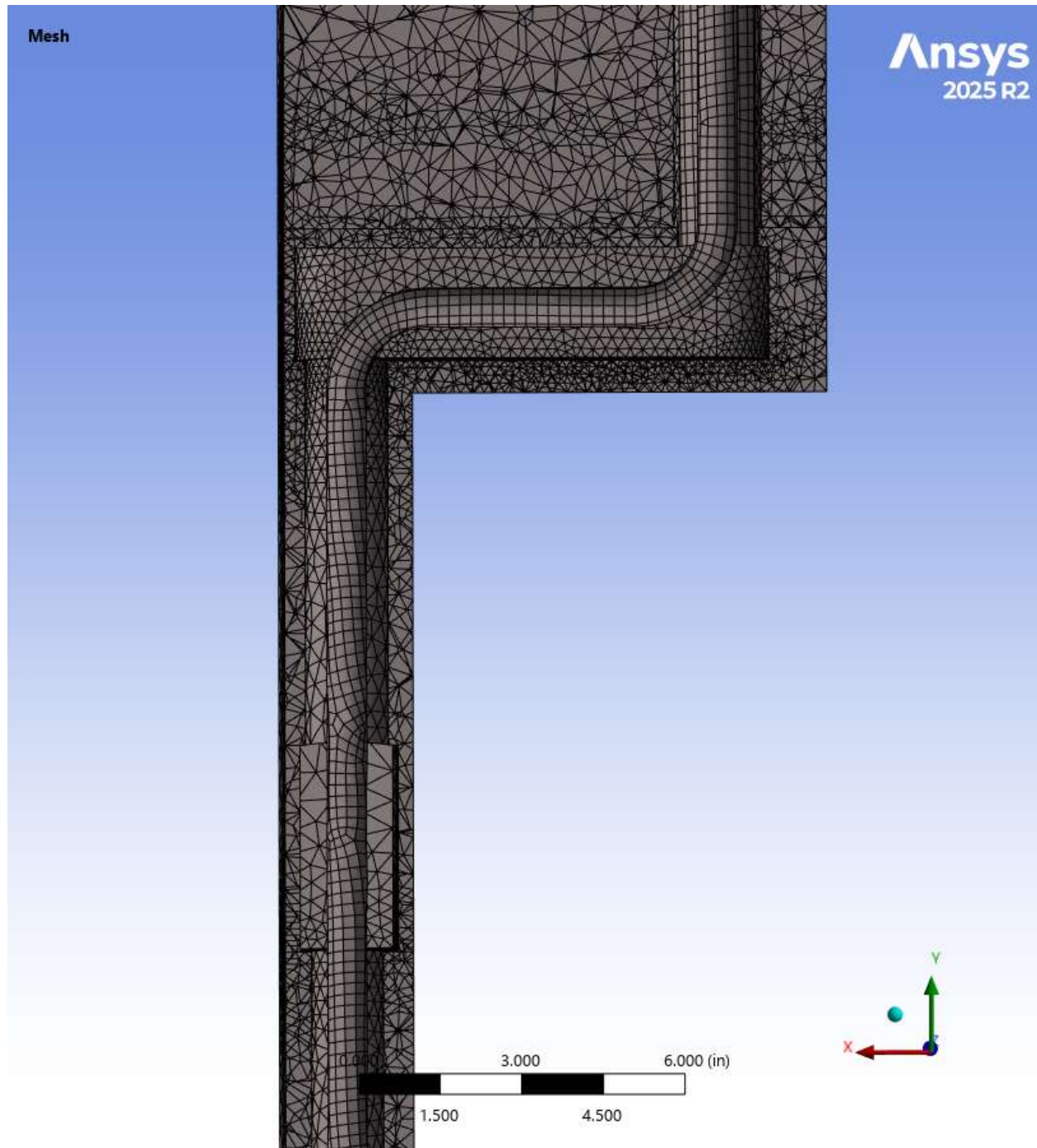


Figure 188 Segment Mesh, Section

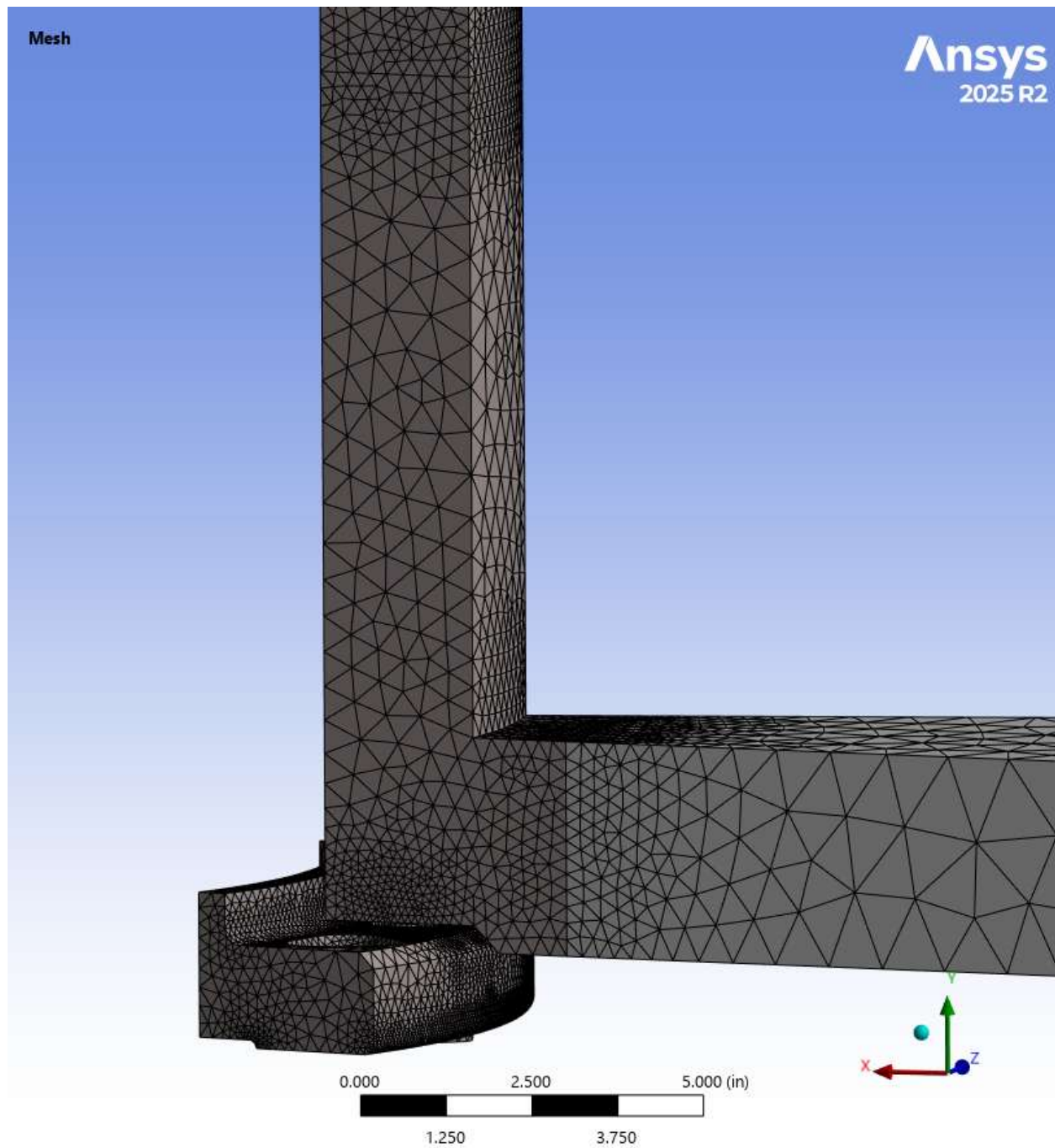


Figure 189 Segment Mesh

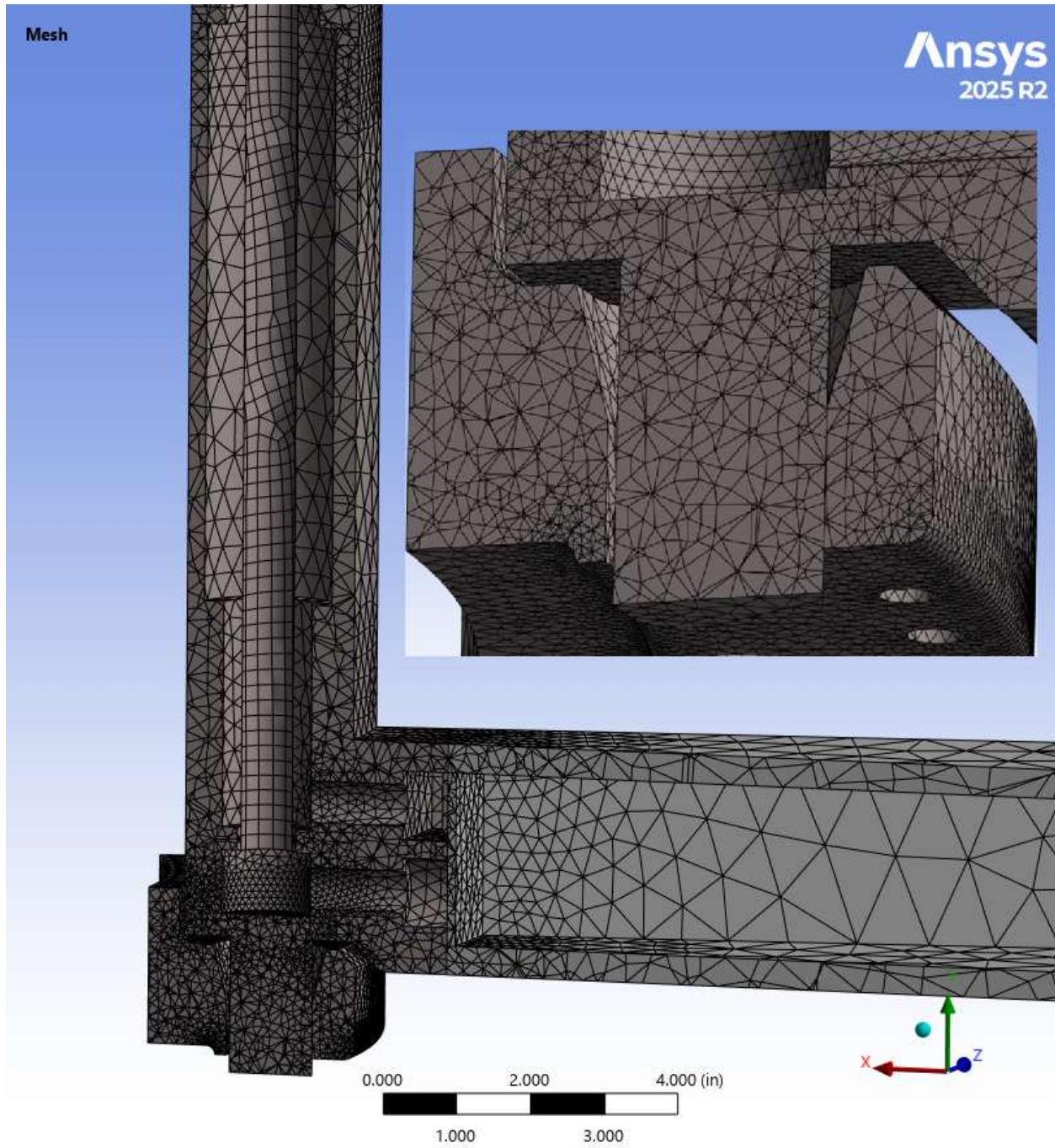


Figure 190 Segment Mesh, Section

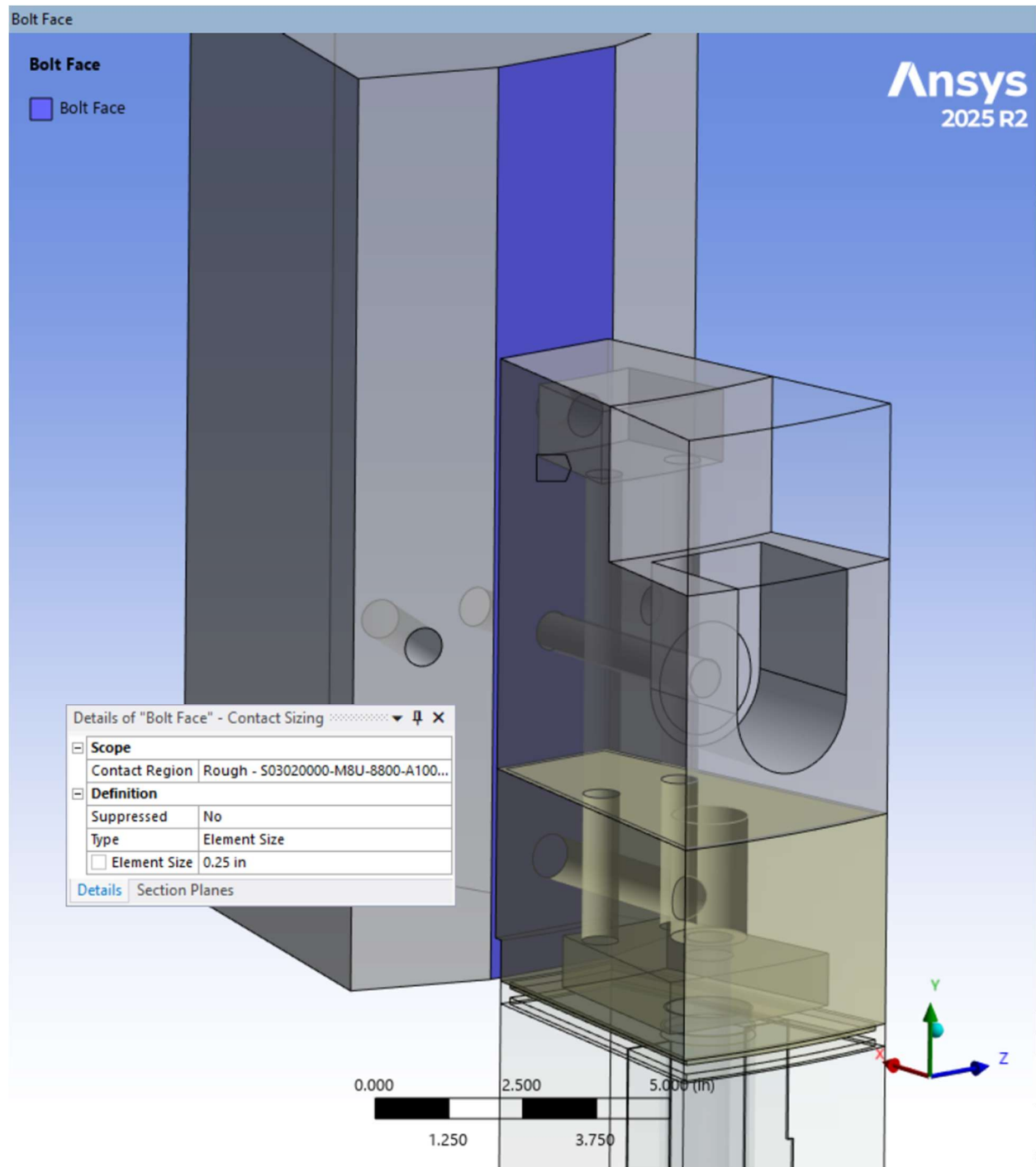


Figure 191 Segment Contact Sizing

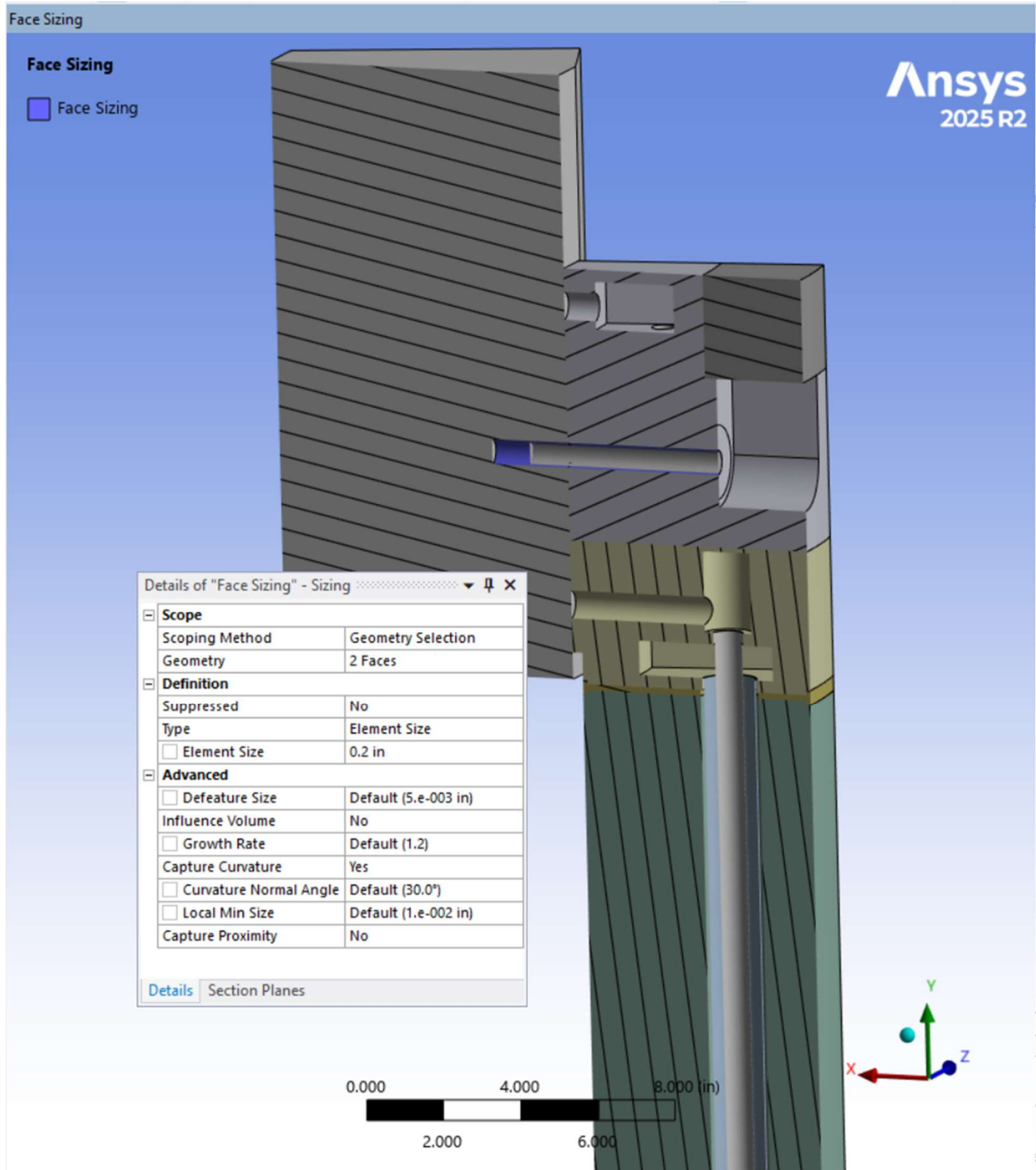


Figure 192 Segment Contact Sizing

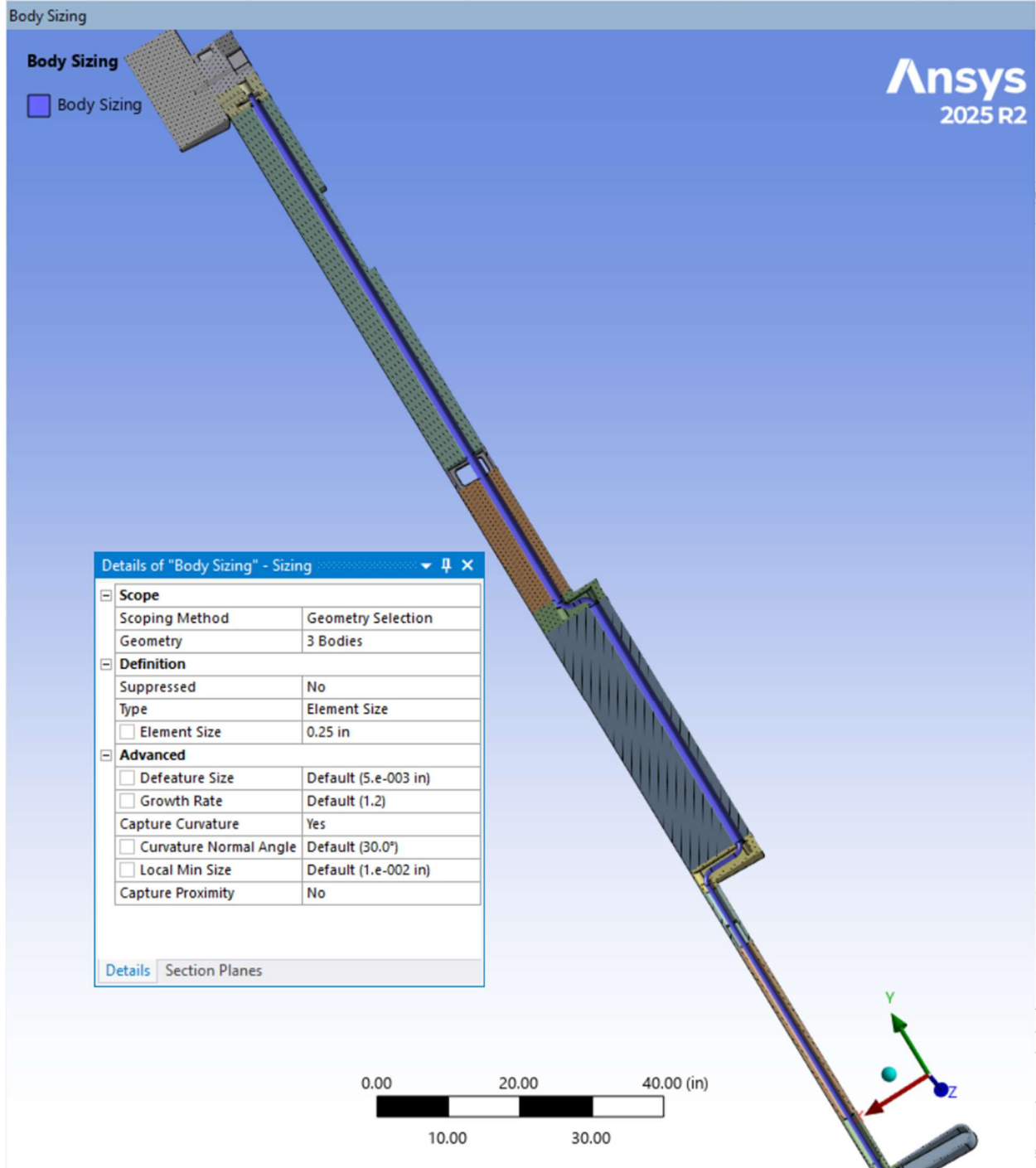


Figure 193 Segment Pipe Sizing

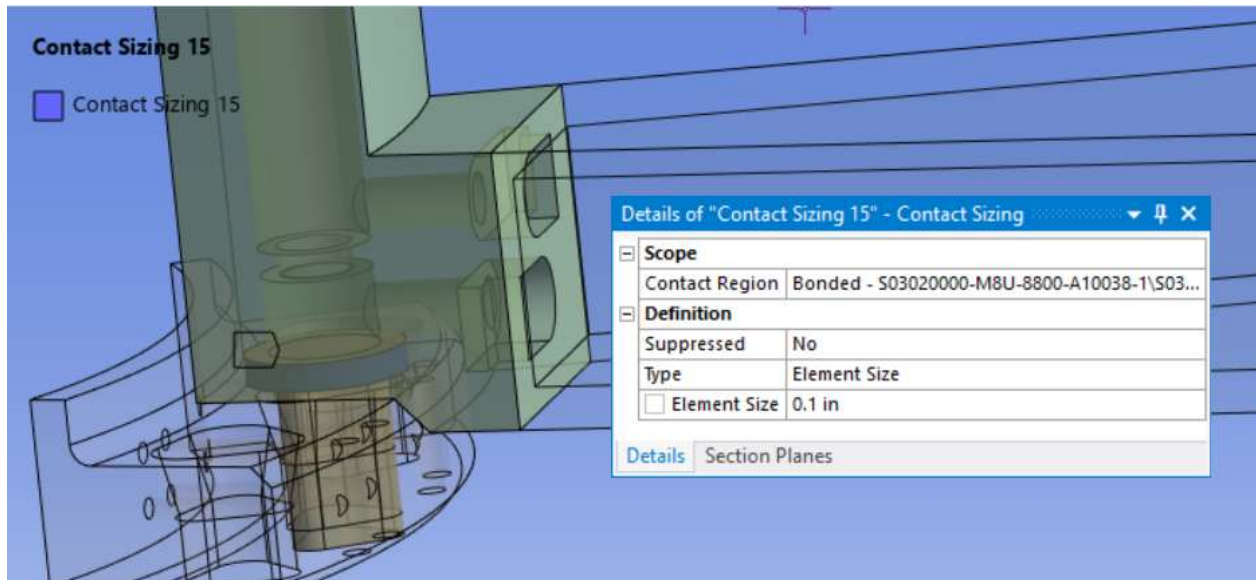
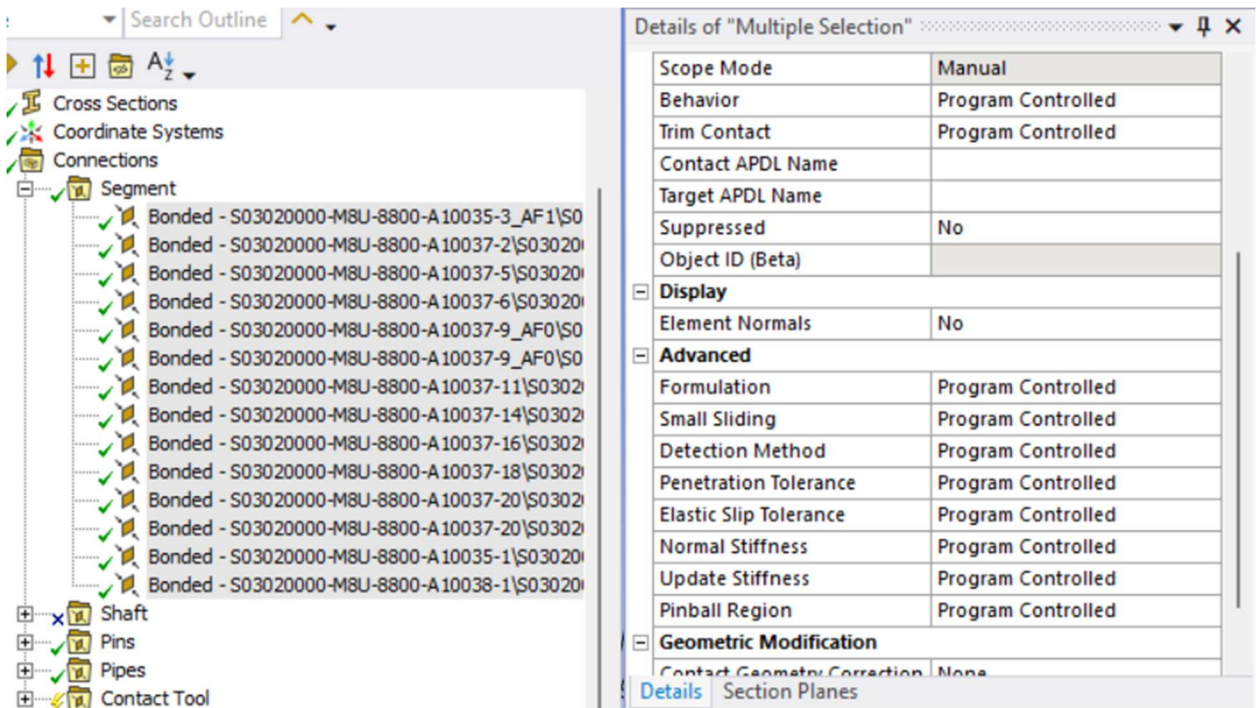


Figure 194 Segment Contact Sizing



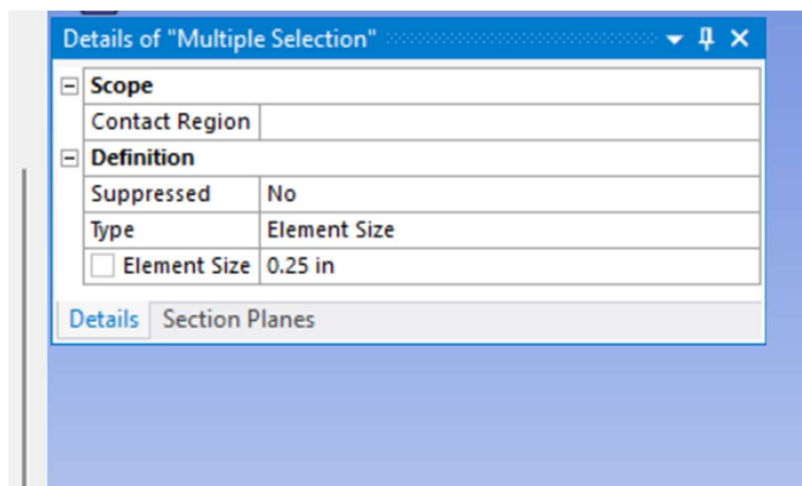


Figure 195 Segment Contact Sizing

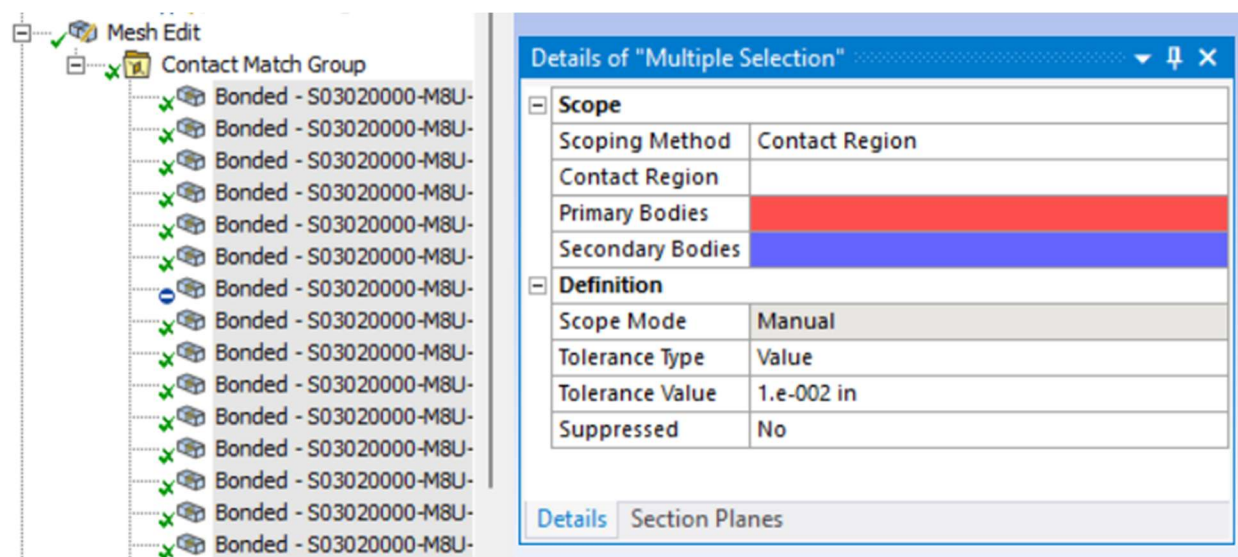


Figure 197 Segment Contact Matching

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	1.0 in
Sizing	
Mesh Sizing (Beta)	Uniform
Use Uniform Size Functi...	Yes
Enable Washers	No
Size Formulation (Beta)	Program Controlled
Bounding Box Diagonal	205.48 in
Average Surface Area	14.982 in ²
Minimum Edge Length	1.4723e-003 in
Enable Size Field (Beta)	No
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Aggressive Mechanical
Target Element Quality	Default (0.1)
Target Jacobian Ratio (C...	Default (4.e-002)
Target Aspect Ratio (Hei...	Default (10.0)
Smoothing	Medium
Mesh Optimization (Beta)	Yes
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
Inflation Element Type	Wedges
View Advanced Options	No
Advanced	
Number of CPUs for Par...	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (9.e-003 in)
Generate Pinch on Refr...	No
Sheet Loop Removal	No
Hex to Tet Transition (Be...	Program Controlled
Auto-Map Fillets	No
Automatic Methods	
Sheet Body Method	Prime Quad Dominant
Sweepable Body Method	Sweep
Statistics	
Nodes	799245
Elements	508150
Show Detailed Statistics	No

Figure 198 Segment General Mesh Settings

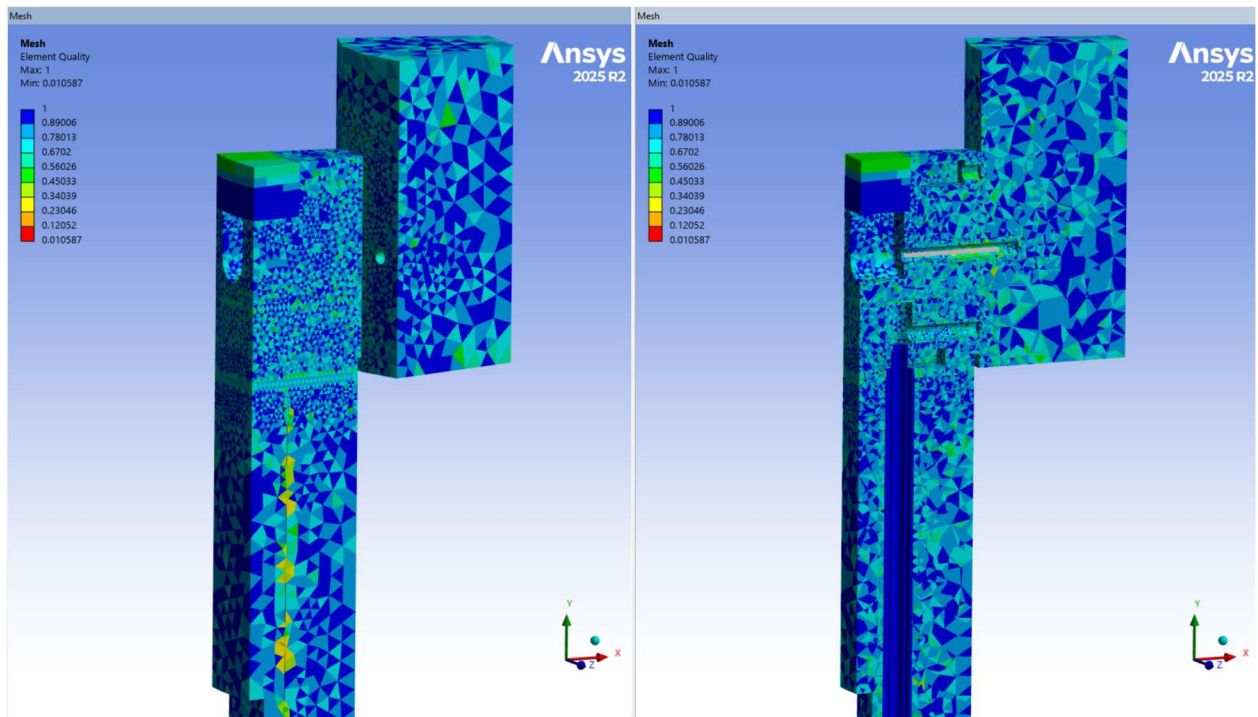


Figure 199 Segment Mesh Quality

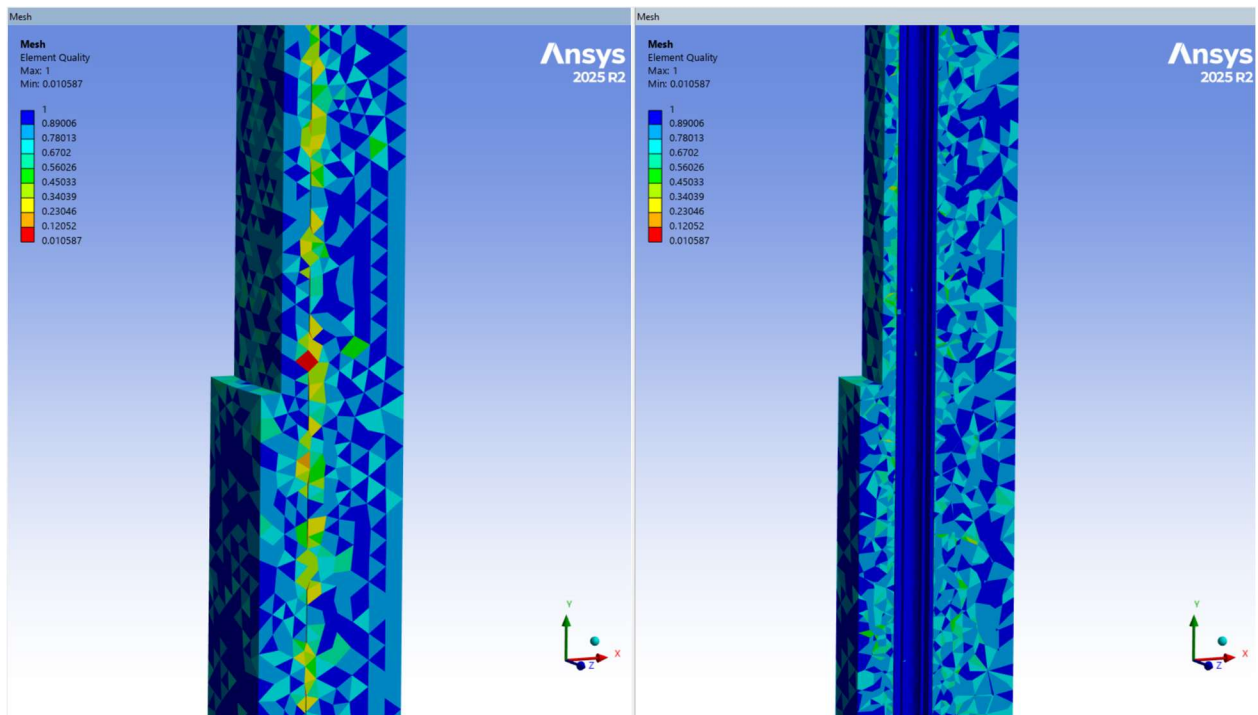


Figure 200 Segment Mesh Quality

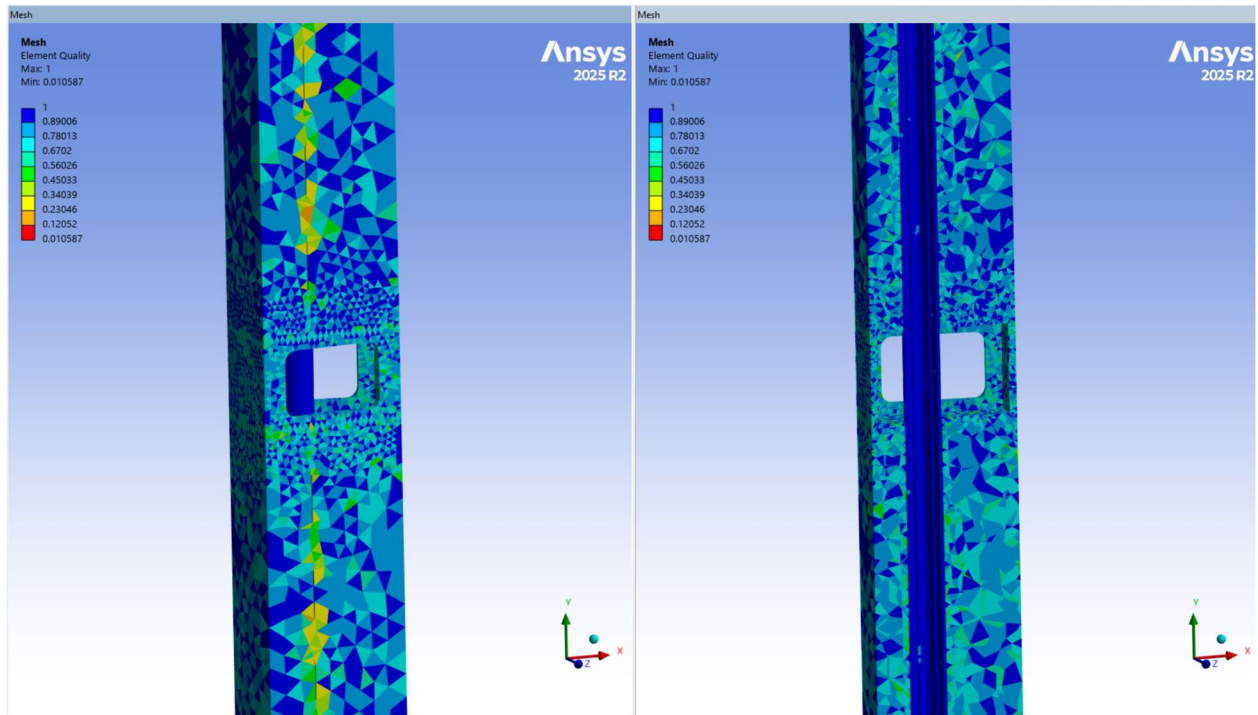


Figure 201 Segment Mesh Quality

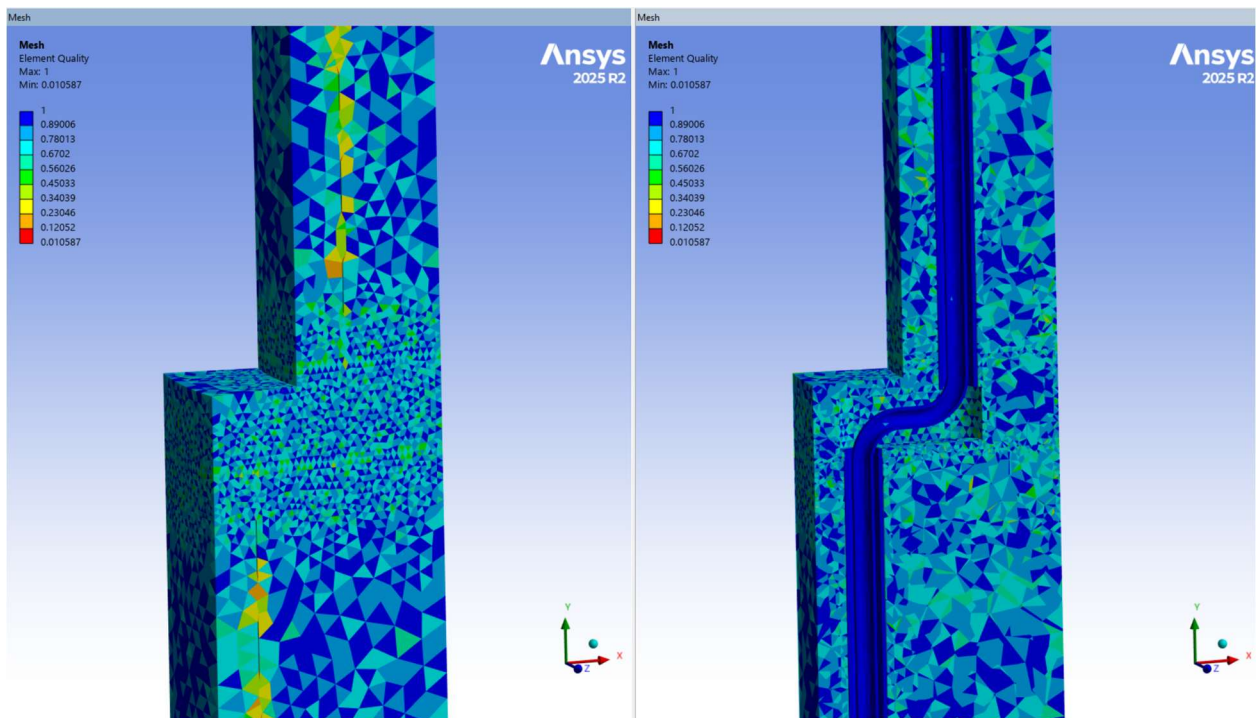


Figure 202 Segment Mesh Quality

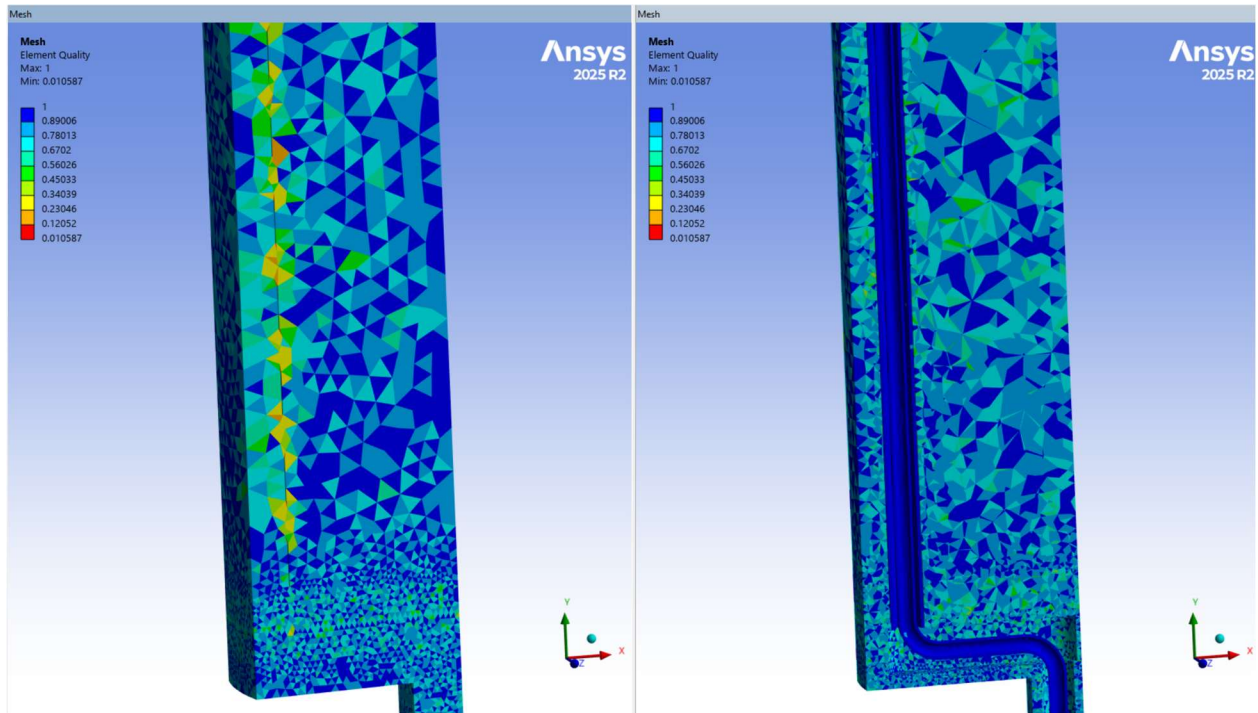


Figure 203 Segment Mesh Quality

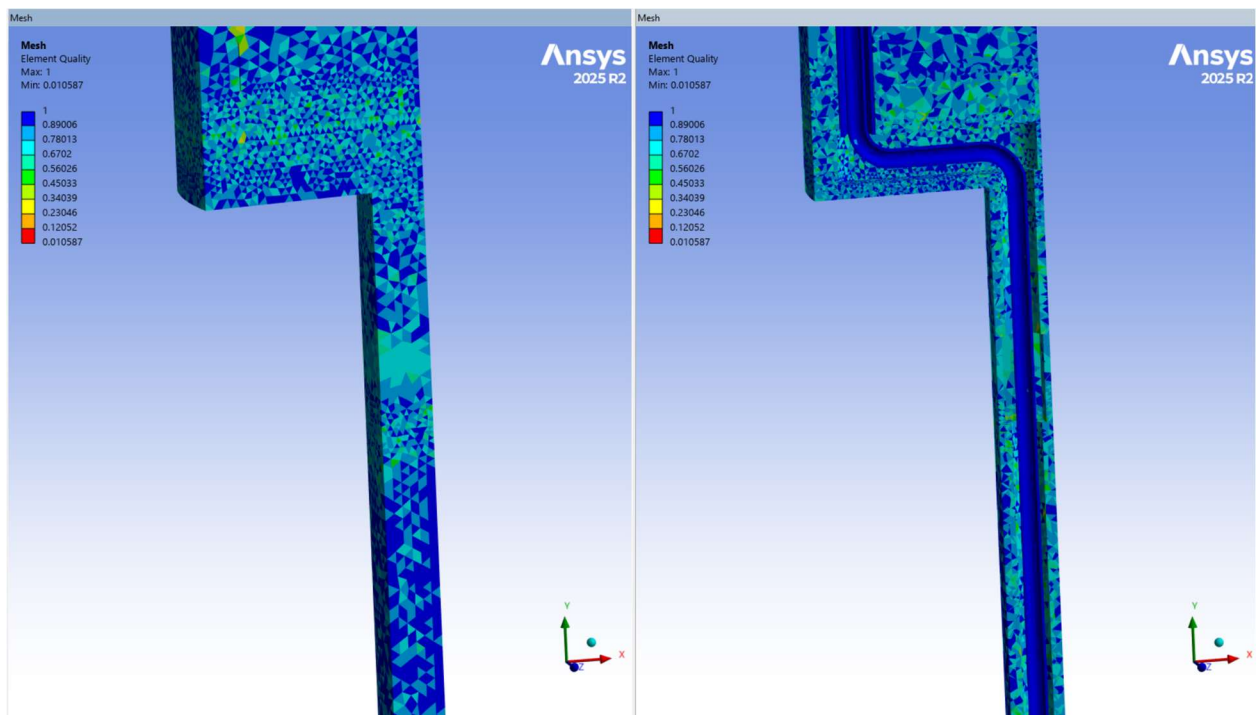


Figure 204 Segment Mesh Quality

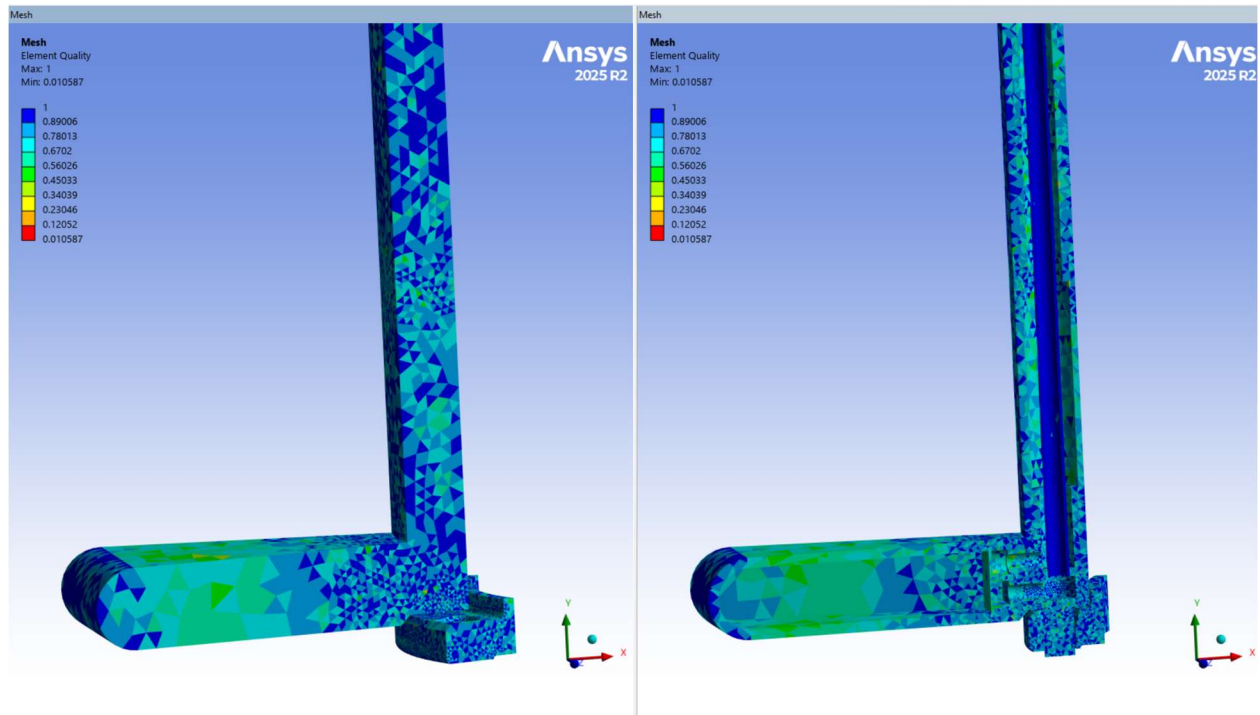


Figure 205 Segment Mesh Quality

4.3.3 Target Shaft

The Target Shaft and Segments use more Contact Sizing and Contact Match Groups to align nodes at part interfaces. The actual segment models are replaced with the beam models and the Tie Rod bolts are replaced with beam elements, the rest are solid elements.

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	1.5 in
Sizing	
Mesh Sizing (Beta)	Medium
Size Formulation (Beta)	Program Controlled
Bounding Box Diagonal	377.69 in
Average Surface Area	23.593 in ²
Minimum Edge Length	4.0972e-004 in
Enable Size Field (Beta)	No
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Aggressive Mechanical
Target Element Quality	Default (0.1)
Target Jacobian Ratio (Corner No...	Default (4.e-002)
Target Aspect Ratio (Height) (Beta)	Default (10.0)
Smoothing	Medium
Mesh Optimization (Beta)	Yes
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
Inflation Element Type	Wedges
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part ...	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (1.35e-002 in)
Generate Pinch on Refresh	No
Sheet Loop Removal	No
Hex to Tet Transition (Beta)	Program Controlled
Auto-Map Fillets	No
Automatic Methods	
Sheet Body Method	Quad Dominant
Sweepable Body Method	Sweep
Statistics	
Nodes	1659698
Elements	1105863
Show Detailed Statistics	No

Figure 206 Shaft General Mesh Settings

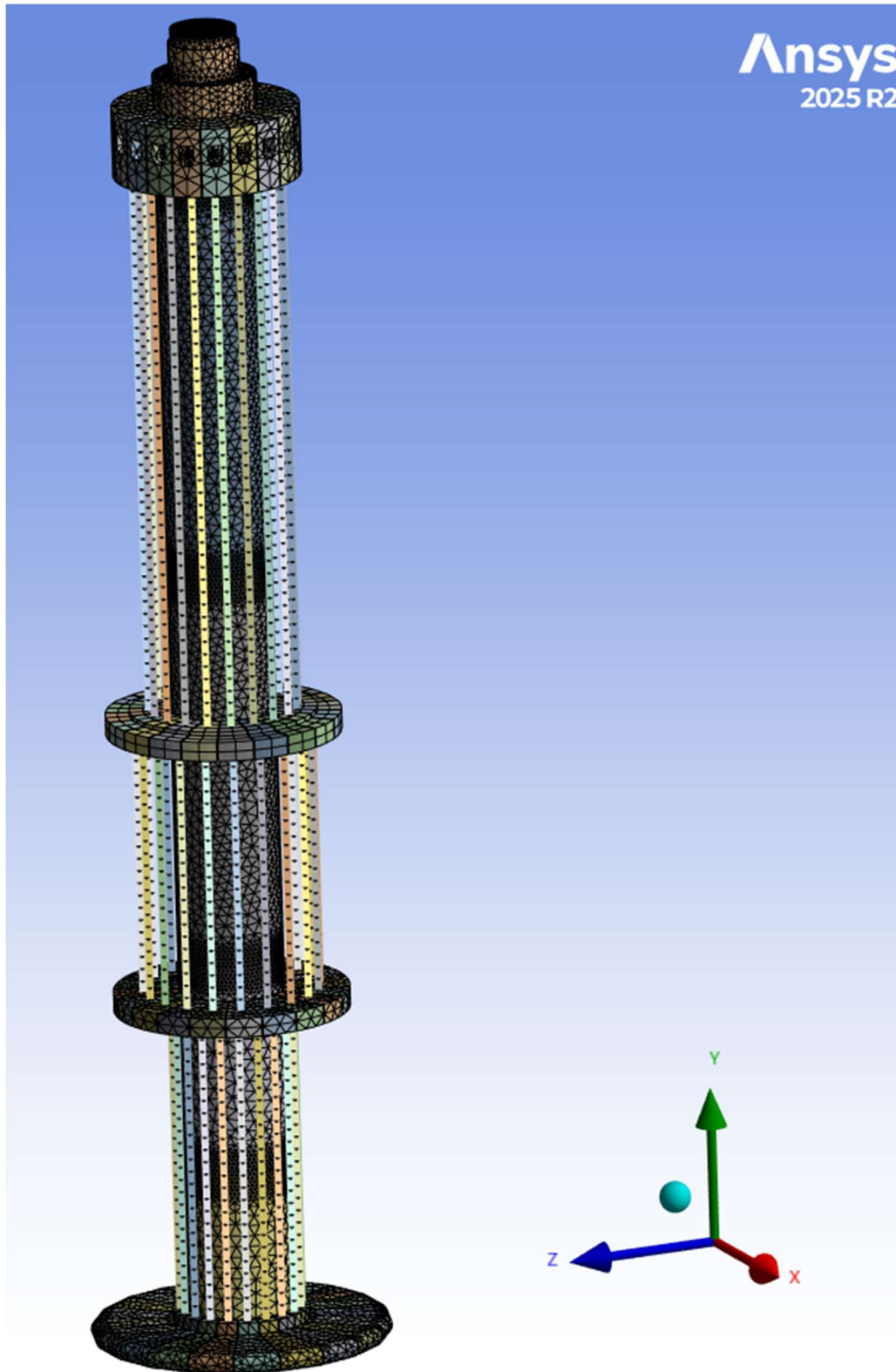


Figure 207 Target Shaft Mesh

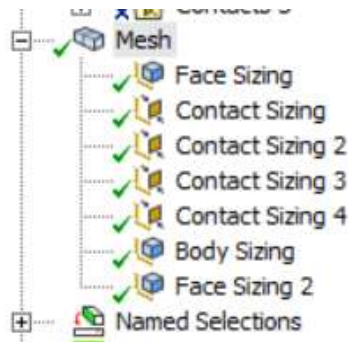


Figure 208 Shaft Additional Mesh Settings

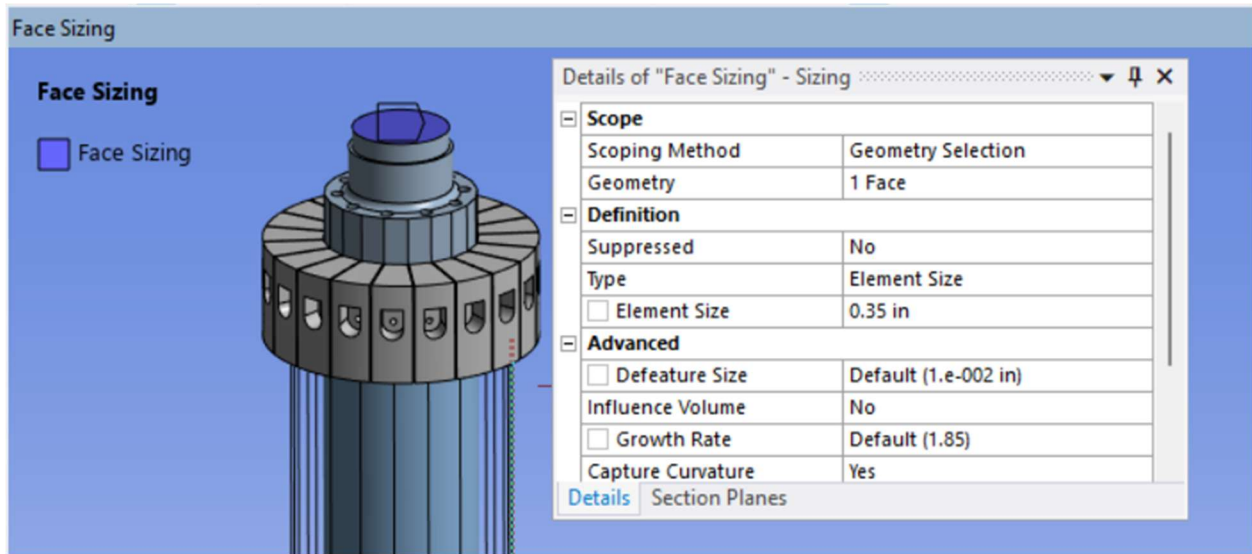


Figure 209 Crown Boundary Condition Mesh Sizing

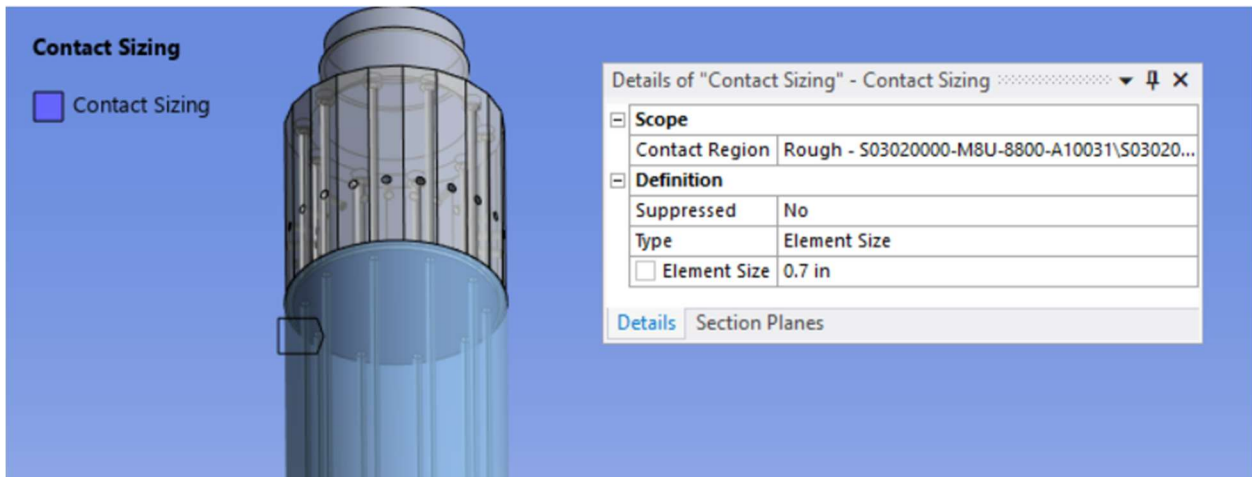


Figure 210 Crown to Shaft Contact Sizing

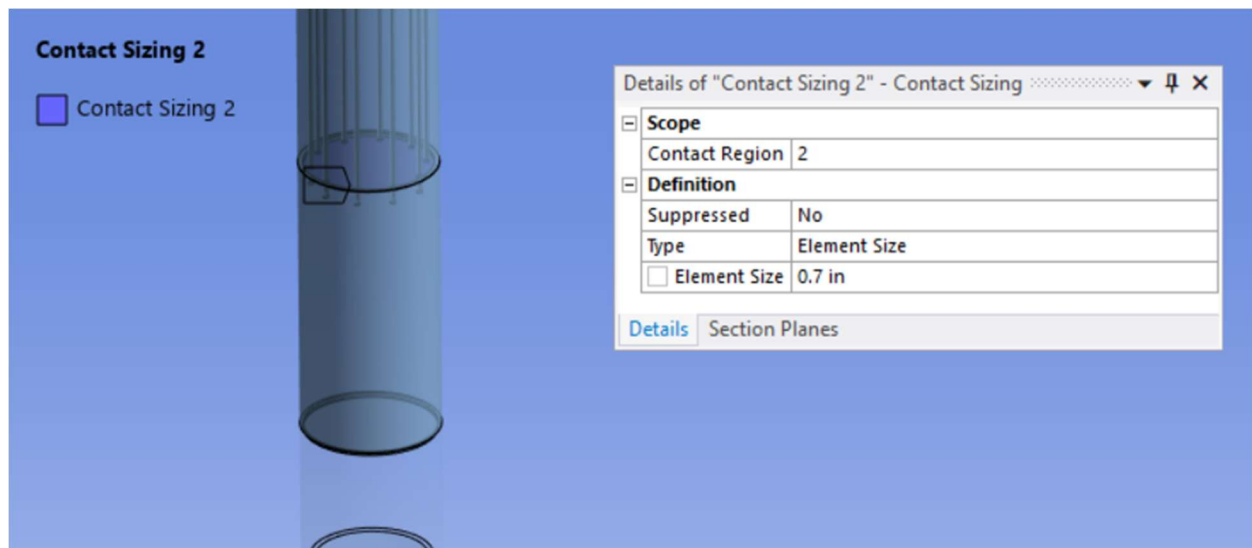


Figure 211 Tie Rod Joint Contact Sizing

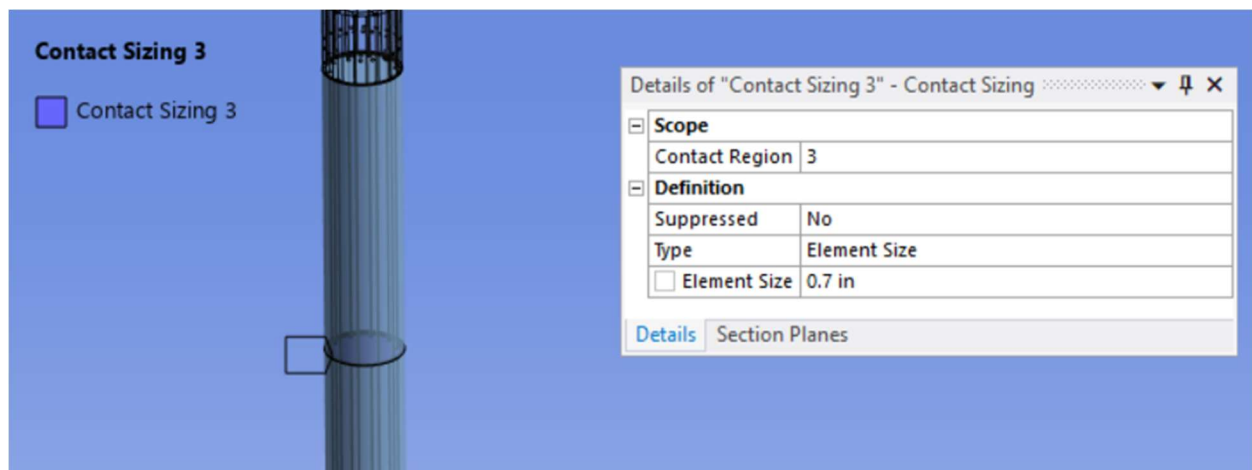


Figure 212 Shaft Middle Joint Contact Sizing

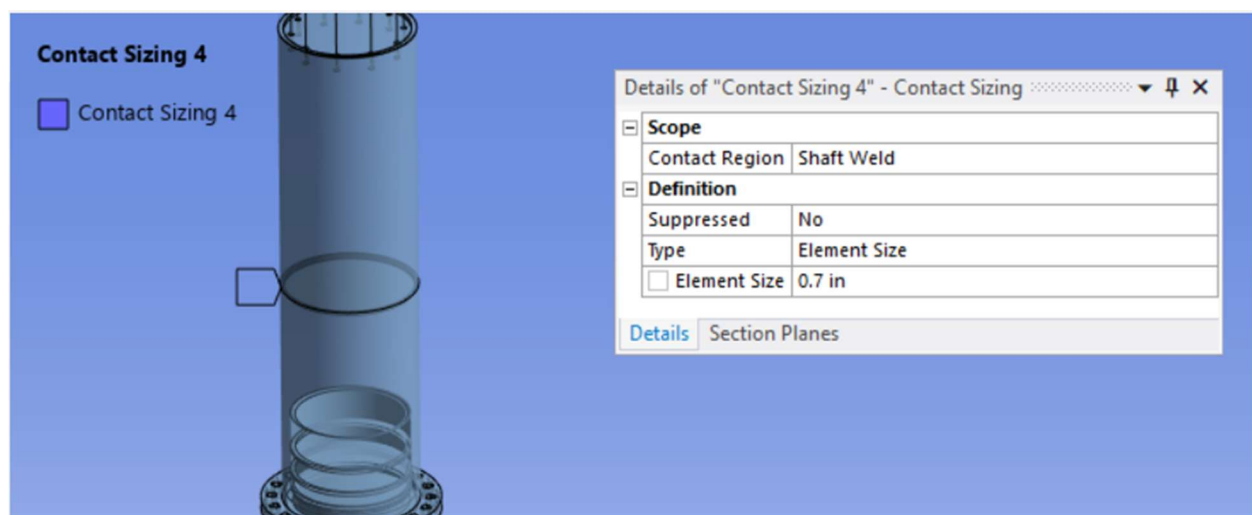


Figure 213 Shaft Weld Contact Sizing

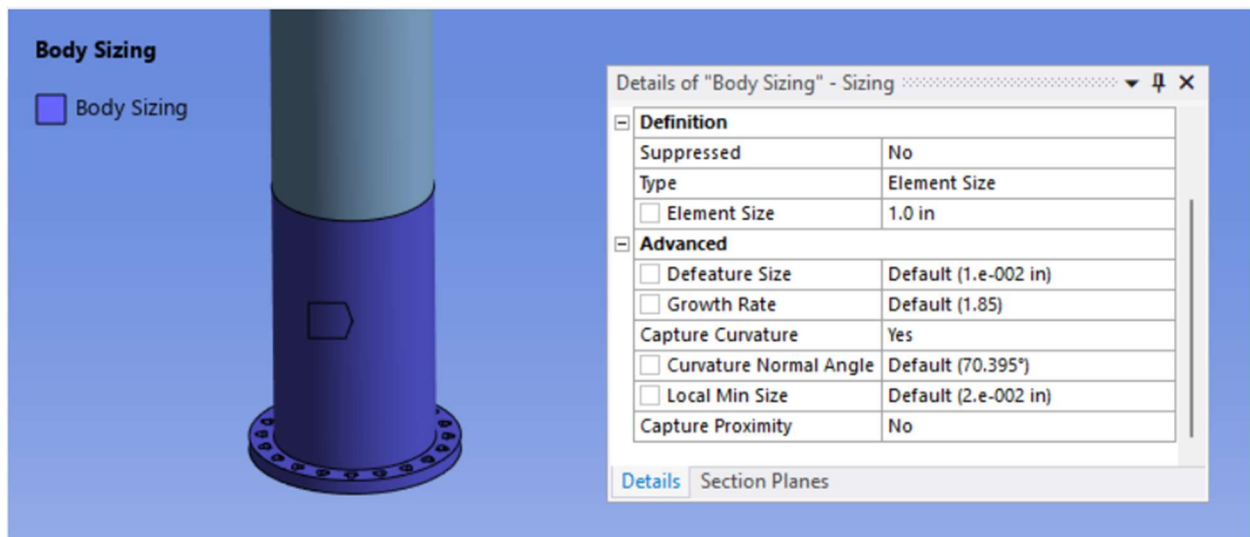


Figure 214 Lower Shaft Mesh Sizing

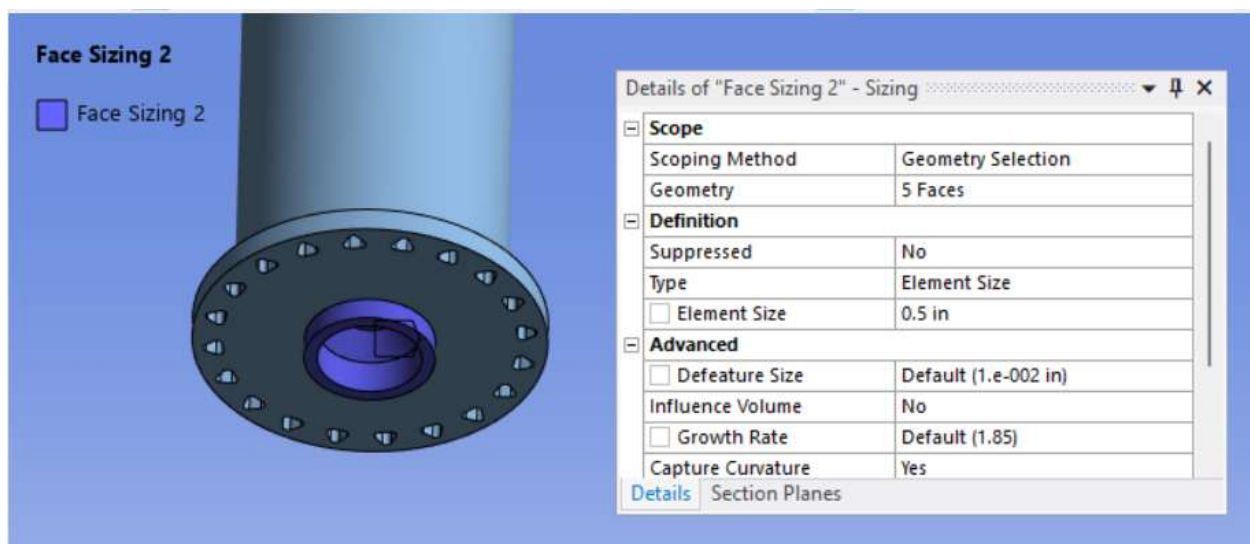


Figure 215 Snubber Ring Face Sizing

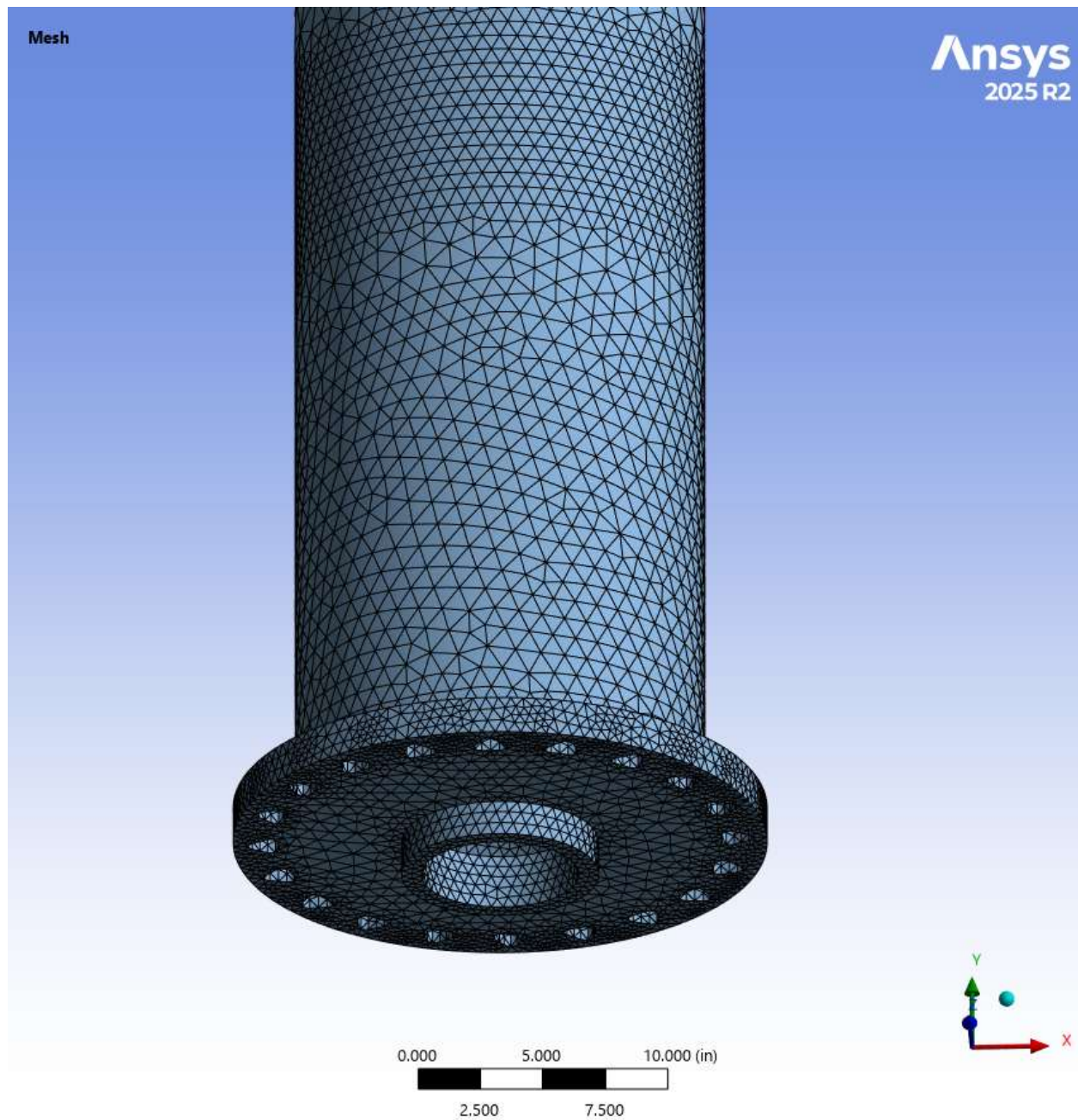


Figure 216 Lower Shaft and Shaft Weld Mesh

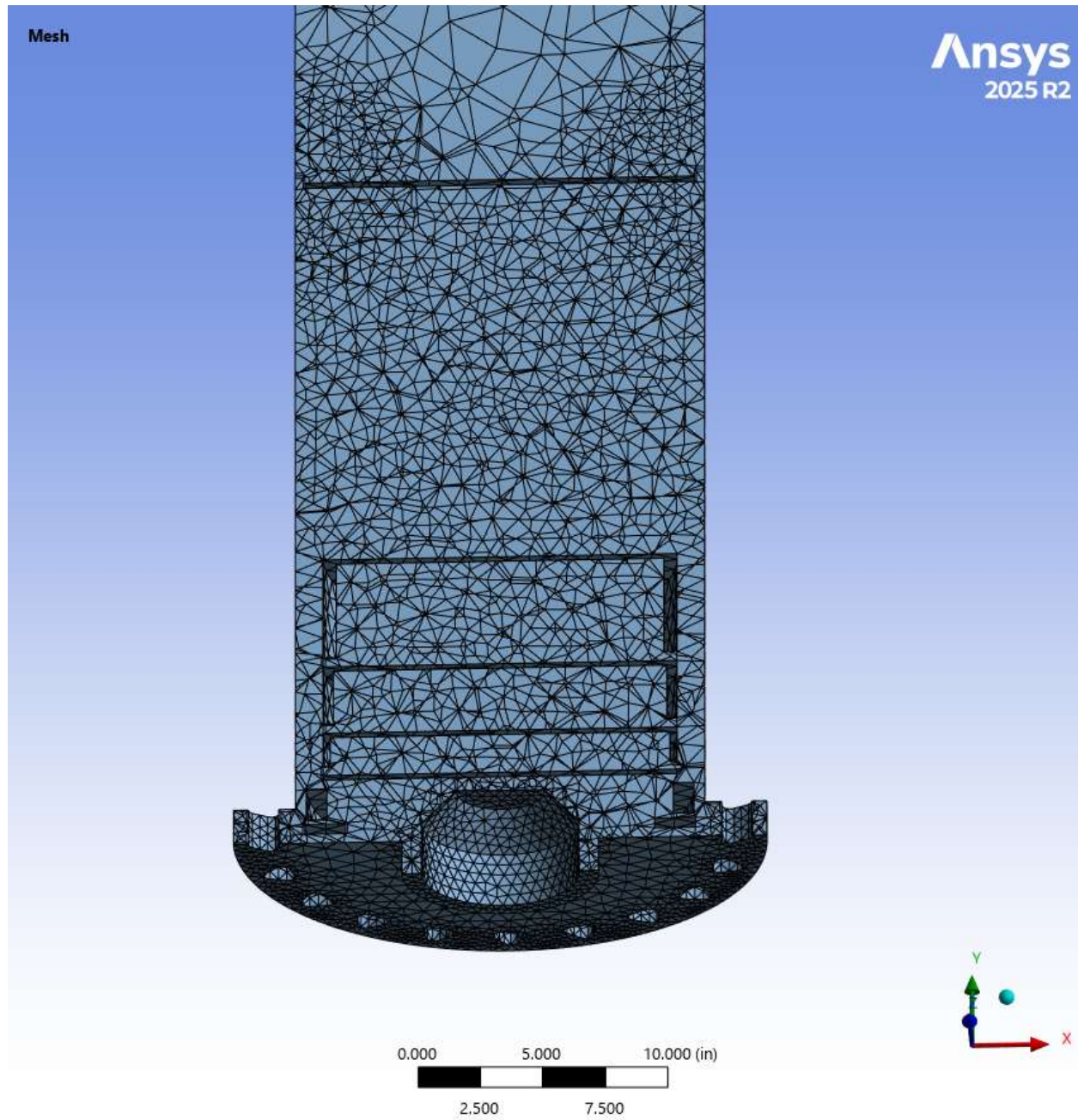


Figure 217 Lower Shaft and Shaft Weld Mesh, Section

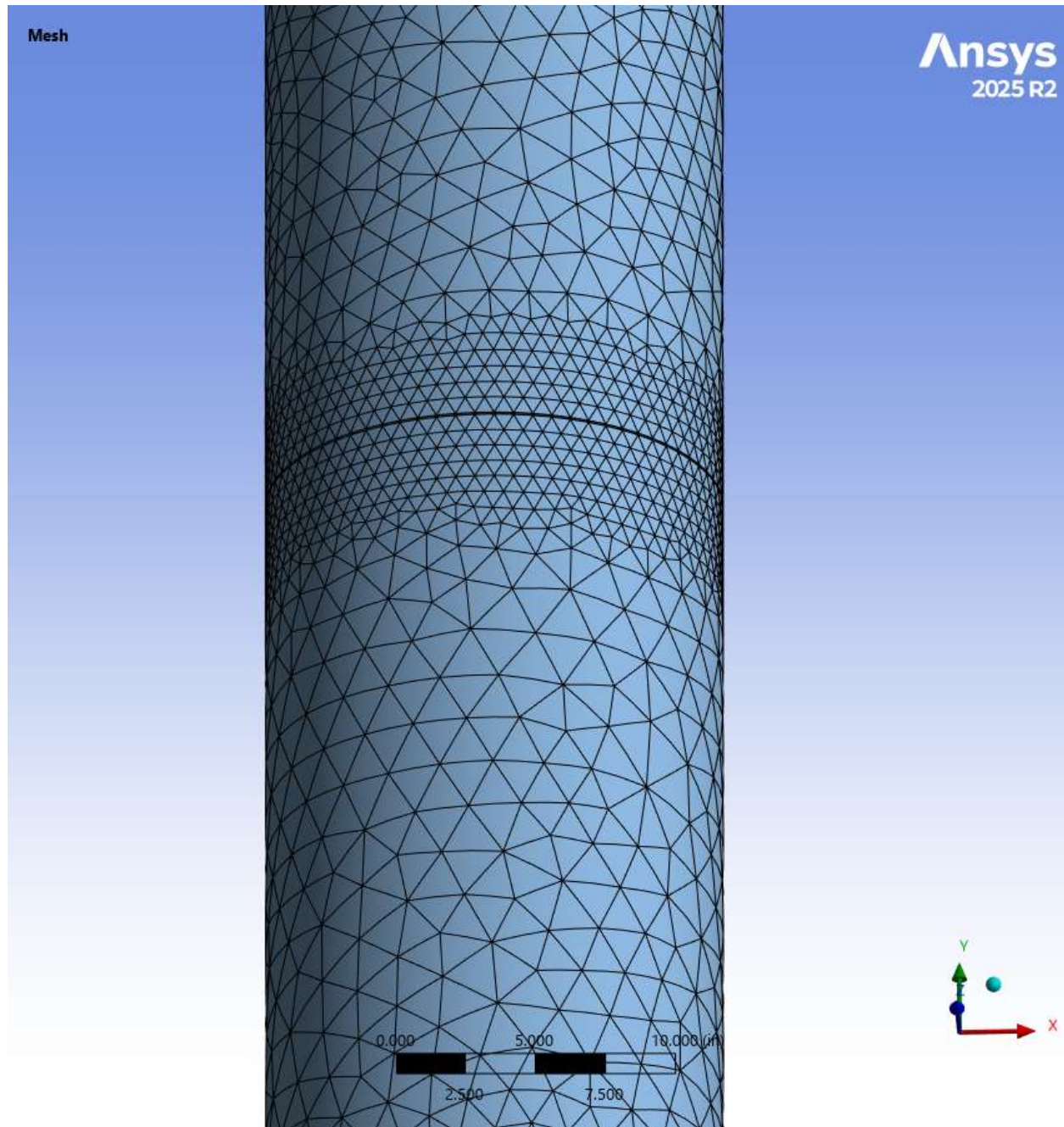


Figure 218 Shaft Tie Rod Joint Mesh

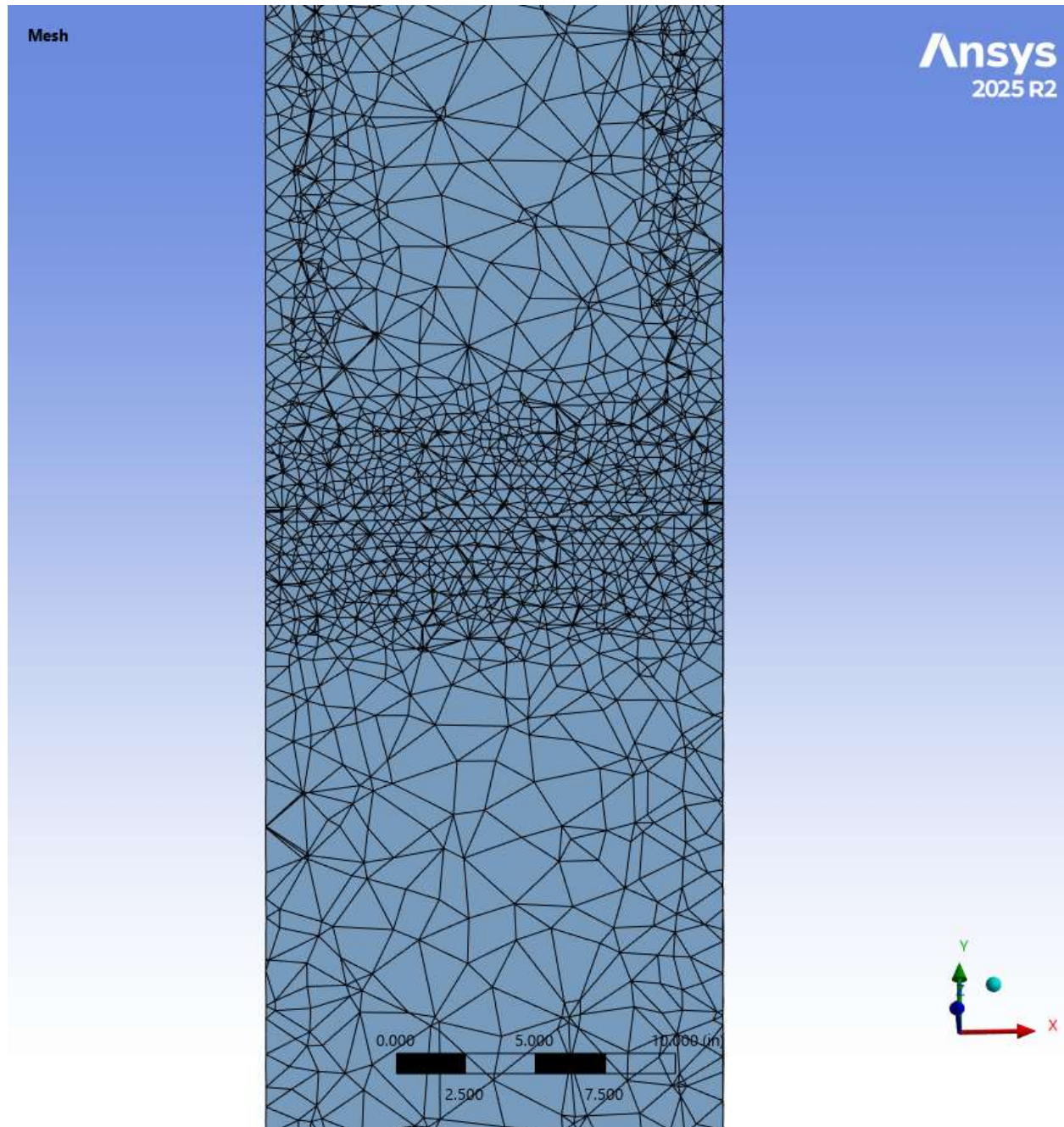


Figure 219 Shaft Tie Rod Joint, Section

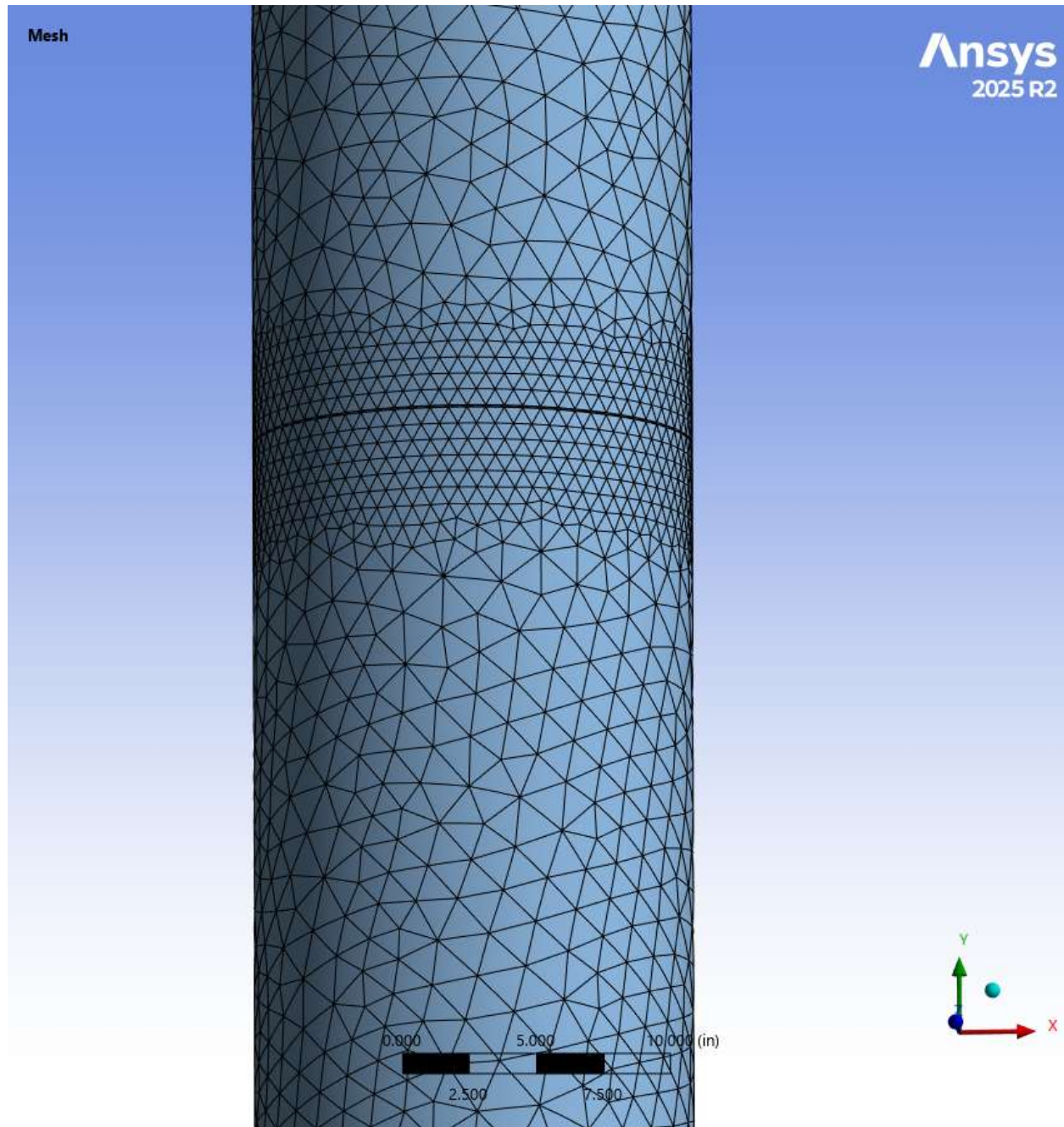


Figure 220 Shaft Middle Joint Mesh

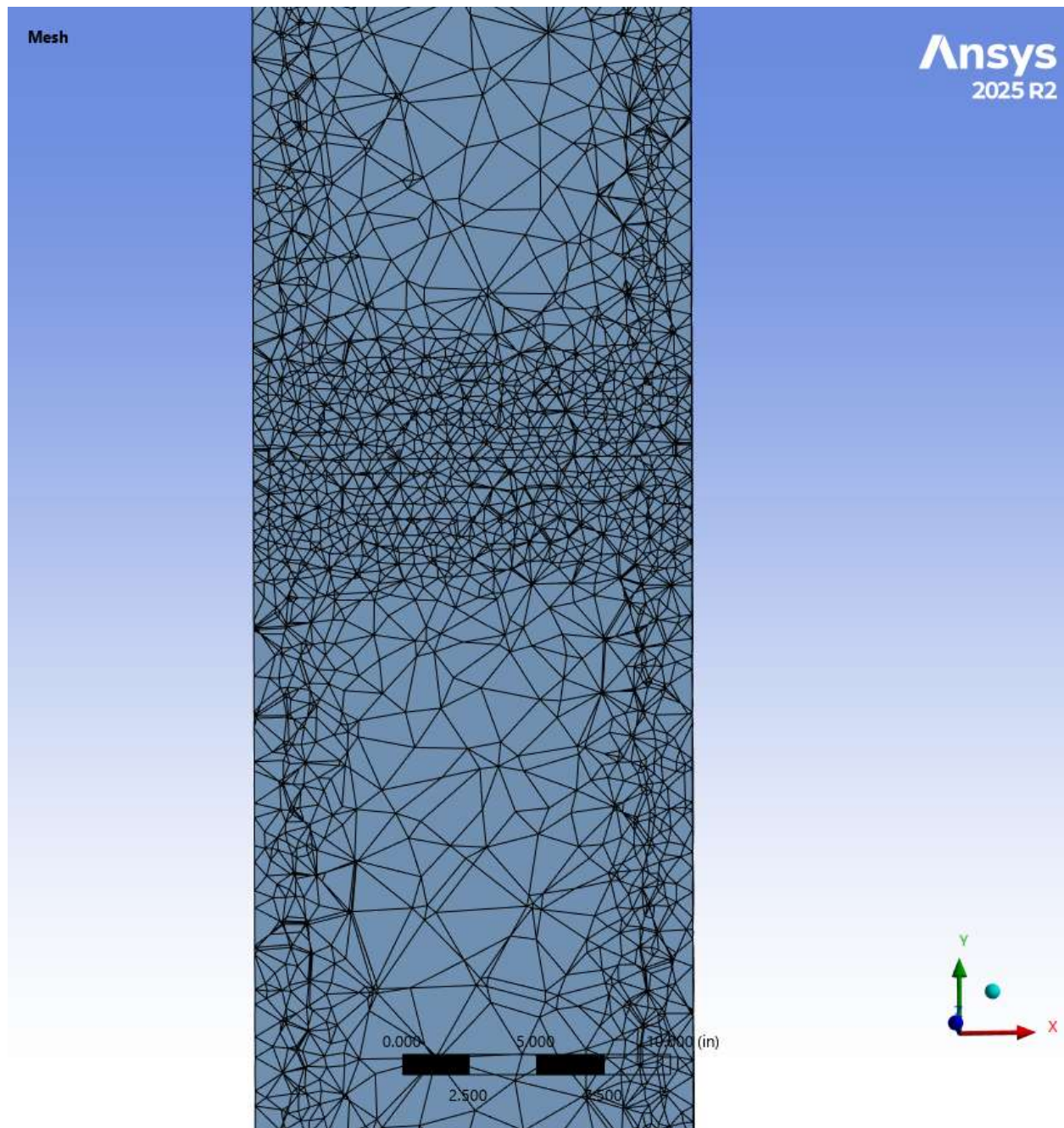


Figure 221 Shaft Middle Joint Mesh, Section

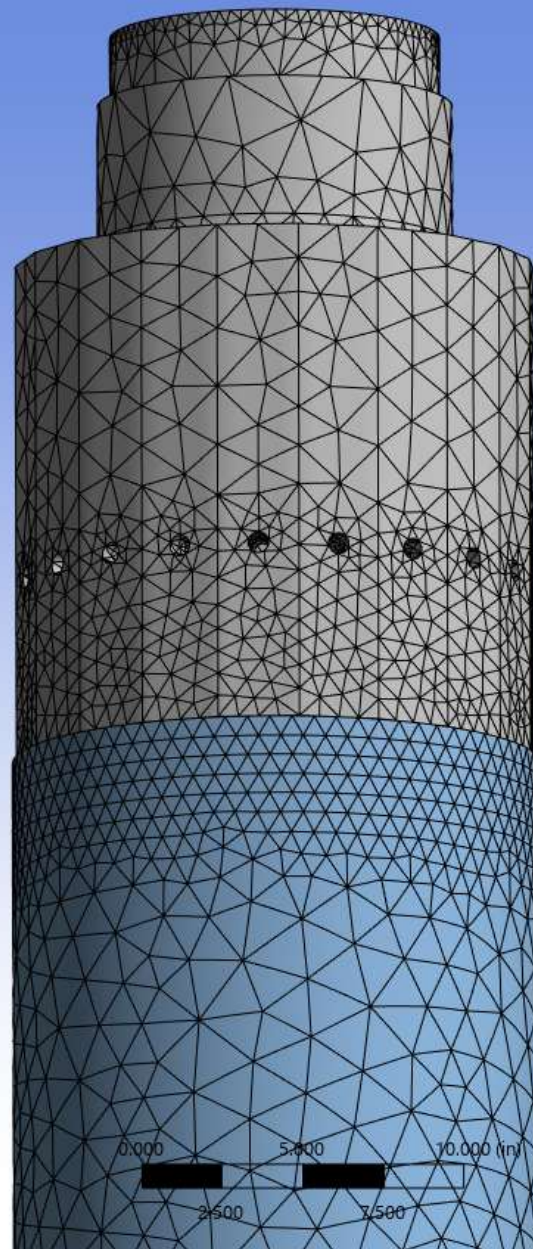


Figure 222 Crown to Shaft Joint Mesh

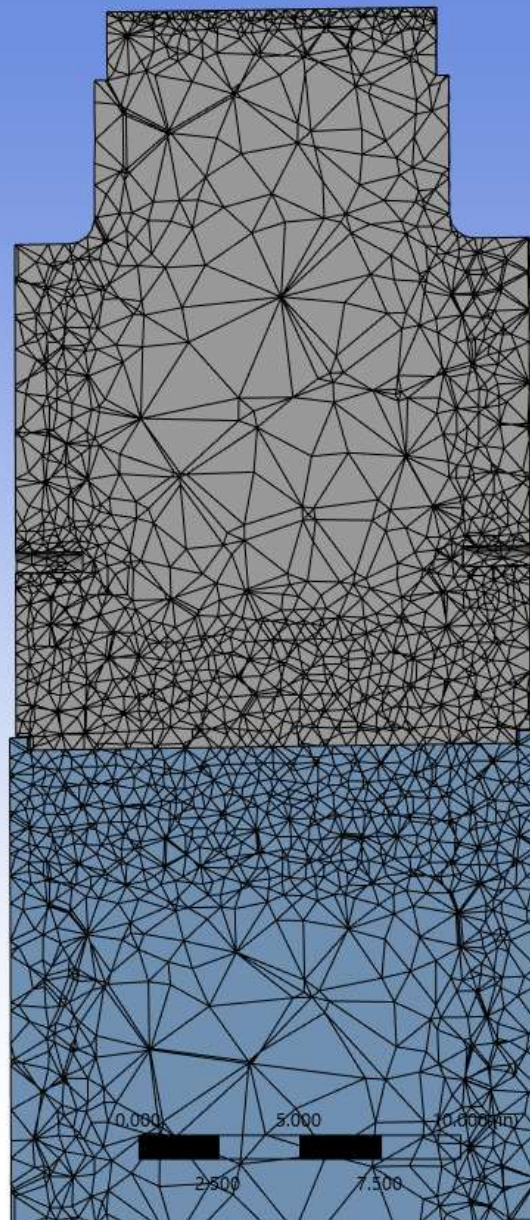


Figure 223 Crown to Shaft Joint Mesh, Section

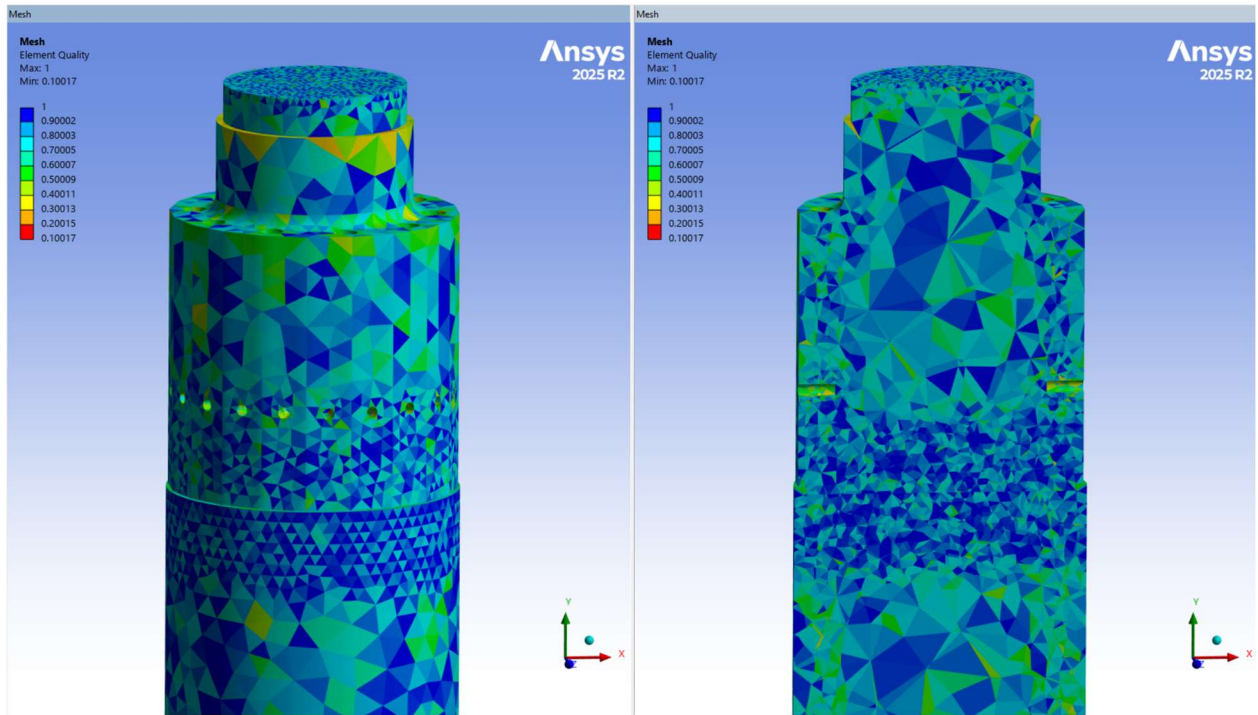


Figure 224 Shaft Mesh Quality

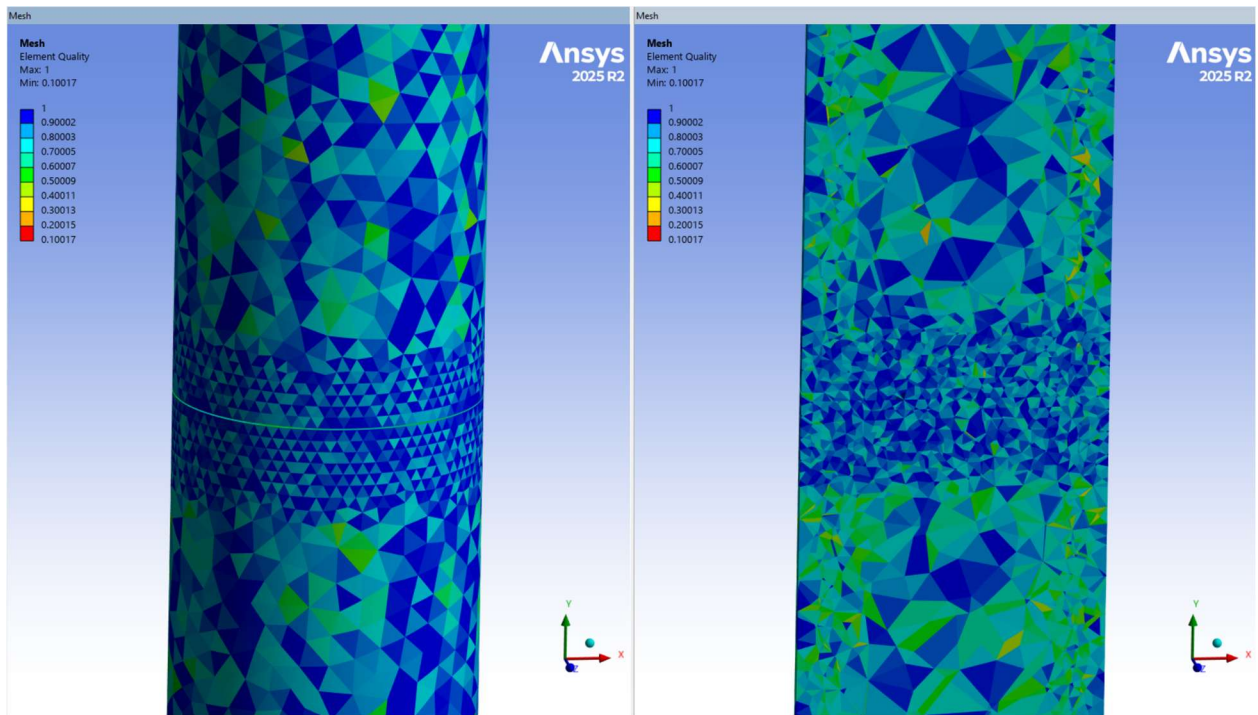


Figure 225 Shaft Mesh Quality

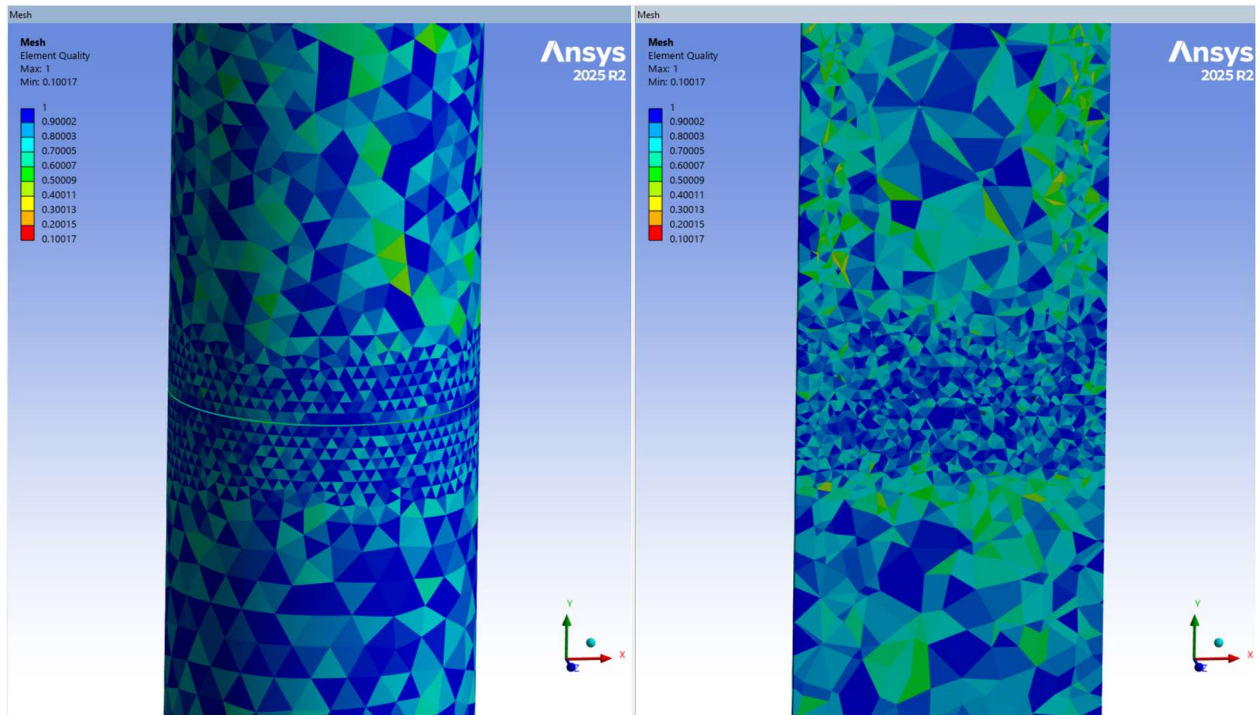


Figure 226 Shaft Mesh Quality

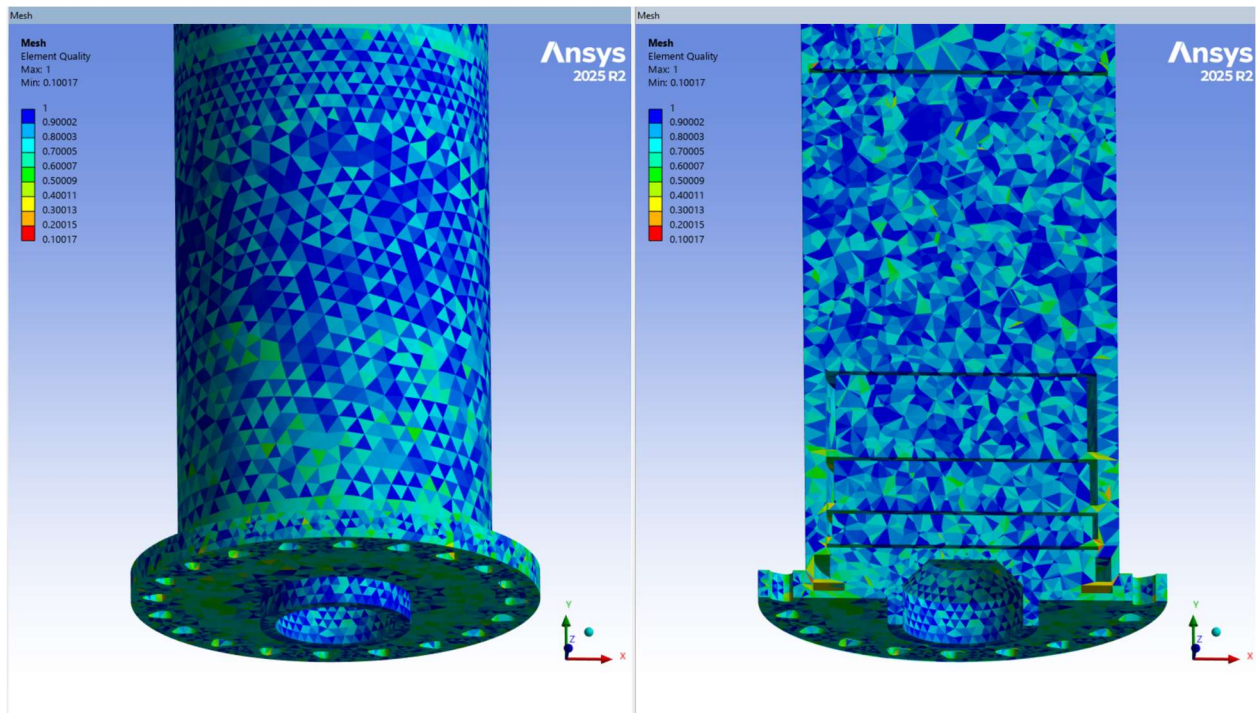


Figure 227 Shaft Mesh Quality

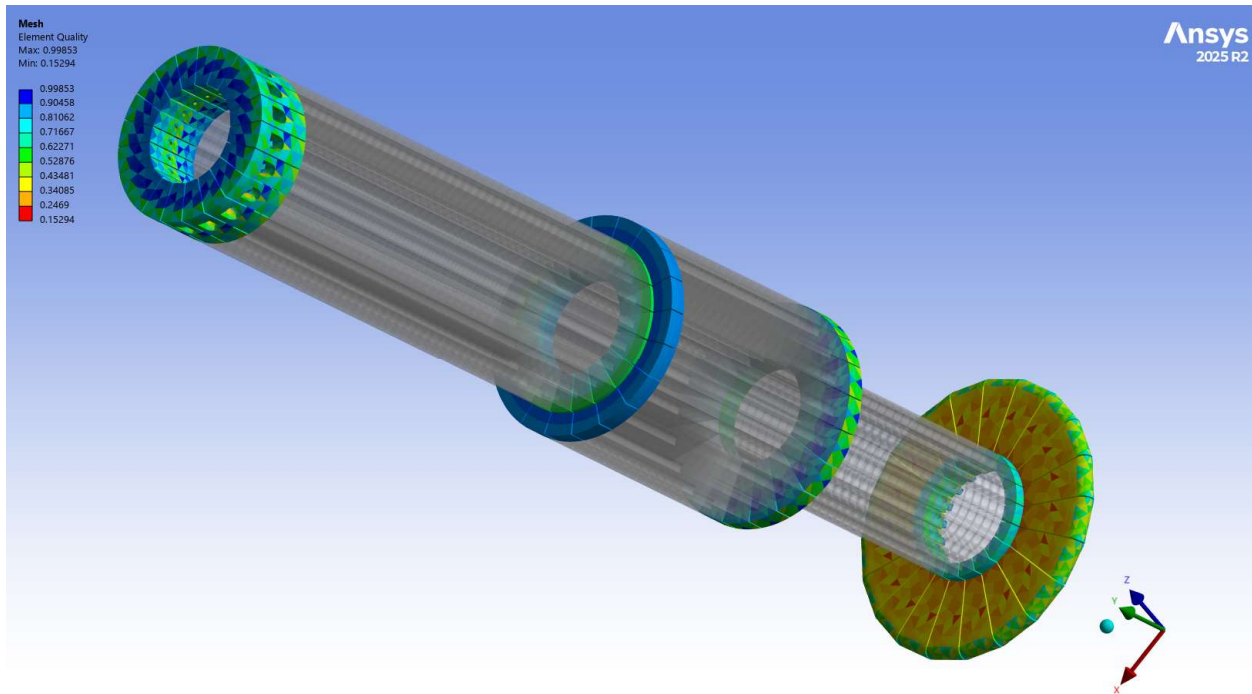


Figure 228 Dummy Segment Mesh Quality

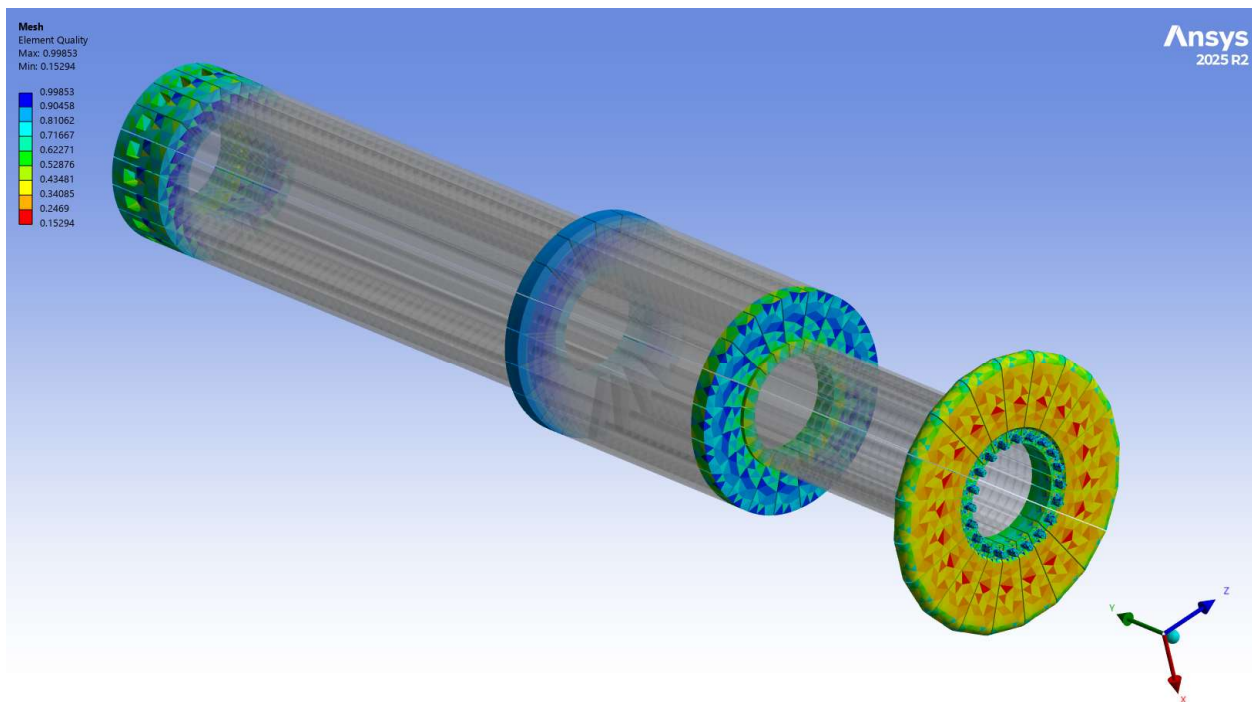


Figure 229 Dummy Segment Mesh Quality

4.3.3.1 Snubber Ring

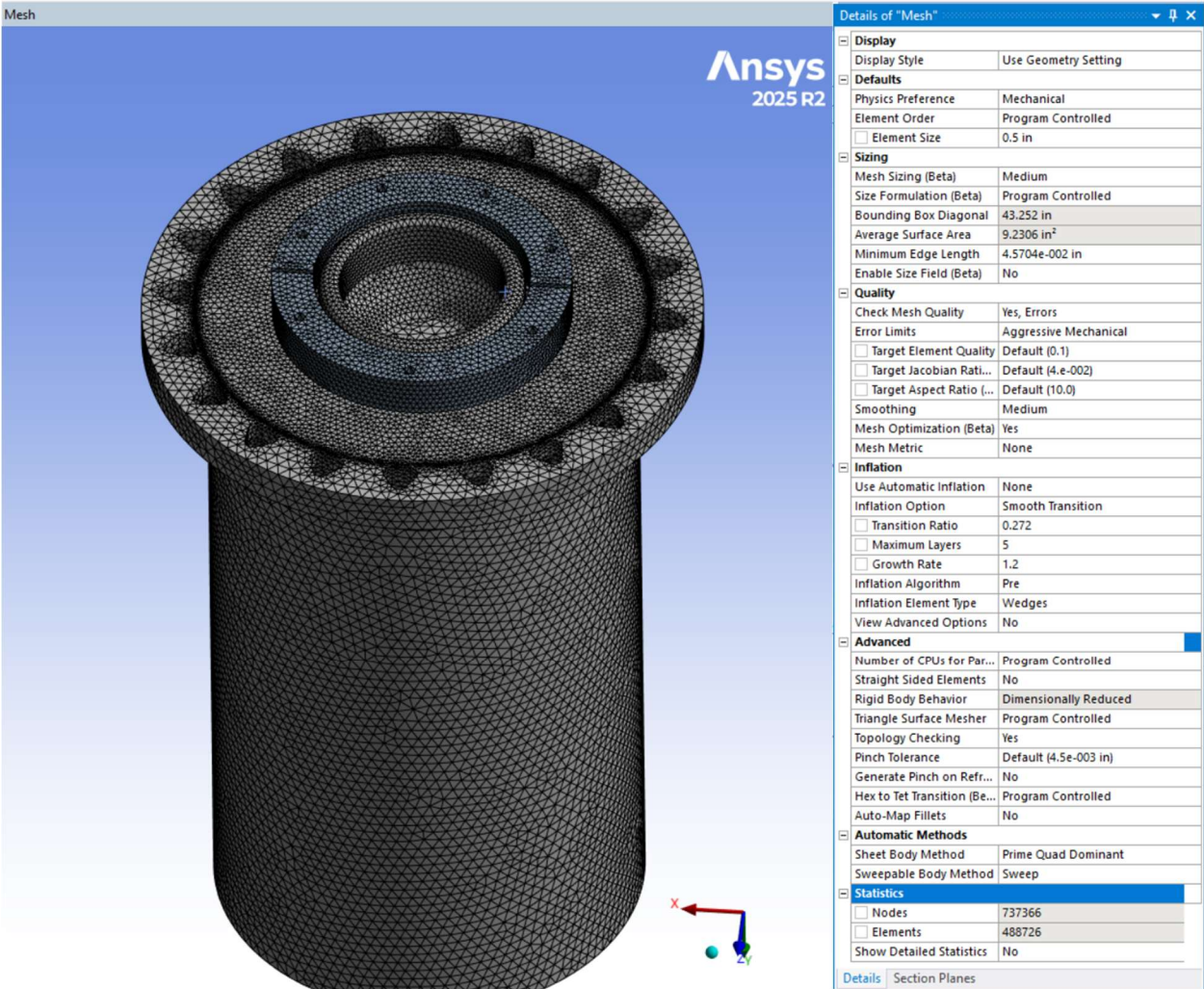


Figure 230 Snubber Ring Mesh Details

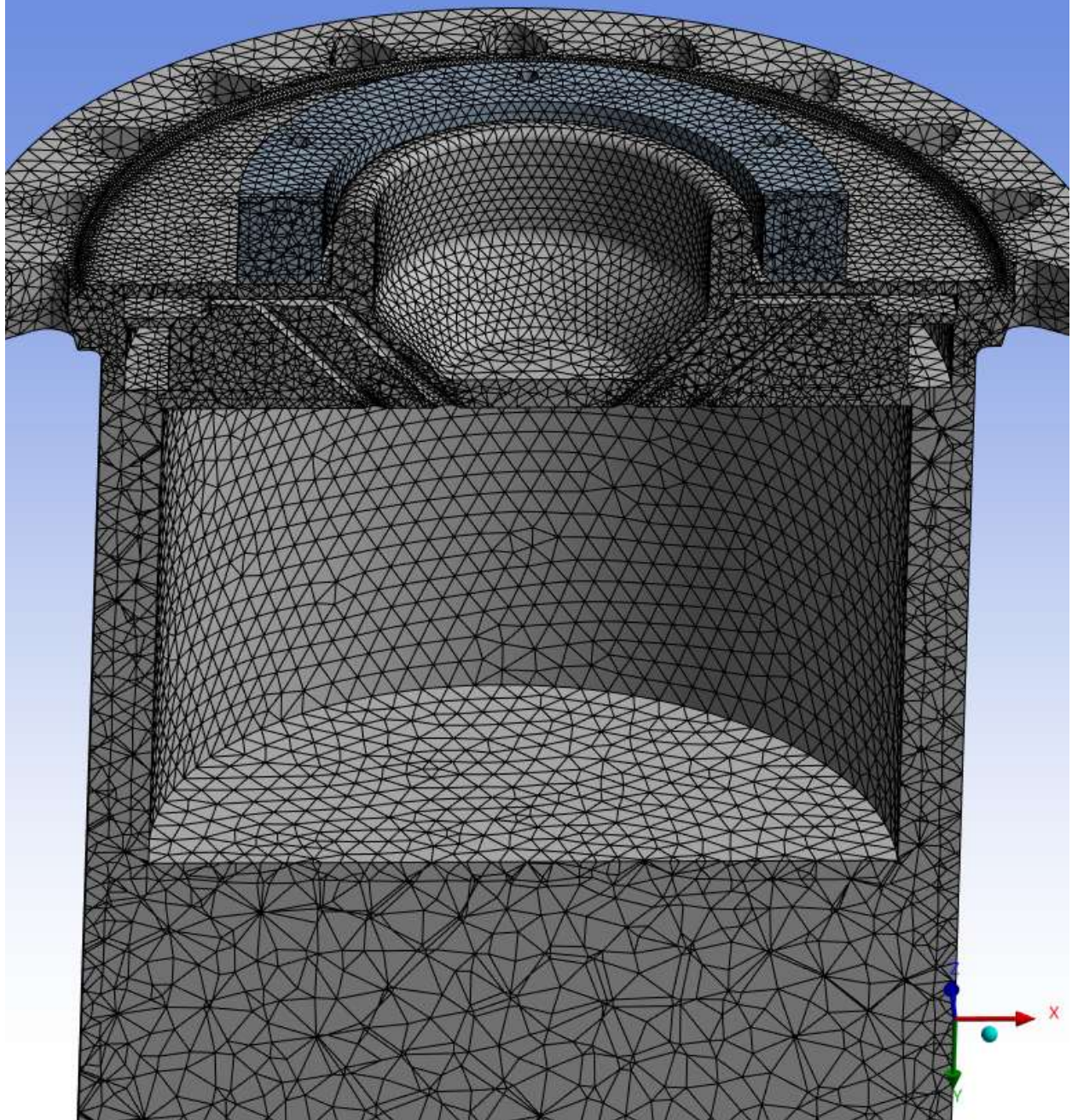


Figure 231 Snubber Ring Mesh, Section View

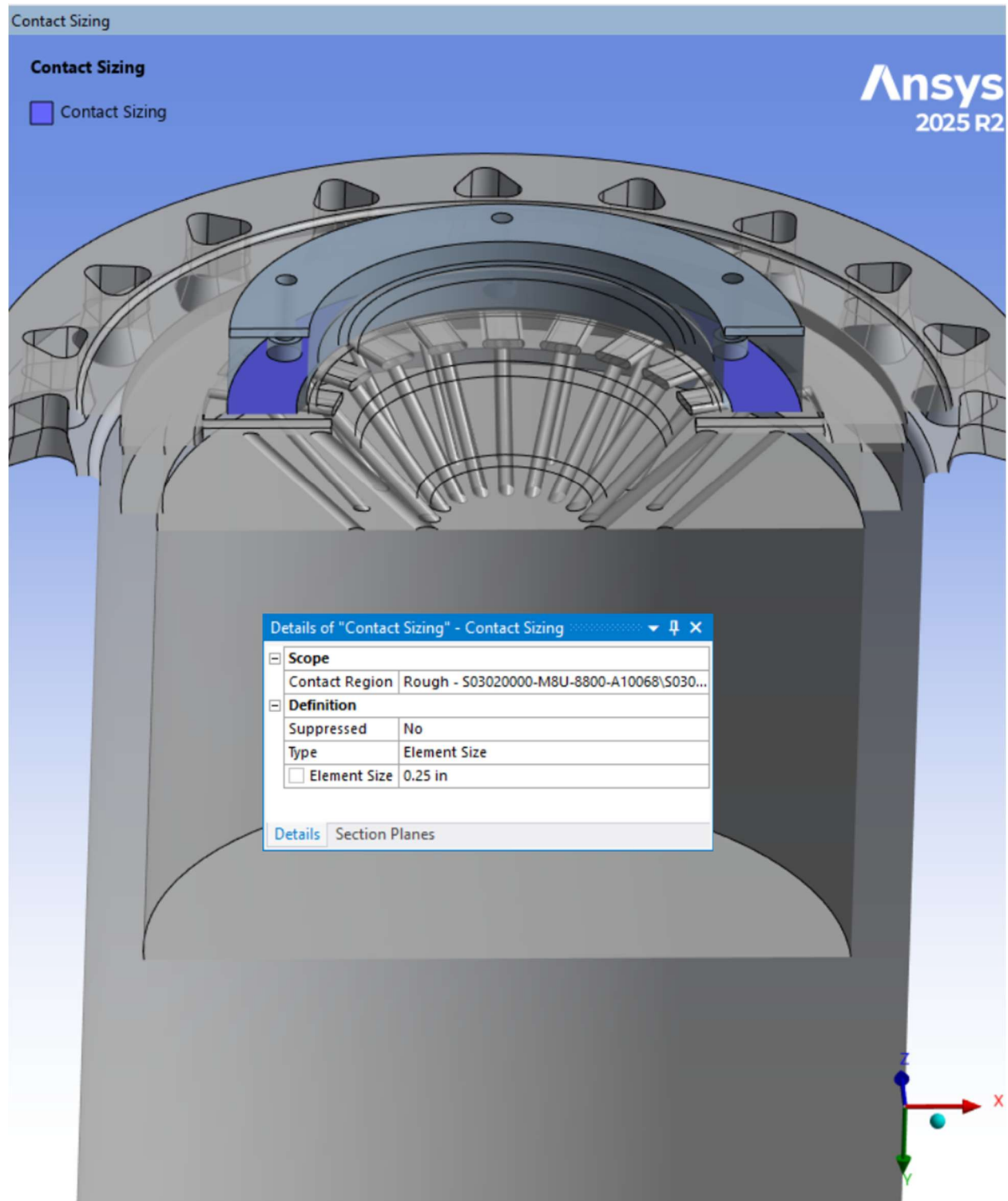


Figure 232 Snubber Ring Mesh Contact Sizing

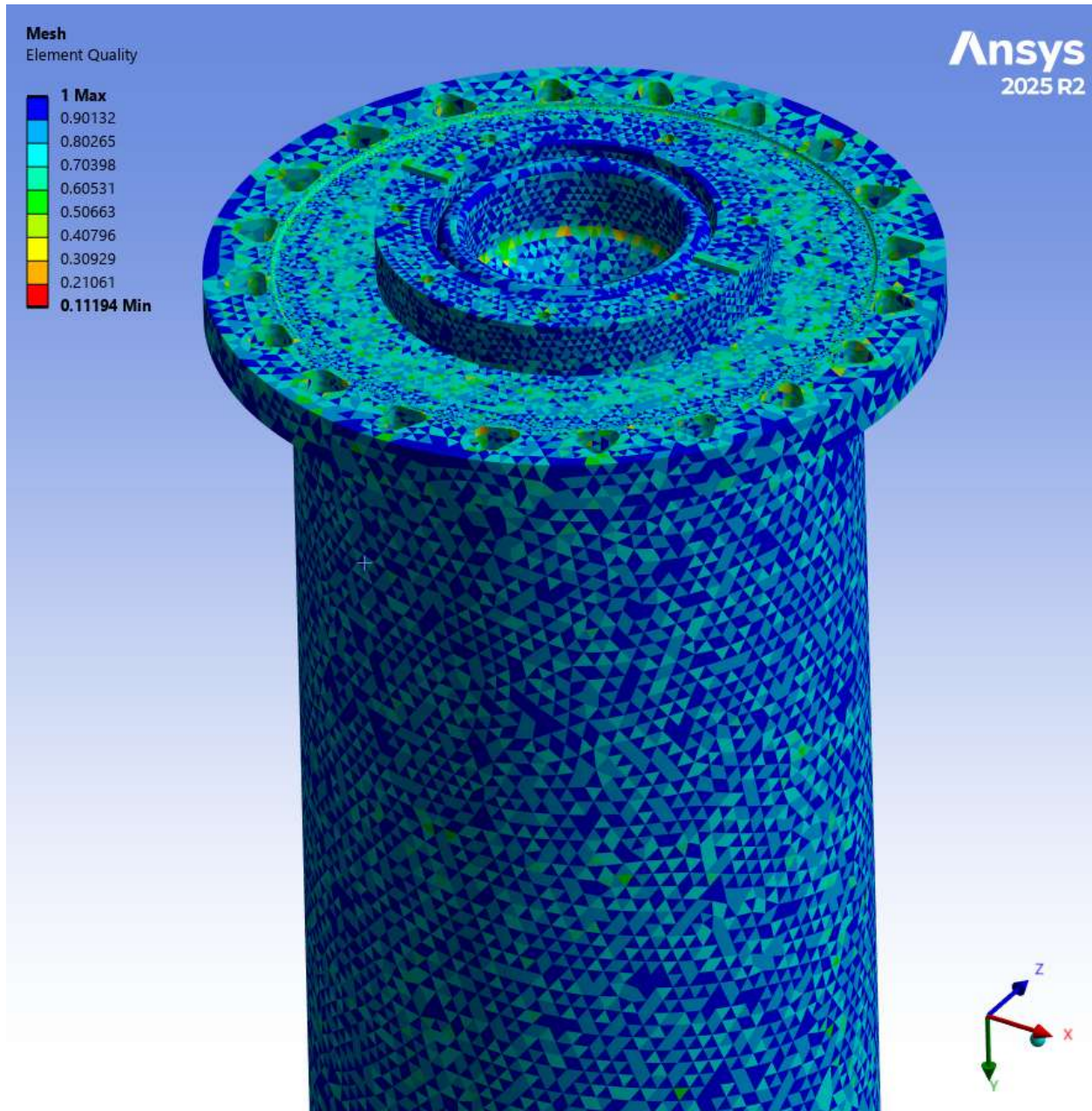
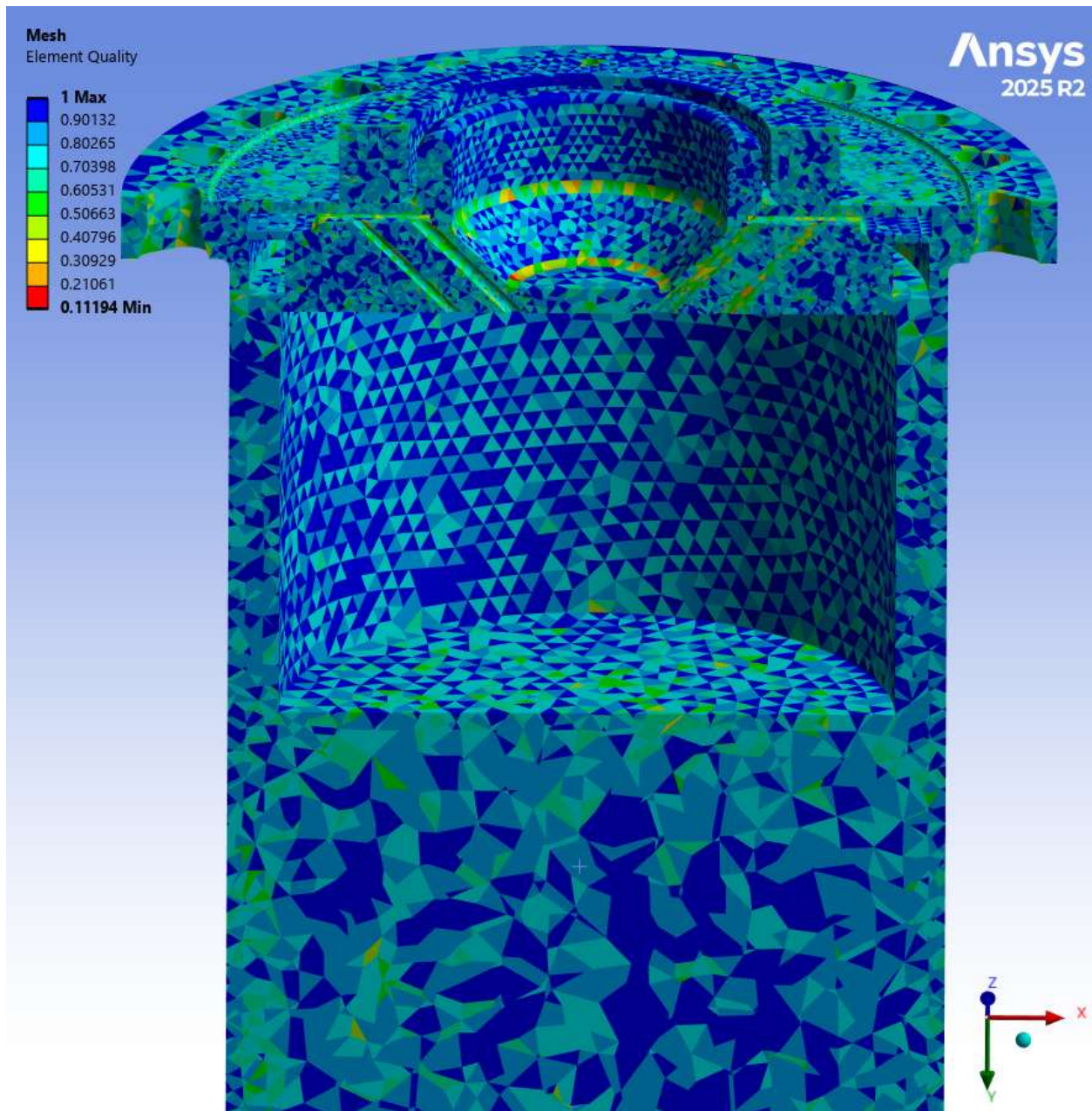


Figure 233 Snubber Ring Mesh Quality



4.3.4 Crown and Drive

The Crown model's mesh was mostly default, the global size was set to 1.5 inches for the Shaft, Union, and Manifold that were included just for weight on the Crown.

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
☐ Element Size	1.5 in
Sizing	
Mesh Sizing (Beta)	Medium
Size Formulation (Beta)	Program Controlled
Bounding Box Diagonal	323.7 in
Average Surface Area	23,262 in ²
Minimum Edge Length	1.5523e-002 in
Enable Size Field (Beta)	No
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Aggressive Mechanical
☐ Target Element Quality	Default (0.1)
☐ Target Jacobian Ratio (Corner No...	Default (4.e-002)
☐ Target Aspect Ratio (Height) (Beta)	Default (10.0)
Smoothing	Medium
Mesh Optimization (Beta)	Yes
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
☐ Transition Ratio	0.272
☐ Maximum Layers	5
☐ Growth Rate	1.2
Inflation Algorithm	Pre
Inflation Element Type	Wedges
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Me...	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (1.35e-002 in)
Generate Pinch on Refresh	No
Hex to Tet Transition (Beta)	Program Controlled
Auto-Map Fillets	No
Automatic Methods	
Sheet Body Method	Quad Dominant
Sweepable Body Method	Sweep
Statistics	
☐ Nodes	1763769
☐ Elements	1020860
Show Detailed Statistics	No

Figure 235 Crown General Mesh Settings

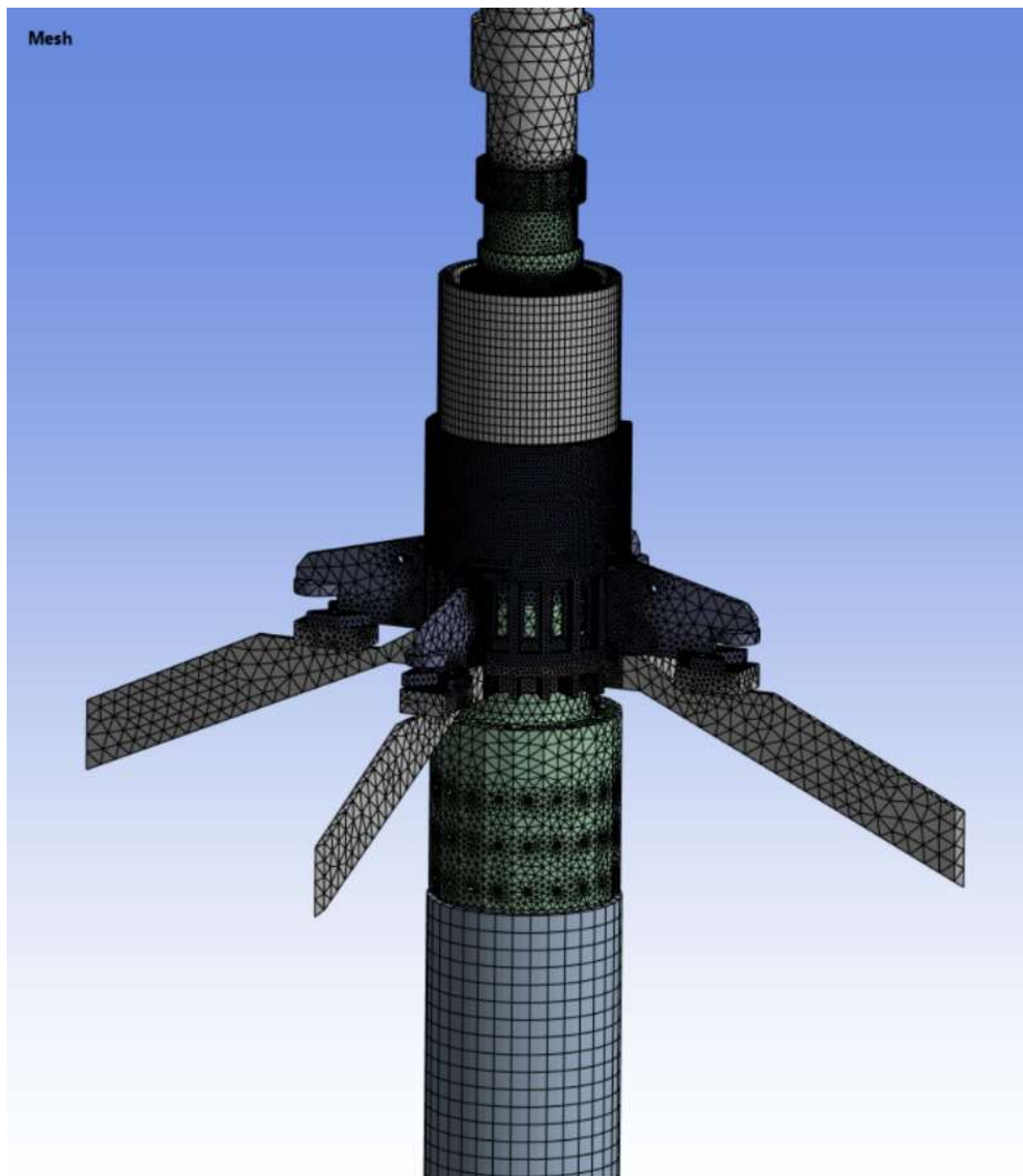


Figure 236 Crown Model Mesh

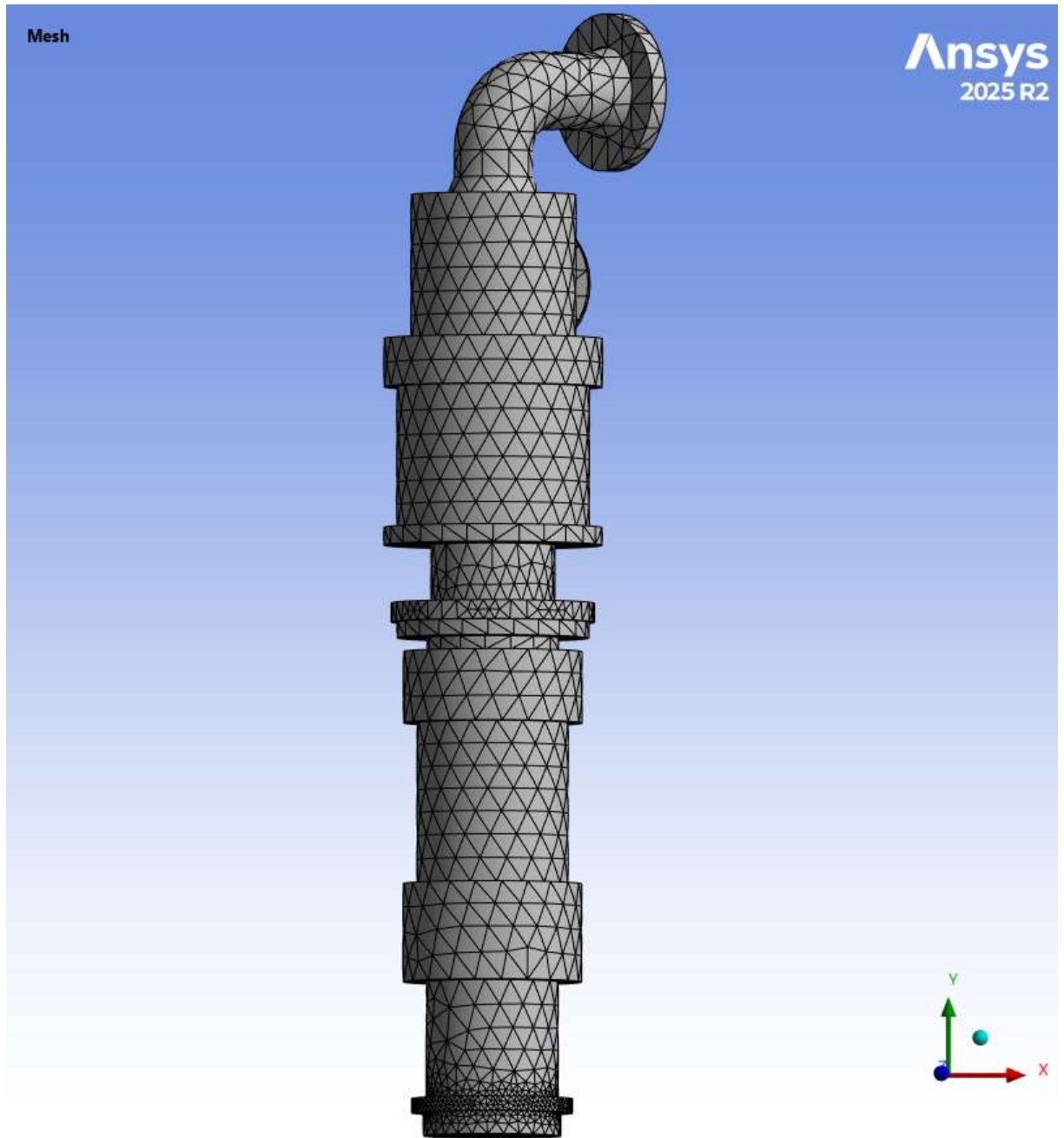


Figure 237 Water Union and Manifold Mesh

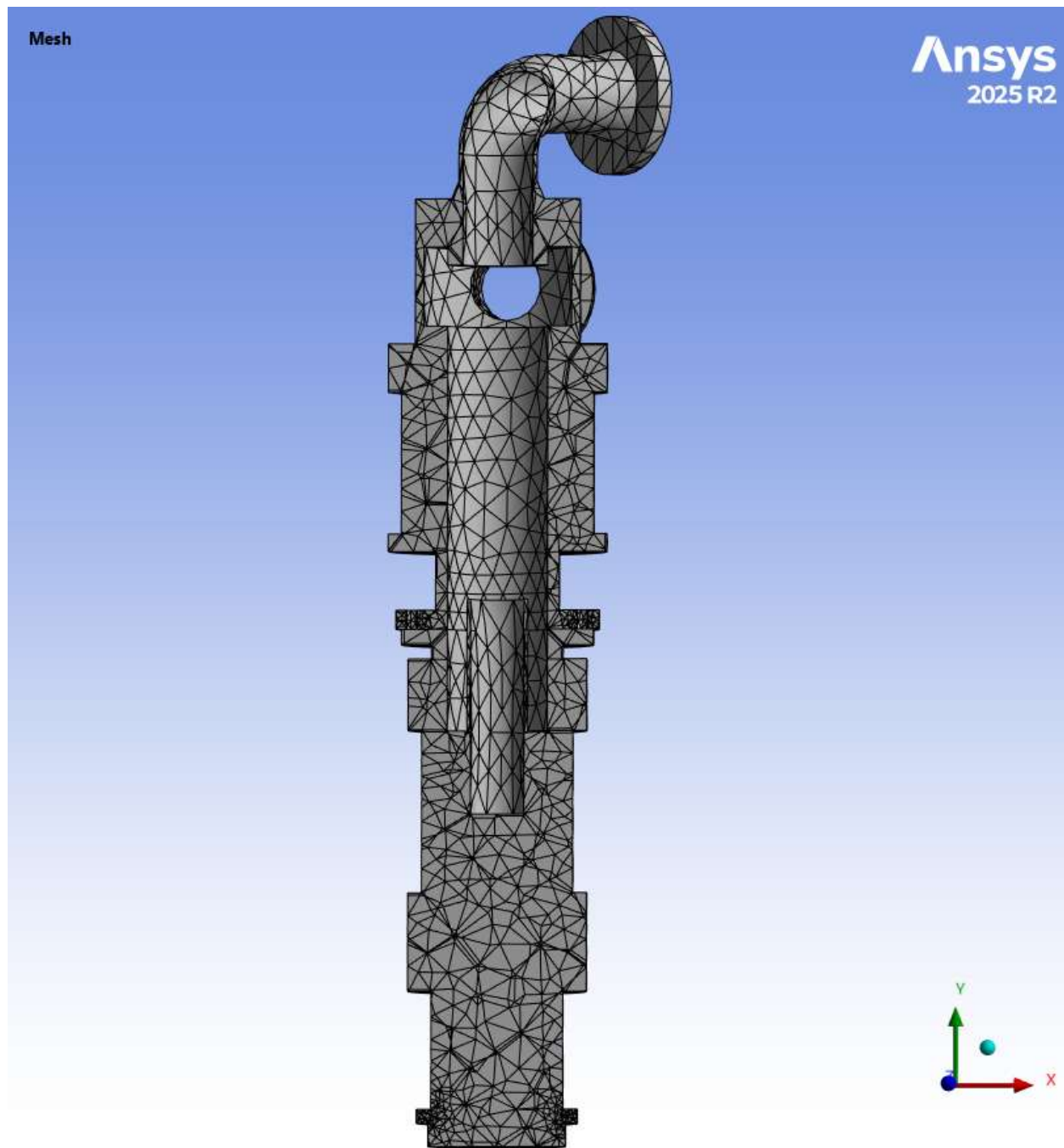


Figure 238 Water Union and Manifold Mesh, Section

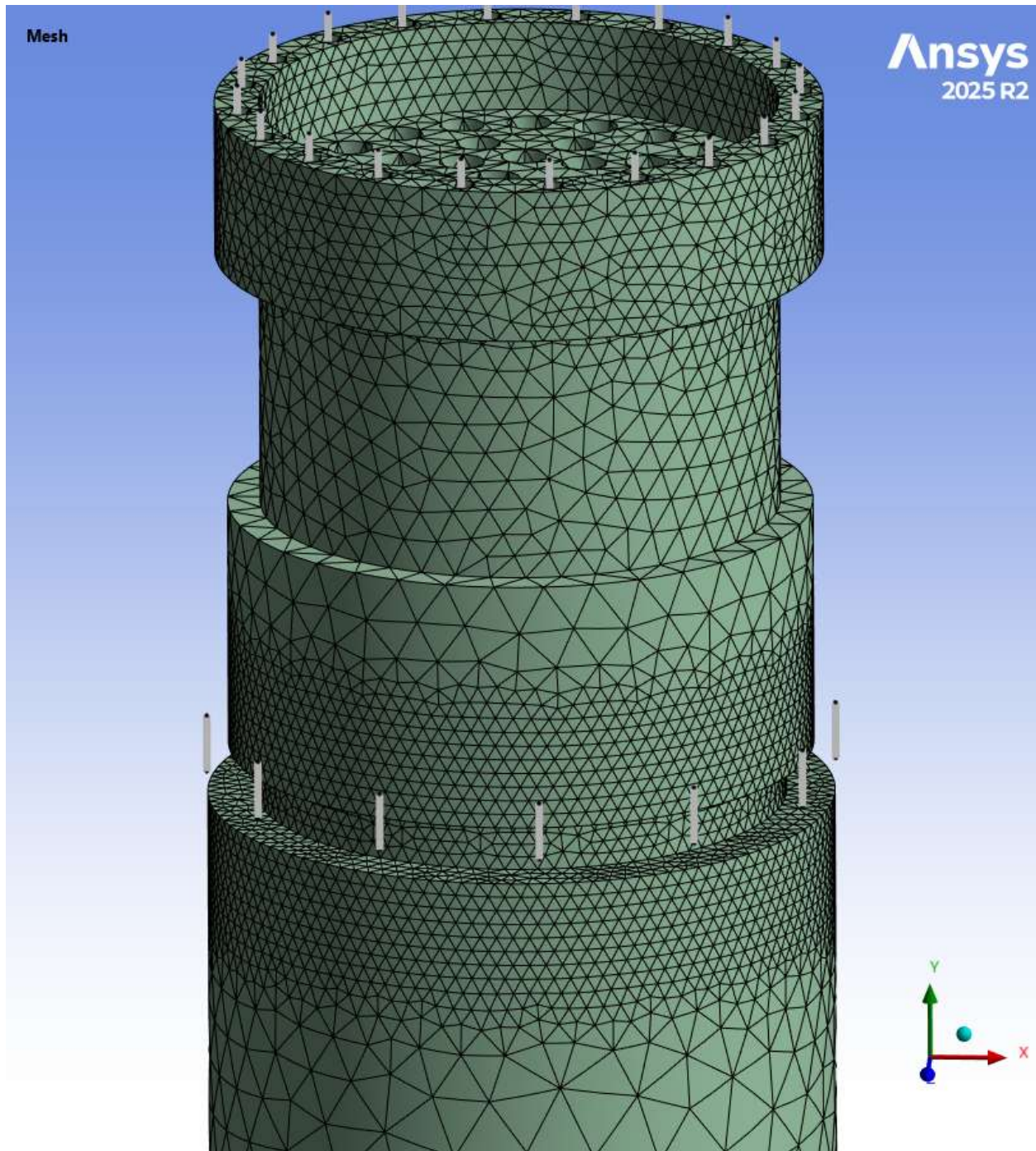


Figure 239 Upper Crown Mesh

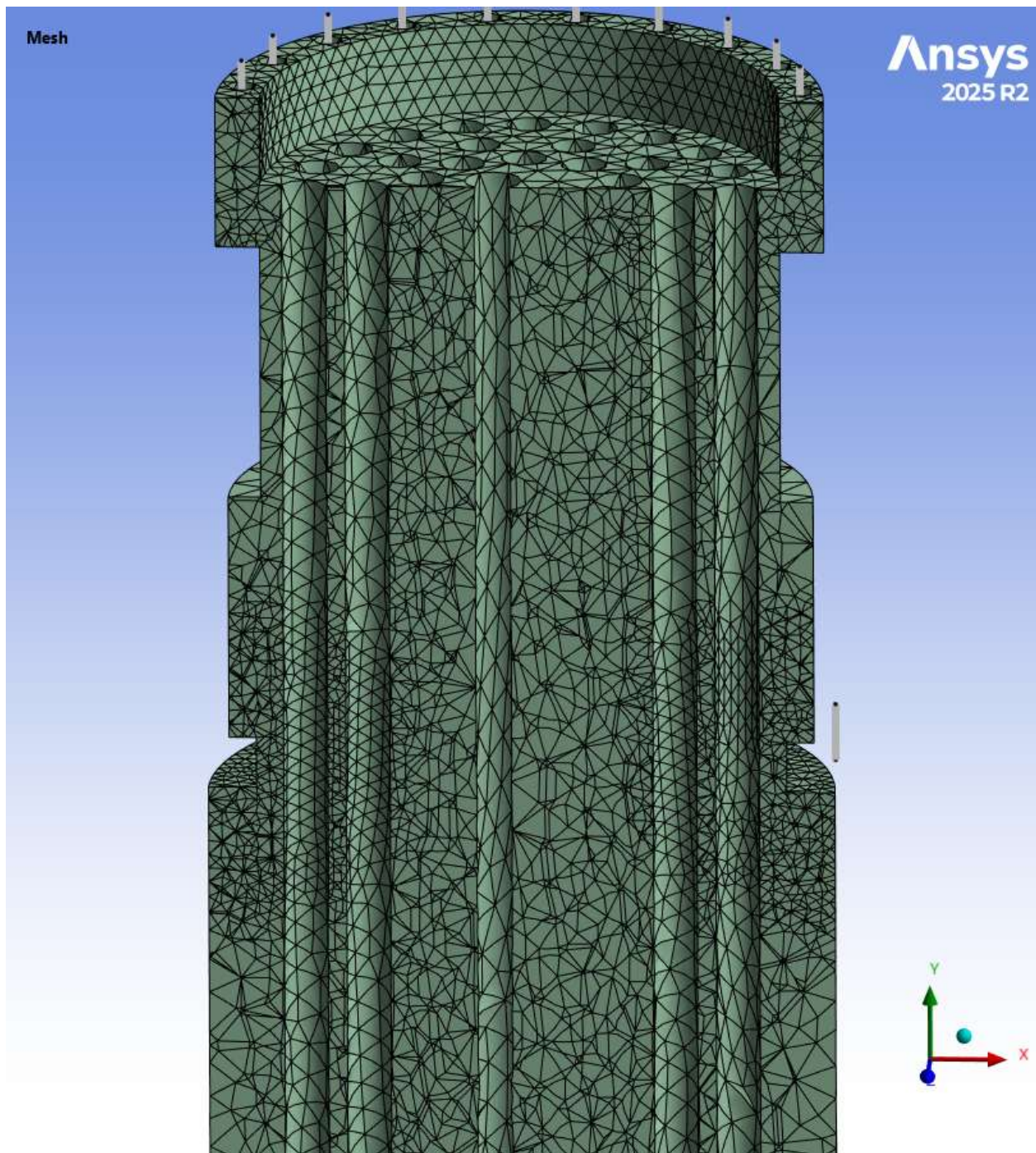


Figure 240 Upper Crown Mesh, Section

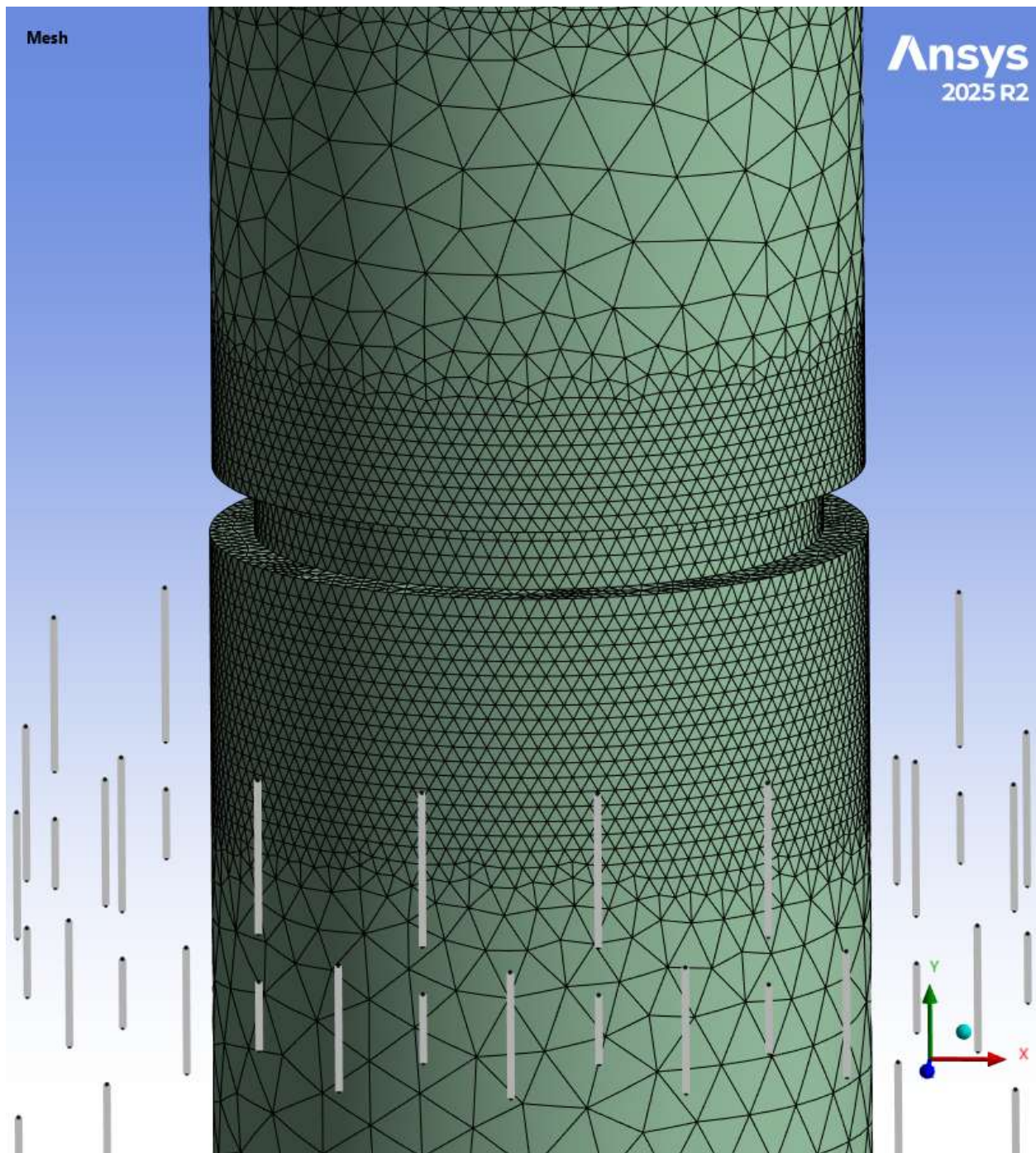


Figure 241 Mid Crown Mesh

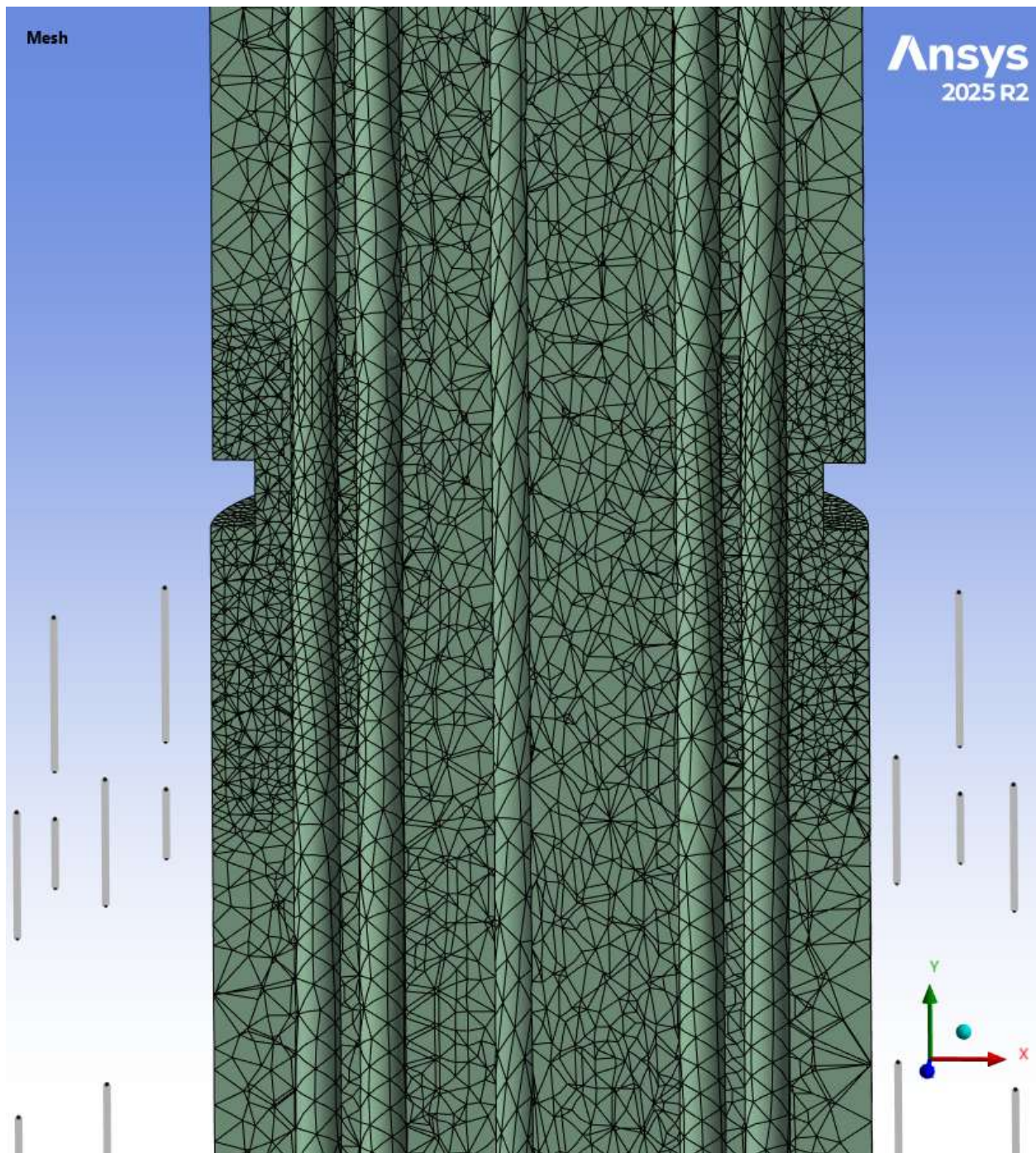


Figure 242 Mid Crown Mesh, Section

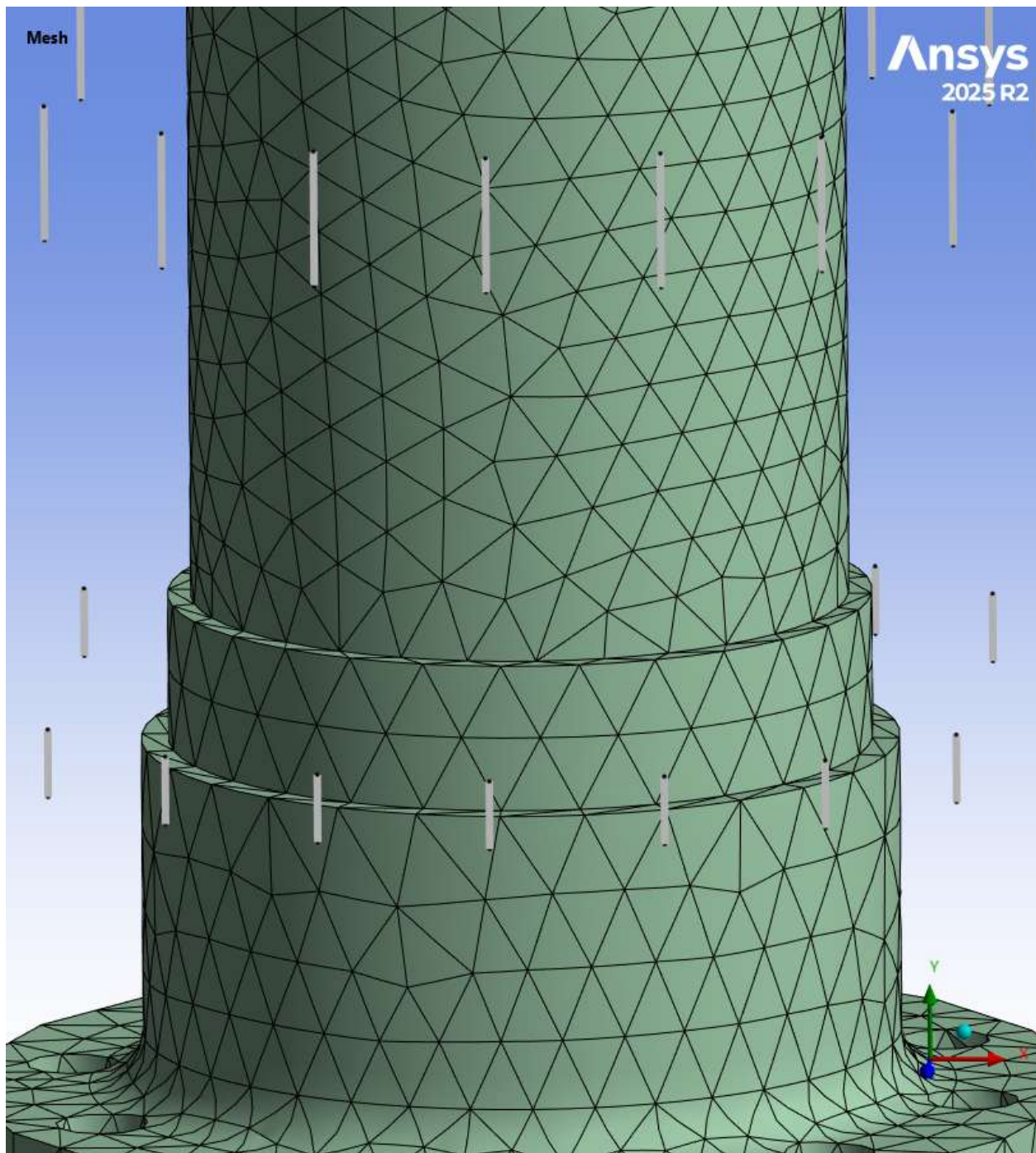


Figure 243 Mid Crown Mesh

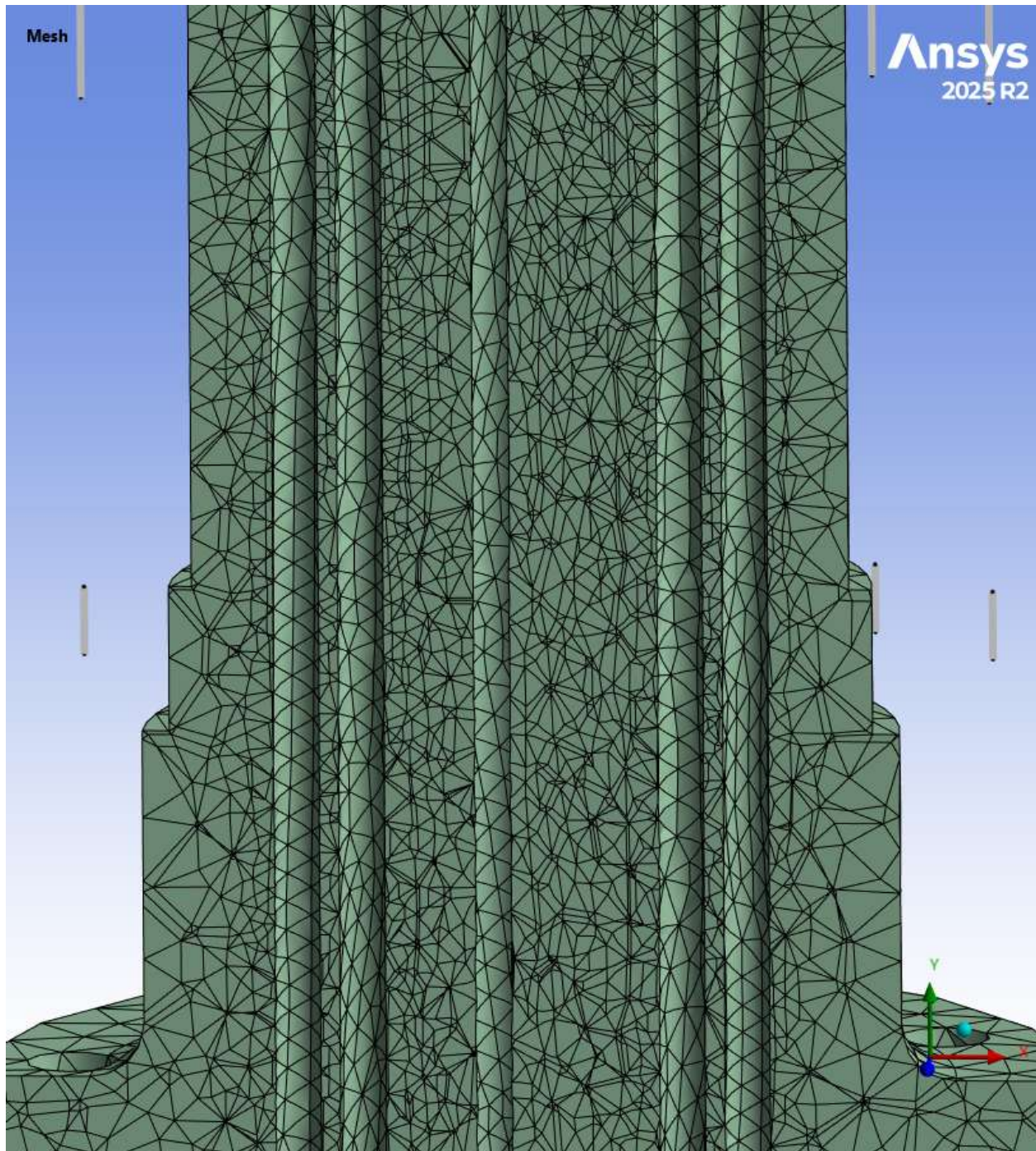


Figure 244 Mid Crown Mesh, Section

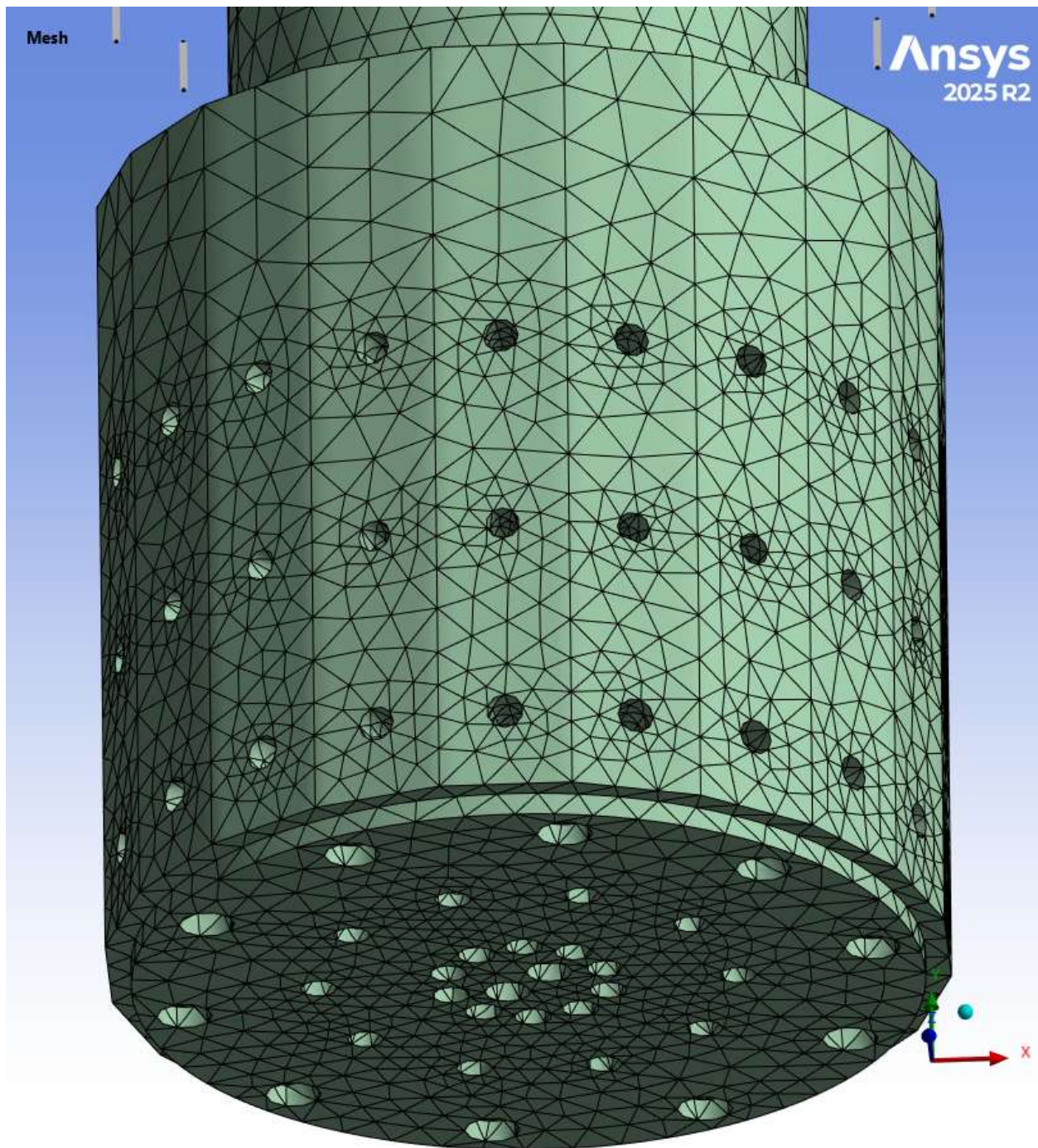


Figure 245 Lower Crown Mesh

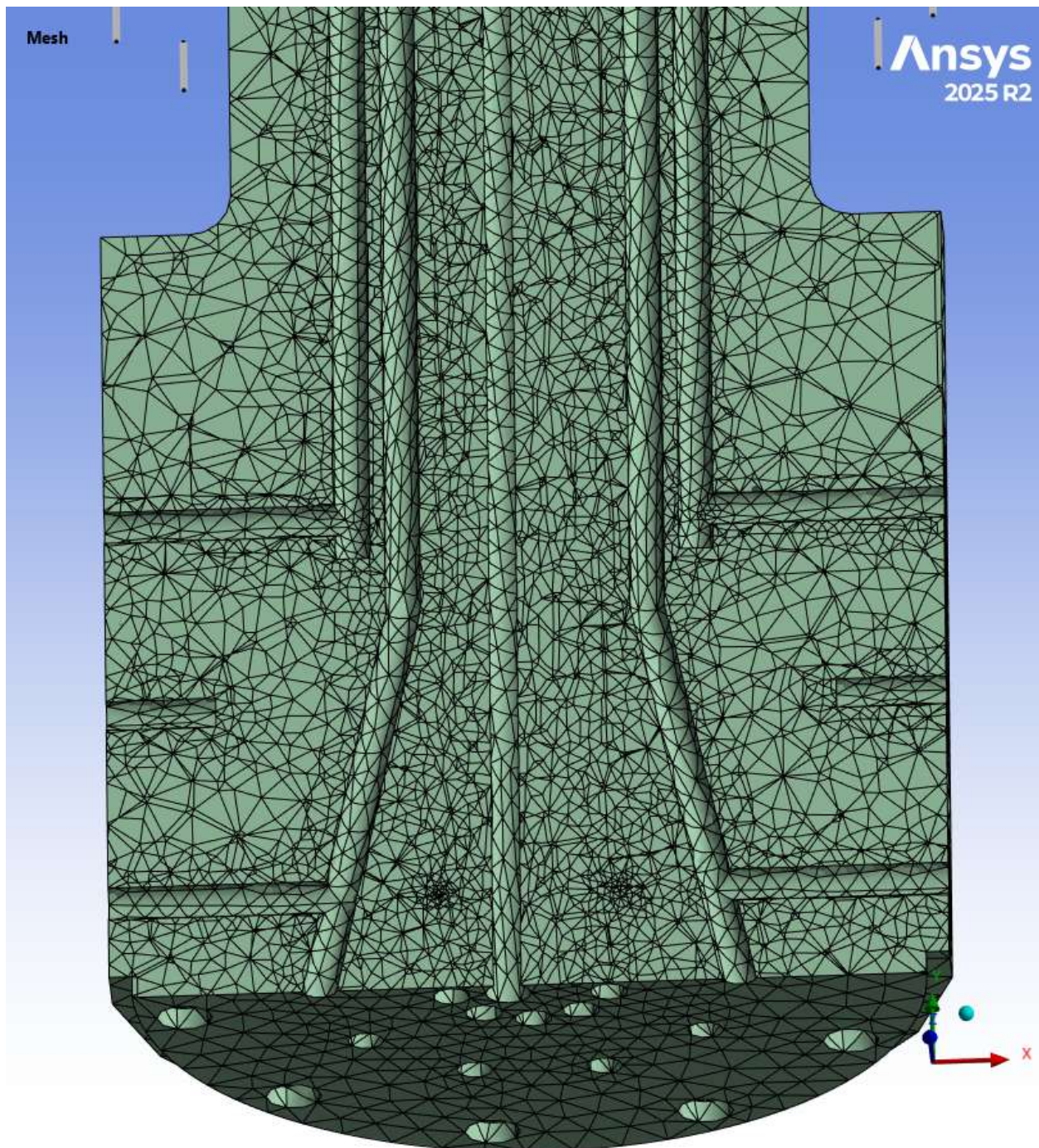


Figure 246 Lower Crown Mesh, Section

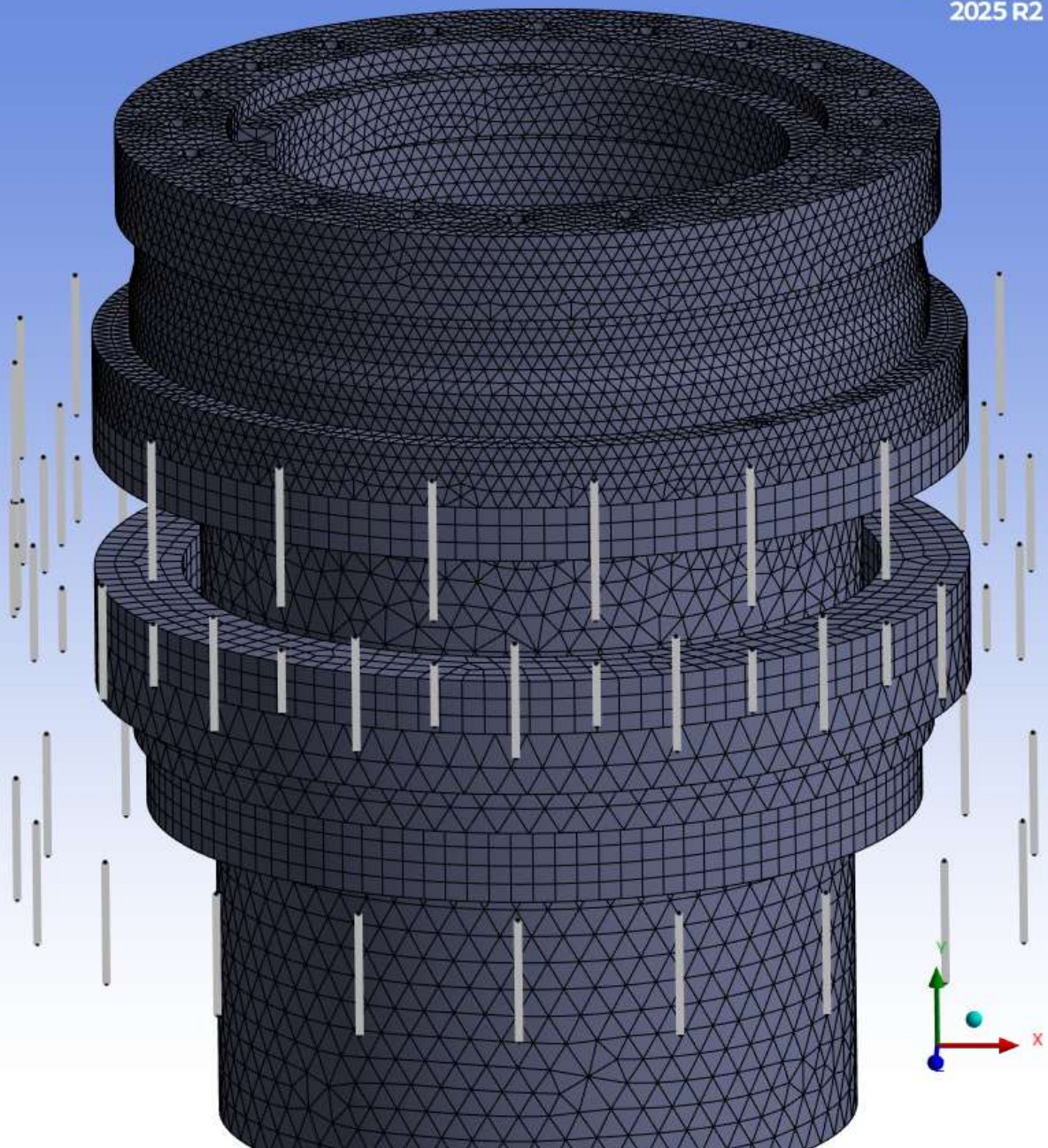


Figure 247 Inner Housing Mesh

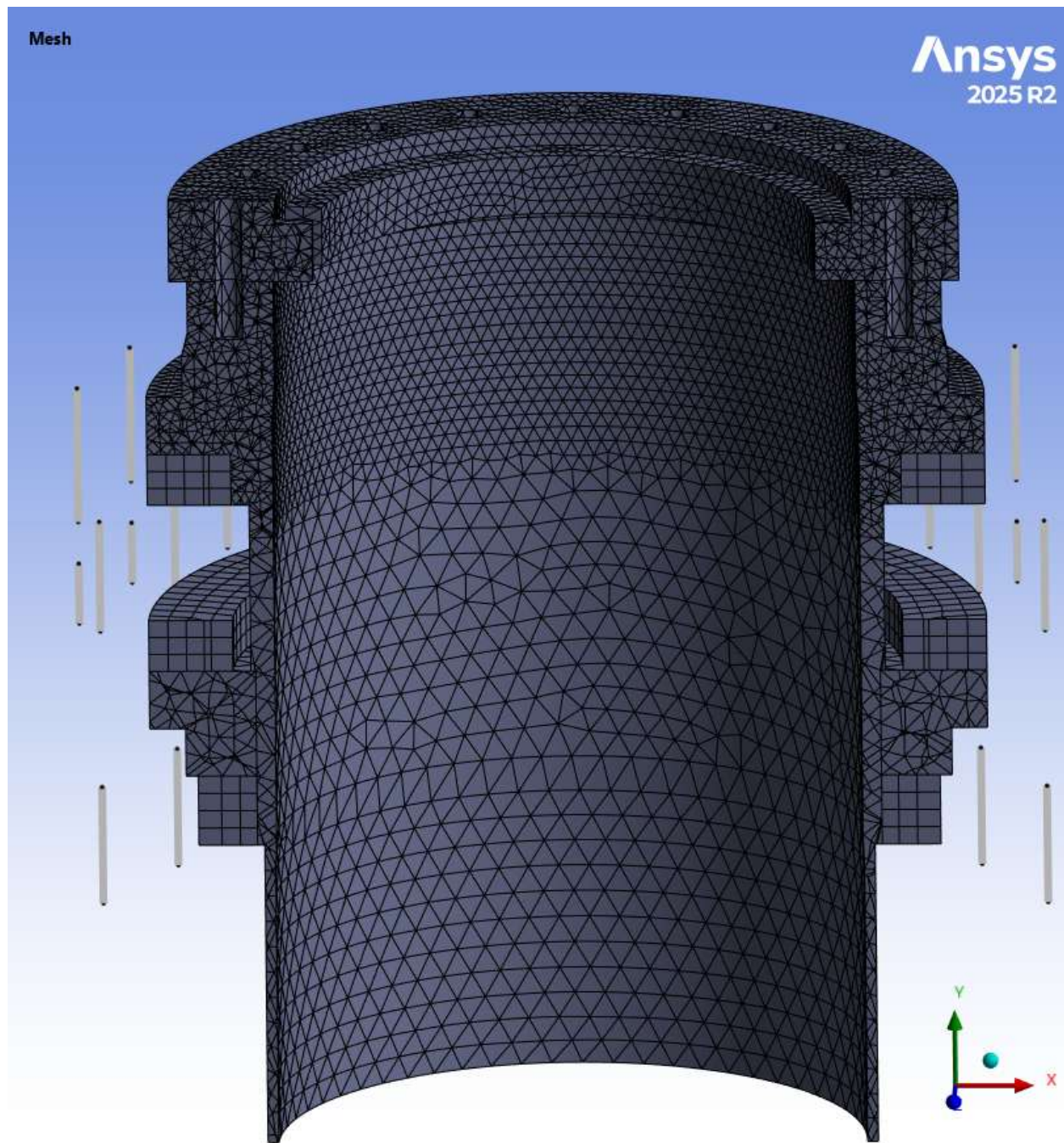


Figure 248 Inner Housing Mesh, Section

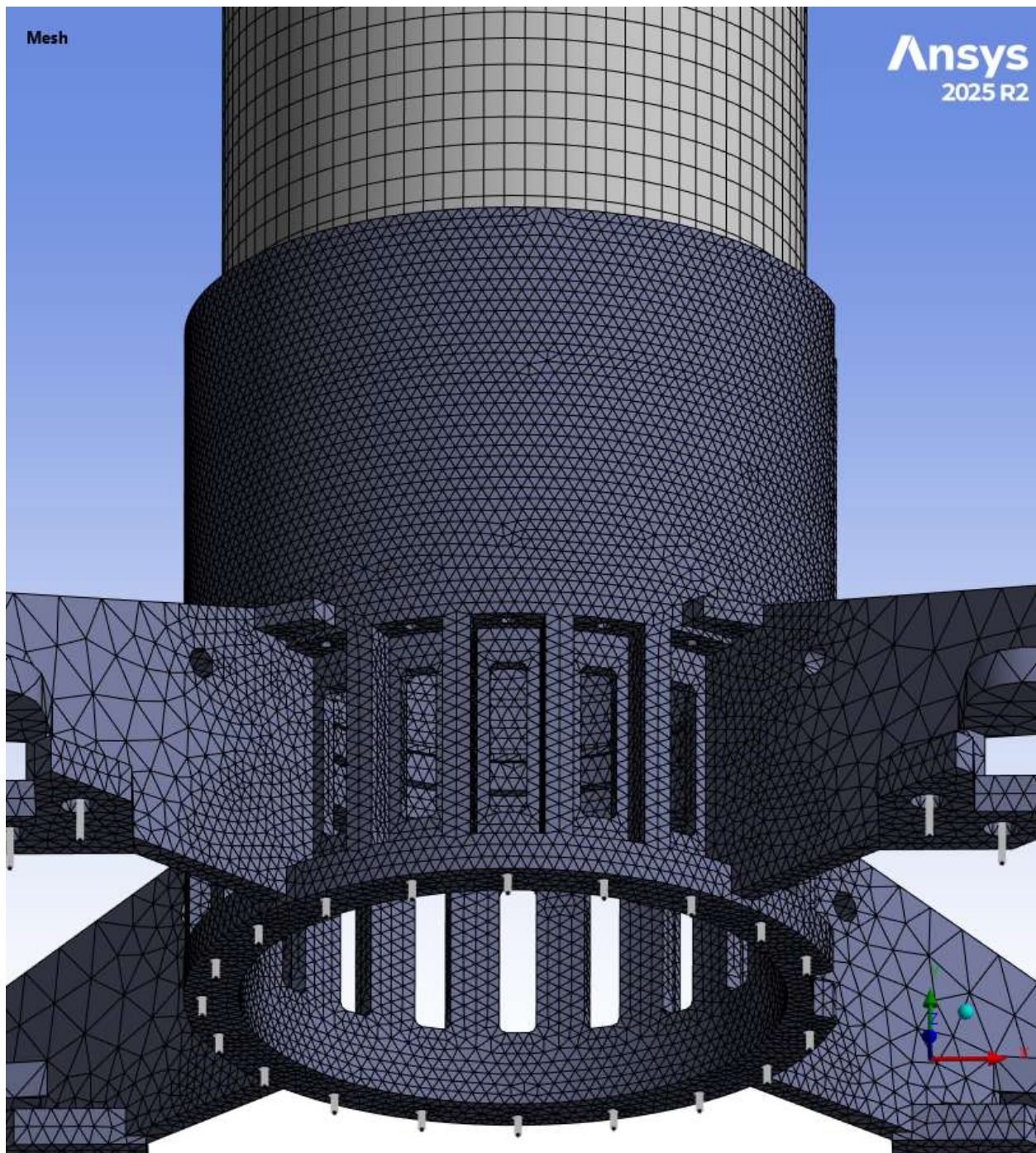


Figure 249 Outer Housing Mesh

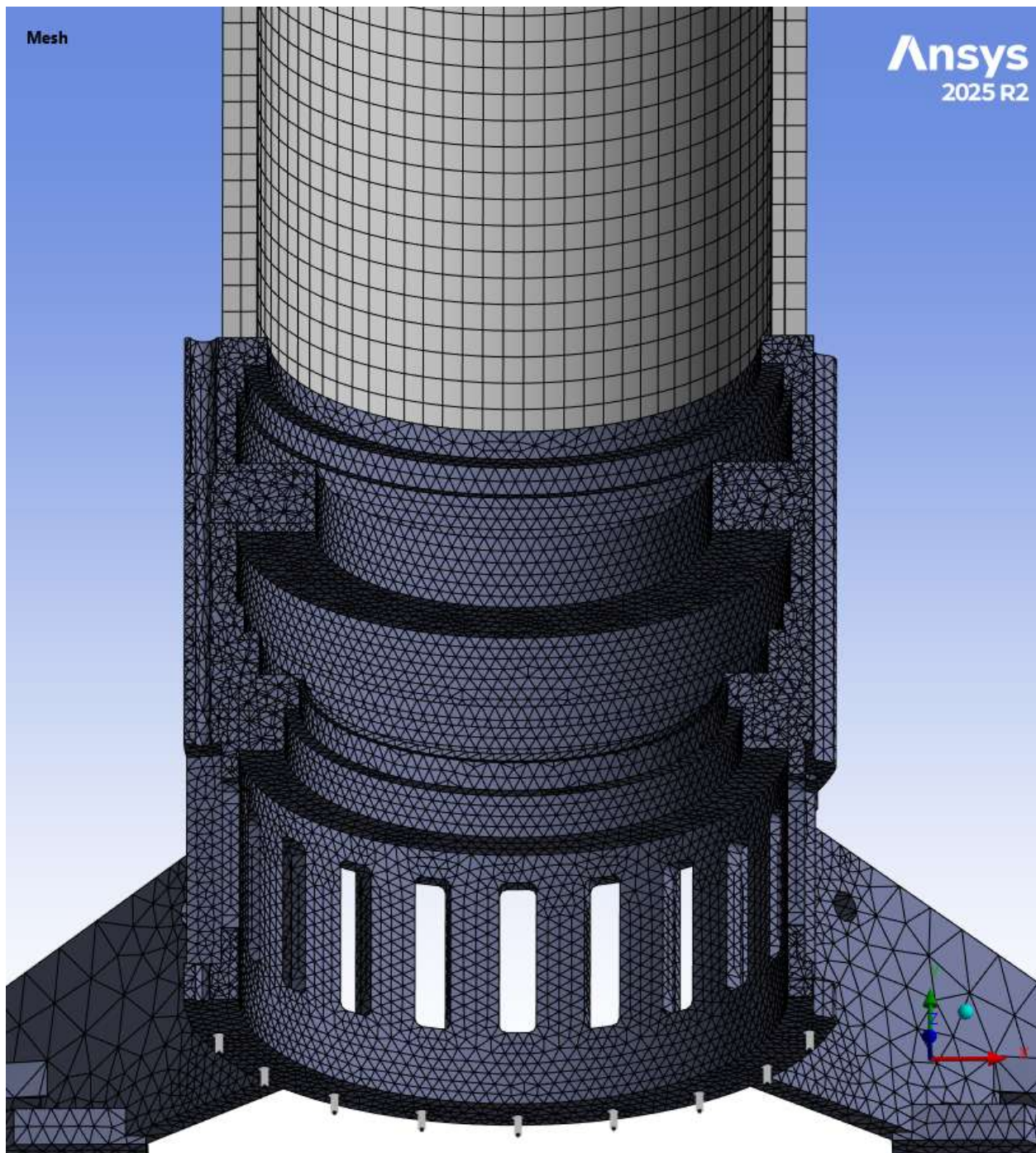


Figure 250 Outer Housing Mesh, Section

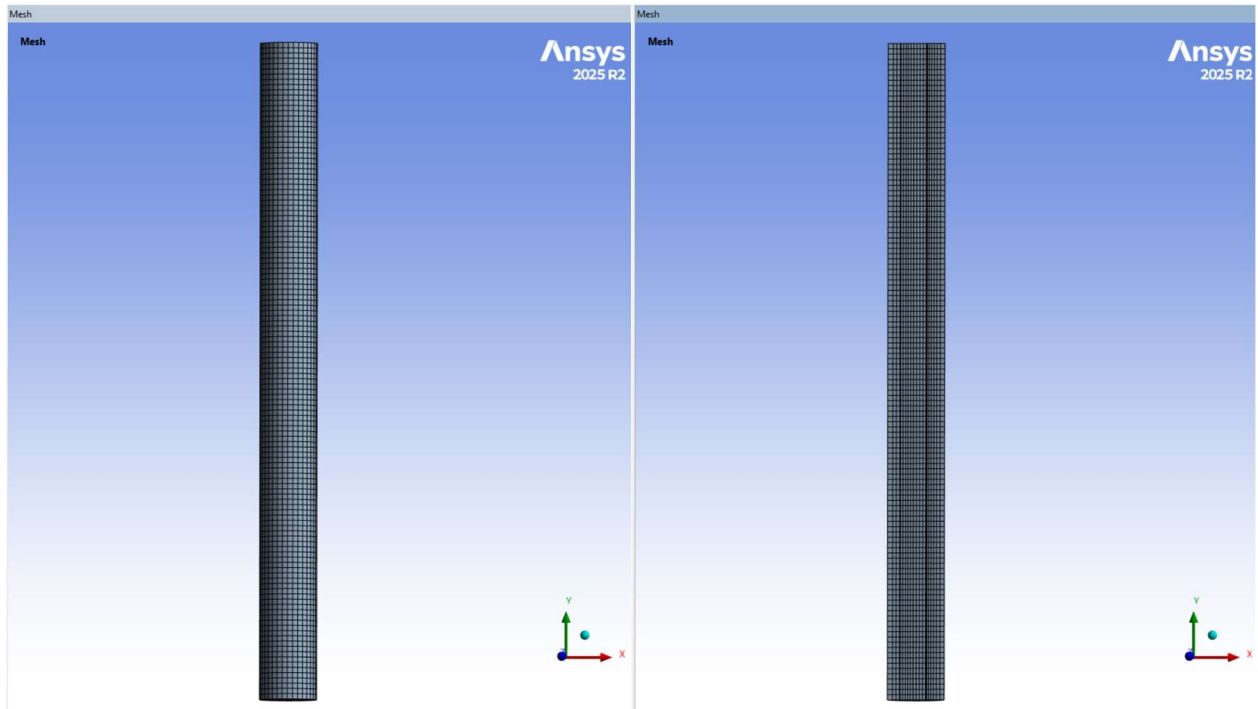


Figure 251 Shaft Mesh

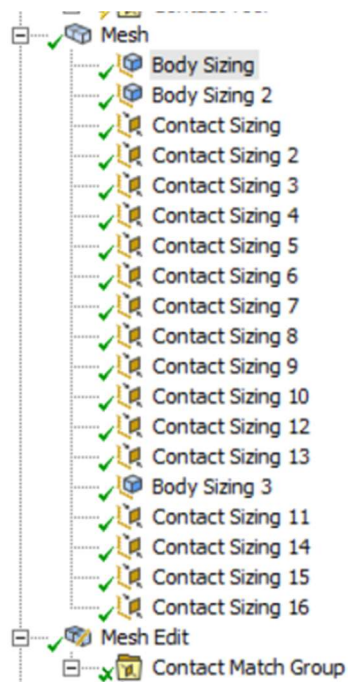


Figure 252 Drive Assembly Additional Mesh Settings

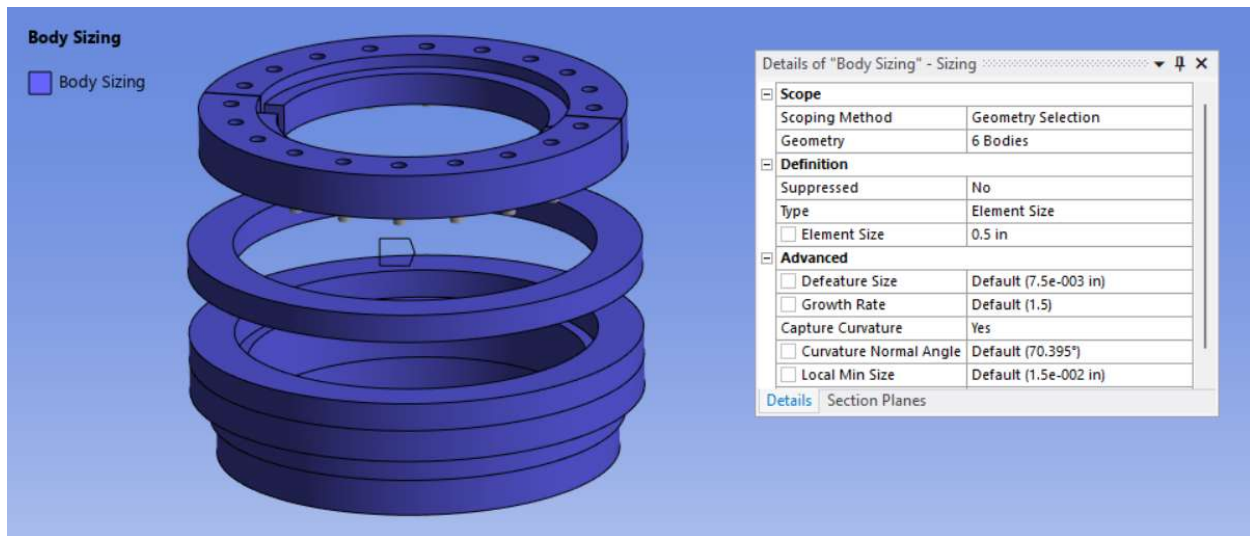


Figure 253 Housing Mesh Sizing

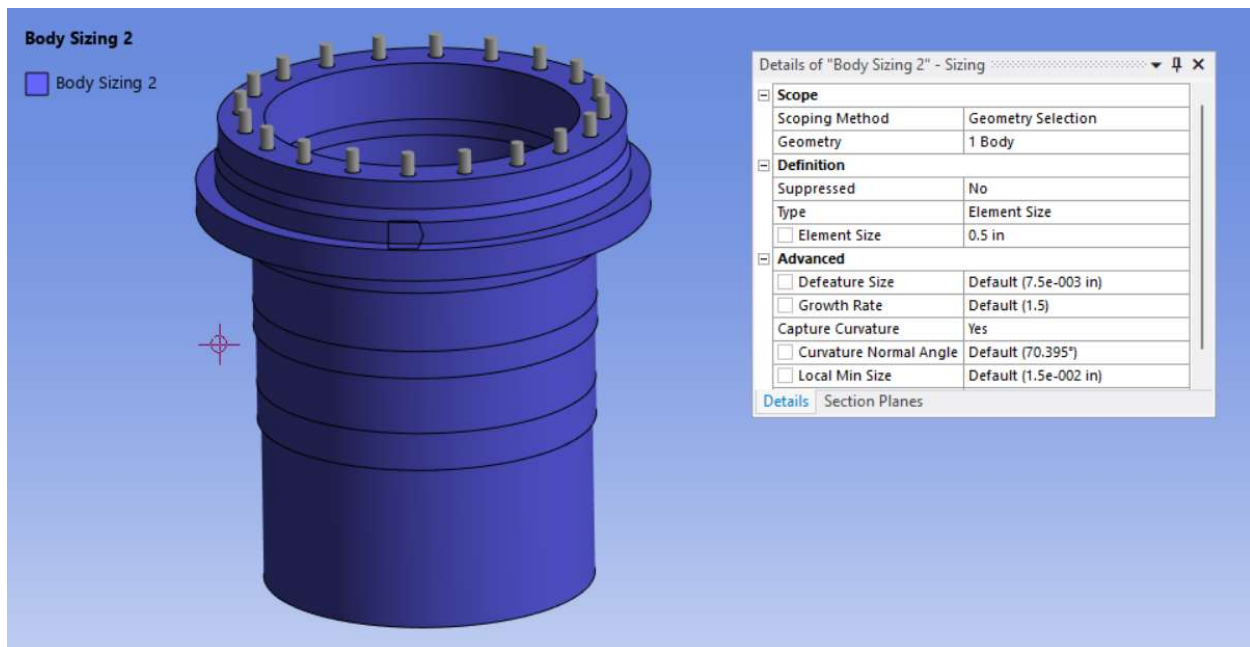


Figure 254 Housing Mesh Sizing

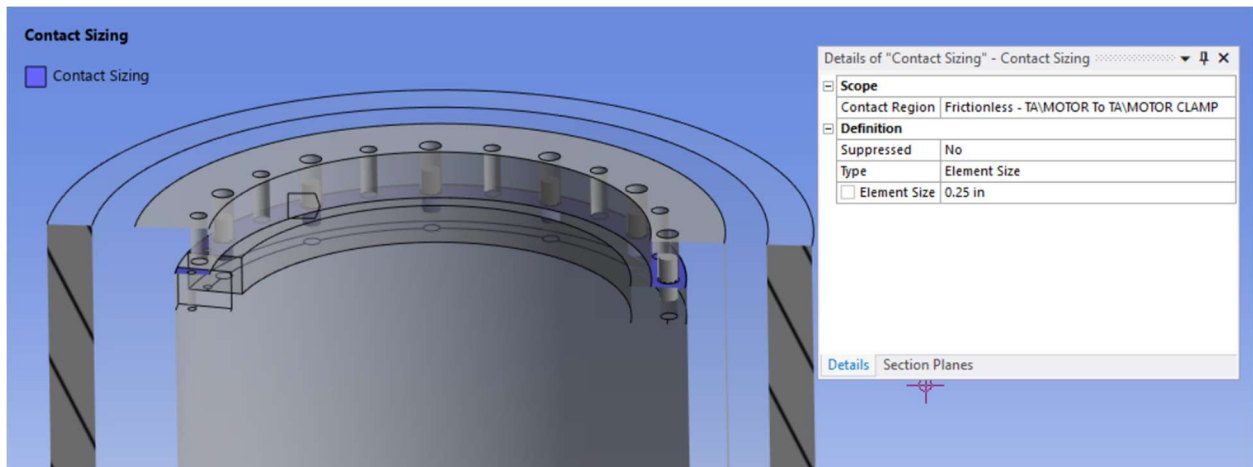


Figure 255 Motor Contact Sizing

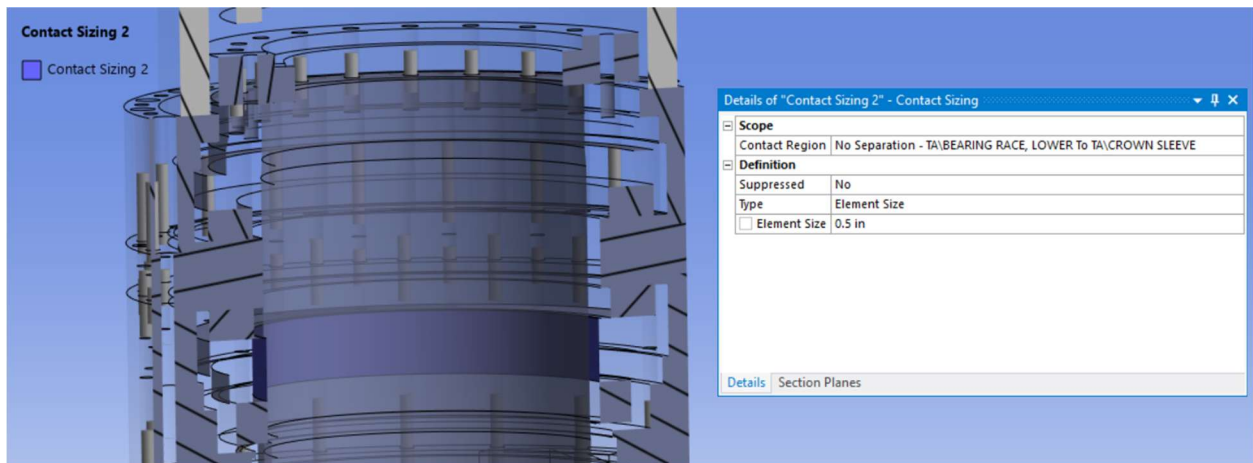


Figure 256 Housing Contact Sizing

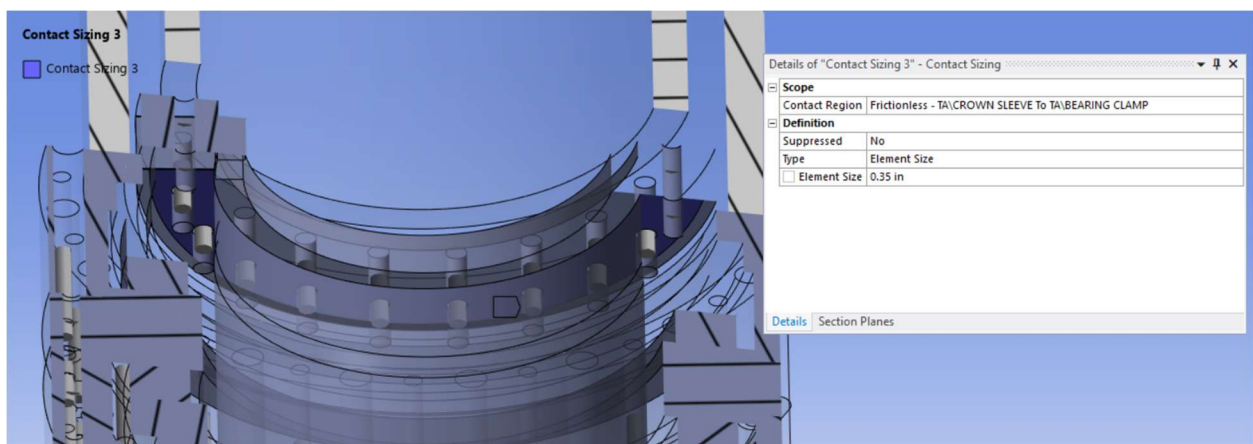


Figure 257 Housing Contact Sizing

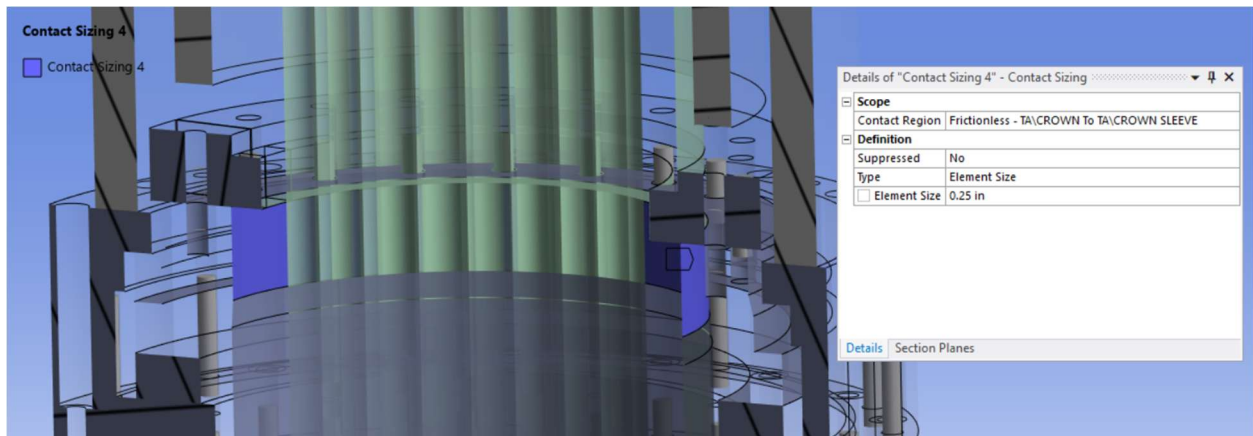


Figure 258 Housing Contact Sizing

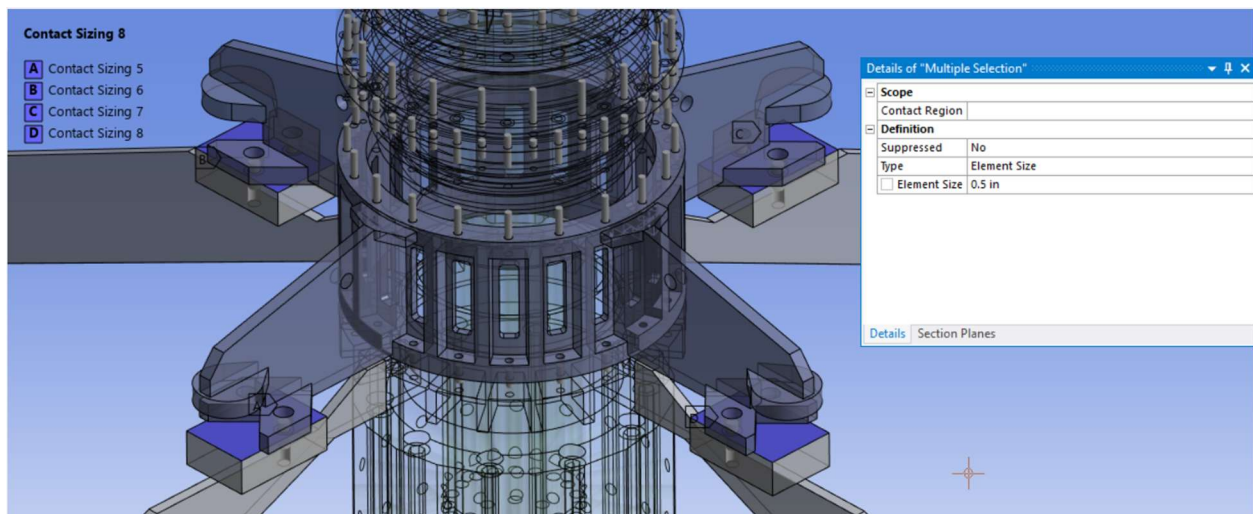


Figure 259 Housing Contact Sizing

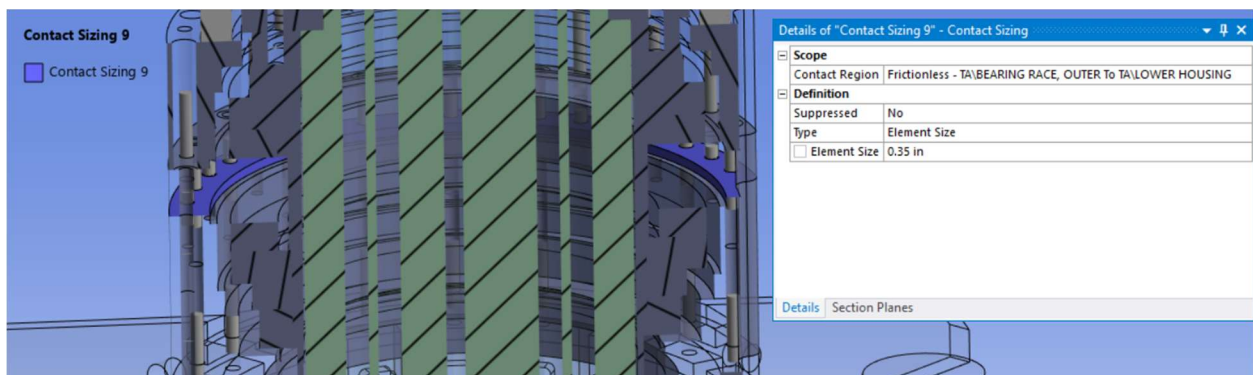


Figure 260 Housing Contact Sizing

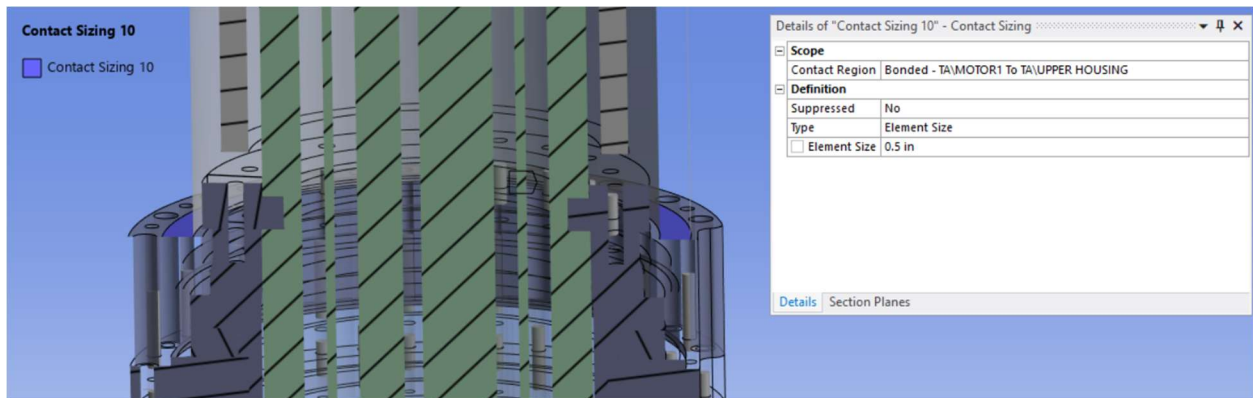


Figure 261 Housing Contact Sizing



Figure 262 Housing Contact Sizing

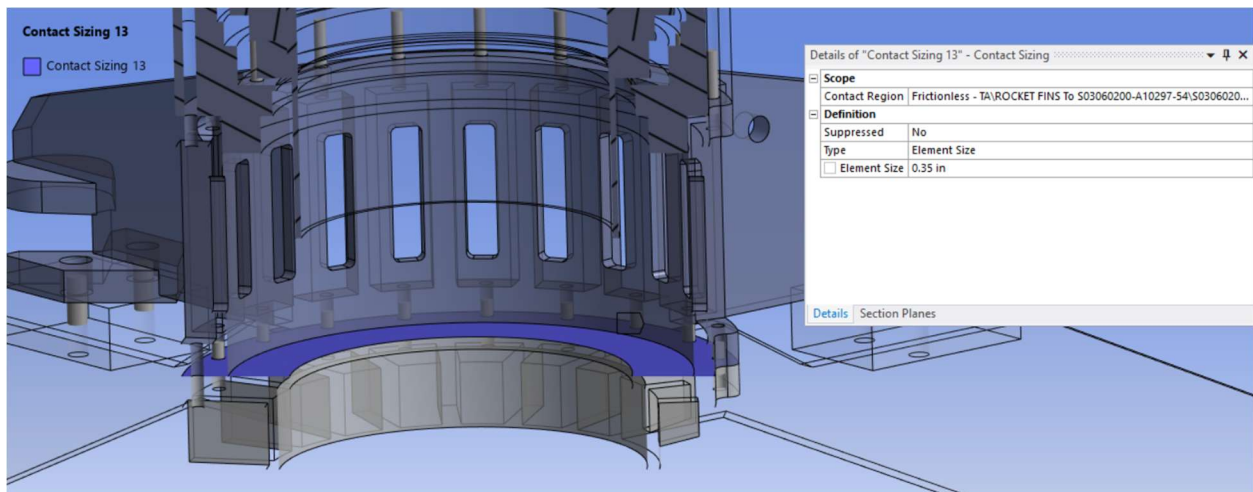


Figure 263 Housing Contact Sizing

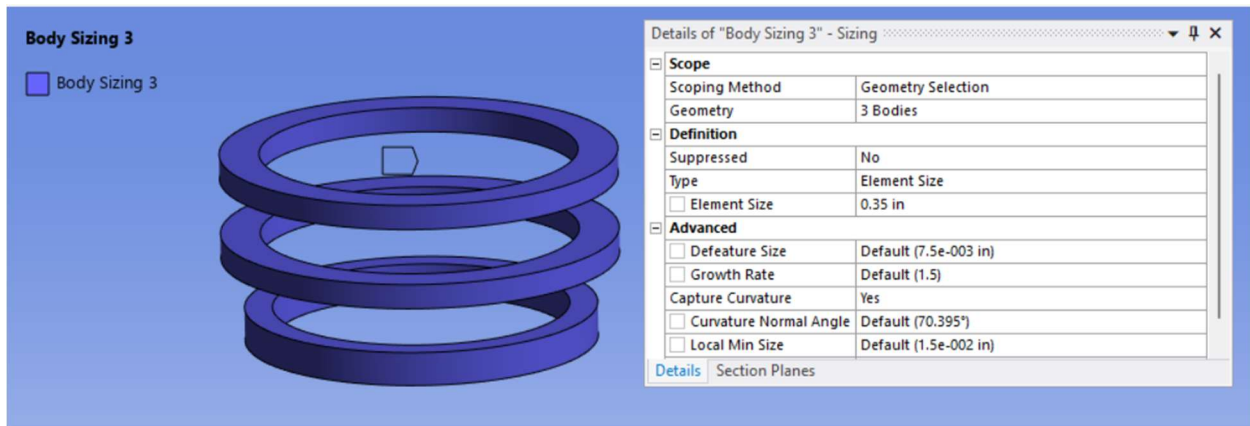


Figure 264 Housing Mesh Sizing

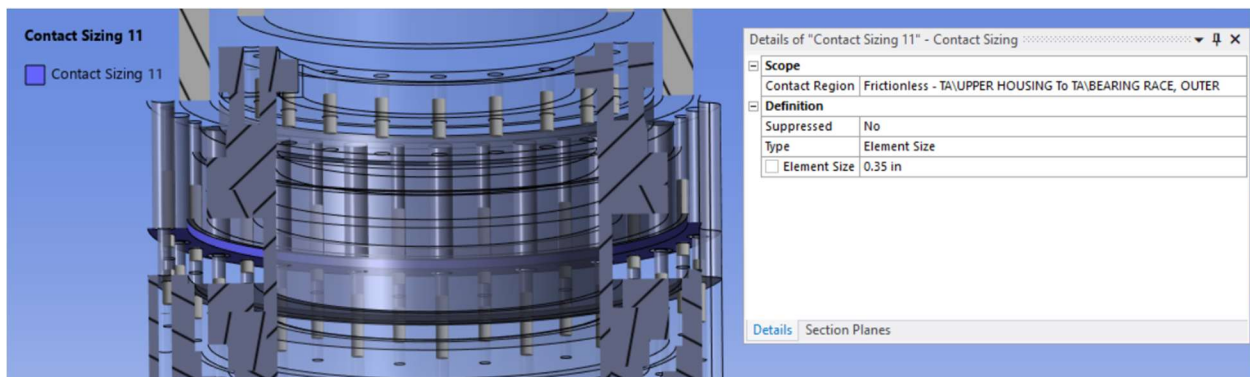


Figure 265 Housing Contact Sizing

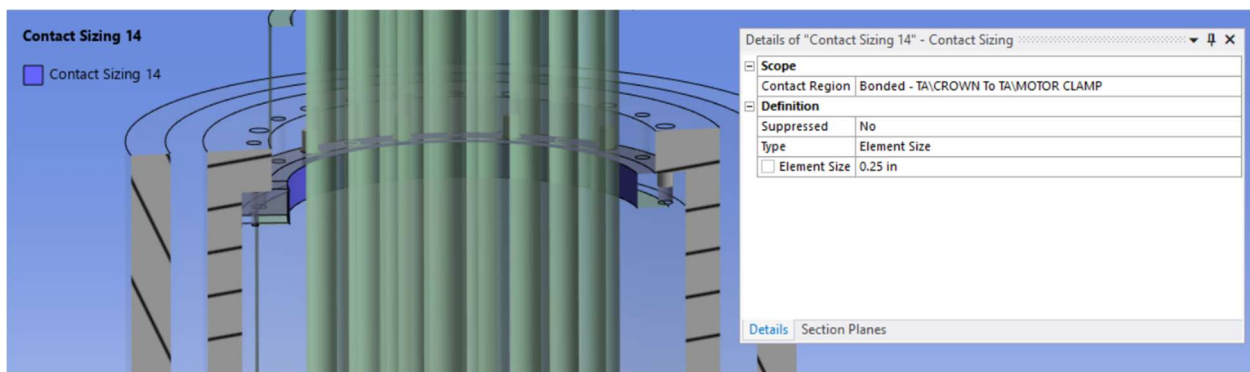


Figure 266 Motor Contact Sizing

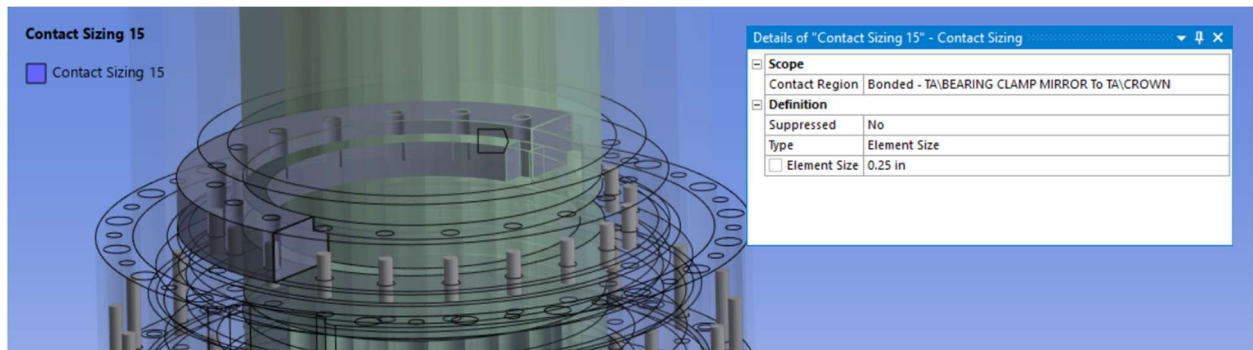


Figure 267 Housing Contact Sizing

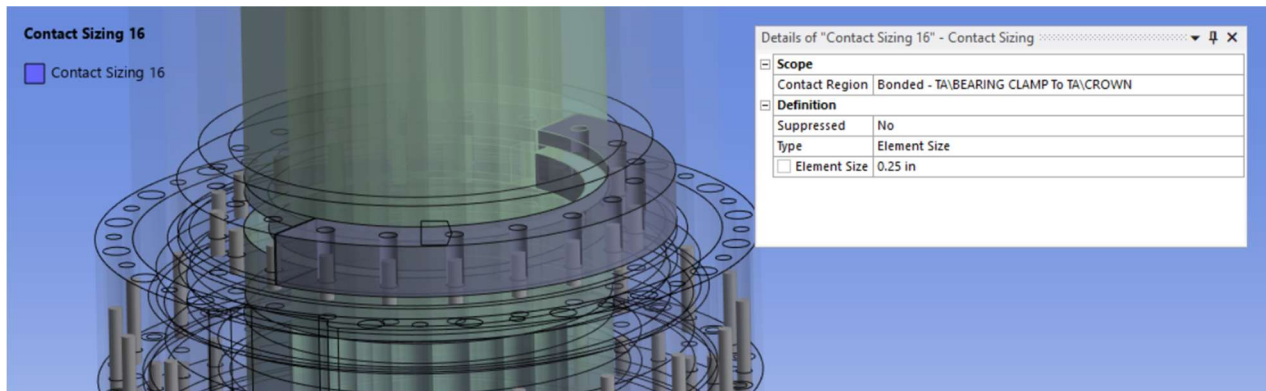


Figure 268 Housing Contact Sizing

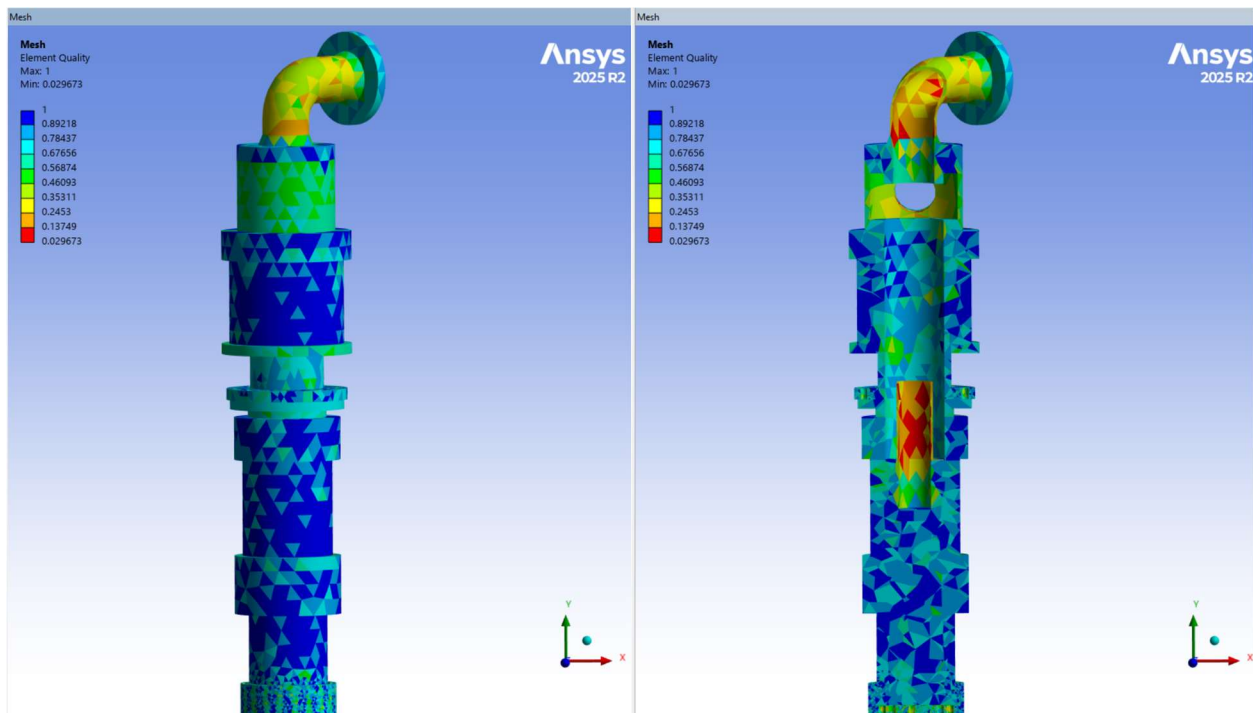


Figure 269 Water Union and Manifold Mesh Quality

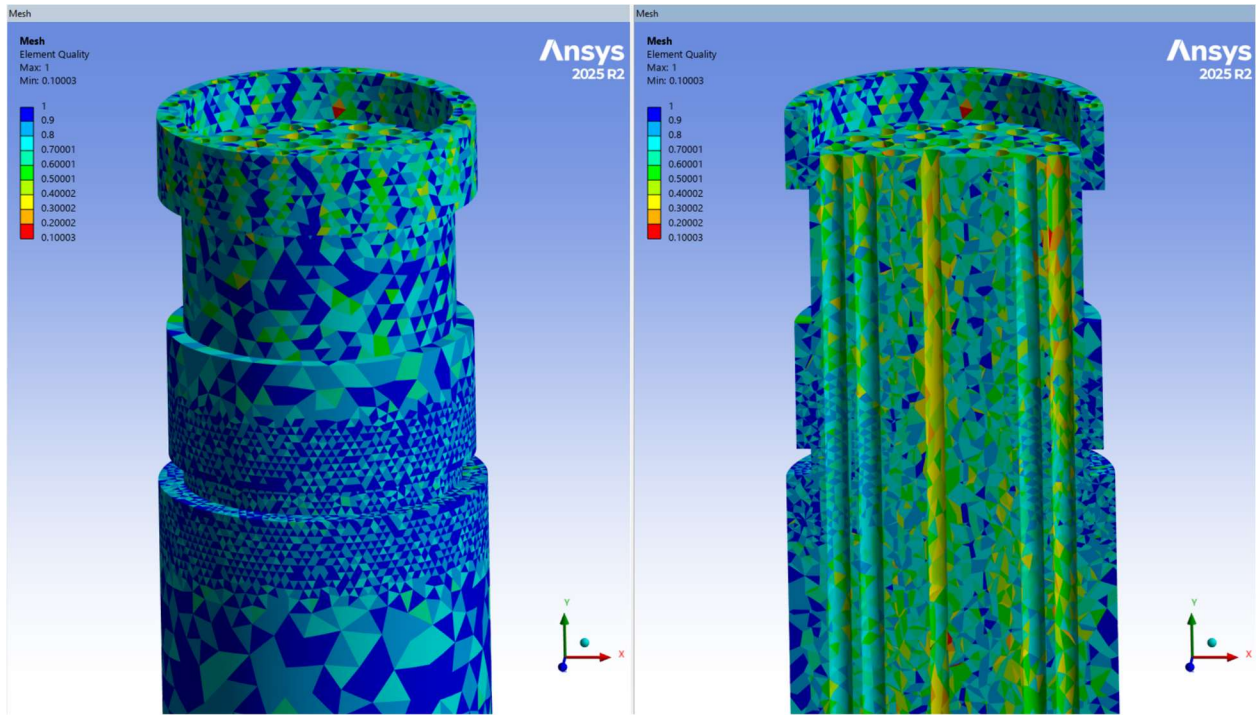


Figure 270 Crown Mesh Quality

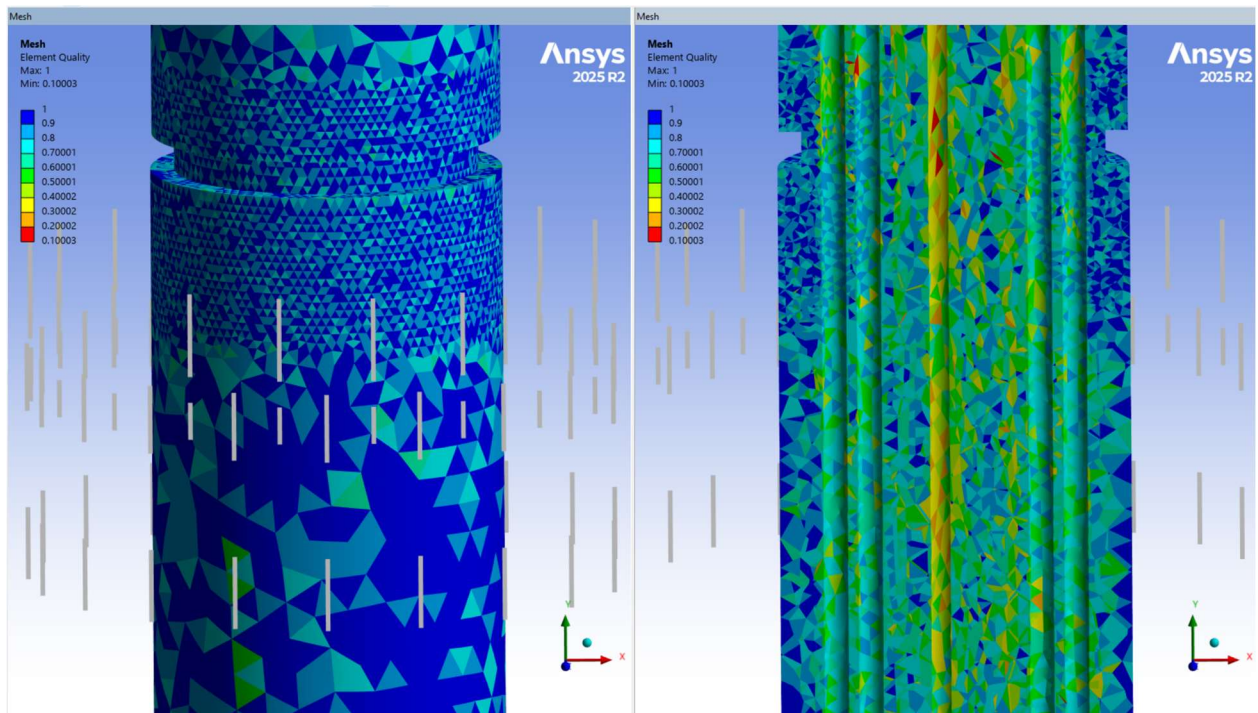


Figure 271 Crown Mesh Quality

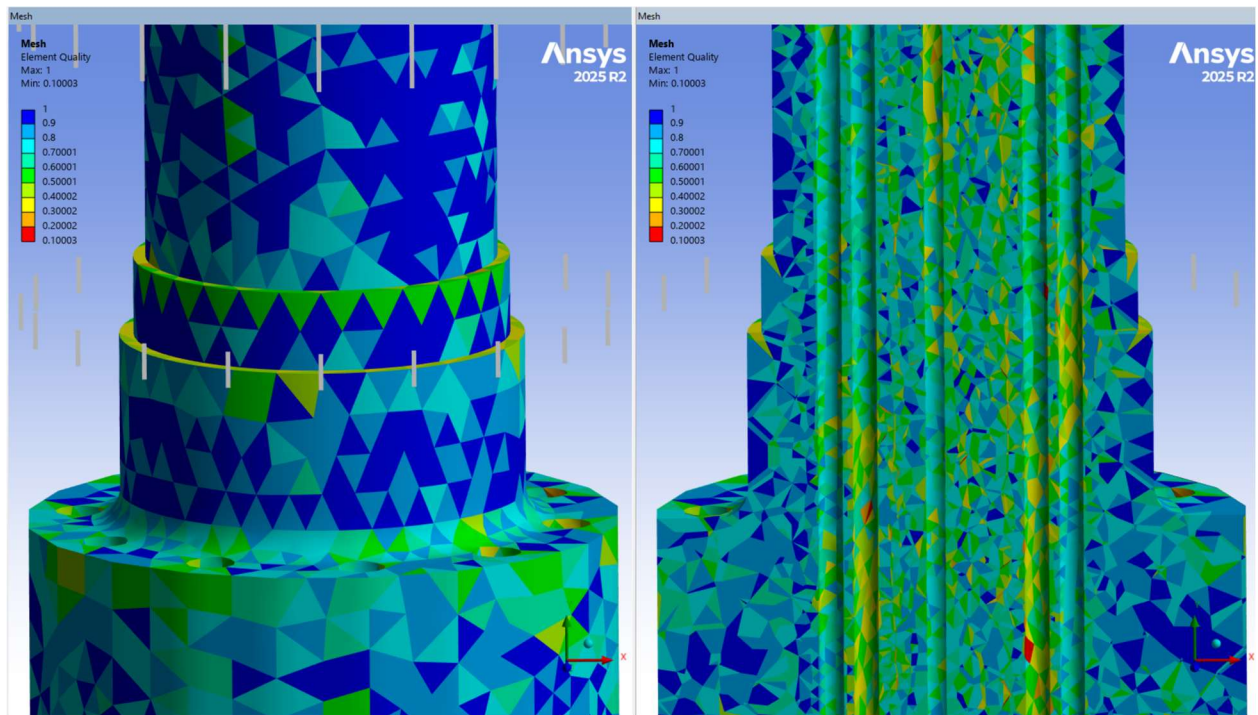


Figure 272 Crown Mesh Quality

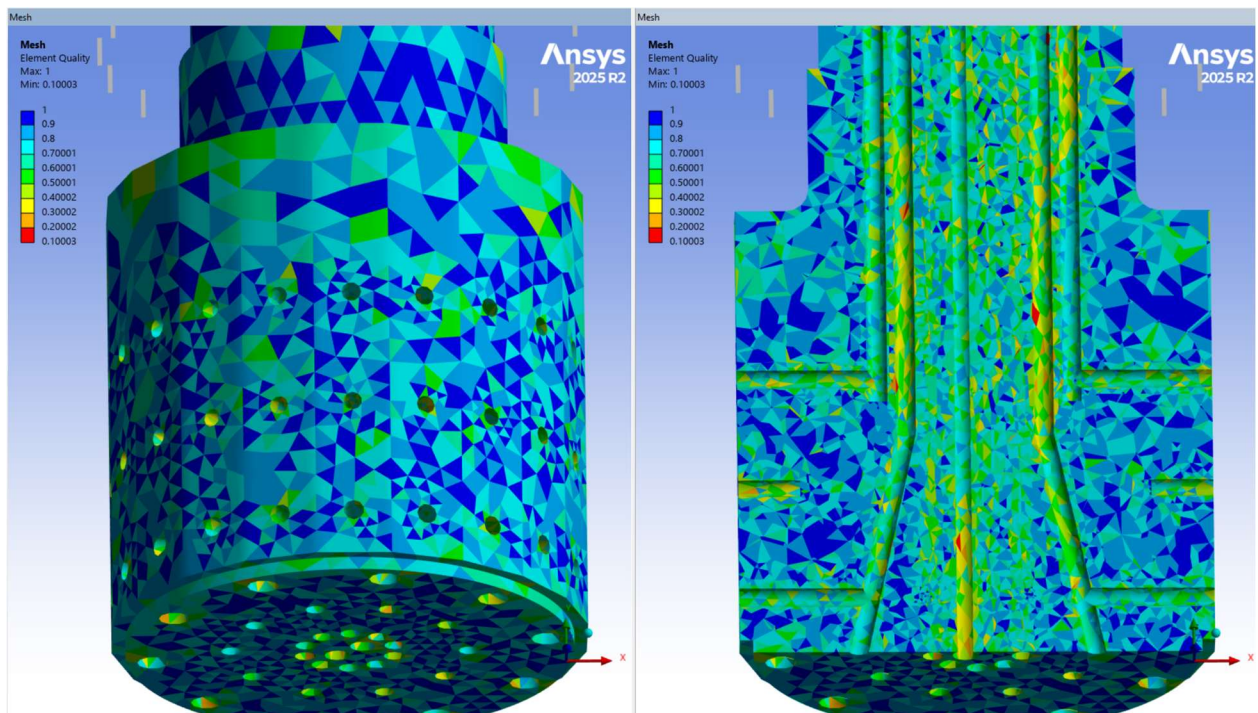


Figure 273 Crown Mesh Quality

4.4 BOUNDARY CONDITIONS

4.4.1 Target Assembly

The Target Assembly is supported by the Core Vessel lid. The Core Vessel lid is only supported around the perimeter by the Core Vessel structure. The boundary condition for the Target Assembly is the outer surface of the Core Vessel lid. The fixed constraints have all DoF fixed.

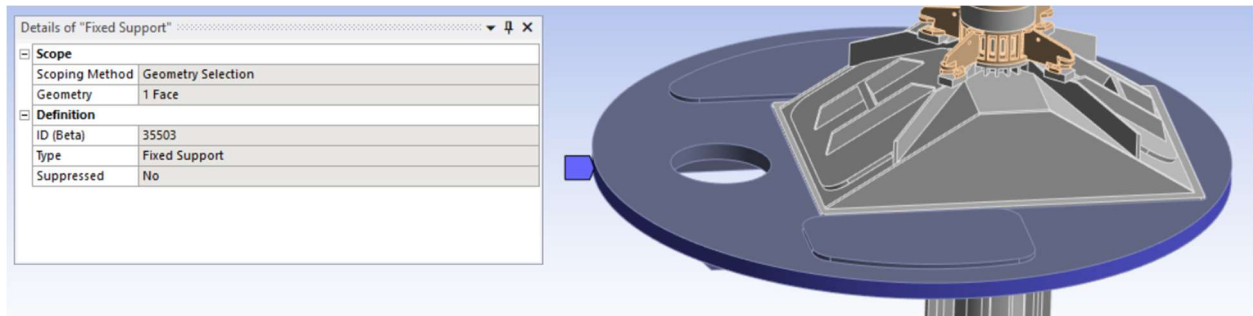


Figure 274 Target Assembly Boundary Condition

4.4.2 Target Segment

The Segment boundary conditions are at two points, the Segment bolt at the top and the foot pin at the bottom. The upper bolt threads into the Crown, to keep the model small, only the portion of the Crown needed to model the bolted joint is used at the upper boundary condition.

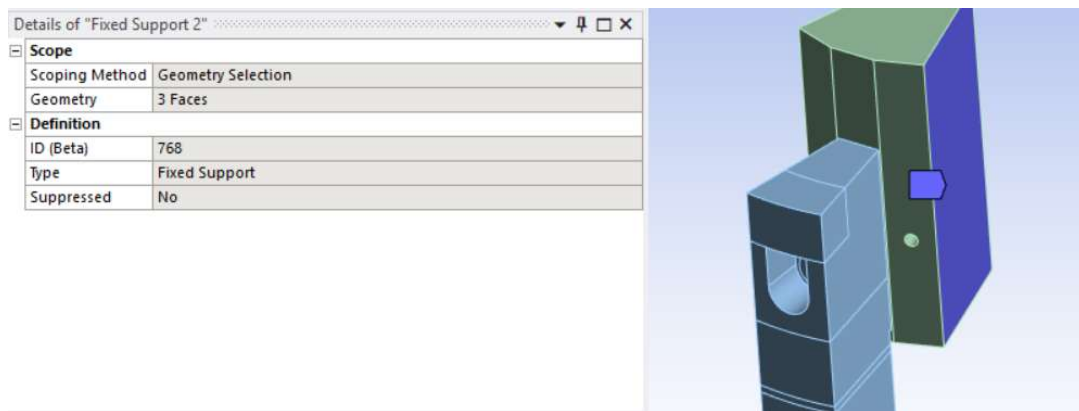


Figure 275 Segment Upper Fixed Constraint

A fixed constraint is applied to the 'inner' surfaces of the Crown cutout. The lower segment uses a cutout of the Target Shaft for the Segment lower pin.

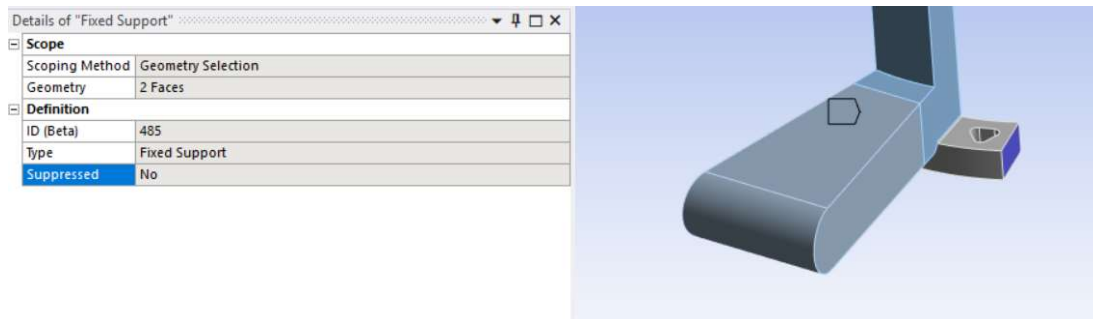


Figure 276 Segment Lower Fixed Constraint

4.4.3 Target Shaft

The Target Shaft model is constrained at a cut through the Crown, the Segments and Shaft are unsupported below the Crown.

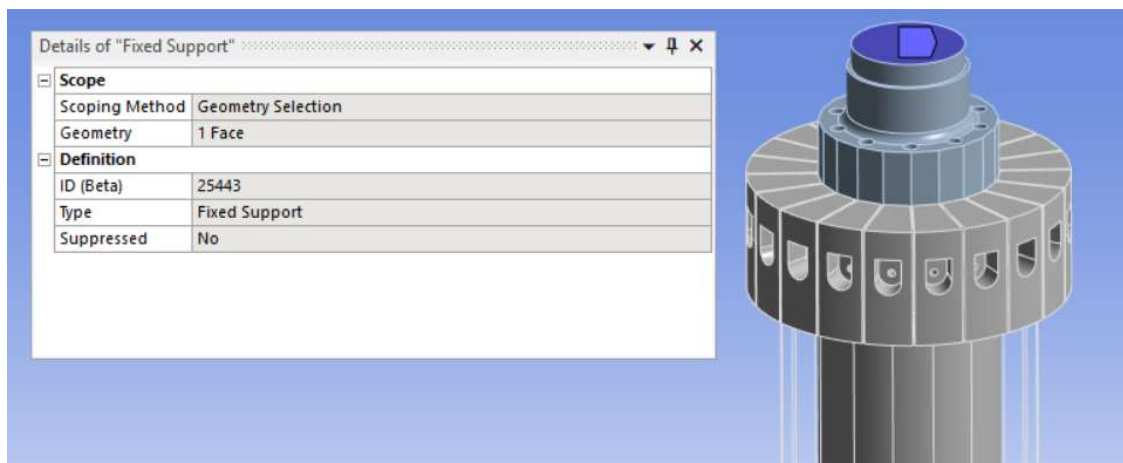


Figure 277 Target Shaft Constraint

4.4.3.1 Snubber Ring

The Snubber Ring analysis uses the ring as the fixed component and the shaft is pushed into the ring to simulate the requirement.

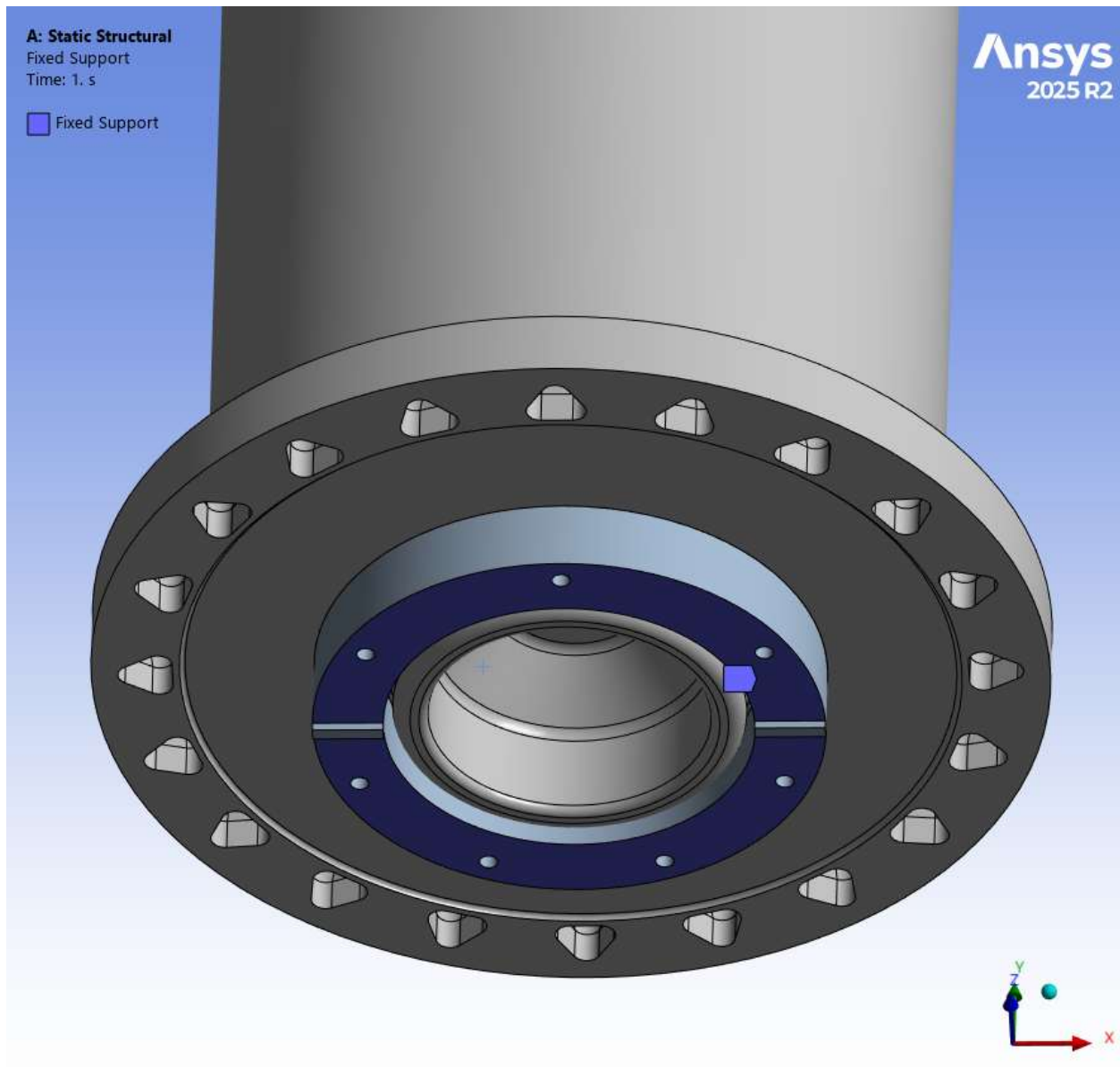


Figure 278 Snubber Ring Fixed Constraint

4.4.4 Crown and Bearings

The Crown model is constrained in two places, to keep the model simple, the load path from the bearings only goes out to the Lower Housing. The interface between the Lower Housing and Tent is where a fixed constraint is applied.

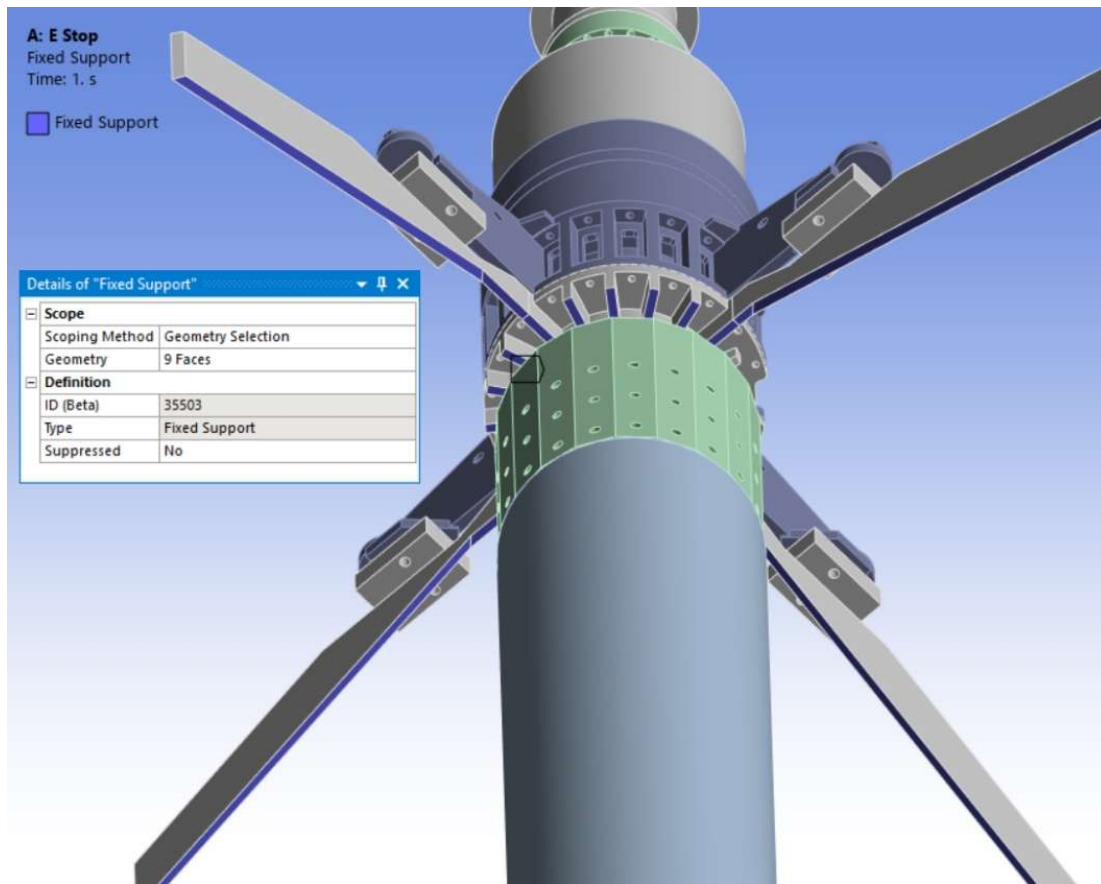


Figure 279 Crown and Drive Model Fixed Constraint

A second constraint was required to fix rotation about the center axis, the contact surfaces were set up with Frictionless surfaces to simulate actual conditions. This leaves rotation about the Y axis free, to fix this, two more constraints were added to the Union at the pipe flanges. X and Z were fixed with Y left free so the vertical force at the bearings wouldn't be affected.

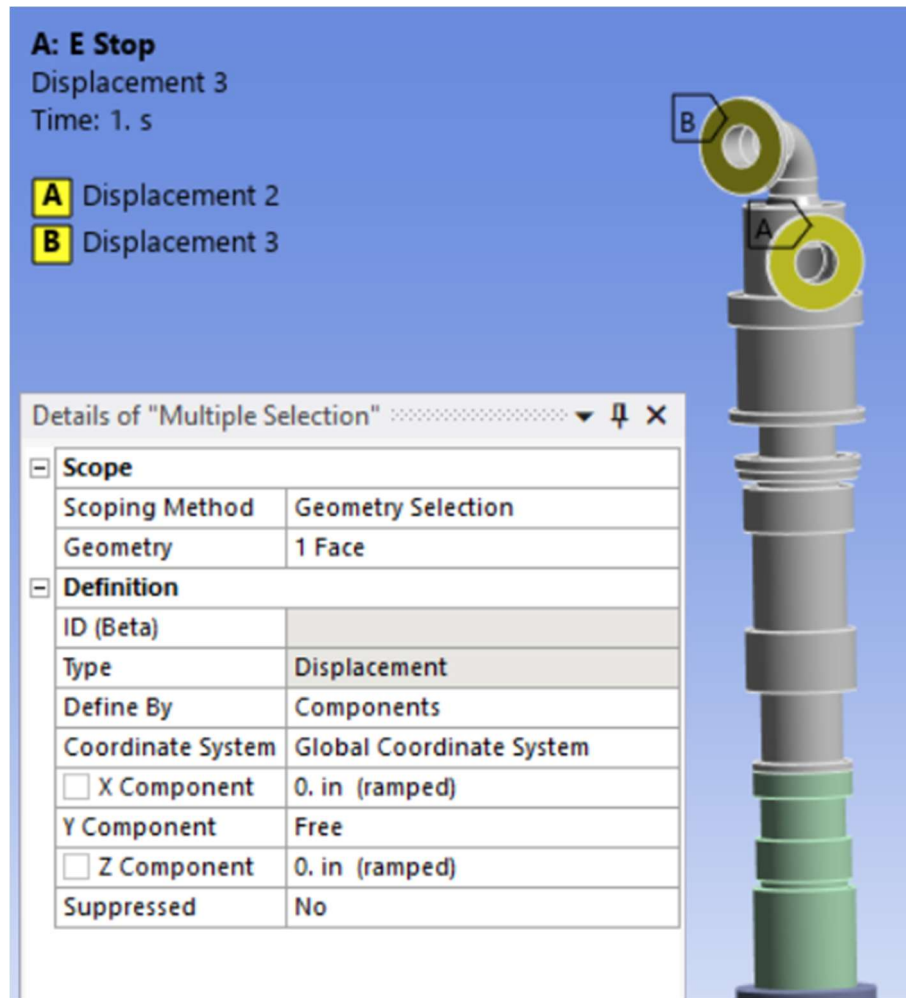


Figure 280 Crown and Drive Model Displacement Constraint

4.5 CONTACT CONDITIONS

Overview of the contact conditions used between different components of the system.

4.5.1 Target Assembly

The Target Assembly model has only linear contact interfaces, this means either Bonded or No Separation. The lid and tent are not the focus of this model so those parts are all bonded together. The welded joints in the Target Assembly are all bonded. There are some bolted joints, mainly in the bearing and drive area, that use fasteners and No Separation, this gives a structure some freedom to flex and deform by the strength of the bolts rather than have one big solid brick of elements. The No Separation joint allows for 'sliding' of the surfaces but the surfaces do not pull apart, to capture the tensile forces a separate submodel is used.

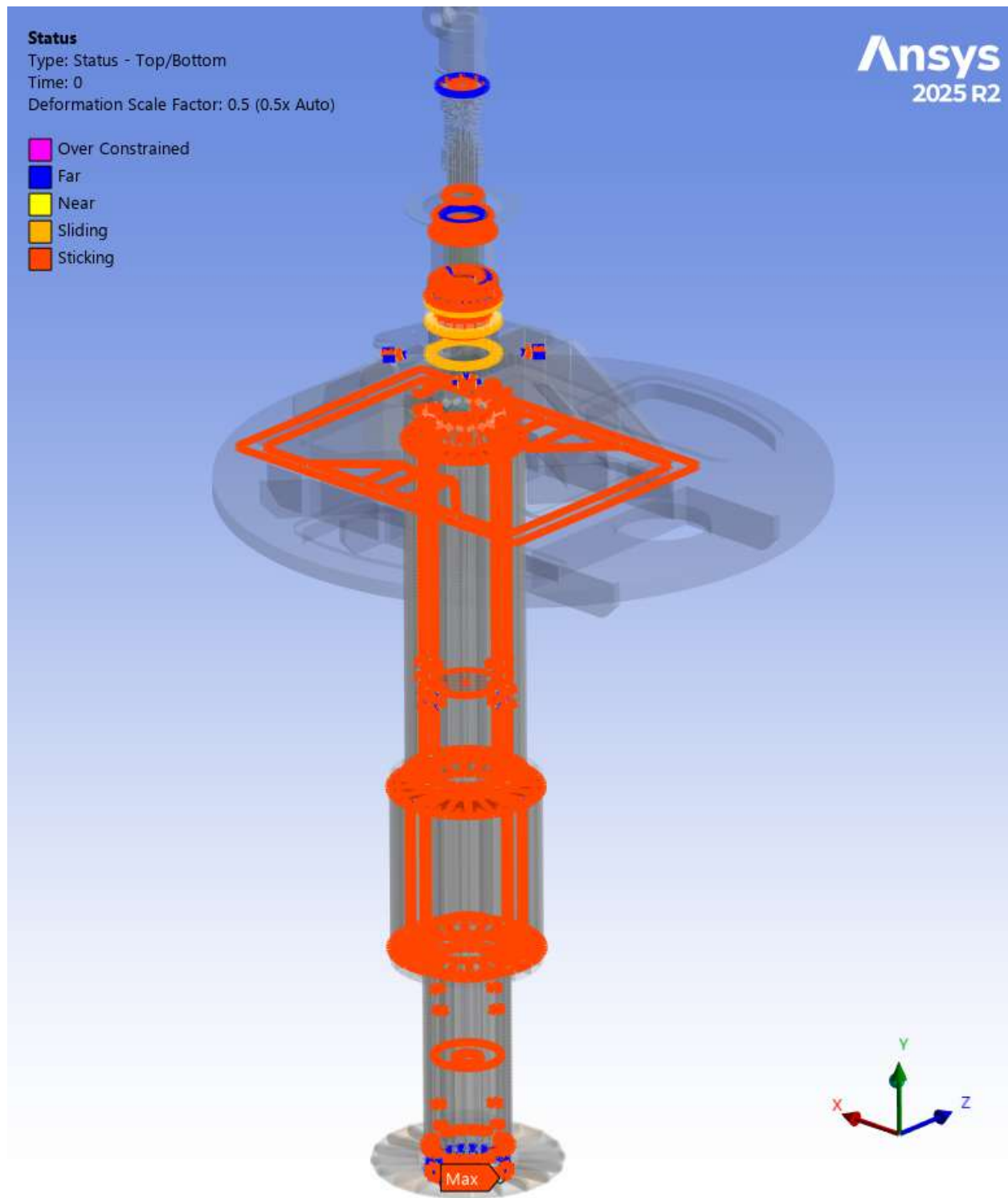


Figure 281 Target Assembly Contacts

4.5.2 Target Segment

The Target Segment used two separate constraining configurations. The reason for this is the Segment proved to be difficult to constrain with a single bolt at the top and a single pin at the bottom. The model had enough DoF free that convergence was difficult to achieve using realistic constraints, so two different models were used. The Bolt Focus model uses a nonlinear contact at the bolt interface and a linear contact at the pin while the Pin Focus model uses a nonlinear contact at the Pin and is bonded at the bolt interface.

4.5.2.1 Bolt Focus

The Target Segment uses several different contact conditions. The main body is a weldment, so each component of the segment uses a 'bonded' interface.

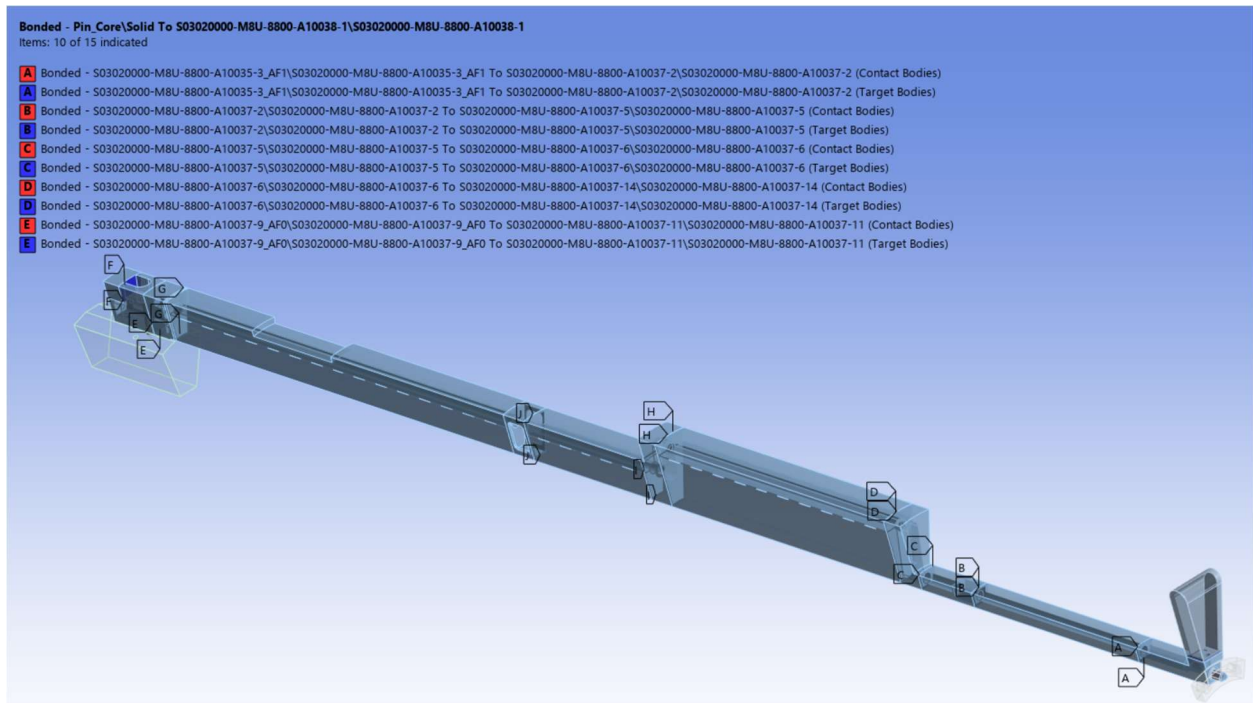


Figure 282 Segment Bonded Interfaces

The settings for all the Bonded Interfaces are kept default.

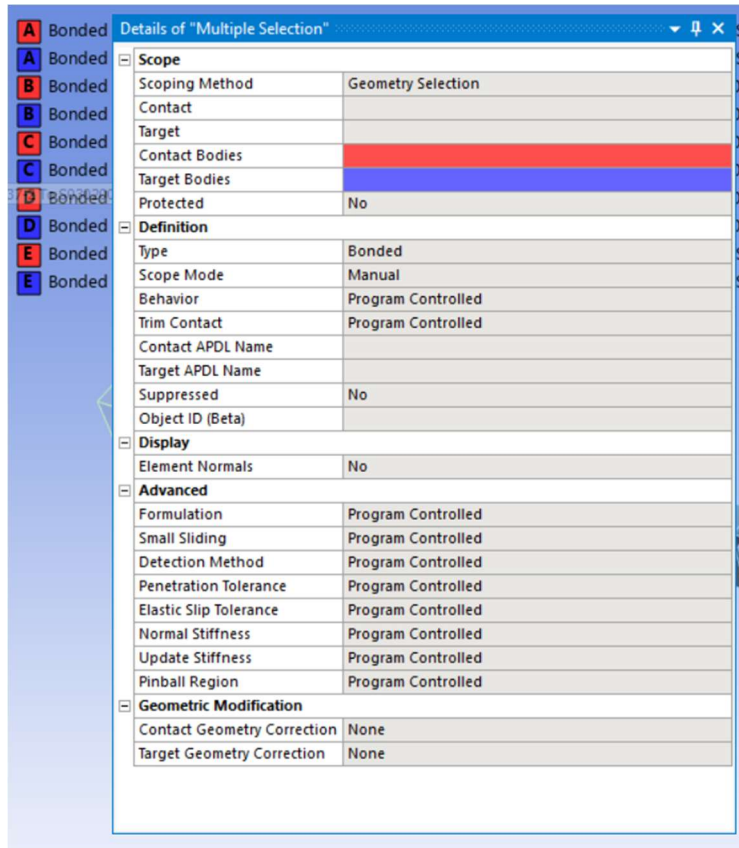


Figure 283 Segment Bonded Interface Settings

The Target Segment has three pipes as part of the weldment, these are 2D bodies and are bonded to the 3D solid bodies but need different settings. The MPC (Multi Point Constraint) setting is used with a Pinball radius set similar to what the weld size would be, in this case roughly the pipe thickness. Figure 284 shows an example of how the 2D to 3D bonded settings are configured.

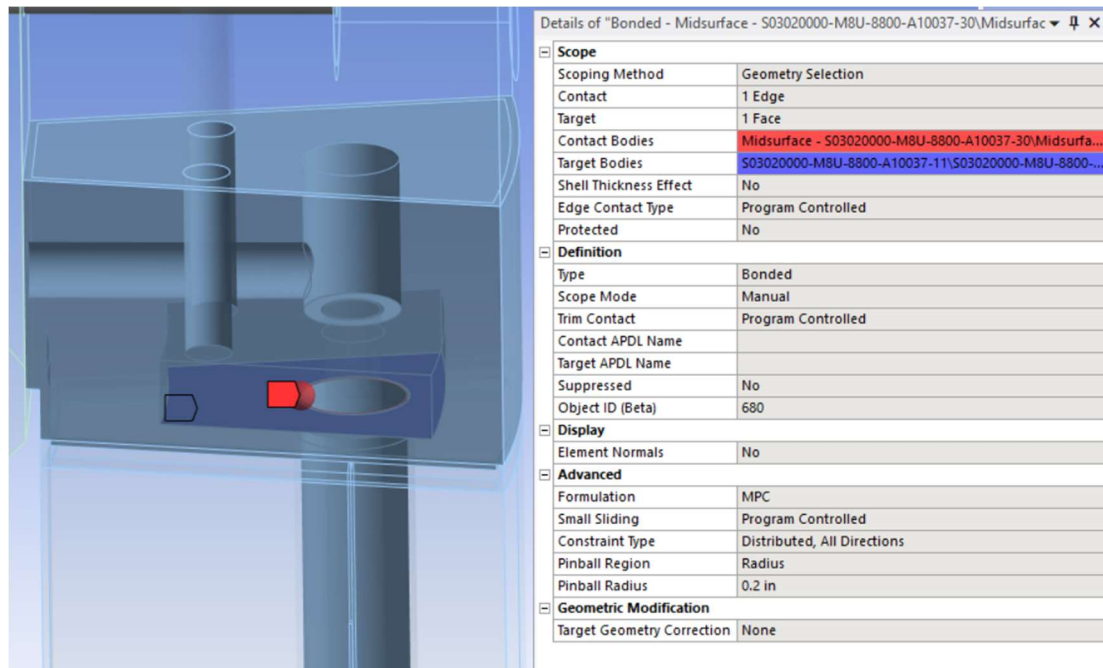


Figure 285 Segment Pipe Interface Settings

The upper bolted joint of the Segment uses a Rough interface between the Segment and the Crown. The Segment model required careful constraining being only held by one bolt and one pin. The actual Segment has nothing to stop rotation about the bolt axis as shown in Figure 28, however the adjacent Segments do provide a constraint. This is the reason a Rough interface is used here, it will show any separation of the bolted interface but not allow any rotation.

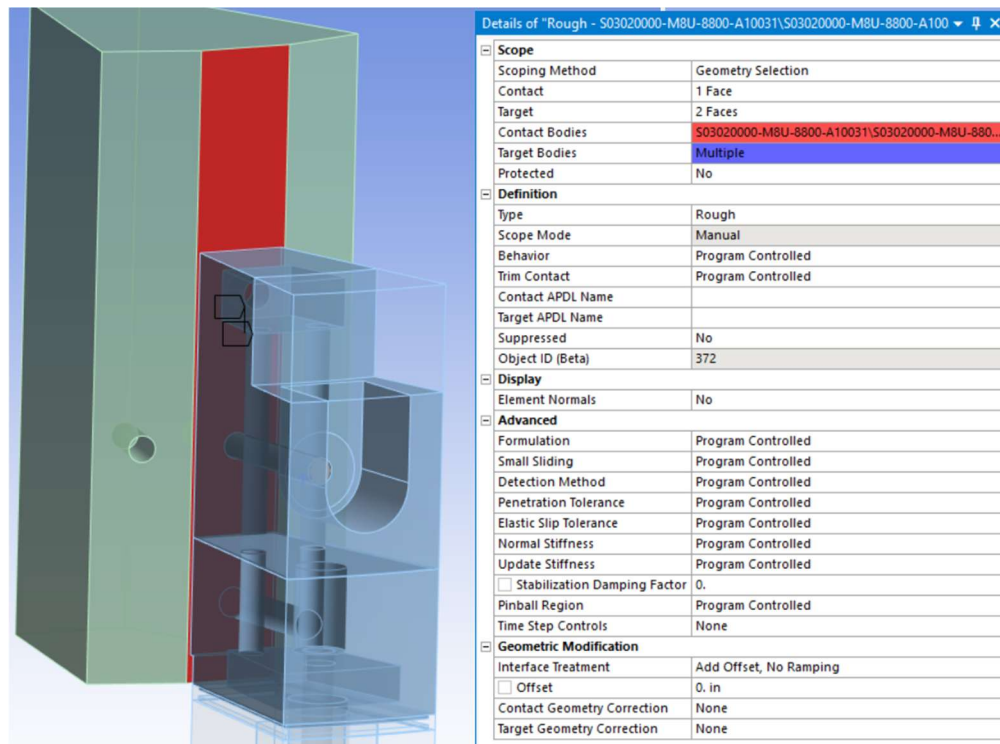


Figure 286 Segment Bolt Interface Settings

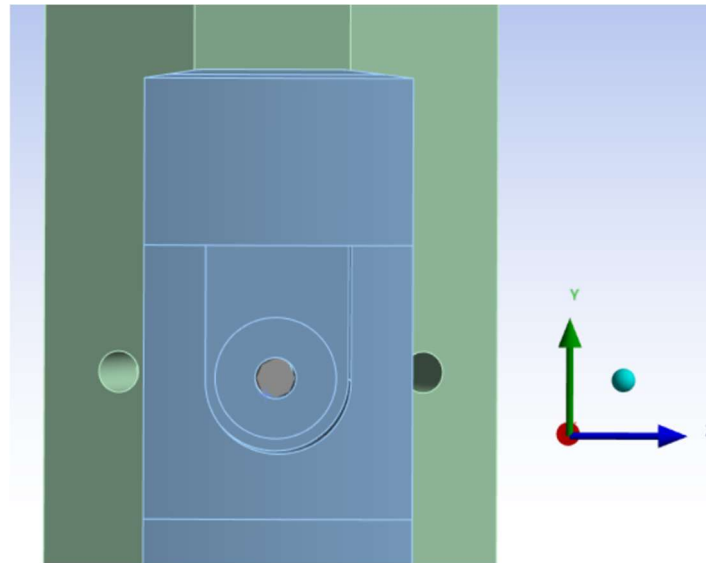


Figure 287 Segment Bolt Connection

The lower pin is triangle shape to prevent rotation but allow translation on the Y axis. The pin is also undersized from the mating hole to help with installation.

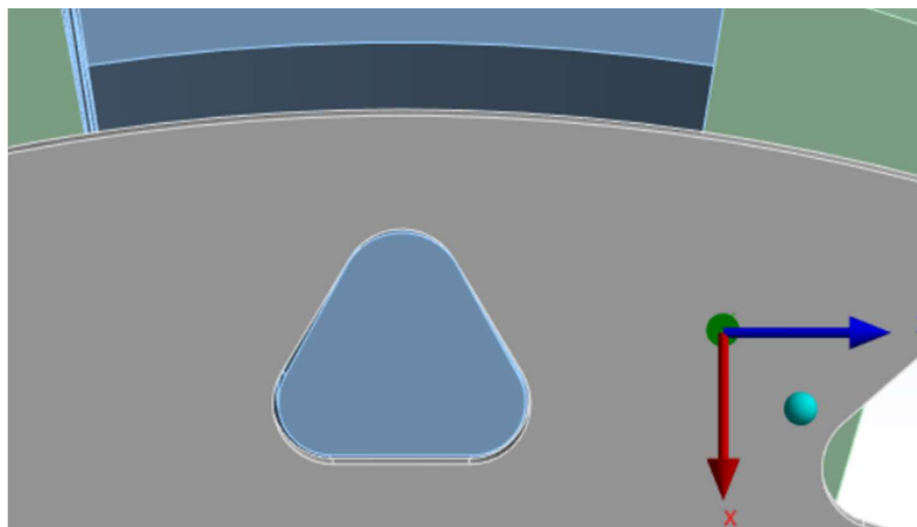


Figure 288 Segment Foot Pin Geometry

The interface used for the lower pin is a No Separation interface, this is a linear option that allows the surfaces to move but not separate, this way the ability for the pin to translate is captured. A pinball radius is used to help with the gap on the backside of the pin, the settings are shown in Figure 47.

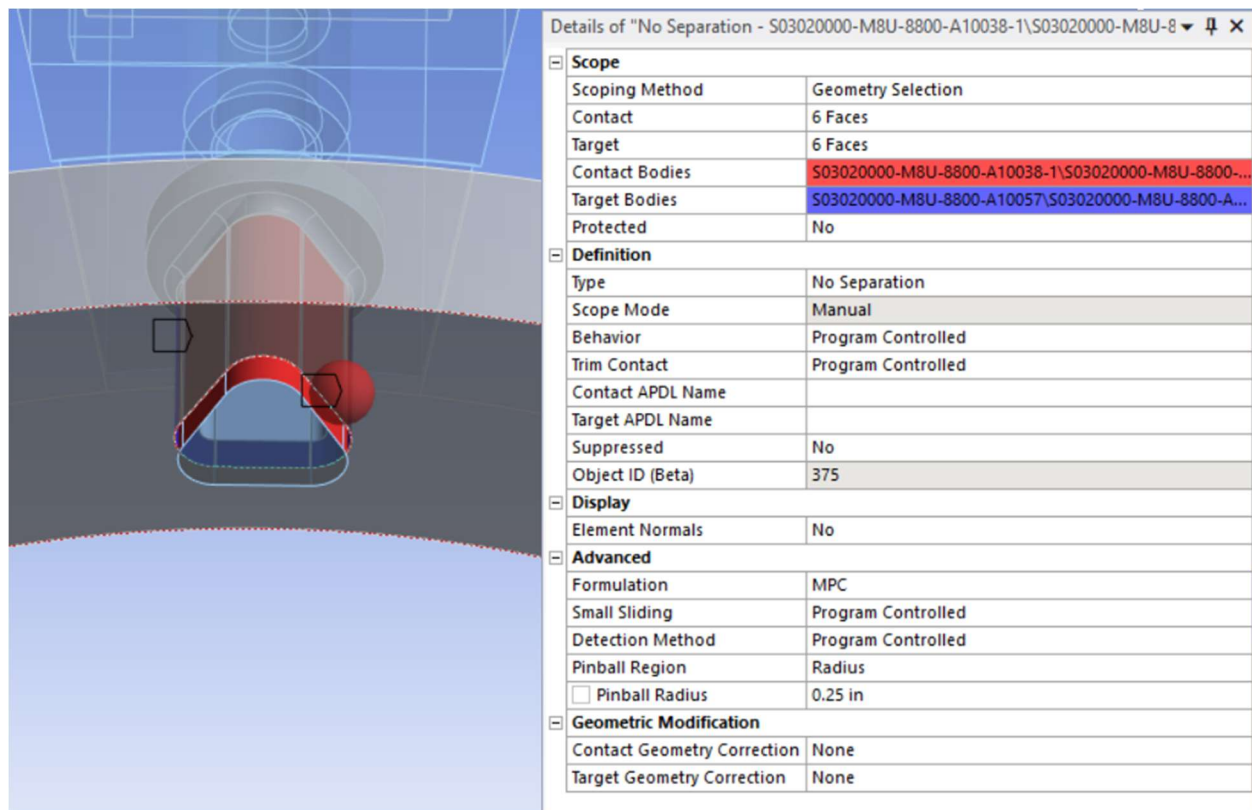


Figure 289 Segment Foot Pin Interface Settings

A second interface is used at the foot pin, this interface is used only to determine if the segment is in contact with the shaft during any of the load combinations. It is a frictionless interface with a Pinball radius to account for the initial gap.

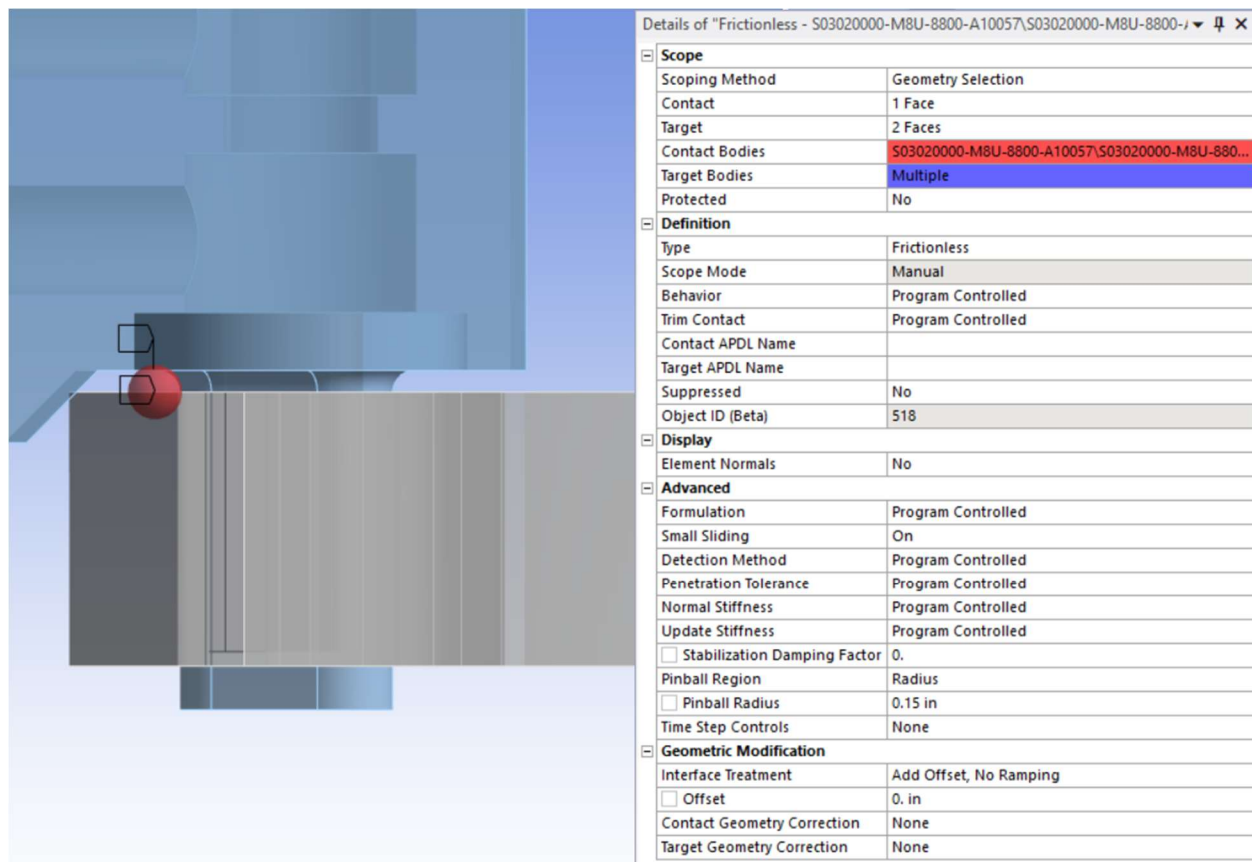


Figure 290 Segment Foot Pin Frictionless Interface Settings

The segment bolt is added in the Connection section is it is appropriate to include its properties here, note this interface is not used in the Elastic Plastic analysis.

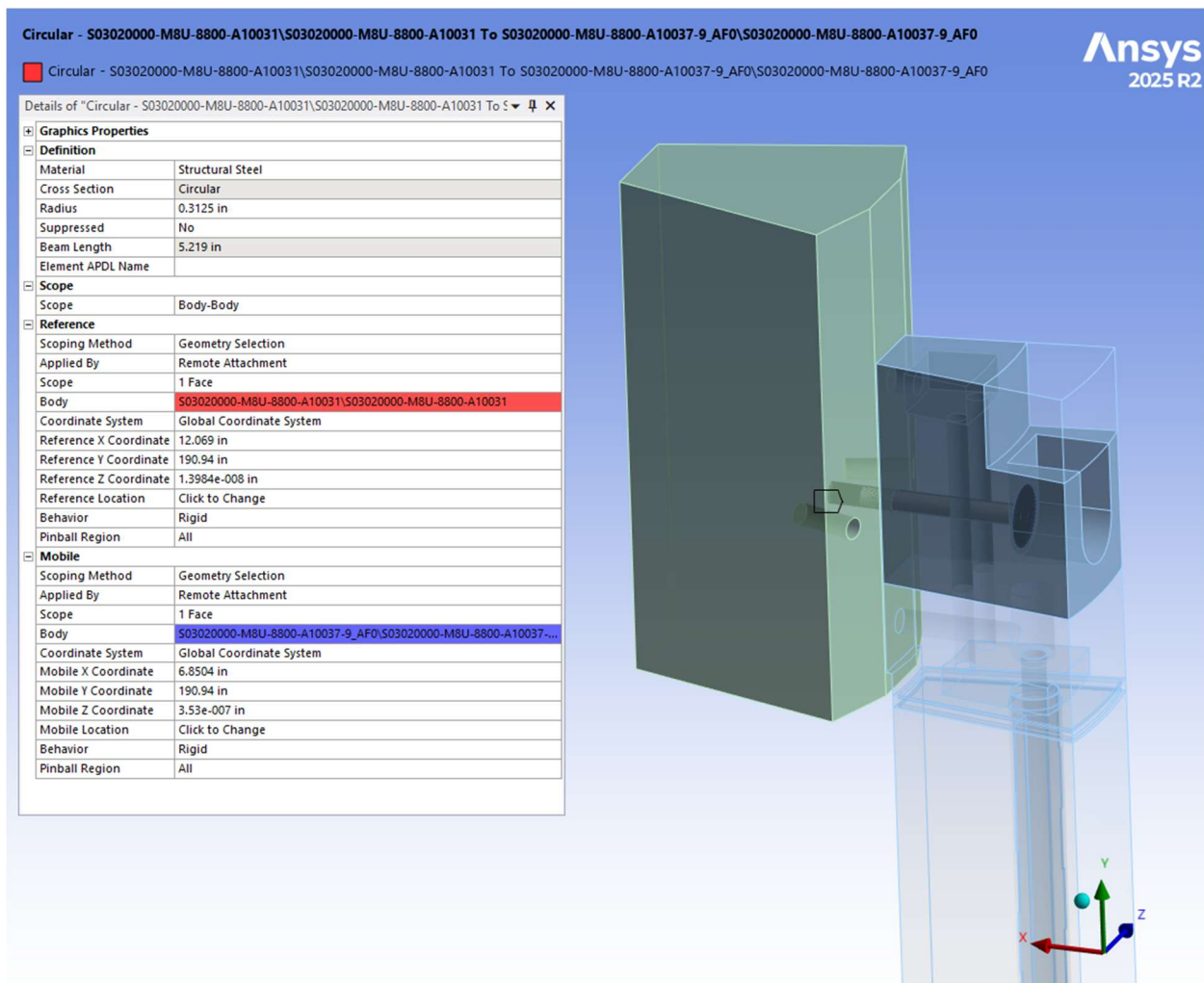


Figure 291 Segment Bolt properties.

4.5.2.2 Pin Focus

The Pin focused model keeps all the same interfaces as the Bolt focused model with just the top and bottom changed. The bolt interface goes to a bonded surface and the pin goes to a frictionless interface. The foot pin is not a tight fit in the shaft, a gap is there to help with installation. The no-separation contact does allow any movement of the pin within the gap, so in this analysis a frictionless contact is used to allow the pin to move freely before contacting the sides of the hole.

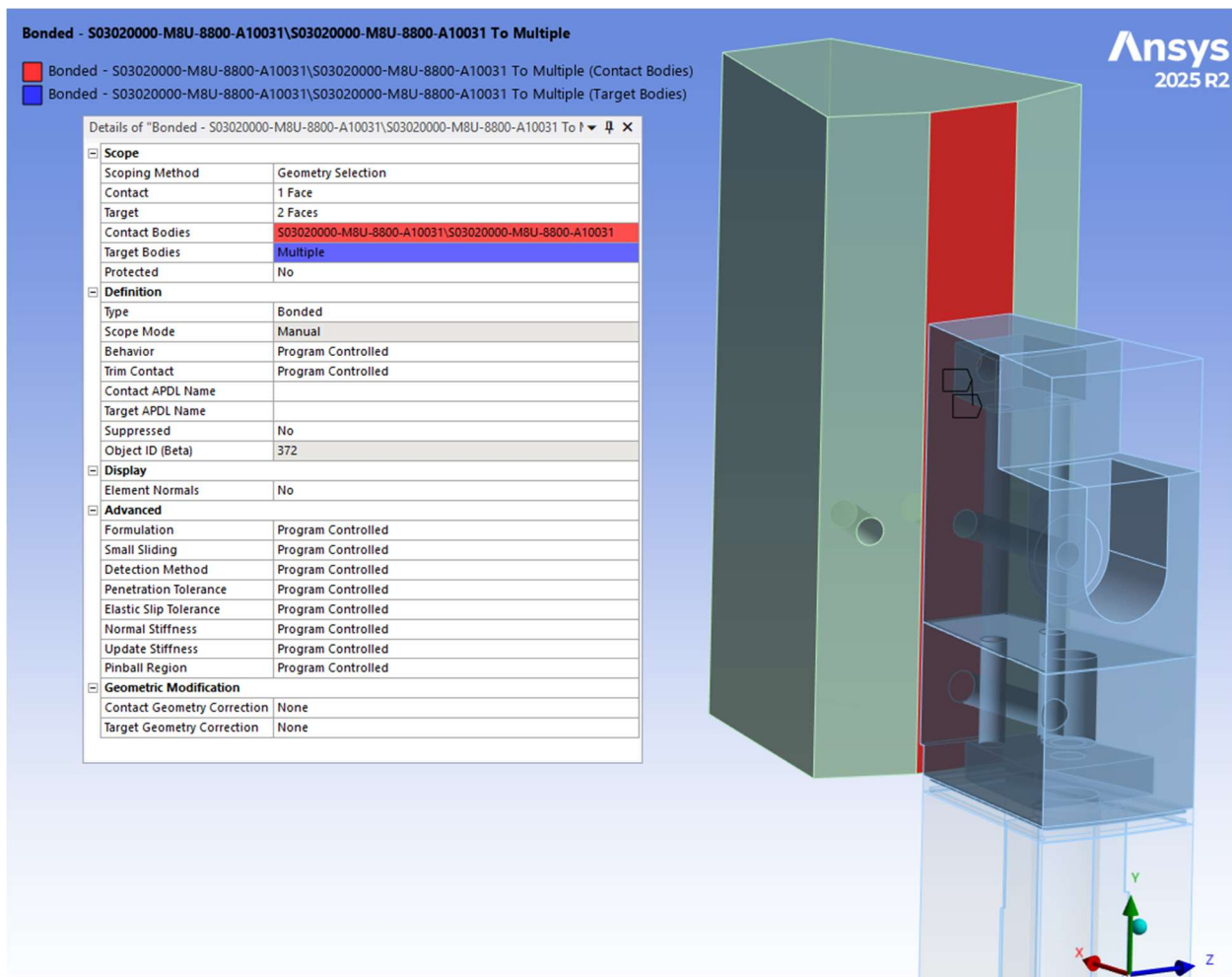


Figure 292 Segment Bolted Interface

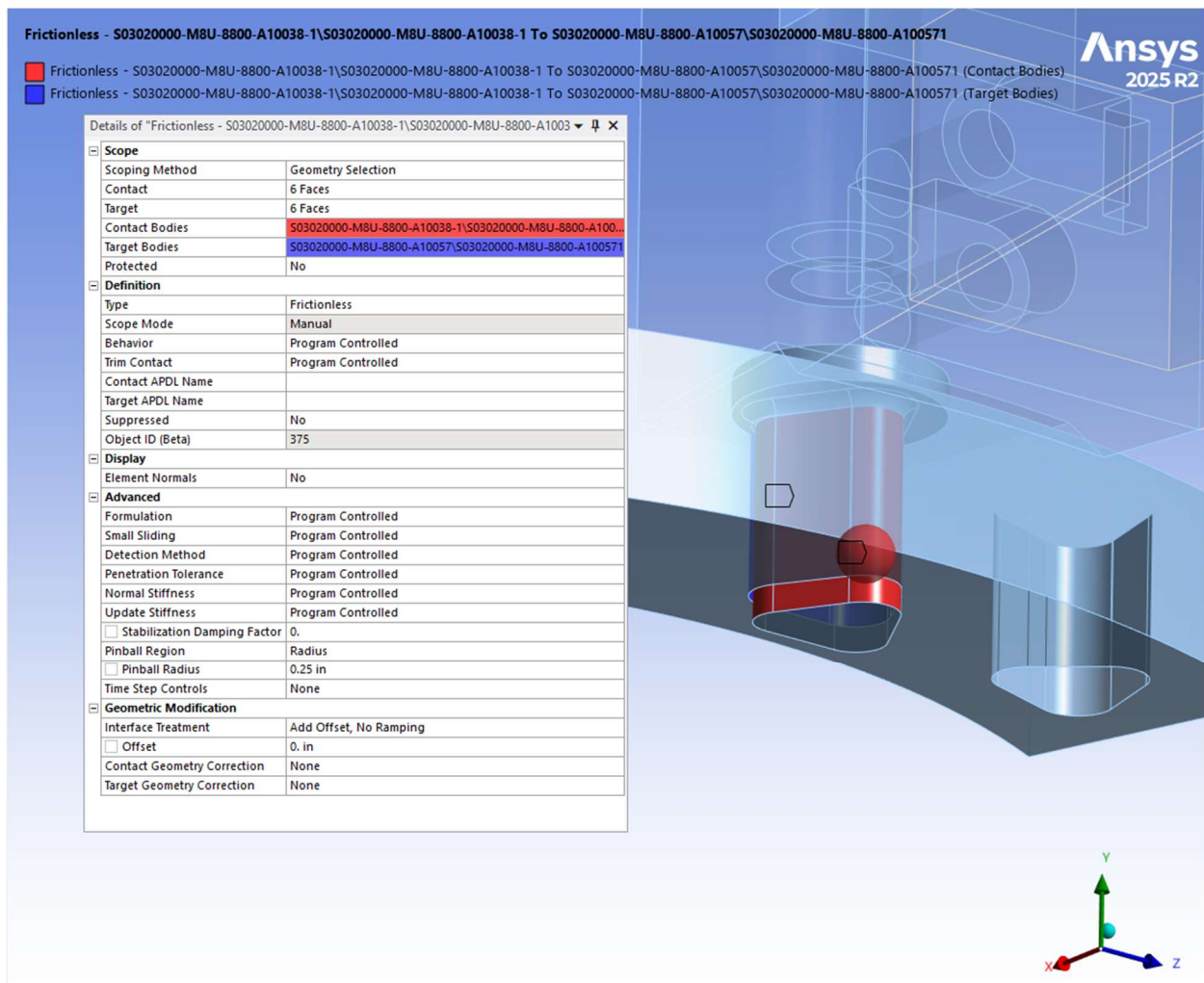


Figure 293 Segment Foot Pin Interface

4.5.3 Target Shaft

The main components of the Target Shaft have one welded joint and two sections are through-bolted and held together by the Tie Rod preload force. The welded joint is a Bonded contact surface shown in Figure 46.

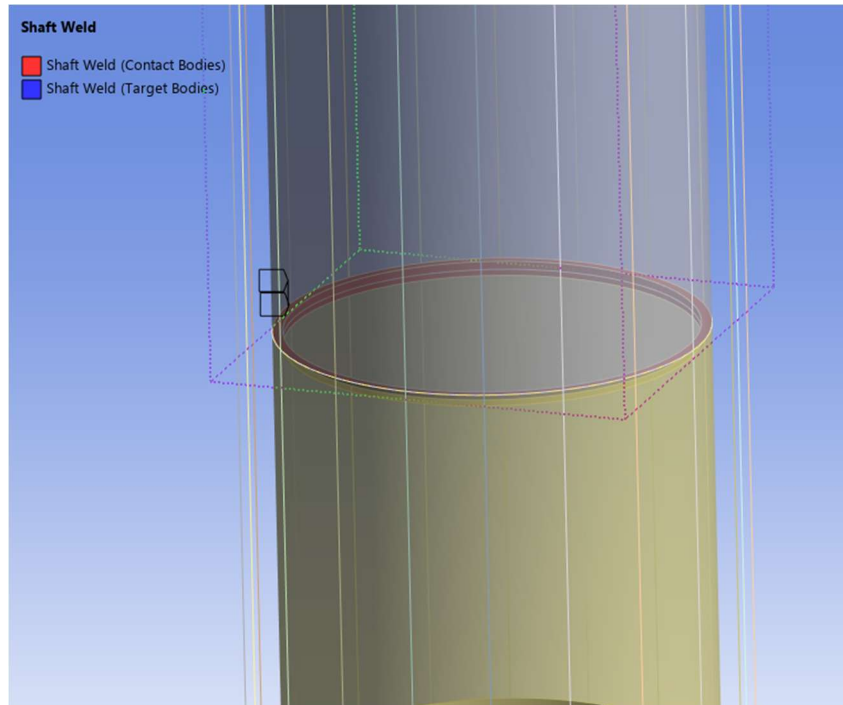


Figure 294 Target Shaft Weld

The three preloaded shaft interfaces use a Rough contact surface modeled in the E Stop and Seismic + Stop load cases. There is a ‘step’ at each interface to constrain the shaft sections from moving laterally, see Figure 53. A Rough interface is infinite friction but allows separation, this is a good approximation of how the joint actually behaves without needing additional constraints. In the Seismic model the top Shaft joint with the Crown is a Frictionless interface. The Seismic load case is the only analysis where this was possible, the rotational loads in E Stop and Seismic + Stop require more constraints at the interfaces since the tie rod beam elements don’t constrain any rotation in the two shaft sections they pass through. The frictionless surface gives a better picture of how the shaft steps interact.

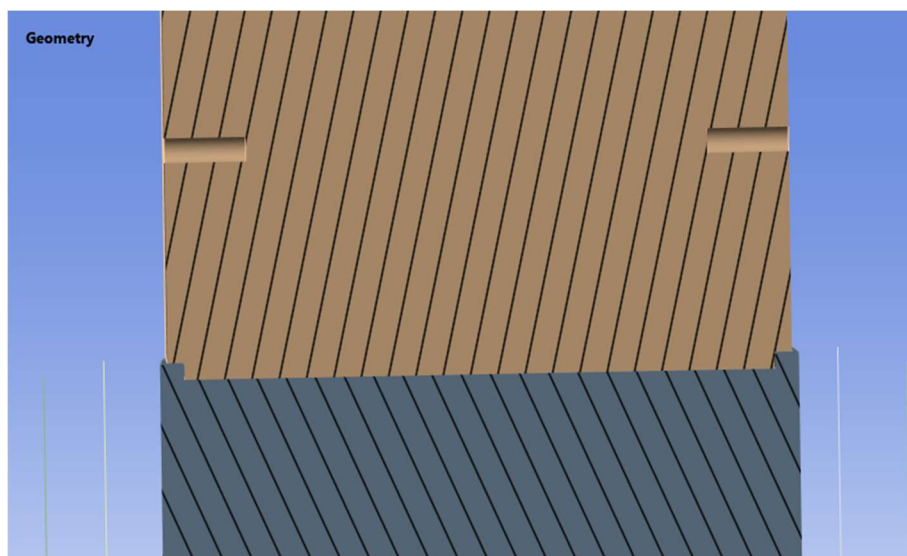


Figure 295 Target Shaft Step

The Tie Rods are beam elements and need a special contact to solid elements. ANSYS has an MPC option that works to tie a vertex, or beam end, to a surface on a solid body and not have rotation about the vertex.

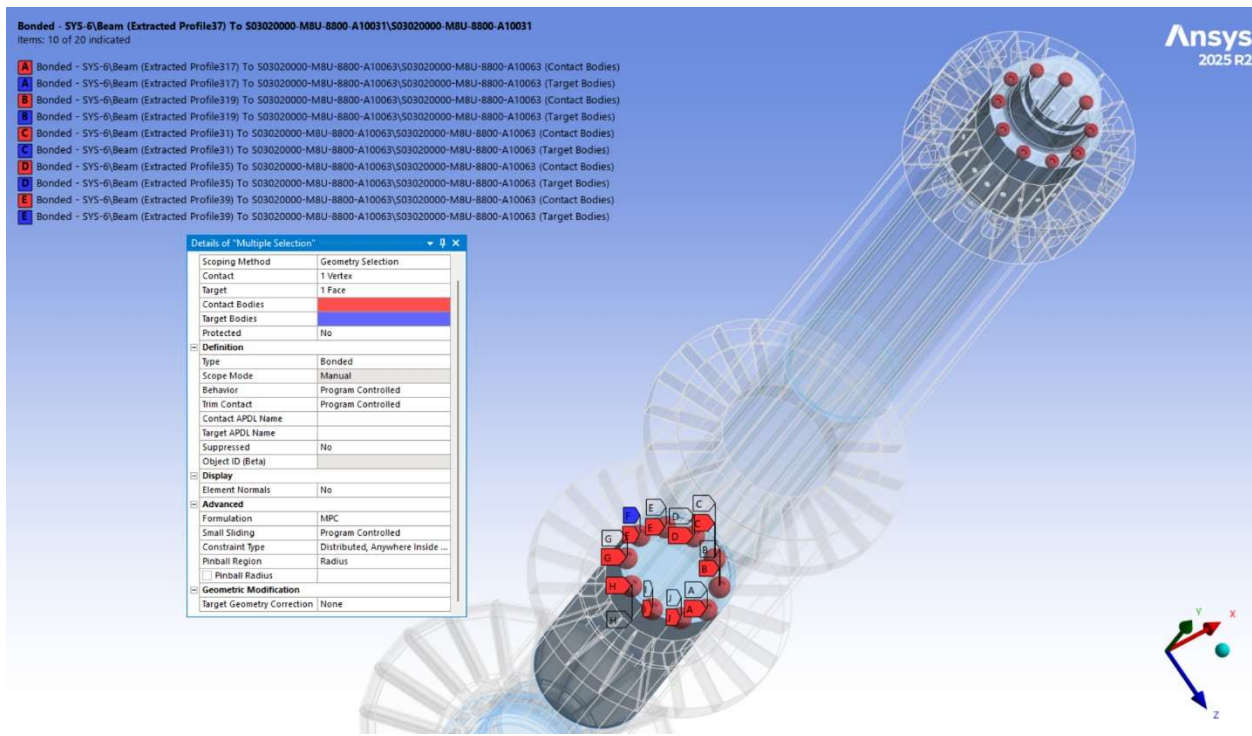


Figure 296 Tie Rod Contacts

The dummy Segments are attached to the Shaft and Crown with Joints, since the Segment bolt and pin are covered in the Segment model analysis all that is needed here is the proper degree of freedom between the components.

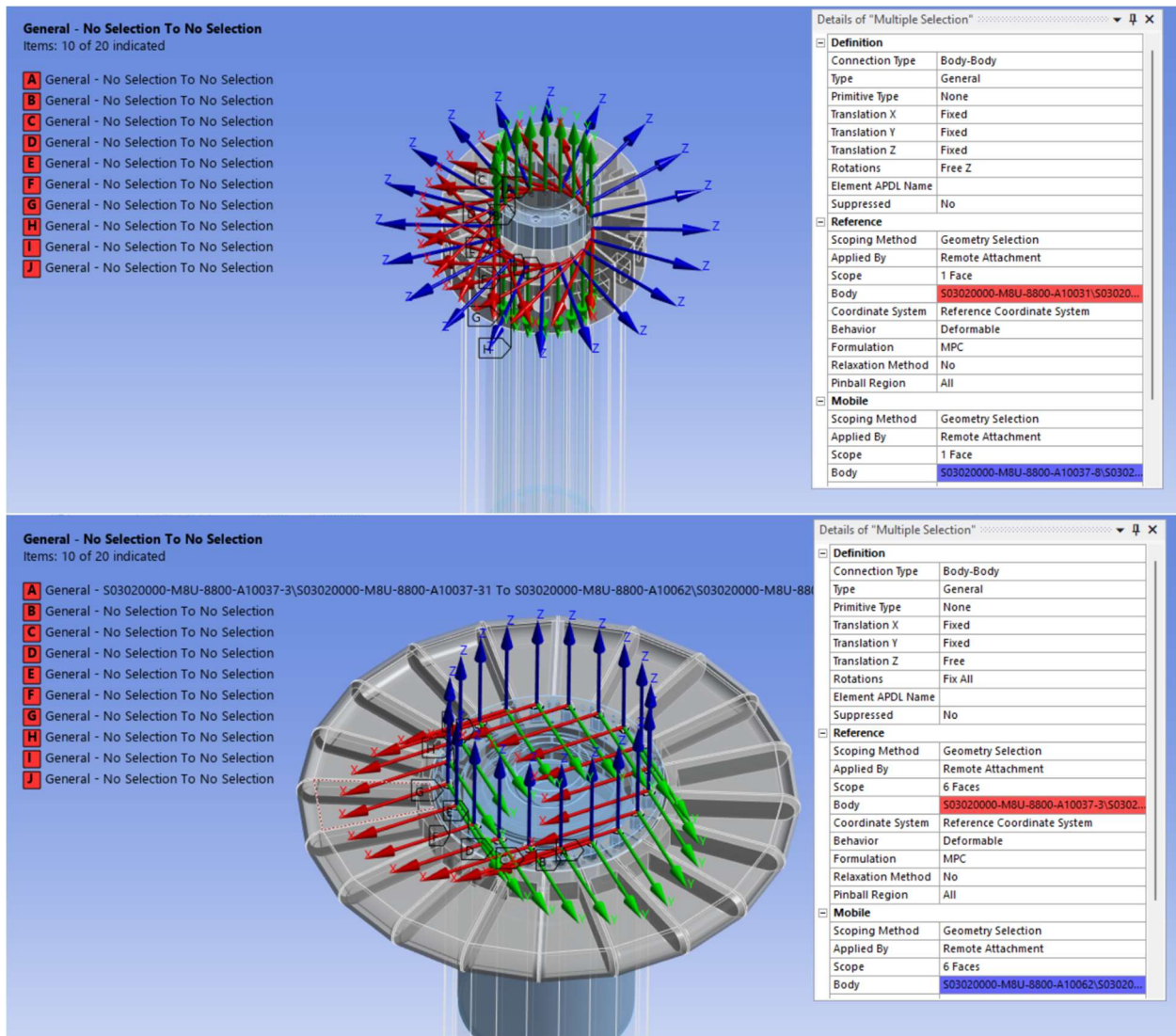


Figure 297 Dummy Segment Joints

4.5.3.1 Snubber Ring

The Snubber Ring uses two nonlinear contacts, first, a Rough interface is between the horizontal surfaces of the shaft and snubber. A Rough contact is used to prevent rotation about the center axis of the shaft and snubber, but it still allows separation. The second interface is frictionless contact between the concentric faces of the shaft and snubber. These surfaces have a gap between them so a pinball radius is used. This interface is in place to help keep the center axis of the shaft and snubber aligned.

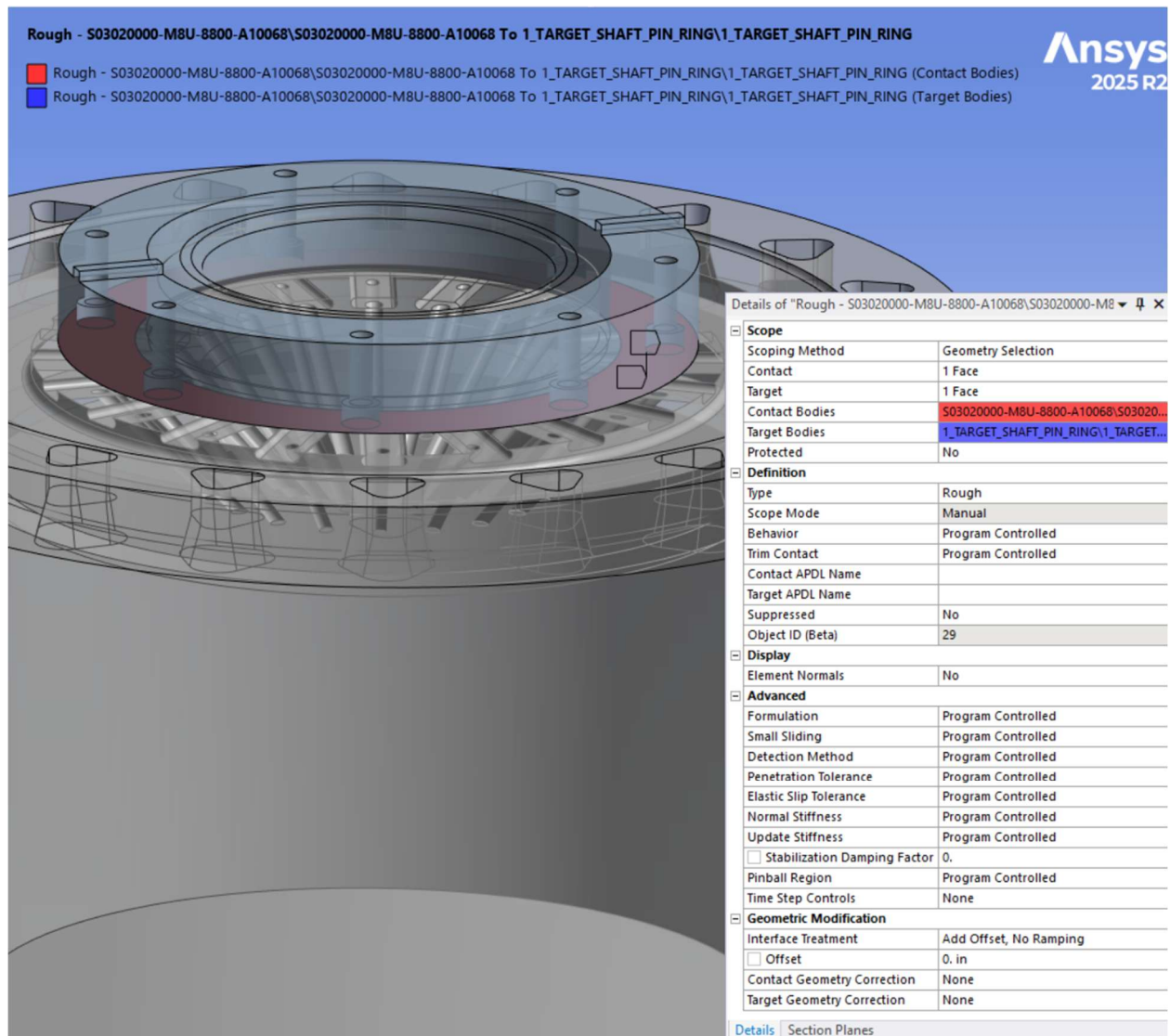


Figure 298 Snubber Ring Rough Interface

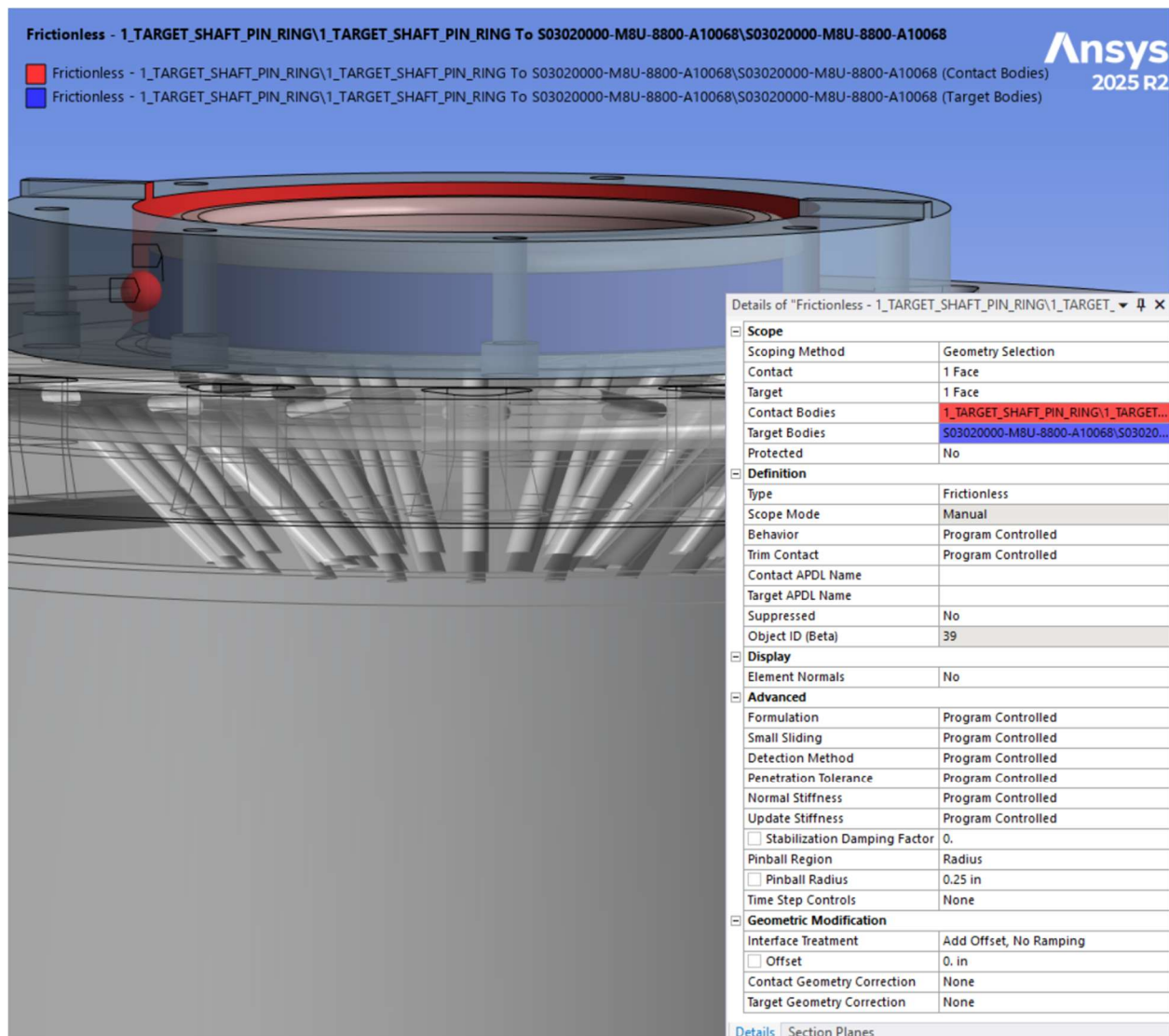


Figure 299 Snubber Ring Frictionless Interface

4.5.4 Crown and Drive

The Crown and Drive model is meant to focus on the bearing area of the Target. The one-piece shaft and segment part is bonded to the bottom of the Crown.

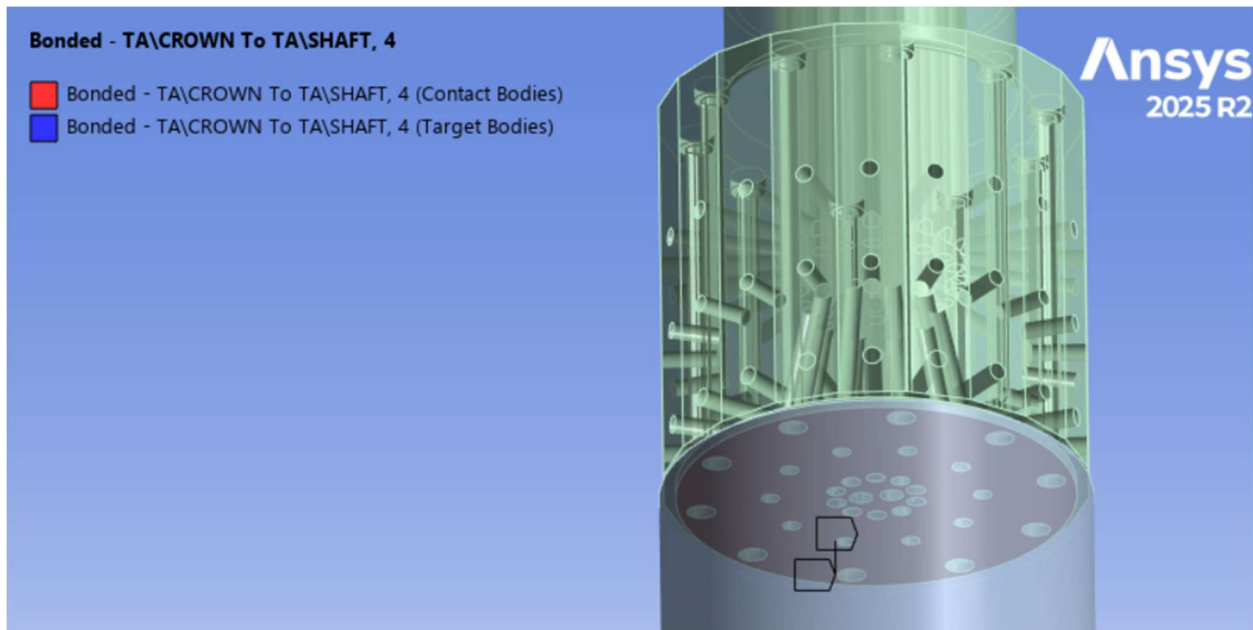


Figure 300 Crown to Shaft Interface

All interfaces that have fasteners (beams) use a frictionless contact so both tension and shear on the fasteners can be captured.

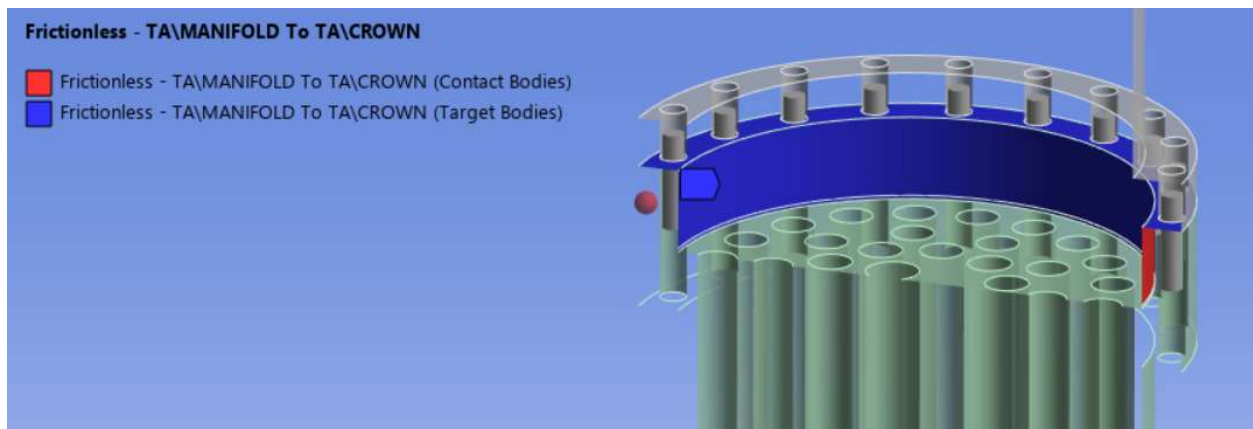


Figure 301 Crown to Manifold Contact

The outer Motor housing is just included for weight in this model, the motor is a purchased component that is designed to withstand it's applied torque.

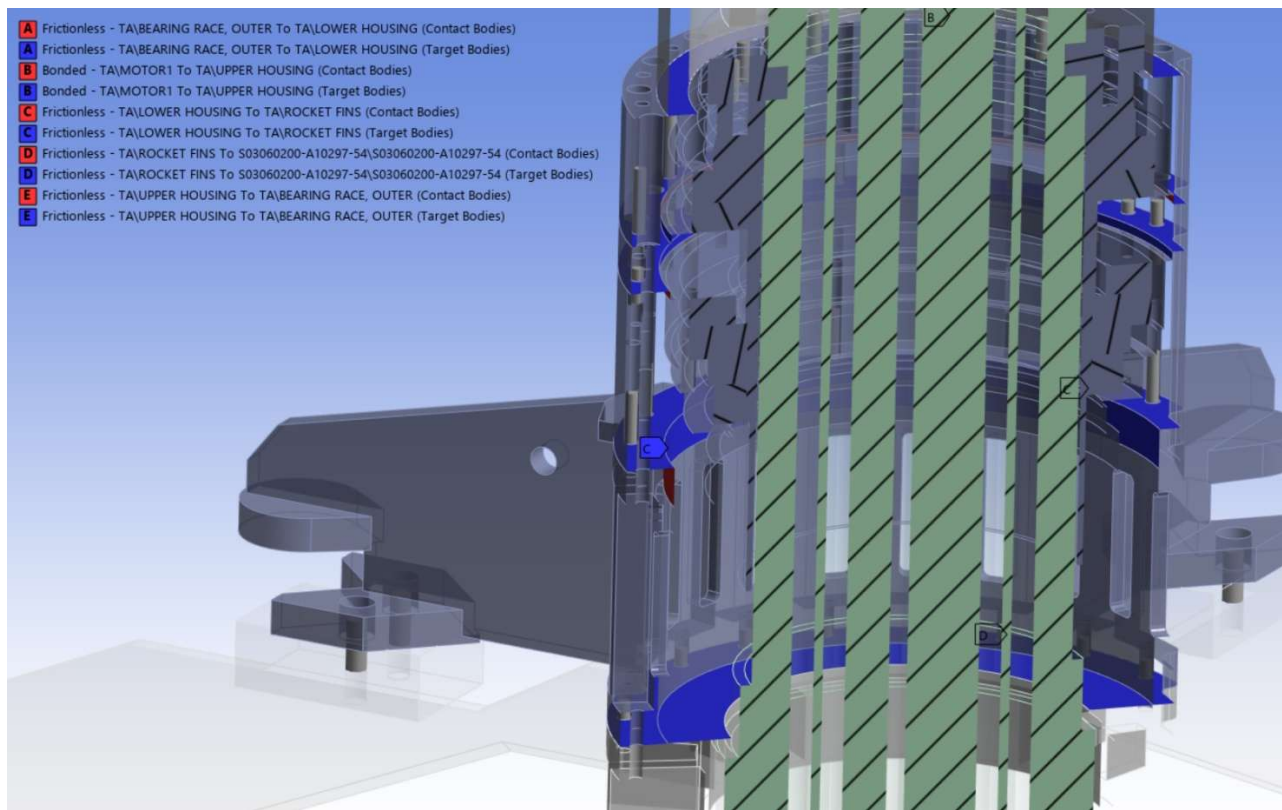


Figure 302 Outer Housing Contacts

The actual bearings are modeled with a bonded interface on one side with a frictionless interface on the other to keep the part constrained but allow the natural rotation of the drive.

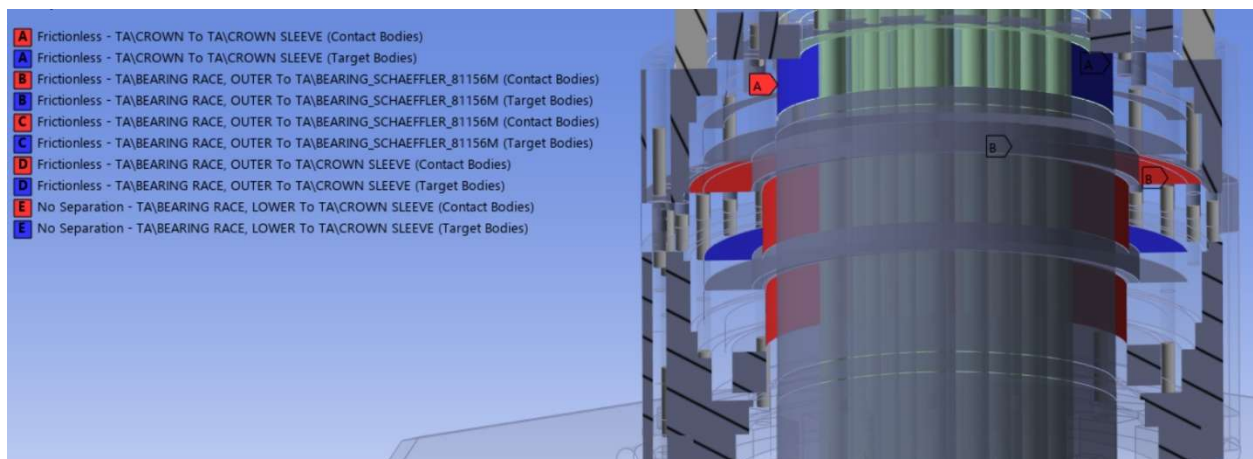


Figure 303 Crown Bearing Surfaces

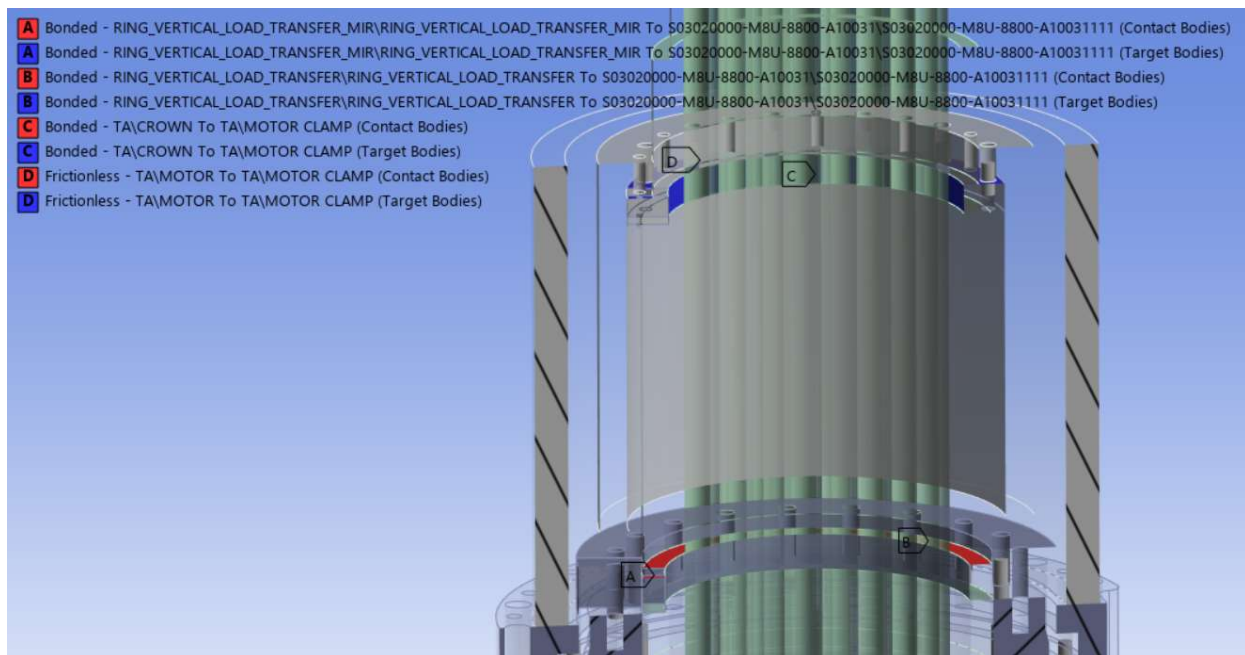


Figure 304 Crown Clamp Rings

All contact settings were left to default except for the type, either Bonded or Frictionless.

Details of "Frictionless - TA\CROWN To TA\CROWN SLEEVE" ▾ □ ✕	
Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	TA\CROWN
Target Bodies	TA\CROWN SLEEVE
Protected	No
Definition	
Type	Frictionless
Scope Mode	Manual
Behavior	Program Controlled
Trim Contact	Program Controlled
Contact APDL Name	
Target APDL Name	
Suppressed	No
Object ID (Beta)	36795
Display	
Element Normals	No
Advanced	
Formulation	Program Controlled
Small Sliding	Program Controlled
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
☐ Stabilization Damping Factor	0.
Pinball Region	Program Controlled
Time Step Controls	None
Geometric Modification	
Interface Treatment	Add Offset, No Ramping
☐ Offset	0. in
Contact Geometry Correction	None
Target Geometry Correction	None

Figure 305 Contact Settings Example

The Crown and Drive model is also the home to all the fasteners. The fasteners are added as beams in the Connection section, this model is simplified enough to use several frictionless contact surfaces. The frictionless surfaces let the bolted joints naturally slide and separate giving more realistic fastener loads.

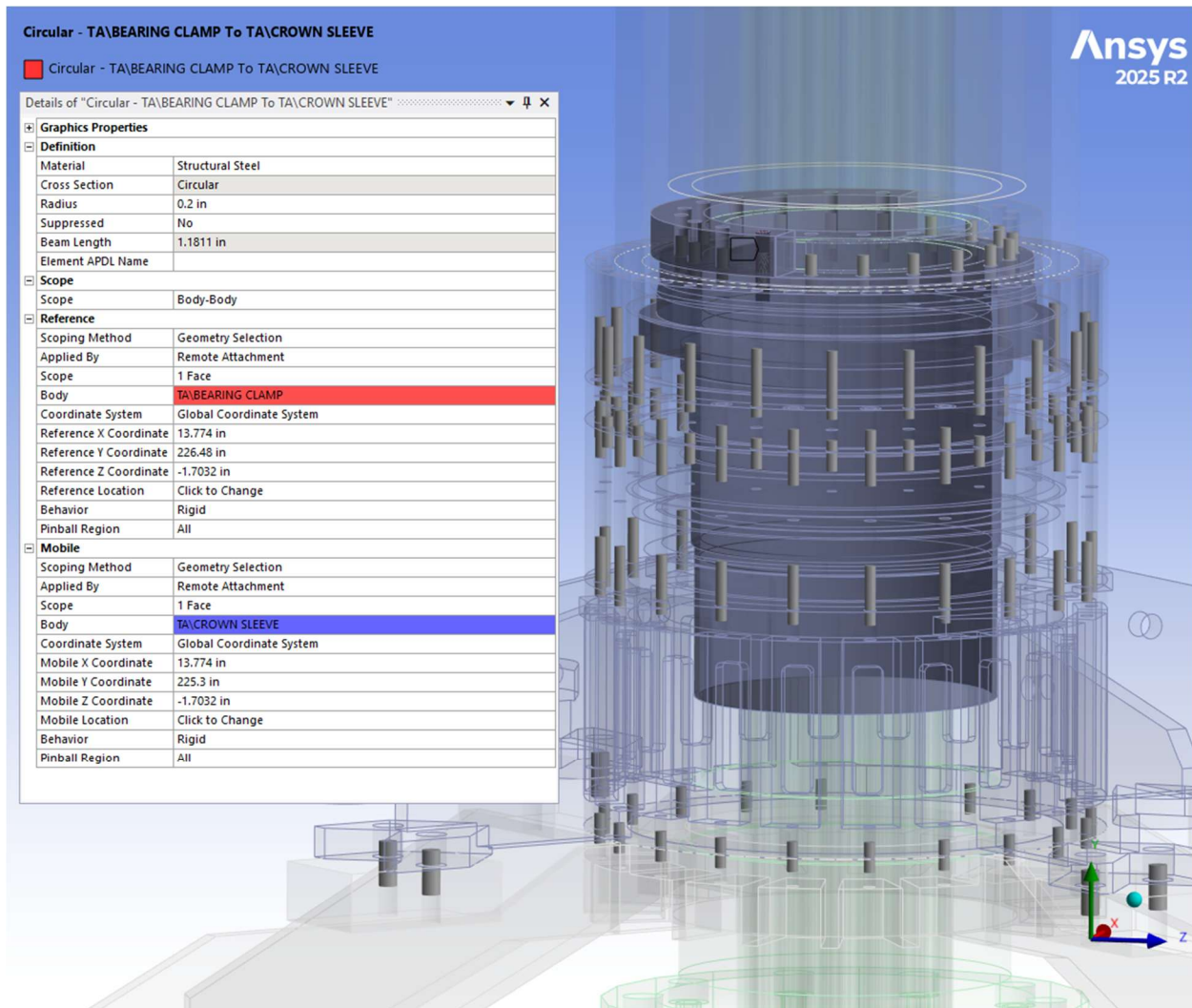


Figure 306 Fastener Example

4.6 LOAD DEFINITIONS

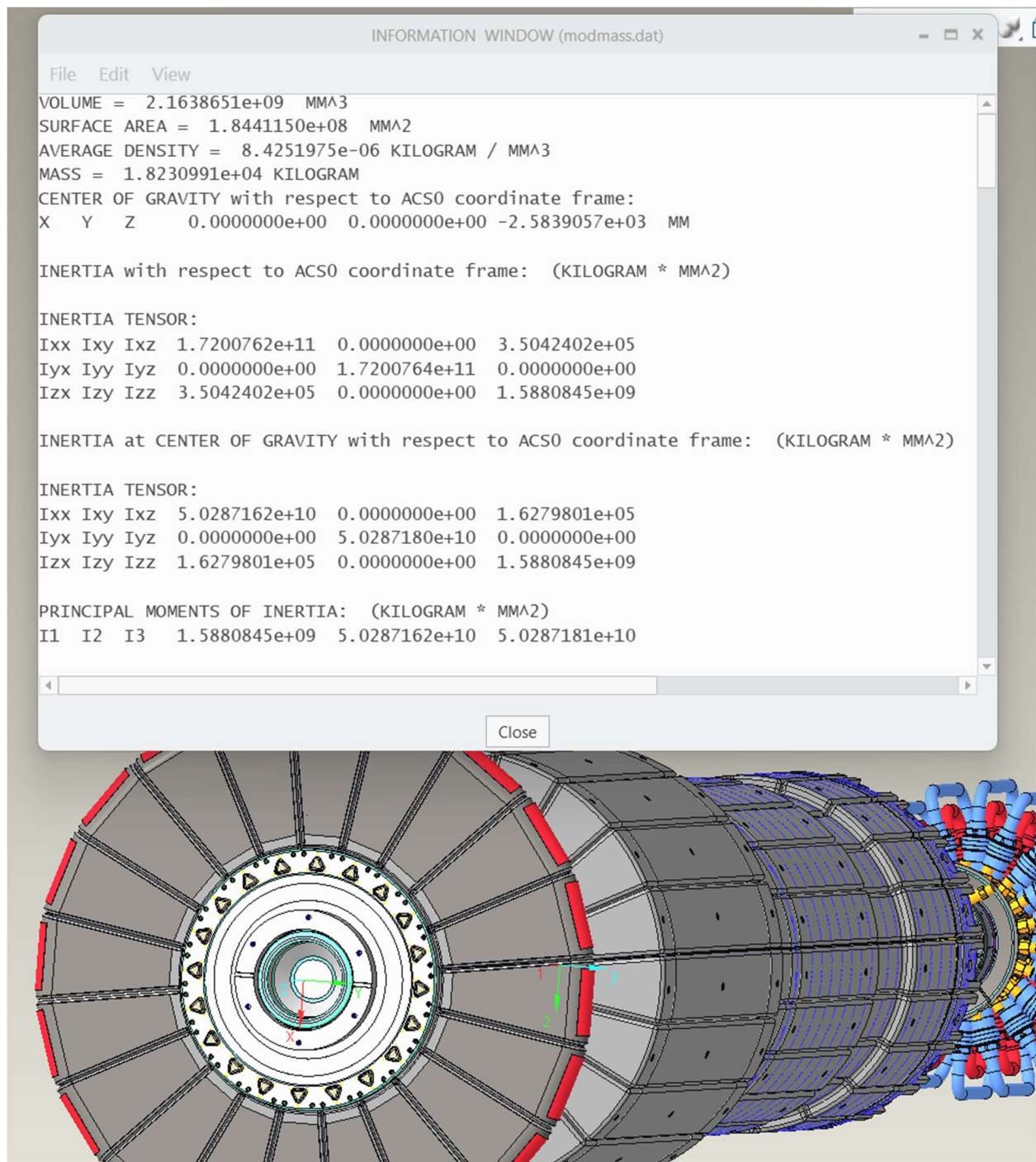
The following load combinations are taken from the code requirements and three Elastic load cases and three Elastic Plastic load cases are used. In the Elastic loads, a case with angular velocity and acceleration applied to the rotating components of the Target. A Seismic load case with a lateral acceleration and third, a combination of the two, Seismic + Stop. The Elastic Plastic load cases are similar, EP1 has a large factor on pressure, live and dead loads. EP2 has a higher factor on the live loads with a lower factor on the pressure and deadload. EP5 adds in the seismic load. An image of the load summary and each applied load is presented in this section. Note that for the loads that are common to each load case an image will only be shown once in the E Stop section to exclude redundant images, these loads include gravity, temperature, and water pressure.

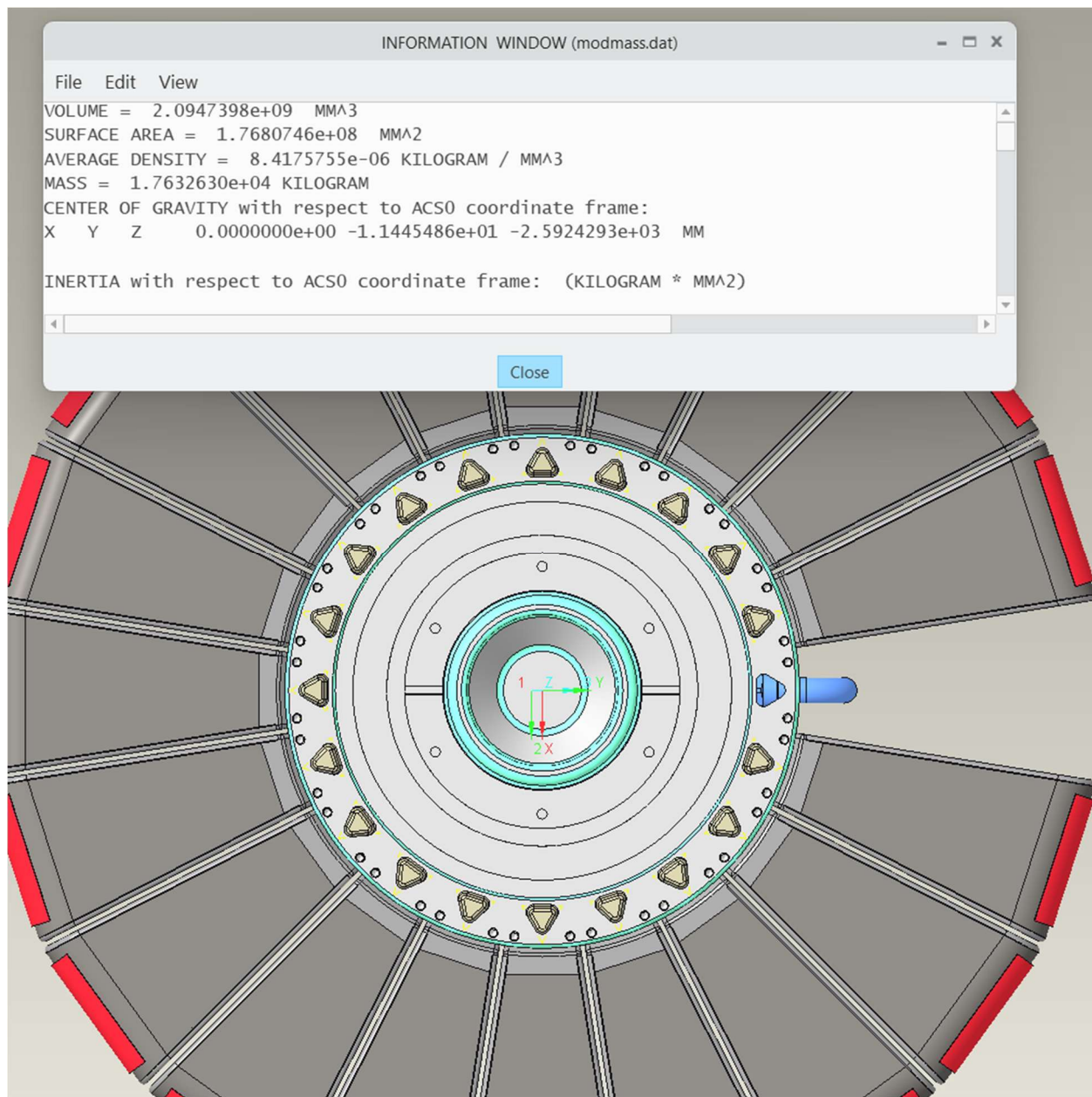
4.6.1 Target Assembly

The Target Assembly model has three Elastic load combinations applied. In the Target Assembly model the displacement load case is different than the submodels. The purpose of the displacement load is to artificially limit the distance the lower shaft can move before it hits the limit of the Snubber Ring. The Snubber Ring is a feature in the Core Vessel that loosely captures the lower shaft, there is 5mm of clearance between the Shaft and Snubber Ring to limit movement during a seismic event. In the Target Model the displacement load is set to 5mm, assuming the Shaft and Snubber Ring are aligned. Note that for the Target Assembly model the temperature data is mapped from external data and is the same for all Target Assembly models. The same is also true for the pressure loads, they are consistent for each analysis.

Table 16 Target Assembly Load Parameters

Load Case	Time	P	D	L	L	T	E	Displacement
3	1	125 psi	1g	4.7 rad/s ²	45 rpm	Imported		
6	1	125 psi	1g			Imported	169 in/s ²	.196 in
8	1	125 psi	1g	3.5 rad/s ²	34rpm	Imported	127 in/s ²	.196 in





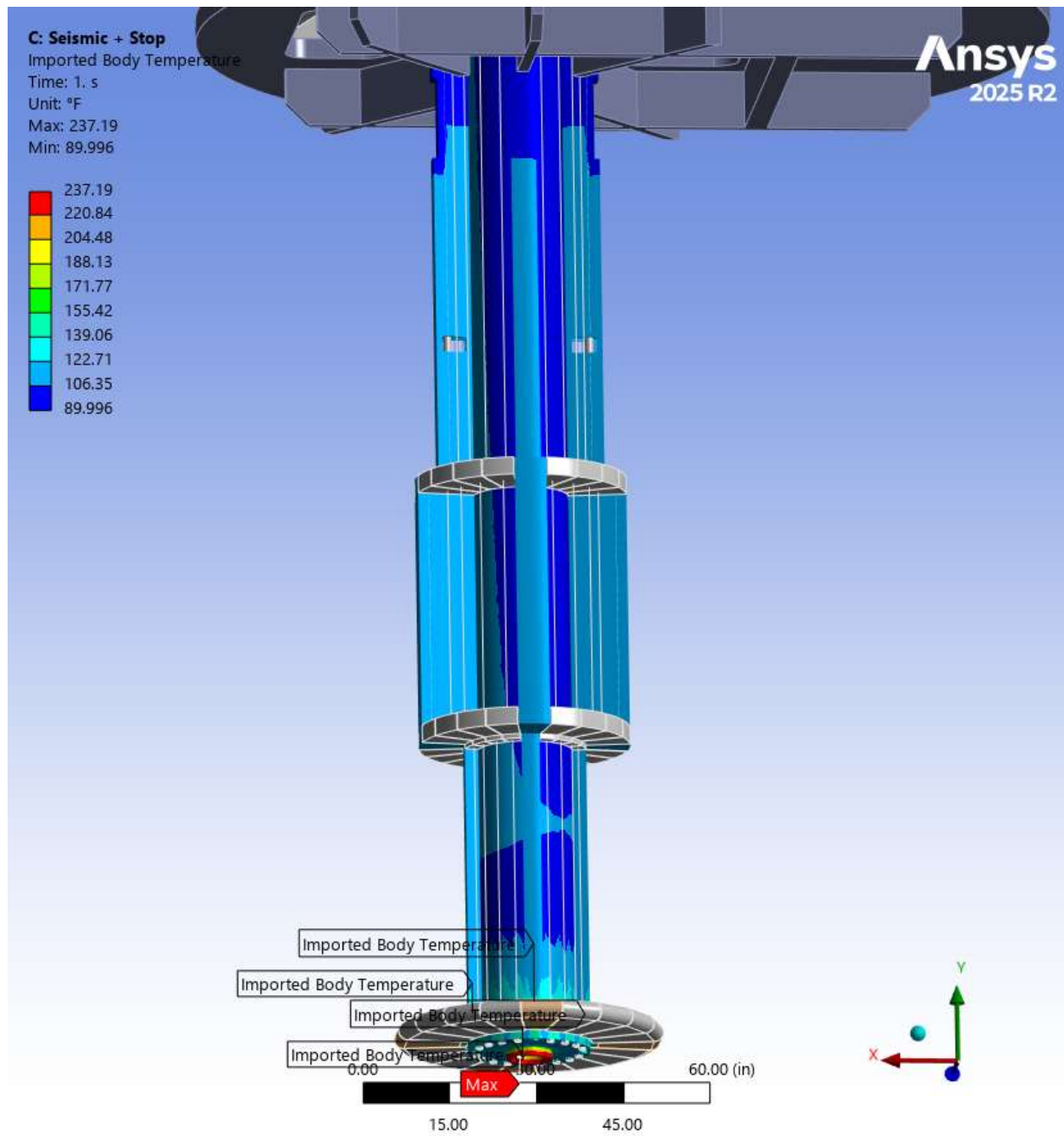


Figure 307 Target Assembly Temperature Load

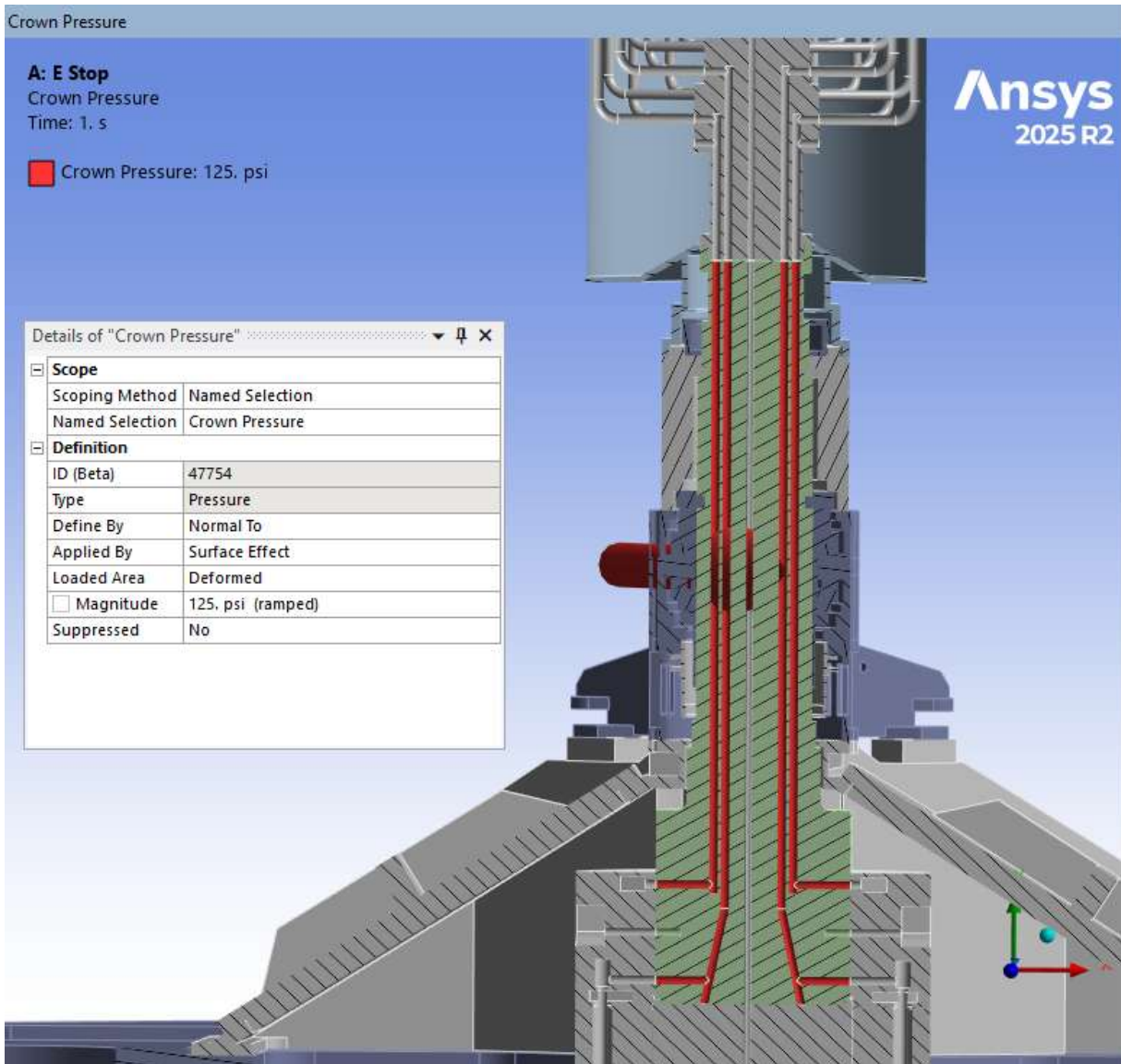


Figure 308 Target Assembly Crown Pressure

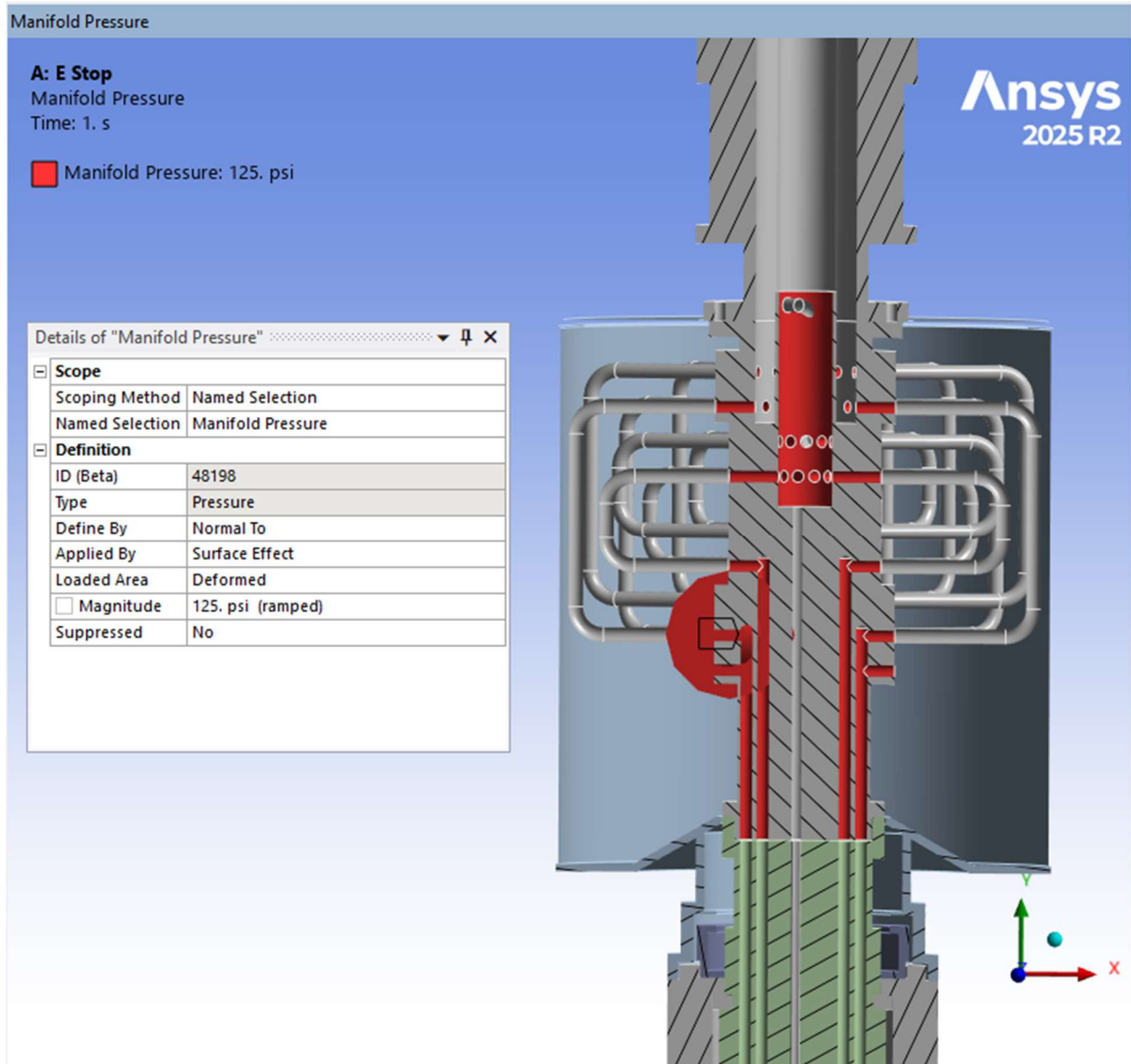


Figure 309 Target Assembly Manifold Pressure

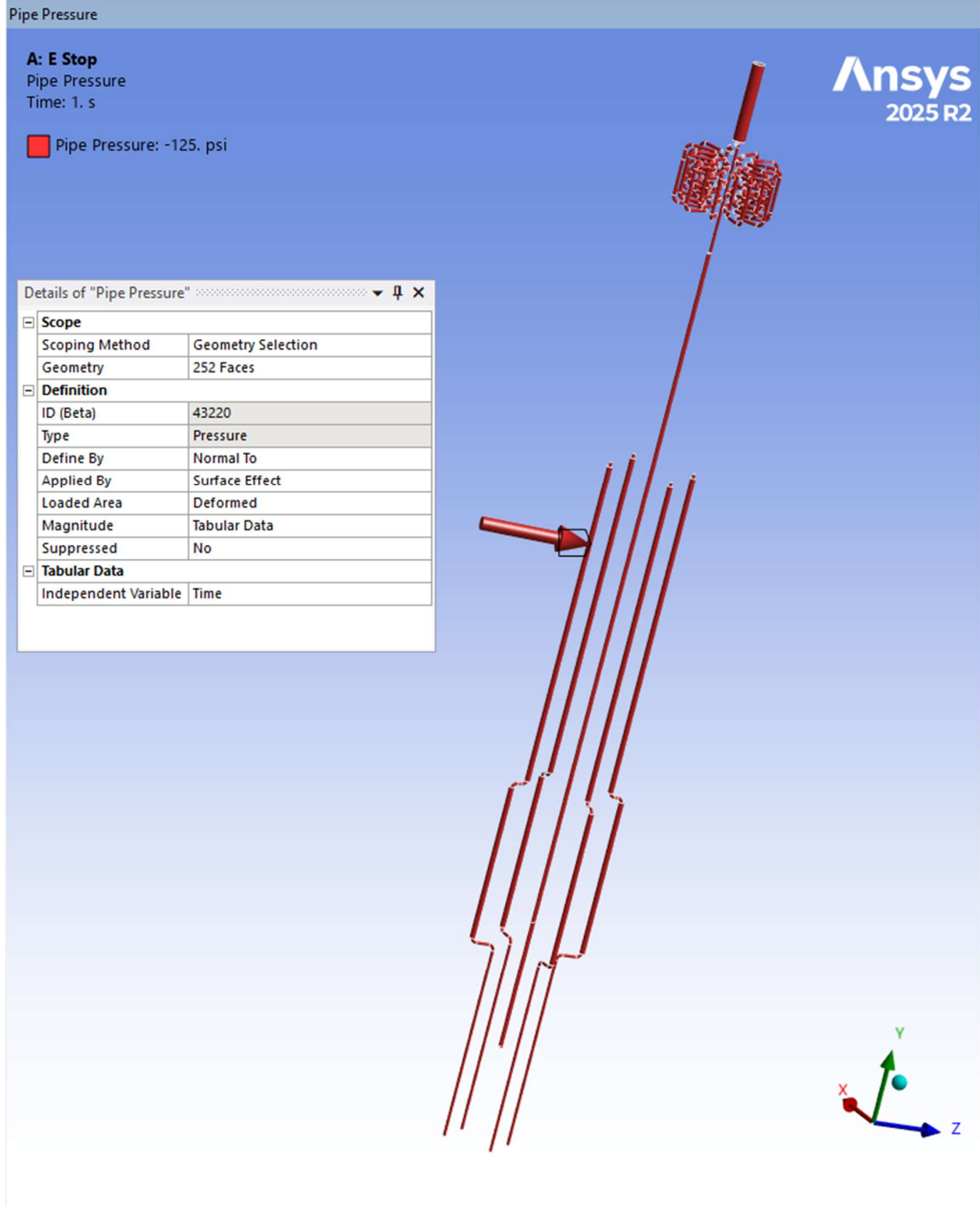


Figure 310 Target Assembly Pipe Pressure

4.6.1.1 Load Combination 3, E Stop

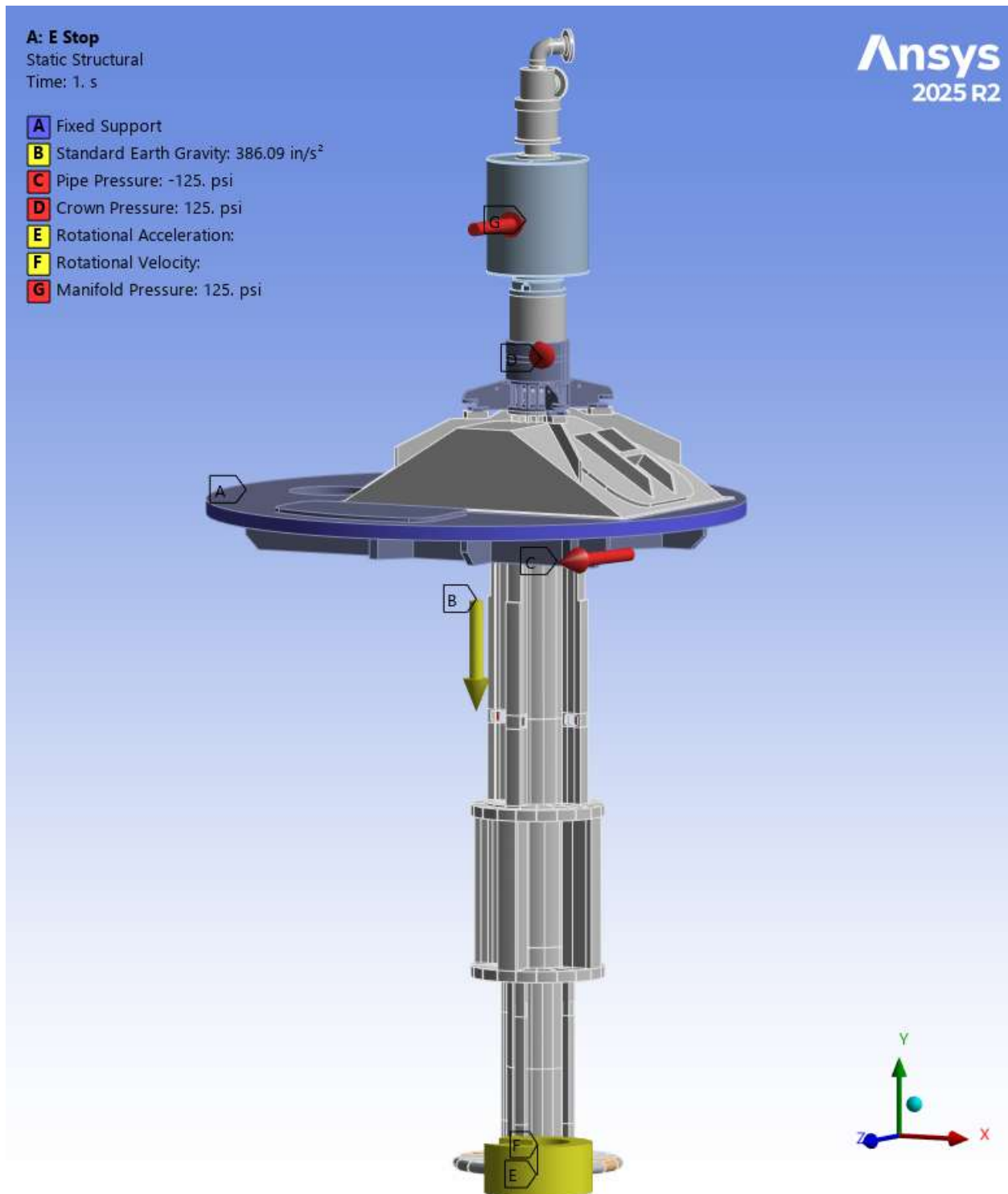


Figure 311 Target Assembly, E Stop Load Summary

A: E Stop

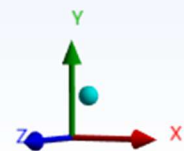
Standard Earth Gravity

Time: 1. s

 Standard Earth Gravity: 386.09 in/s²
Components: 0., -386.09, 0. in/s²

Ansys
2025 R2

Details of "Standard Earth Gravity"   	
Scope	
Geometry	All Bodies
Definition	
Coordinate System	Global Coordinate System
X Component	0. in/s ² (ramped)
Y Component	-386.09 in/s ² (ramped)
Z Component	0. in/s ² (ramped)
Suppressed	No
Direction	-Y Direction

*Figure 312 Target Assembly, E Stop Gravity Load*

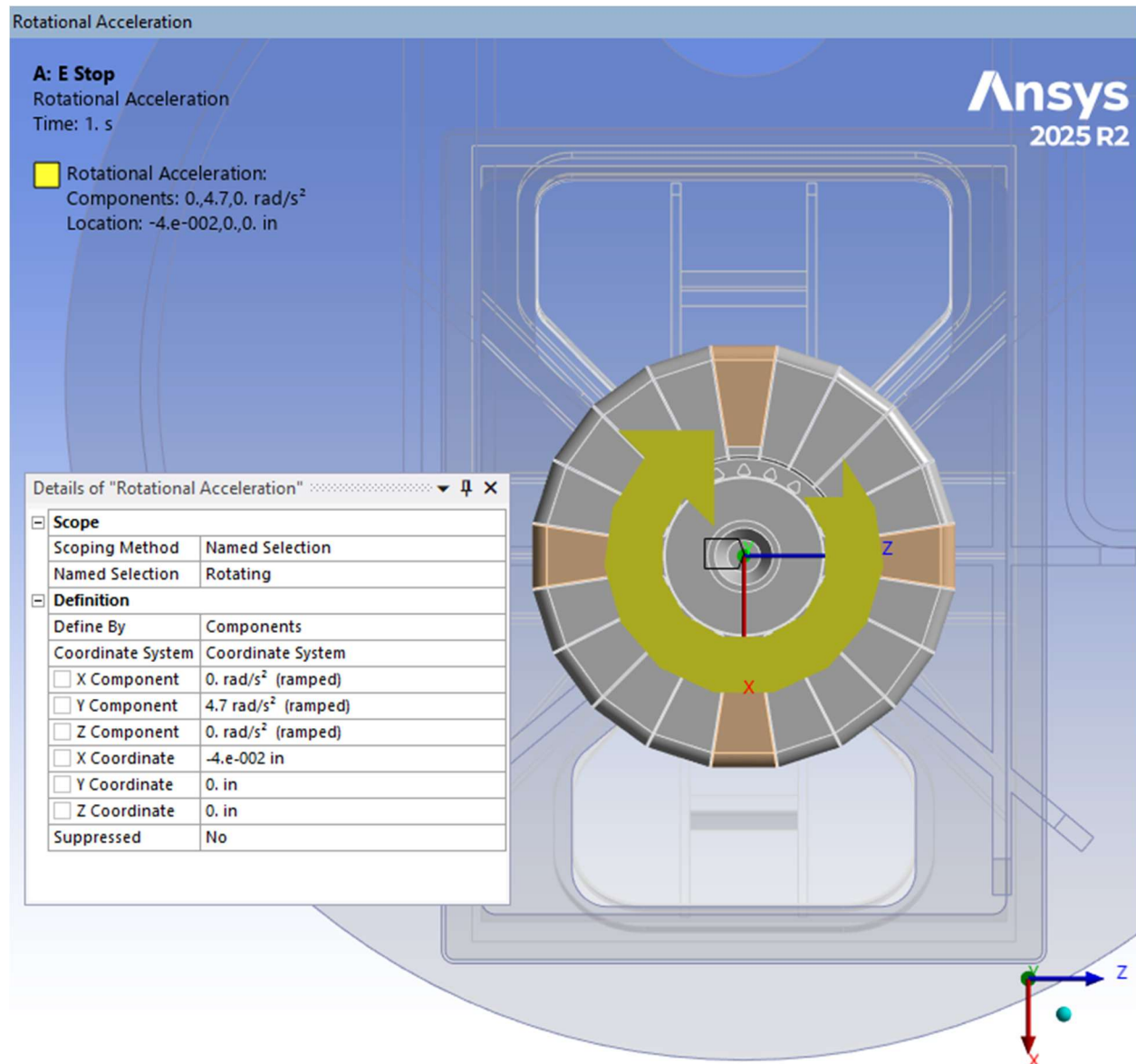


Figure 313 Target Assembly, E Stop Rotational Acceleration

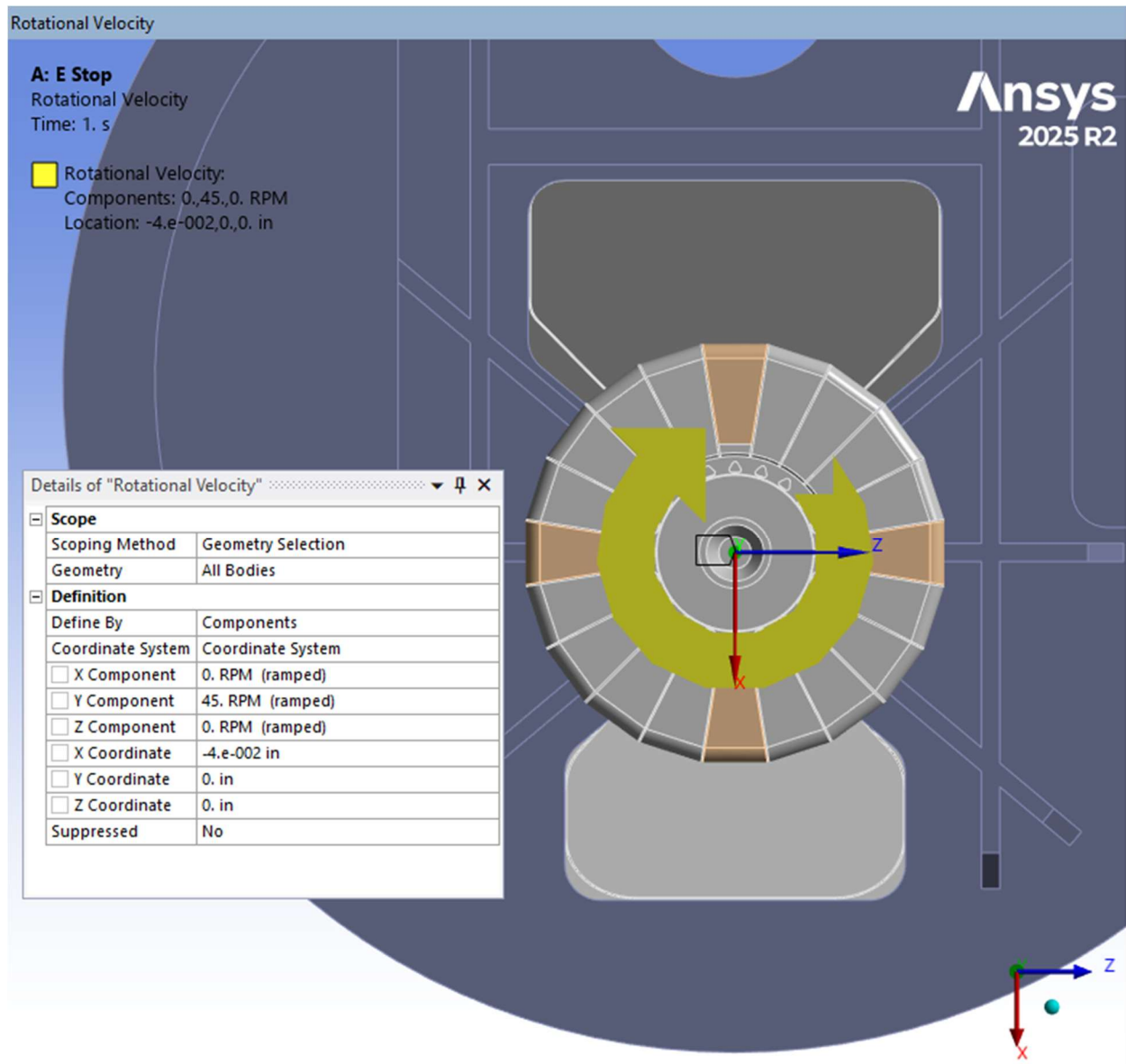


Figure 314 Target Assembly, E Stop Rotational Velocity

Note the X Coordinate offset is the Eccentric Load, the rotational axis is moved to where the axis would be if the assembly was missing one Segment.

4.6.1.2 Load Combination 6, Seismic

C: Seismic

Static Structural

Time: 1. s

- A** Fixed Support
- B** Standard Earth Gravity: 386.09 in/s²
- C** Pipe Pressure: -125. psi
- D** Displacement
- E** Crown Pressure: 125. psi
- F** Manifold Pressure: 125. psi
- G** Acceleration: 169. in/s²

Ansys
2025 R2

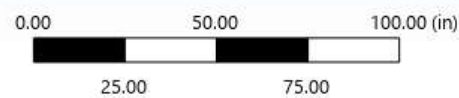
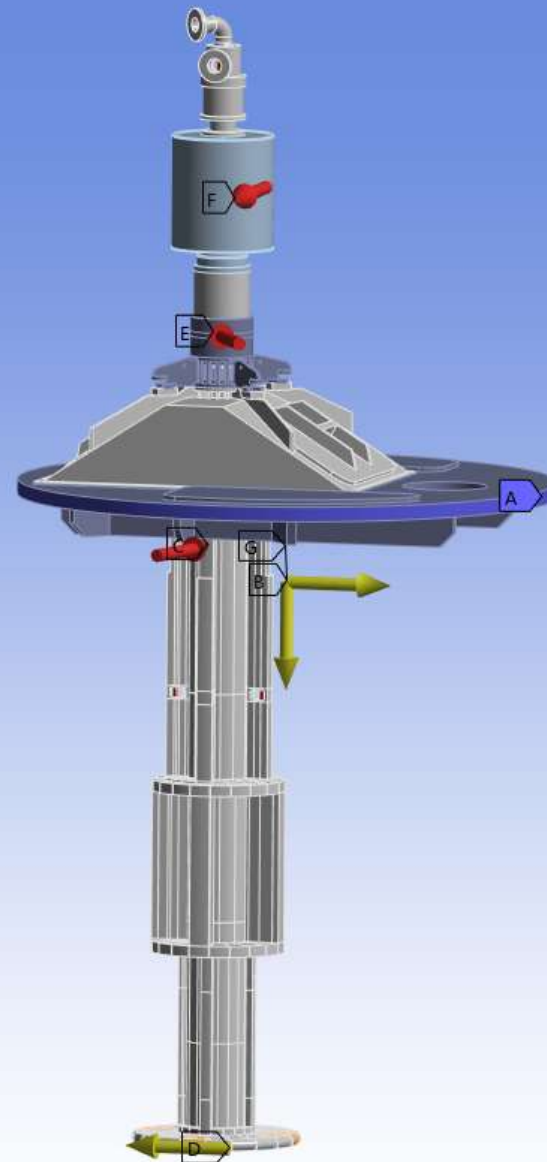


Figure 315 Target Assembly, Seismic Load Summary

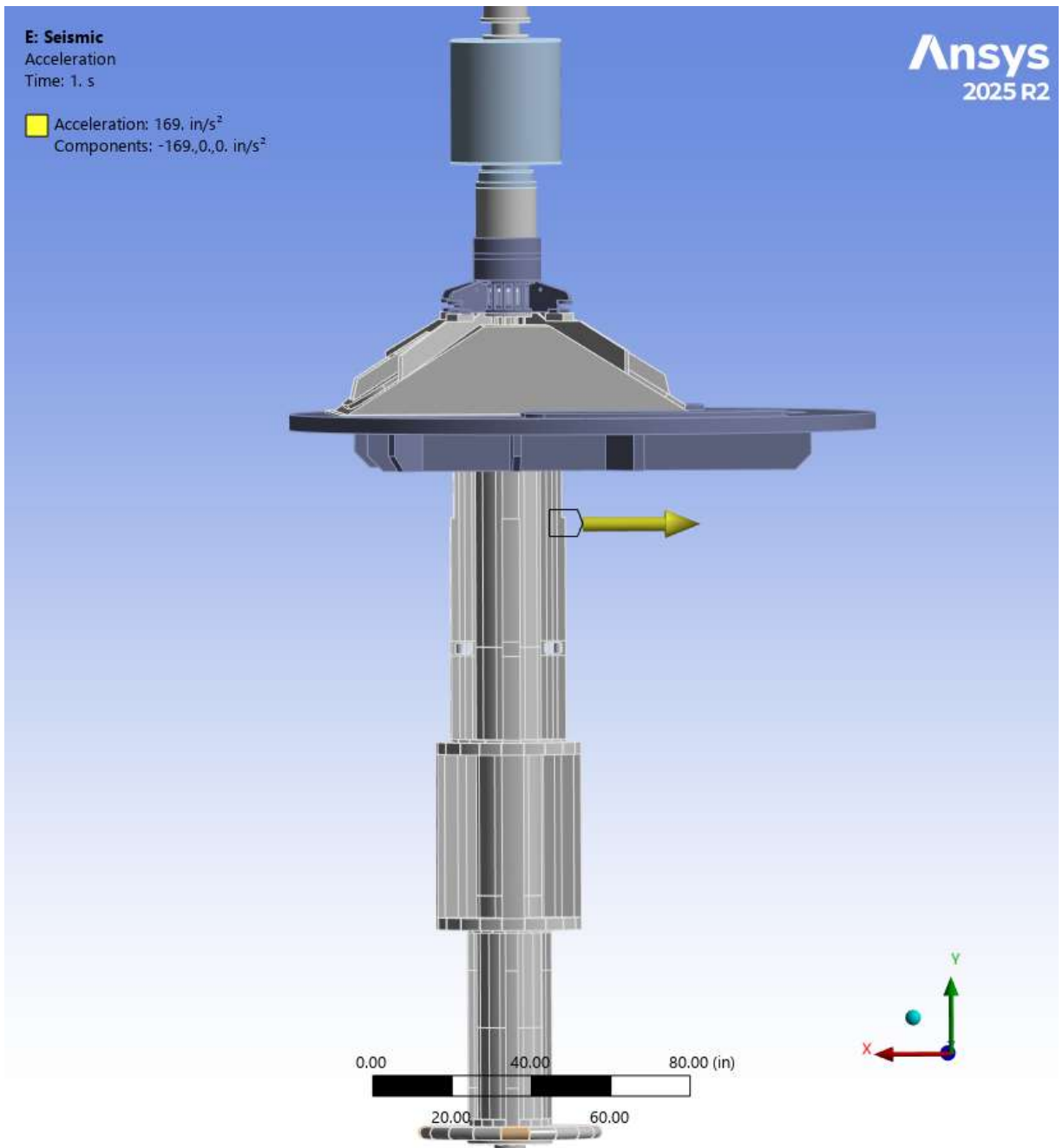


Figure 316 Target Assembly, Seismic Acceleration

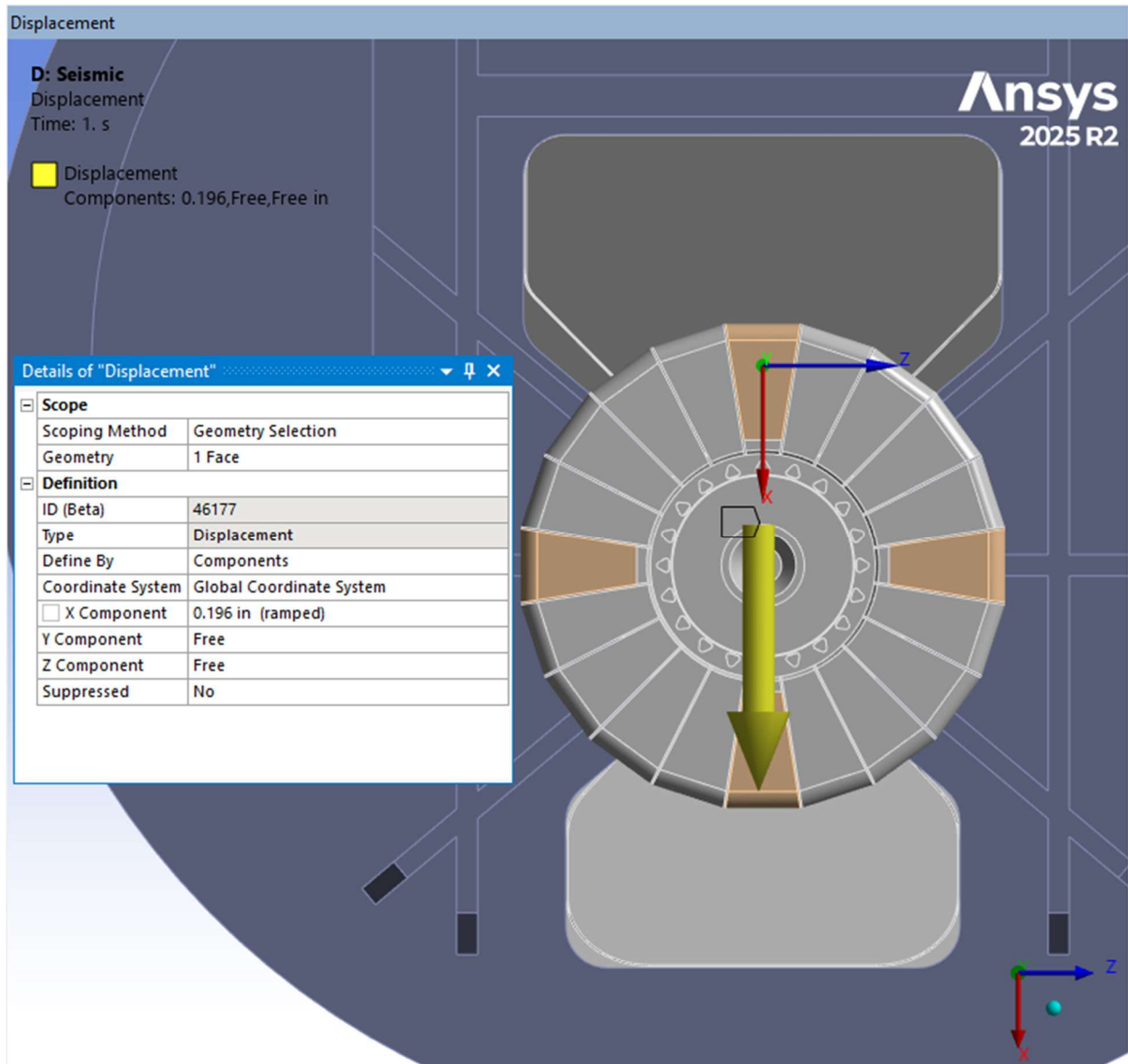


Figure 317 Target Assembly, Seismic Displacement Load

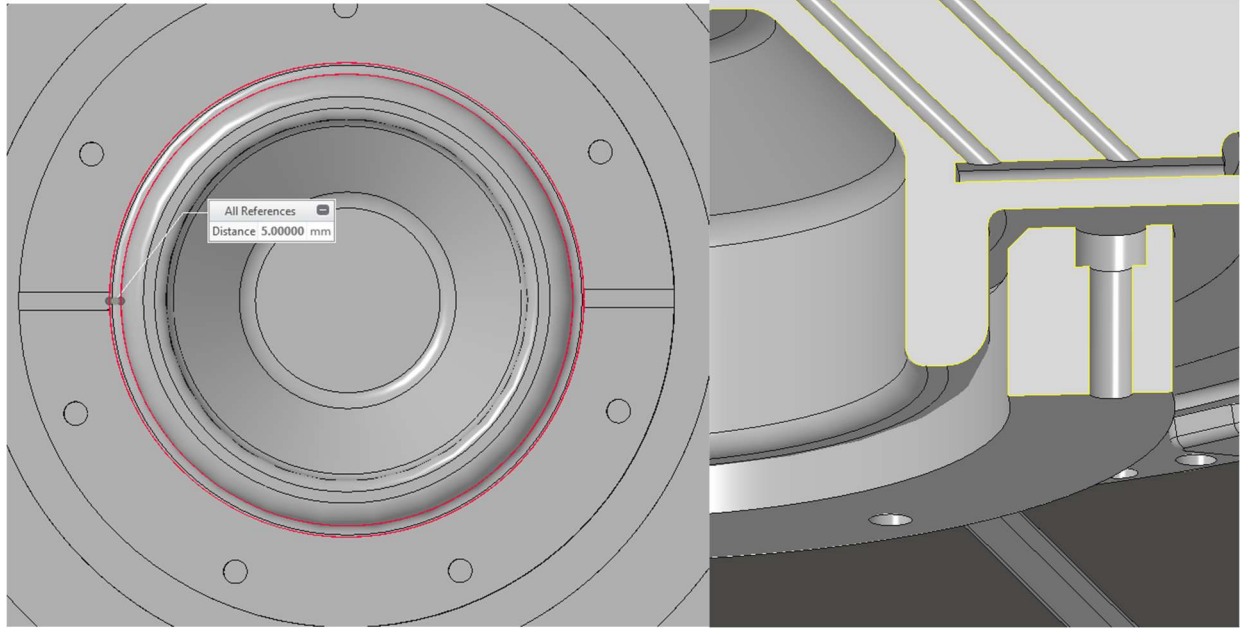


Figure 318 Snubber Ring Clearance

4.6.1.3 Load Combination 8, Seismic + Stop

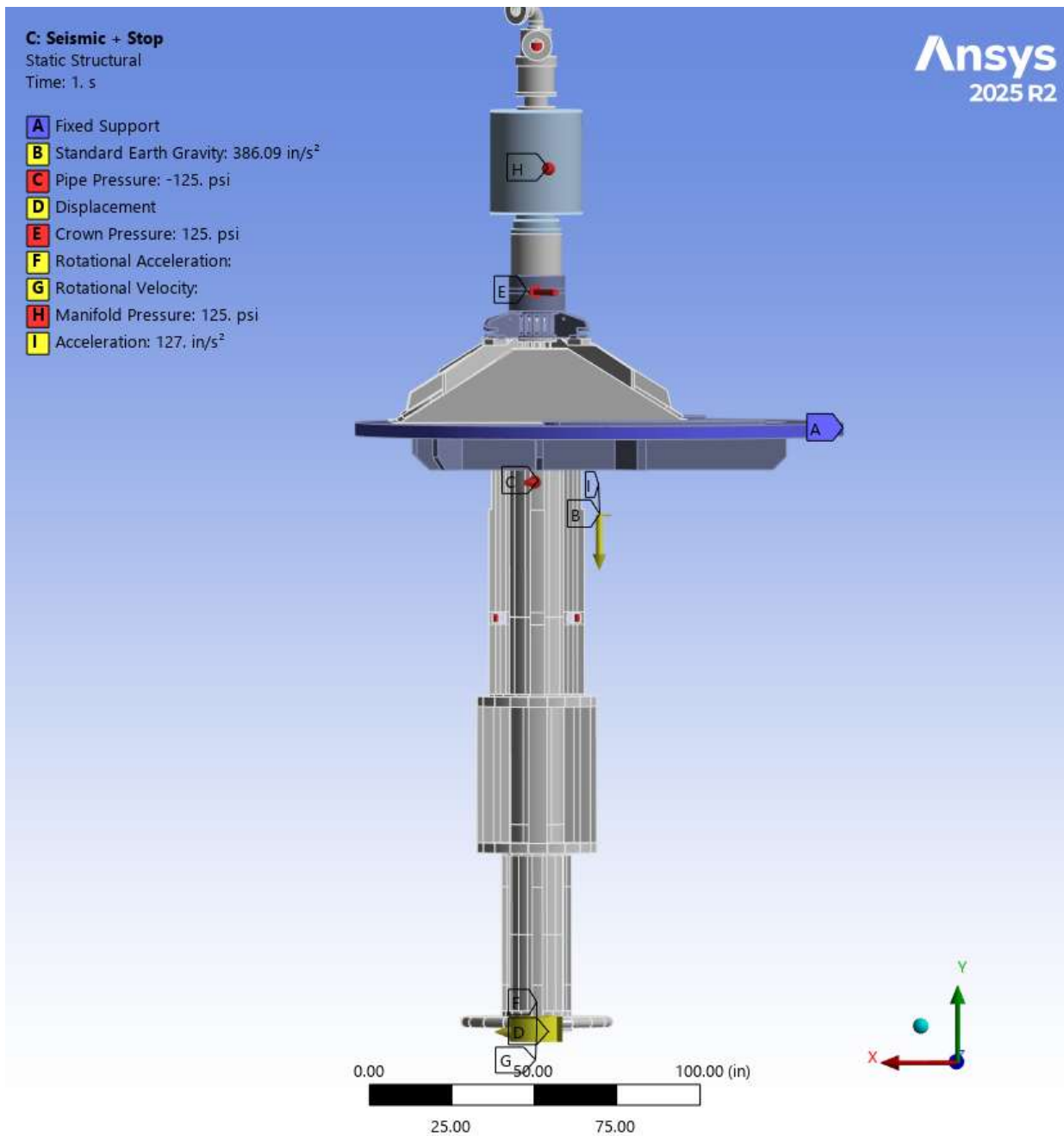


Figure 319 Target Assembly, Seismic + Stop Load Summary

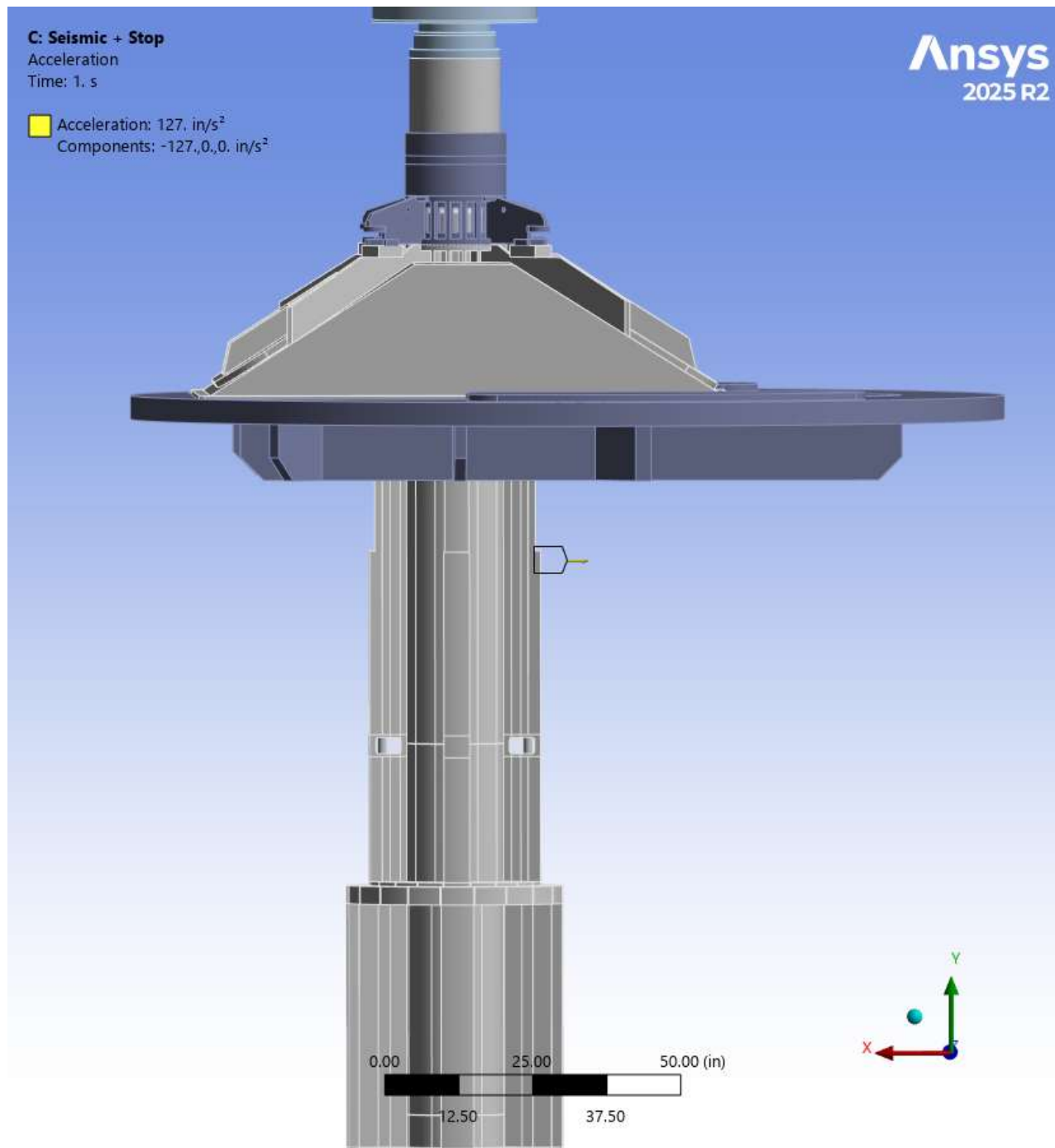


Figure 320 Target Assembly, Seismic + Stop Acceleration

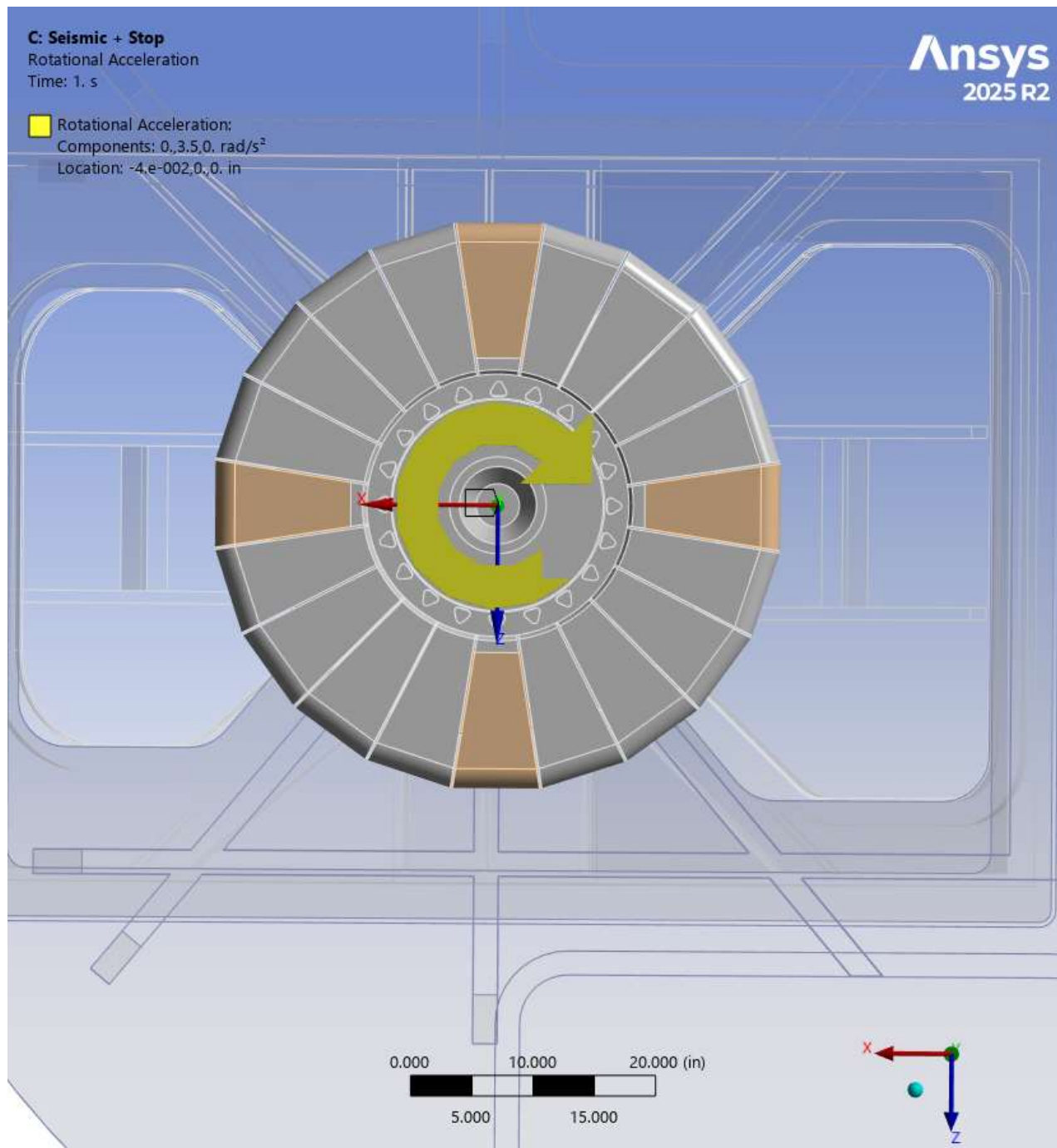


Figure 321 Target Assembly, Seismic + Stop Rotational Acceleration

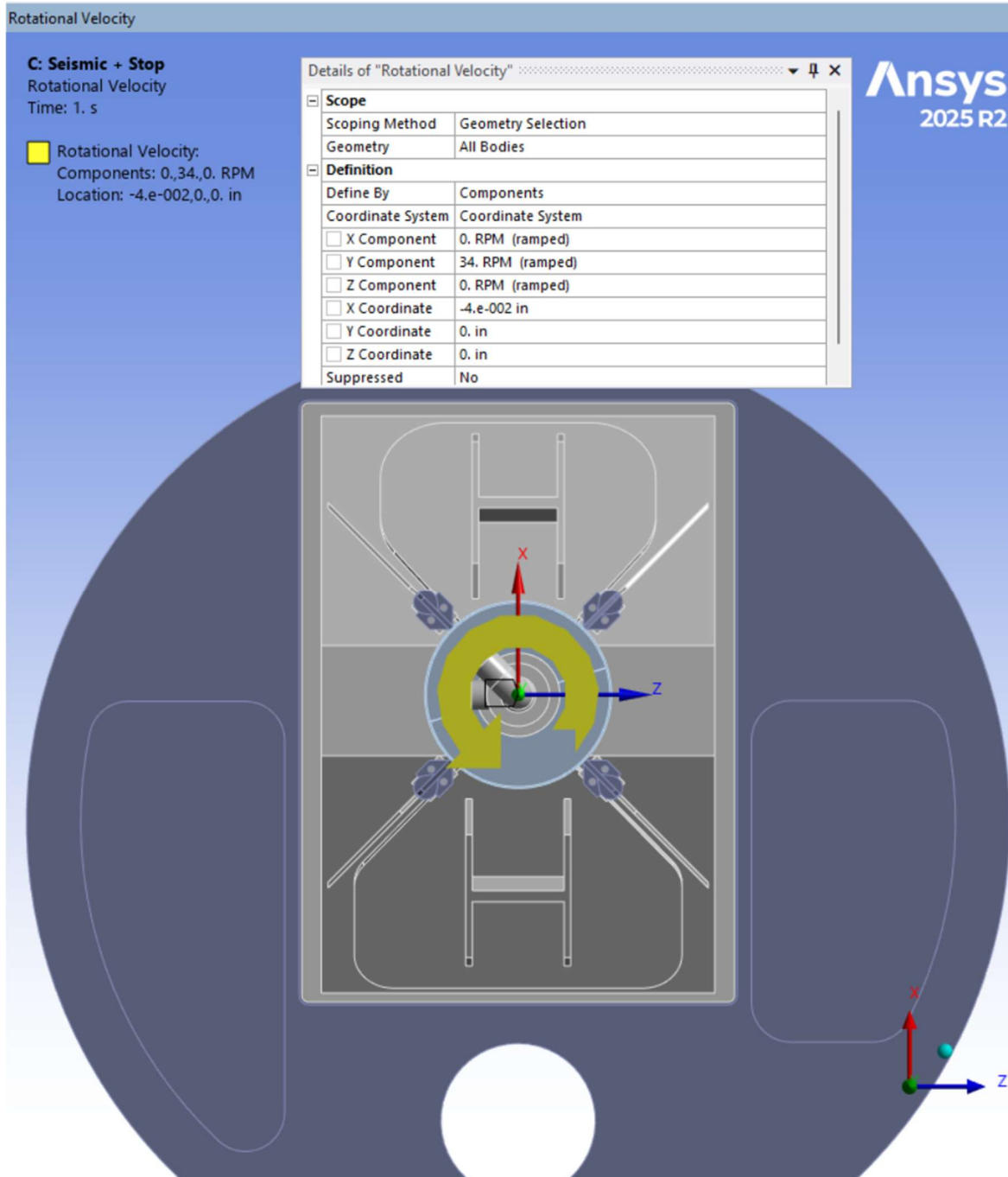


Figure 322 Target Assembly, Seismic + Stop Rotational Velocity

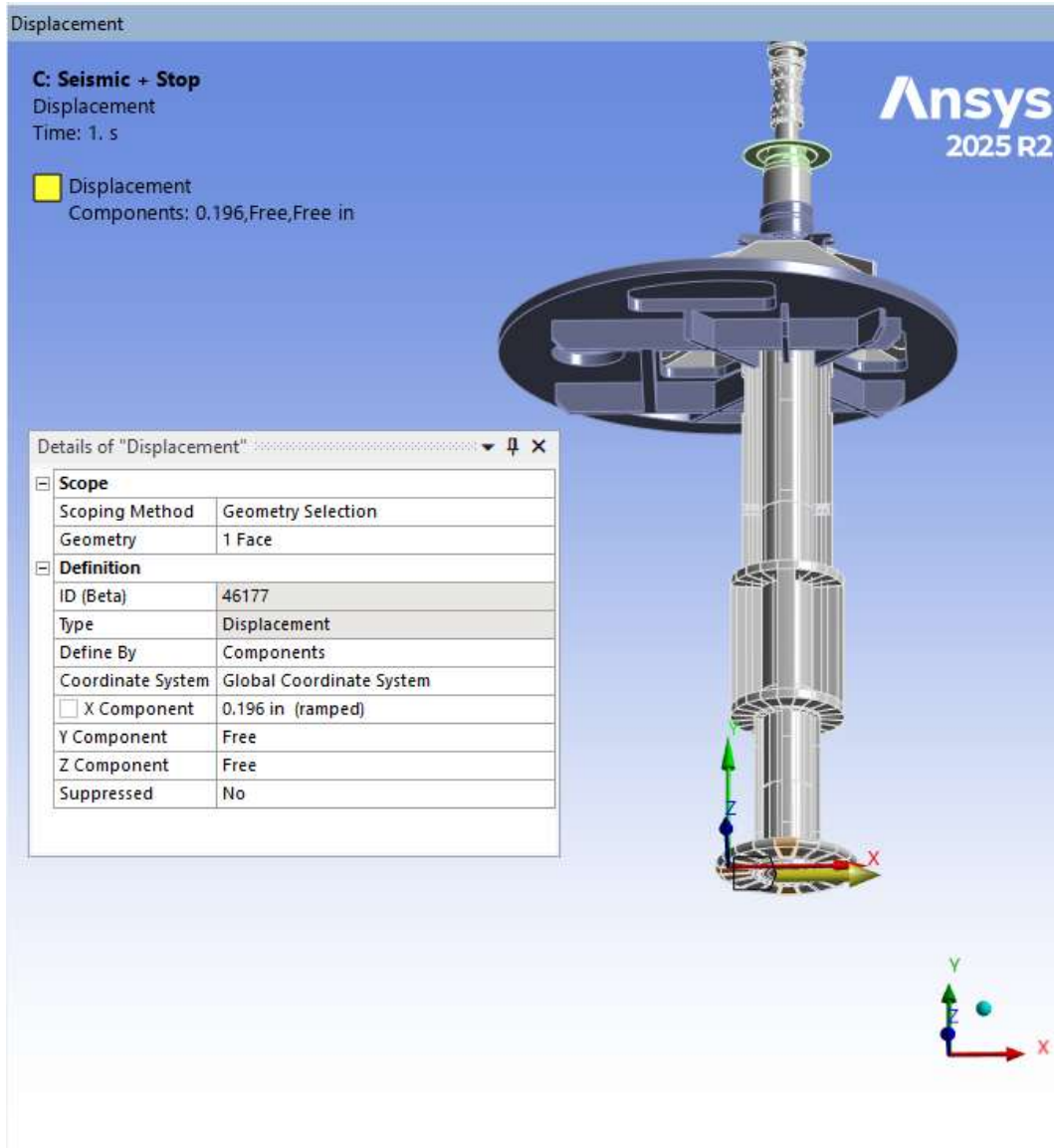


Figure 323 Target Assembly, Seismic + Stop Displacement Load

4.6.2 Target Segment Load Cases

The Target Segment uses the same Elastic load cases as the Assembly and also includes the Elastic Plastic load cases. One addition to the loads used from the Assembly model is the Segment bolt has a preload force applied. The preload value is taken from the RCSC [8] Table 5.2, 24kips for a 5/8" diameter bolt, which is the equivalent of an M16 bolt. The pretension load is used to tighten up the bolted joint in step 1, then in step 2 set the pretension to 'lock' and apply the appropriate loads for each load case. The Elastic Plastic load combinations have a higher factor such as 2.4D or 2.7L, in the case of the inertia loads the density is factored instead. For example, in EP1, the density is increased by 2.4 and there is 1g gravity for the dead load and 45 rpms rotational velocity applied. The same technique is used for temperature loads, the CTE is factored instead of the temperature increasing.

4.6.2.1 Elastic Case 3, E Stop

Table 17 Segment, Elastic Case 3

Load Case	Time	P	D	L	L	T	Preload
Elastic 3	1		1g			Imported	24000 lbf
	2	125 psi	1g	4.7 rad/s ²	45 rpm	Imported	Locked

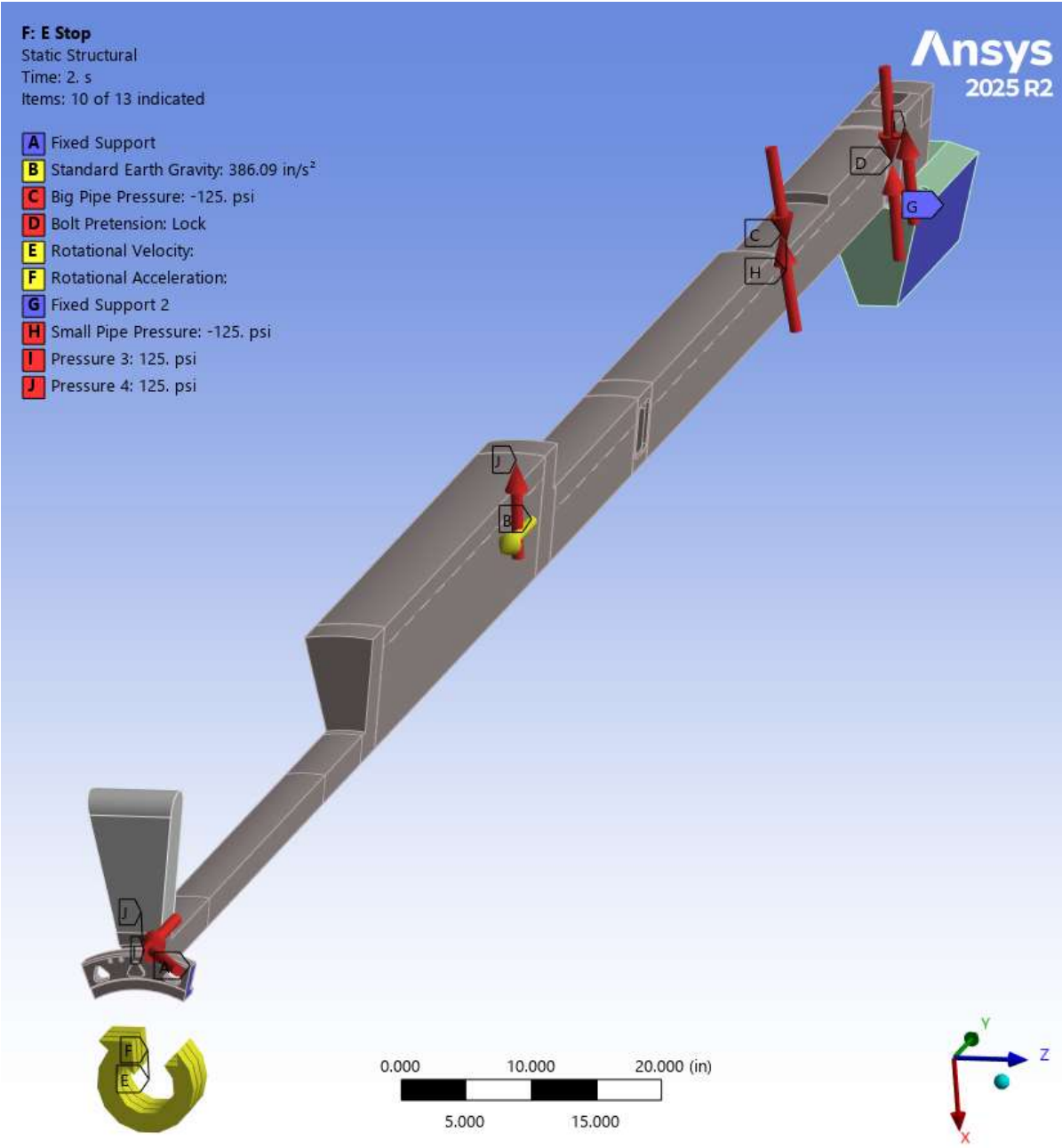


Figure 324 Segment, E Stop Load Summary

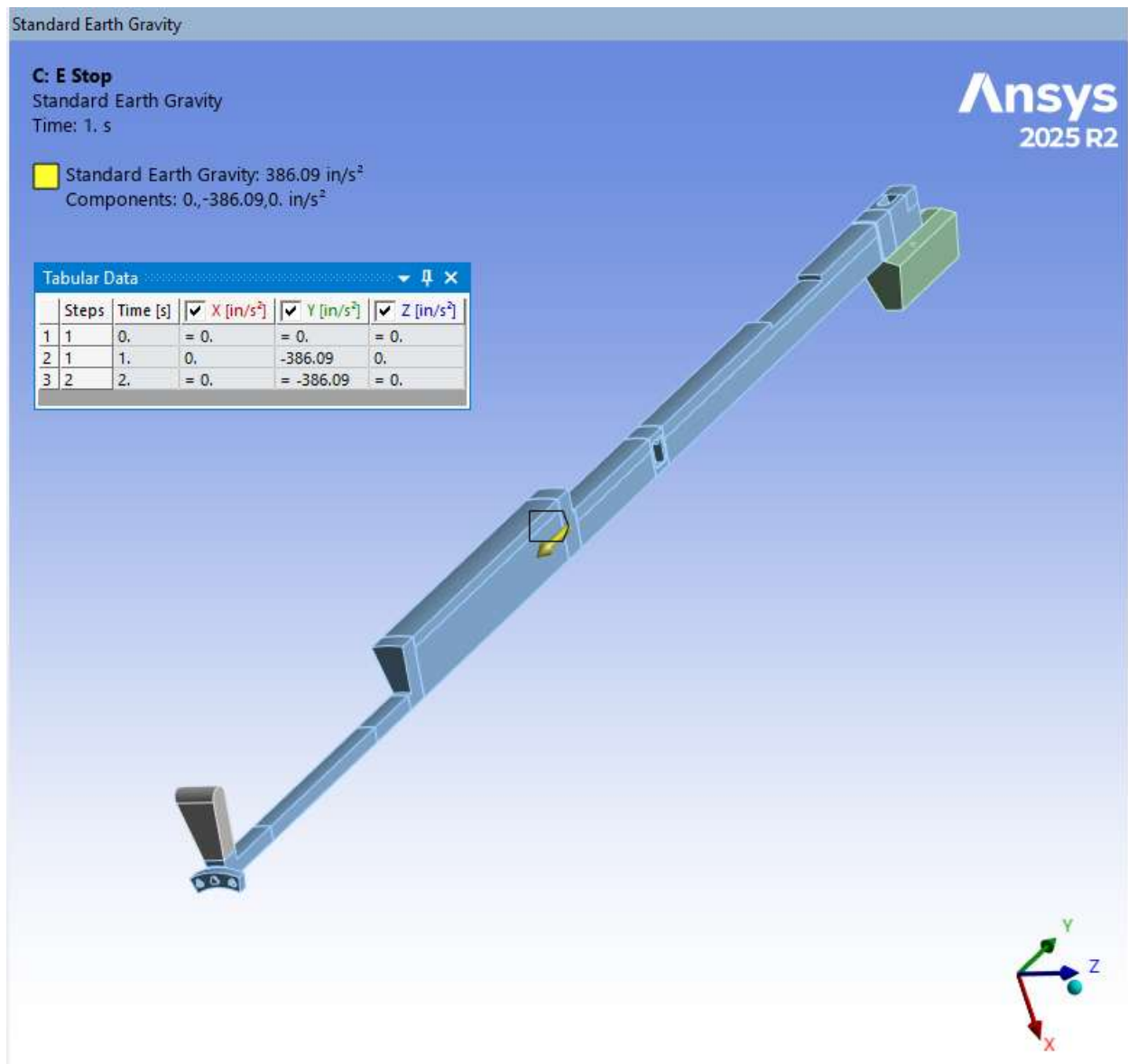


Figure 325 Segment, E Stop Gravity

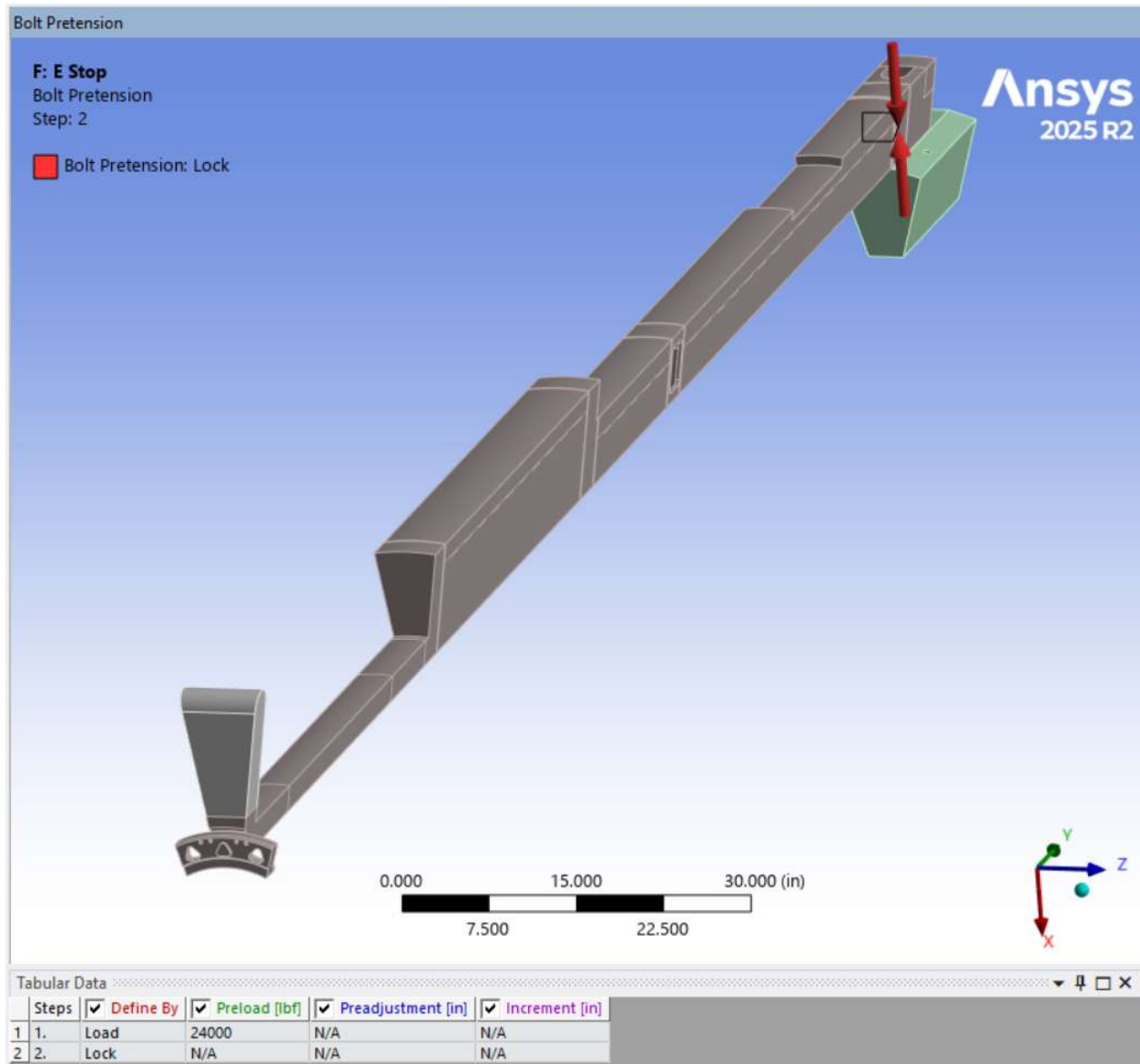


Figure 326 Segment, E Stop Bolt Pretension

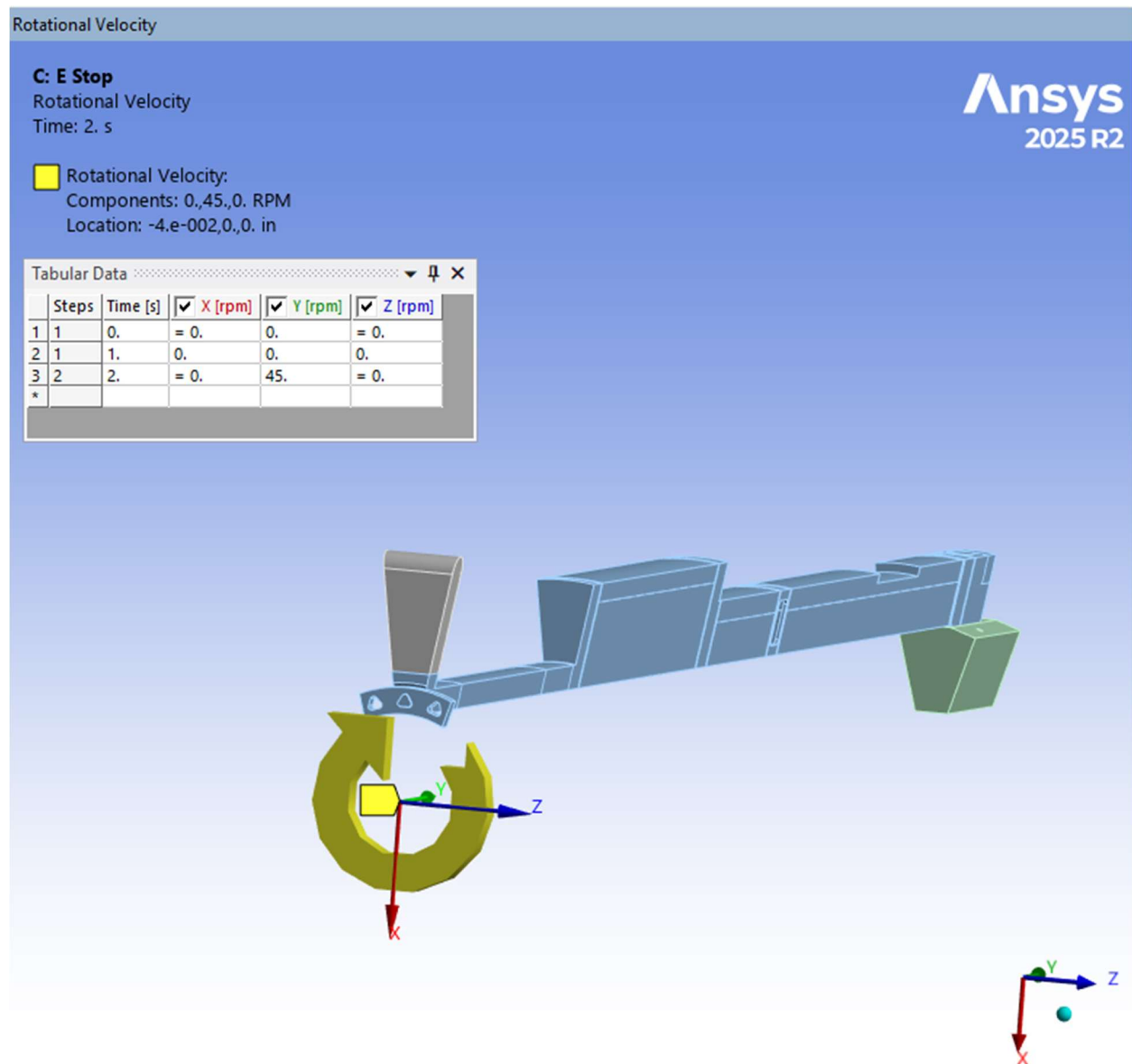


Figure 327 Segment, E Stop Rotational Velocity

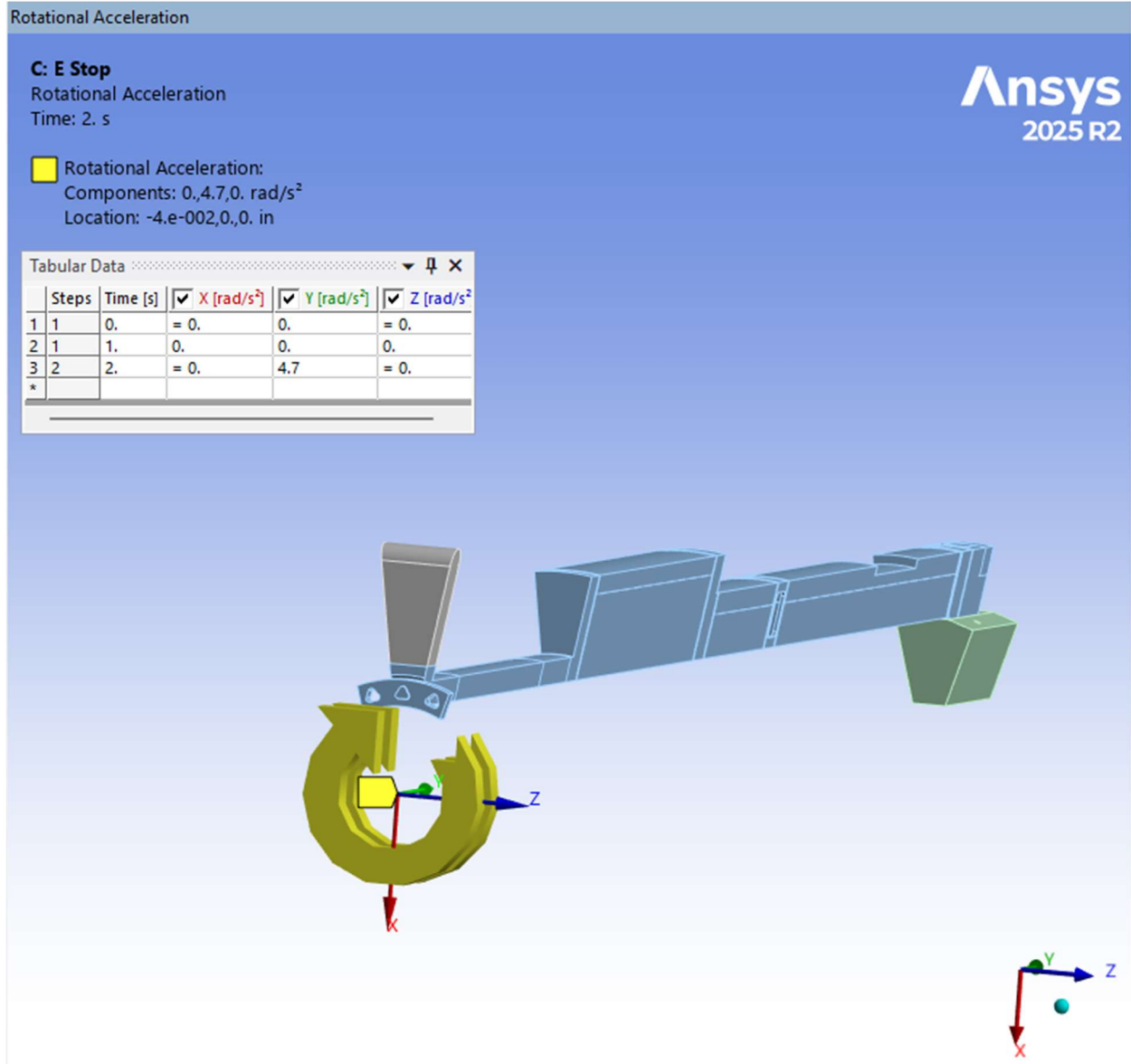


Figure 328 Segment, E Stop Rotational Acceleration

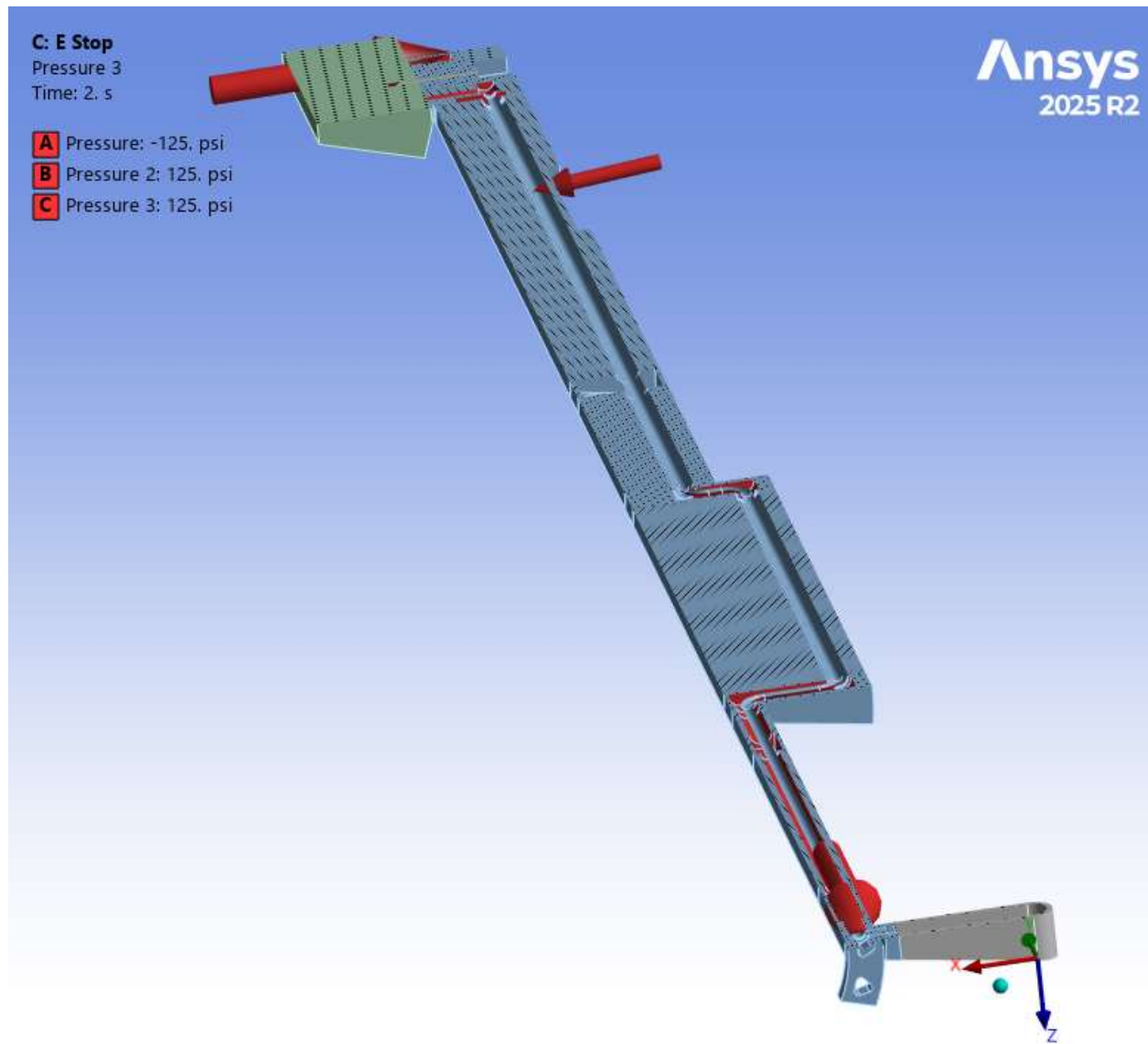


Figure 329 Segment, E Stop Water Pressure

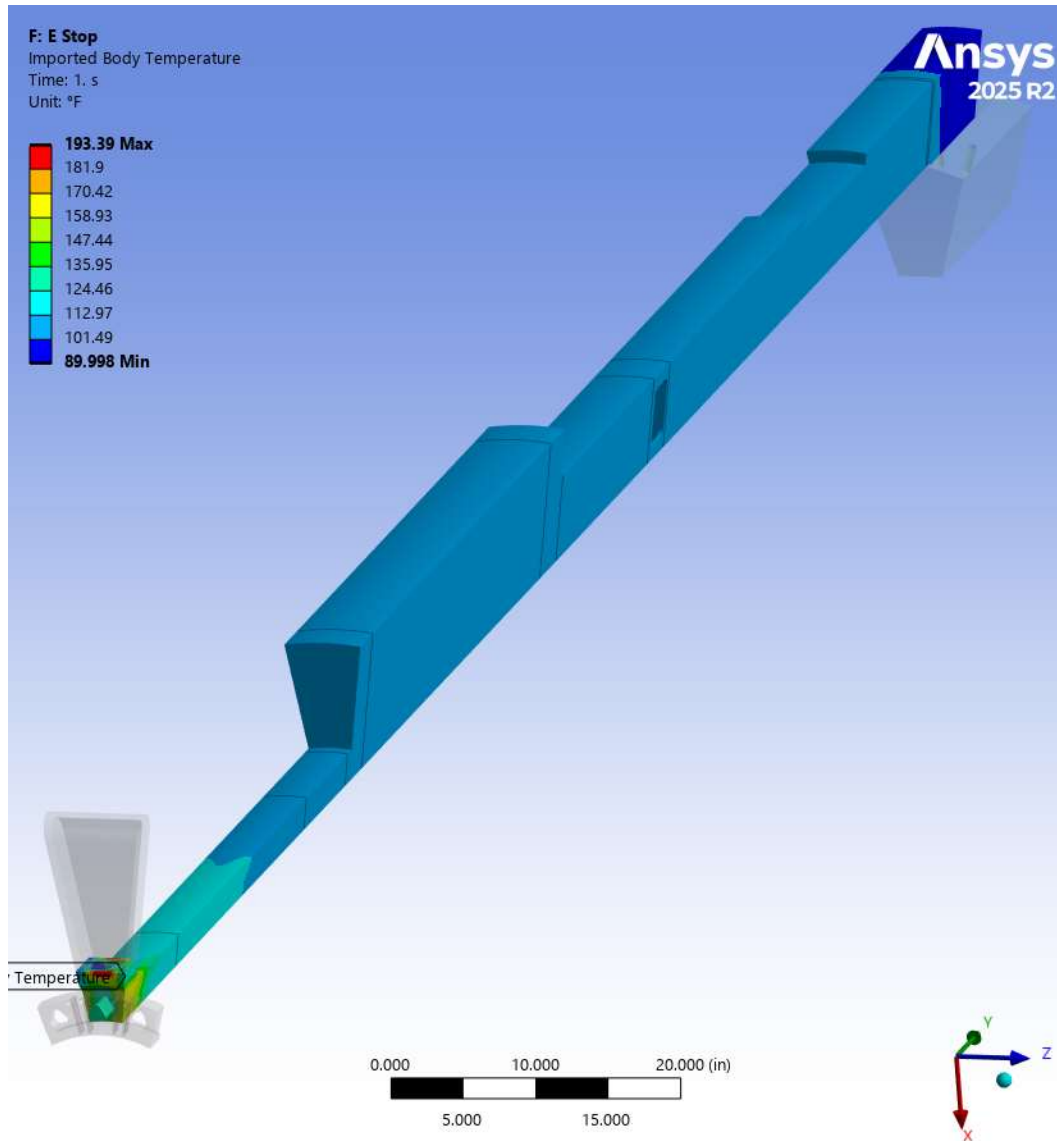


Figure 330 Segment, E Stop Thermal Conditions

4.6.2.2 Elastic Case 6, Seismic

Table 18 Segment, Elastic Case 6

Load Case	Time	P	D	T	E	E Direction	Preload
Elastic 6	1		1g	Imported			24000 lbf
	2	125 psi	1g	Imported	169 in/s ²	+Z	Locked
	3	125 psi	1g	Imported	169 in/s ²	+X	Locked

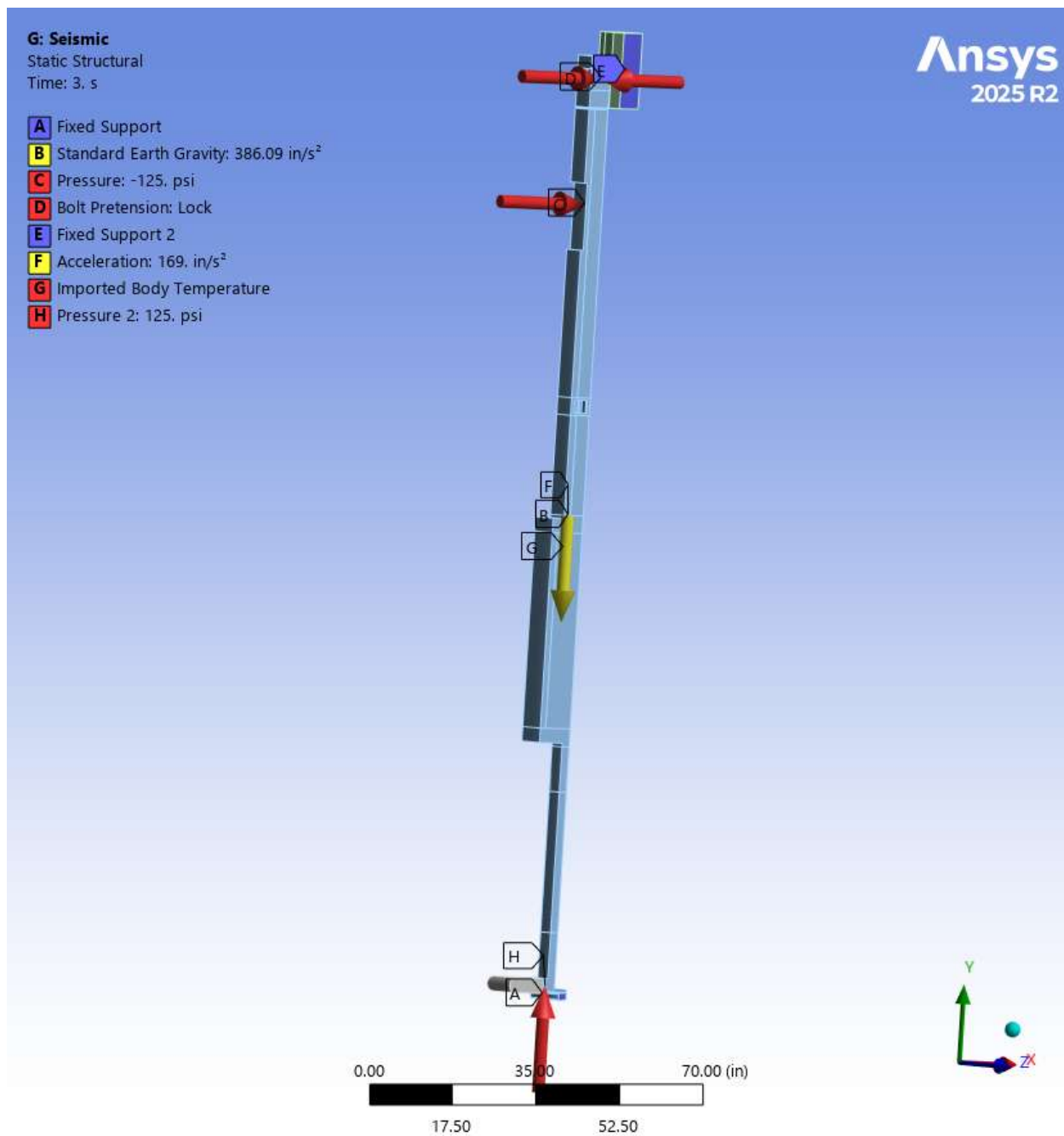


Figure 331 Segment, Seismic Load Summary

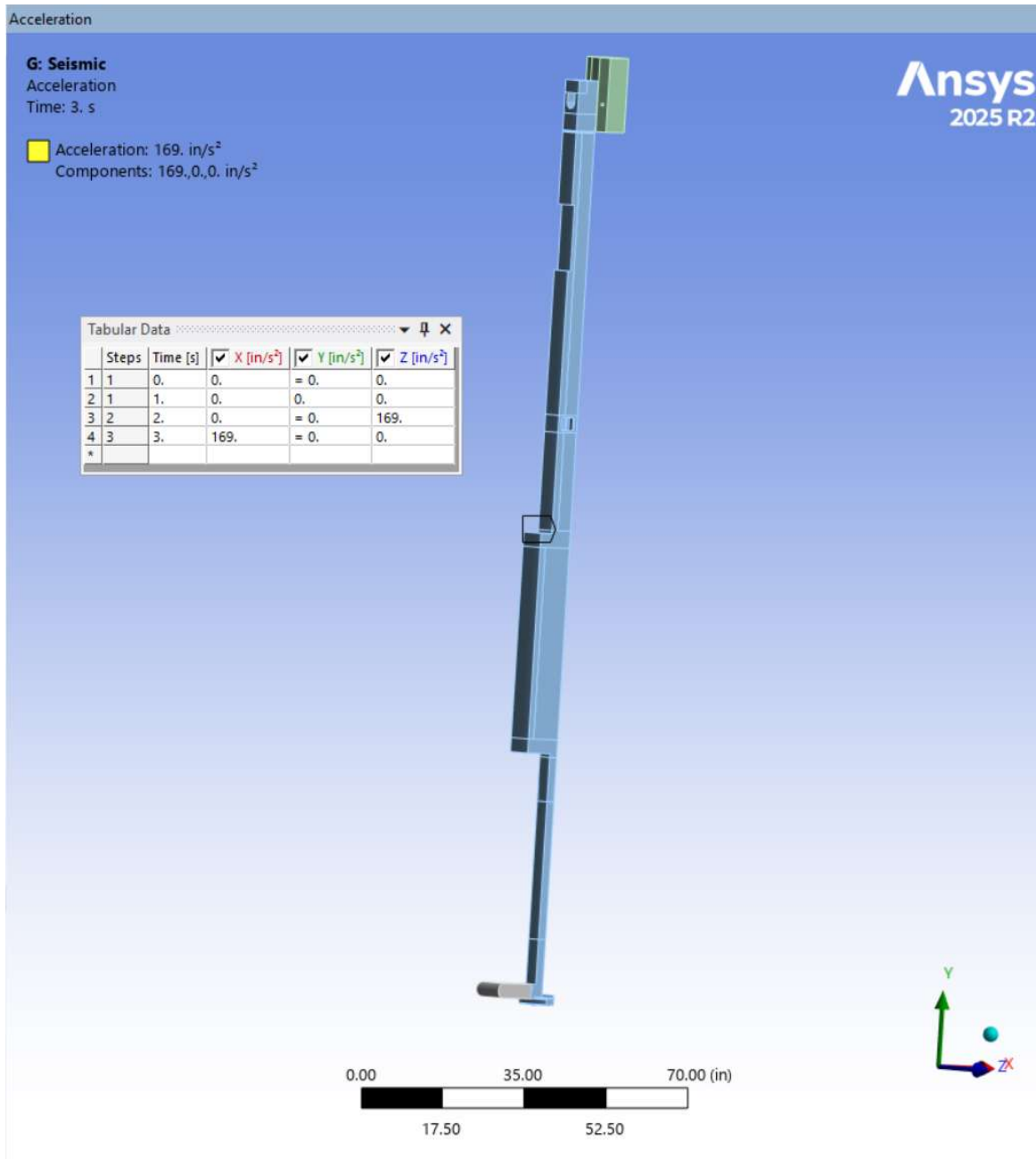


Figure 332 Segment, Seismic Acceleration

The Seismic load case needs 3 steps to account for a seismic load applied in the two principal shear directions X and Z. This setup is also used in the next load case, Seismic + Stop.

4.6.2.3 Elastic Case 8, Seismic + Stop

Table 19 Segment, Elastic Case 8

Load Case	Time	P	D	L	L	T	E	Preload
Elastic 8	1		1g			Imported		24000 lbf
	2	125 psi	1g	3.5 rad/s ²	34 rpm	Imported	+Z 127 in/s ²	Locked
	3	125 psi	1g	3.5 rad/s ²	34 rpm	Imported	+X 127 in/s ²	Locked

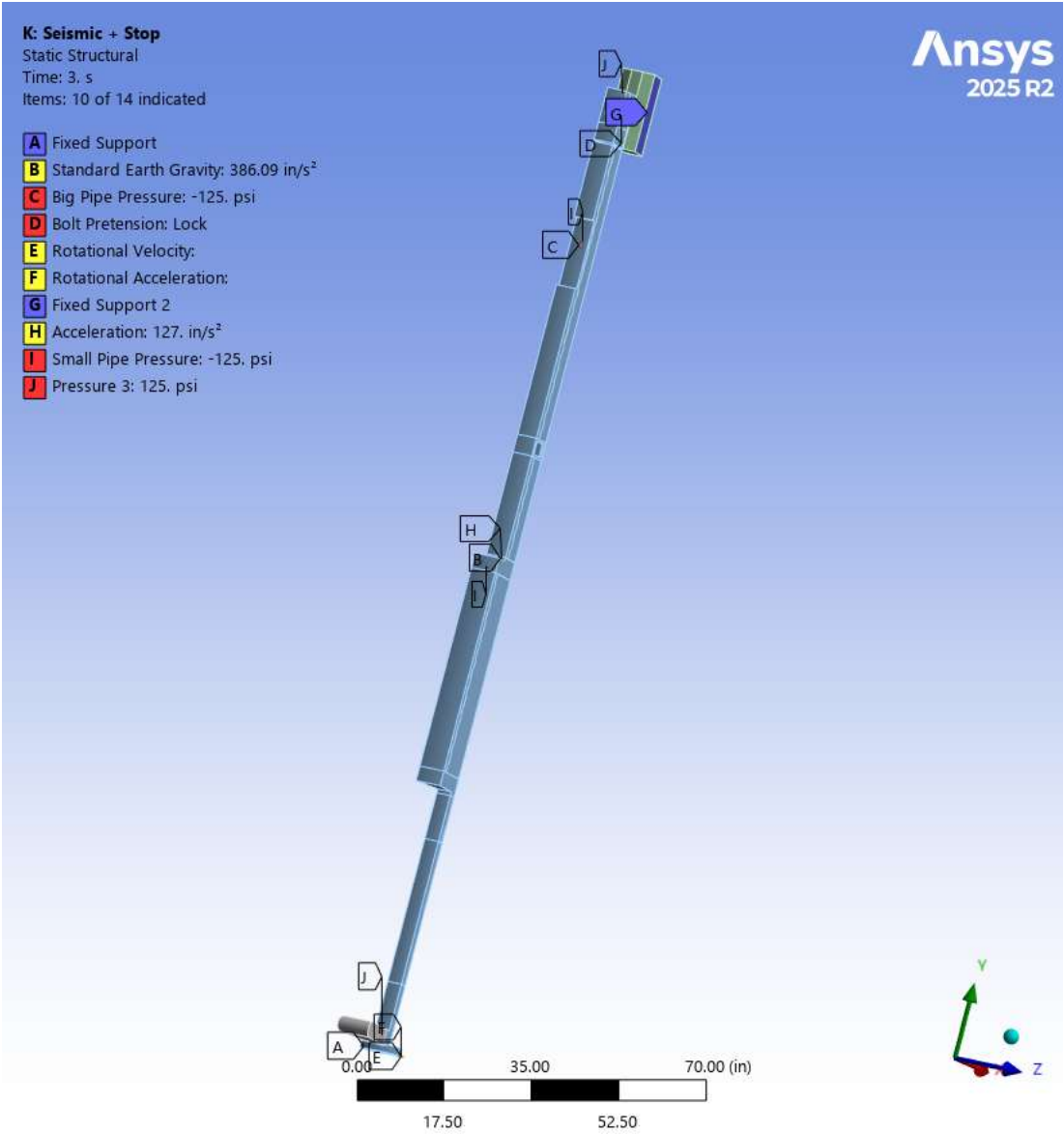


Figure 333 Segment, Seismic + Stop Load Summary

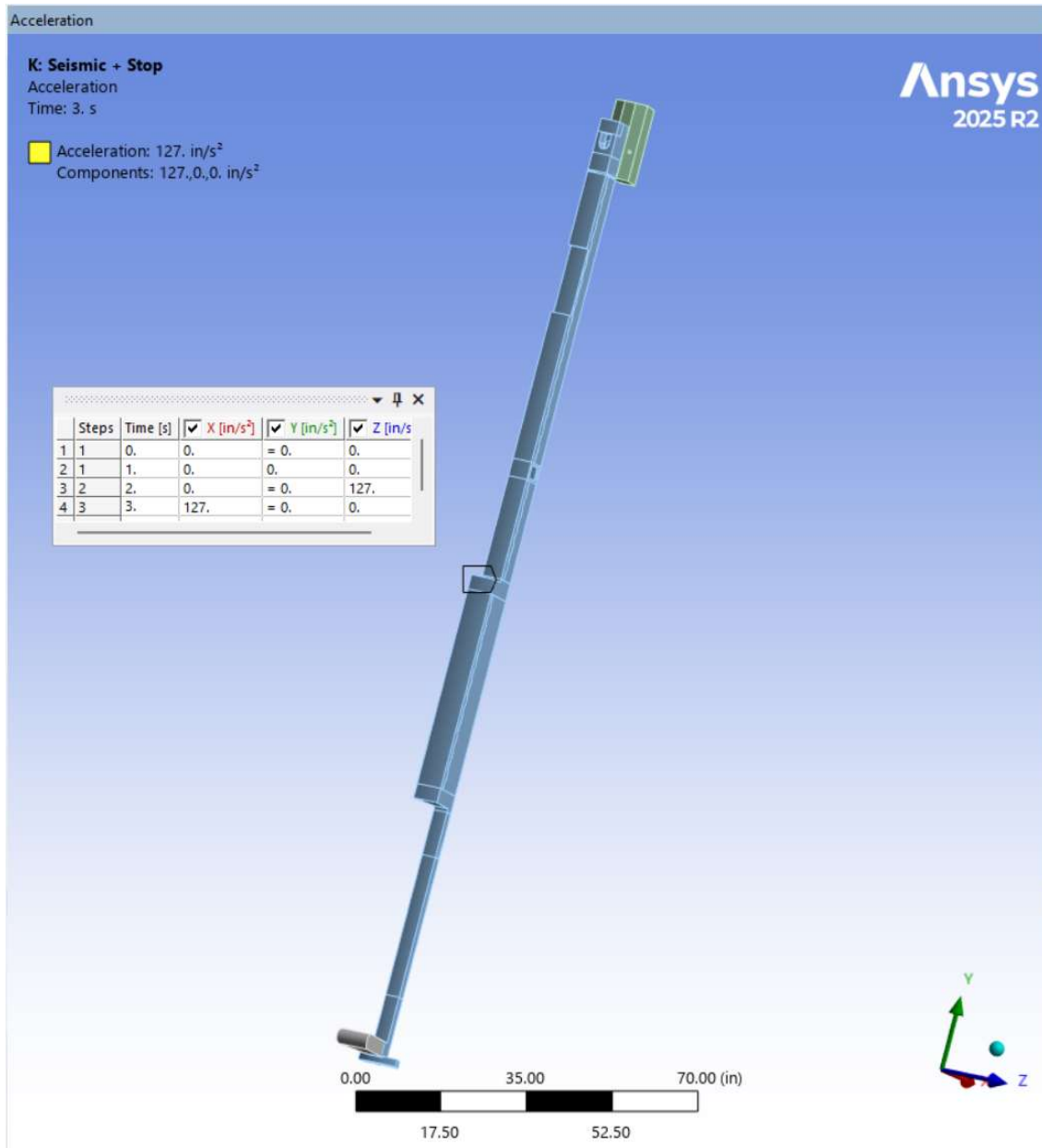


Figure 334 Segment, Seismic + Stop Acceleration

F: Seismic + Stop

Rotational Velocity

Time: 3. s

Ansys
2025 R2

 Rotational Velocity:
Components: 0.,34.,0. RPM
Location: -4.e-002,0.,0. in

Tabular Data

	Steps	Time [s]	☒ X [rpm]	☒ Y [rpm]	☒ Z [rpm]
1	1	0.	= 0.	0.	= 0.
2	1	1.	0.	0.	0.
3	2	2.	= 0.	34.	= 0.
4	3	3.	= 0.	= 34.	= 0.
*					

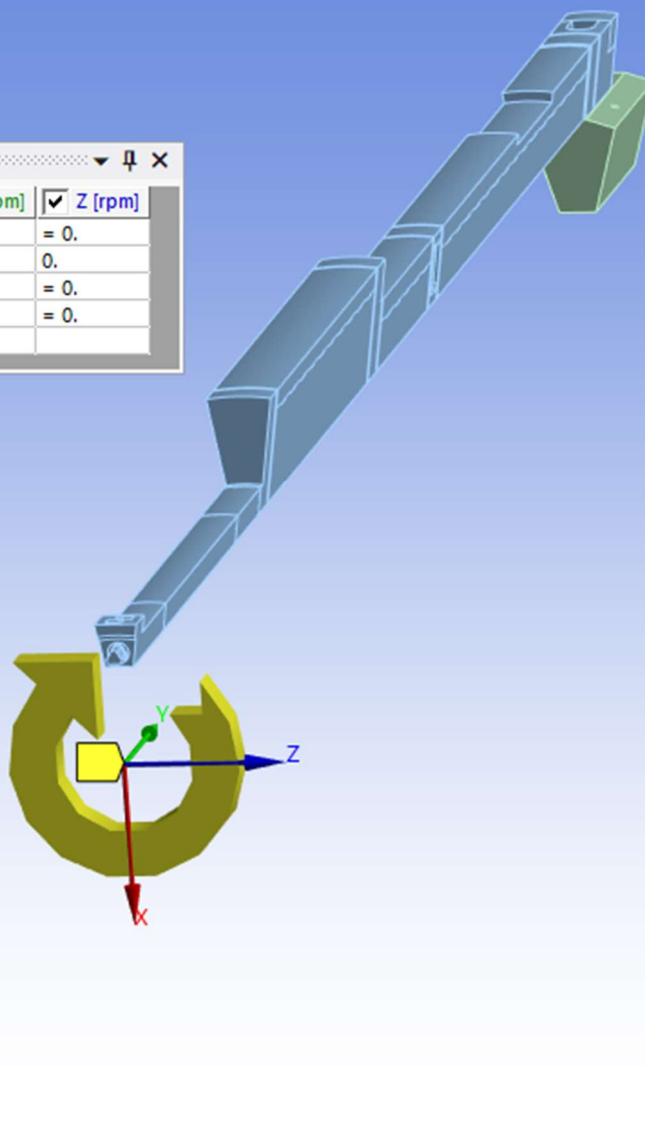


Figure 335 Segment, Seismic + Stop Rotational Velocity

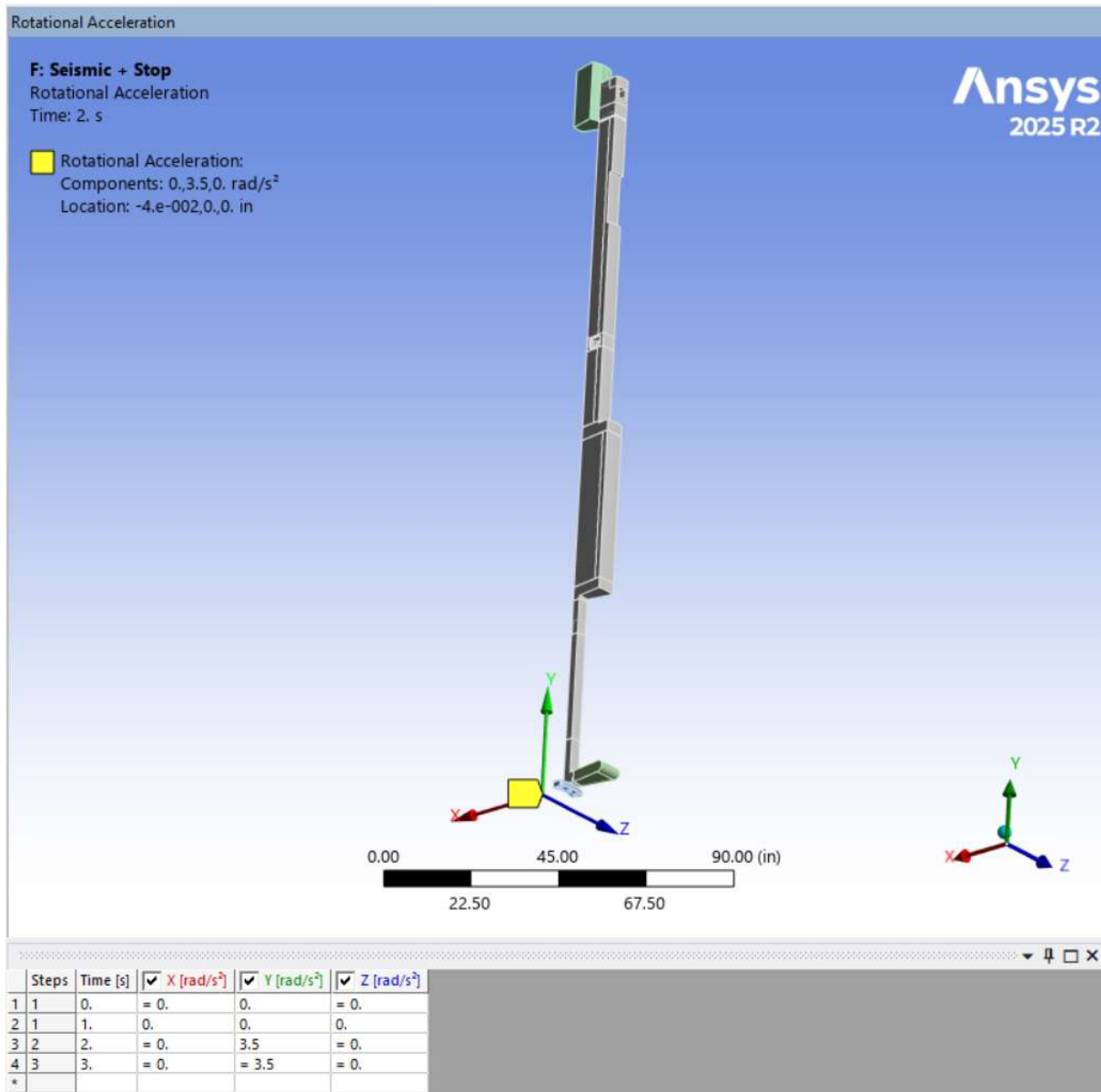


Figure 336 Segment, Seismic + Stop Rotational Acceleration

4.6.2.4 Elastic Plastic Case 1

Table 20 Segment, EP Case 1

Load Case	Time	P	D	L	L	T	Preload	Density Factor
EP 1	1		1g			Imported	24000 lbf	2.4X
	2	300 psi	1g	4.7 rad/s ²	45 rpm	Imported	Locked	2.4X

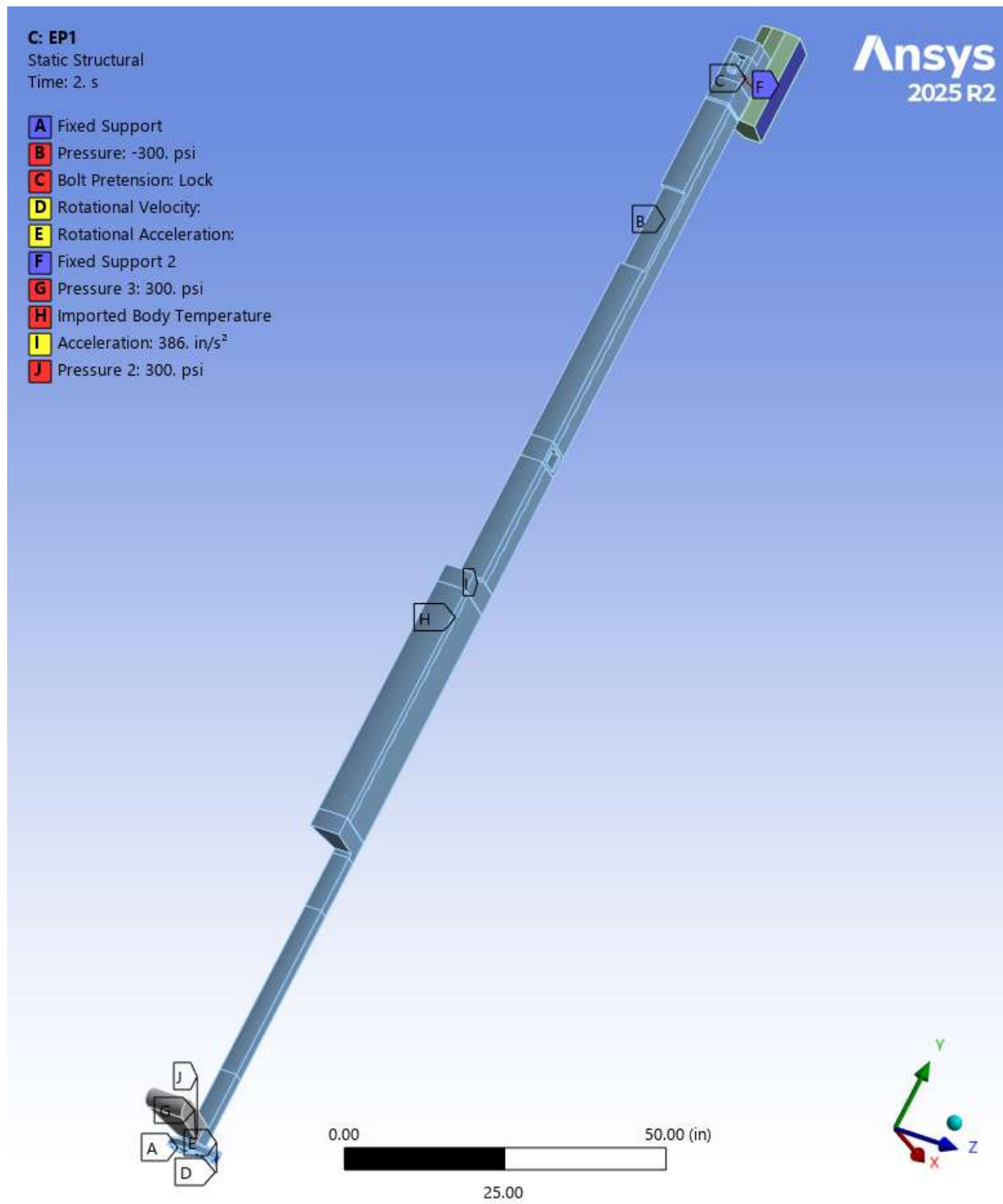


Figure 337 Segment, Elastic Plastic Load Case 1

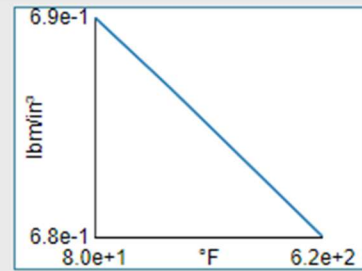


316 Plastic 2.4



Sample data representative of 316 Stainless Steel

Density



316 Foot 2.4



Density

2.4 lbm/in³

Figure 338 Segment, Elastic Plastic 1 Density Factor

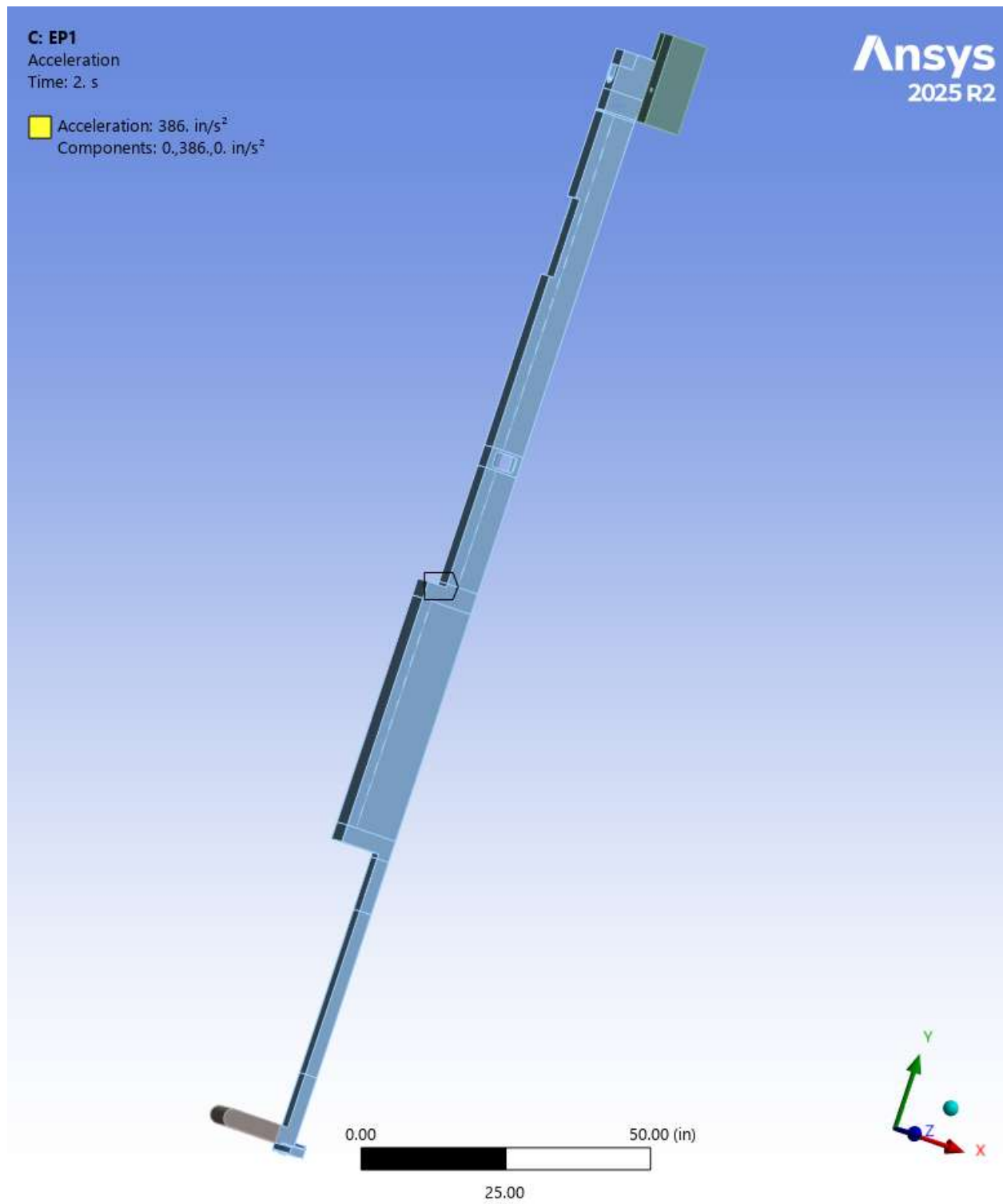


Figure 339 Segment, Elastic Plastic 1, Acceleration

C: EP1

Rotational Velocity

Time: 2. s

Ansys
2025 R2

Rotational Velocity:
Components: 0,45,0. RPM
Location: -4.e-002,0,0. in

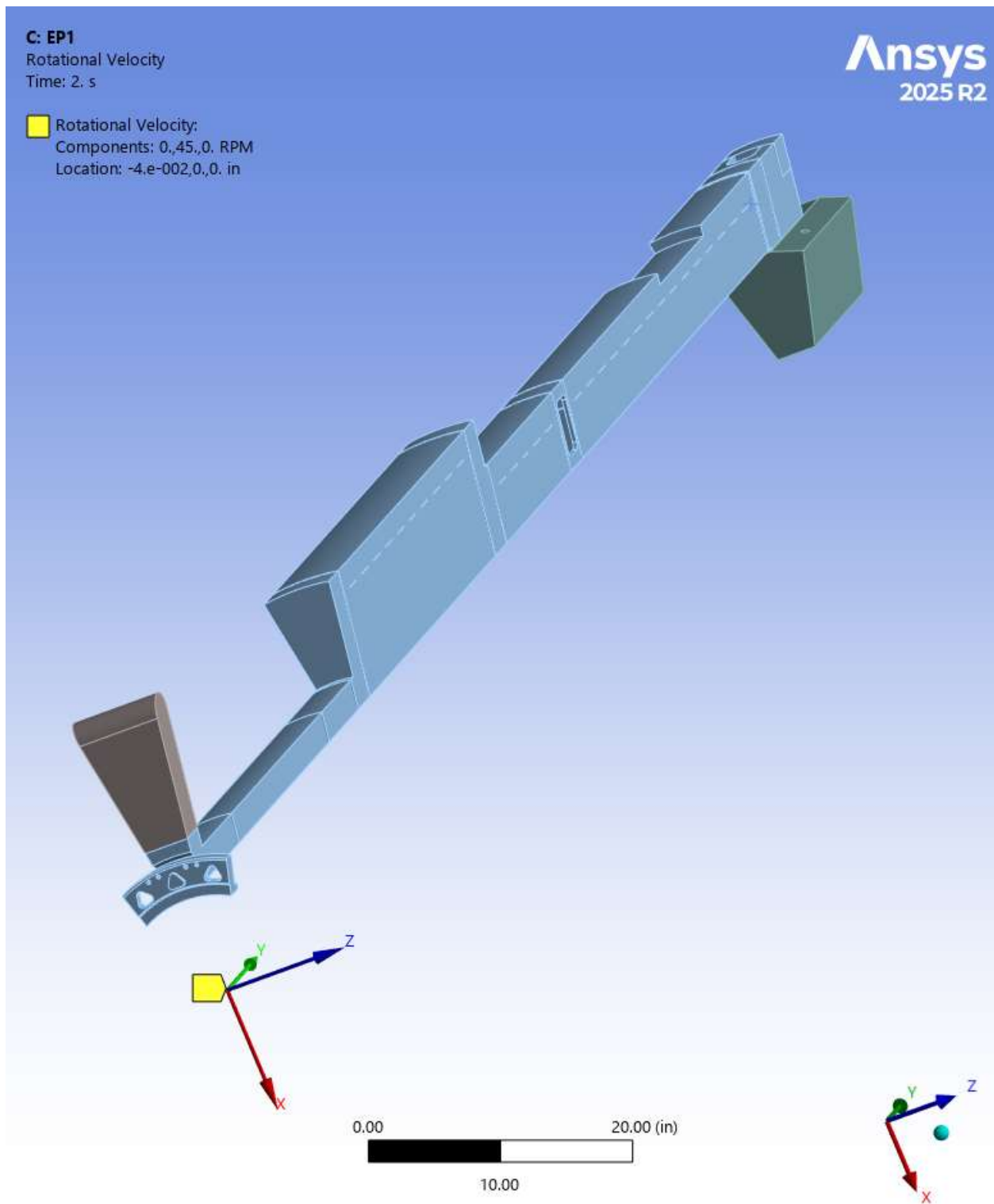


Figure 340 Segment, Elastic Plastic 1, Rotational Velocity

C: EP1

Rotational Acceleration

Time: 2. s

Rotational Acceleration:
Components: 0,4.7,0. rad/s^2
Location: -4.e-002,0,0. in

Ansys
2025 R2

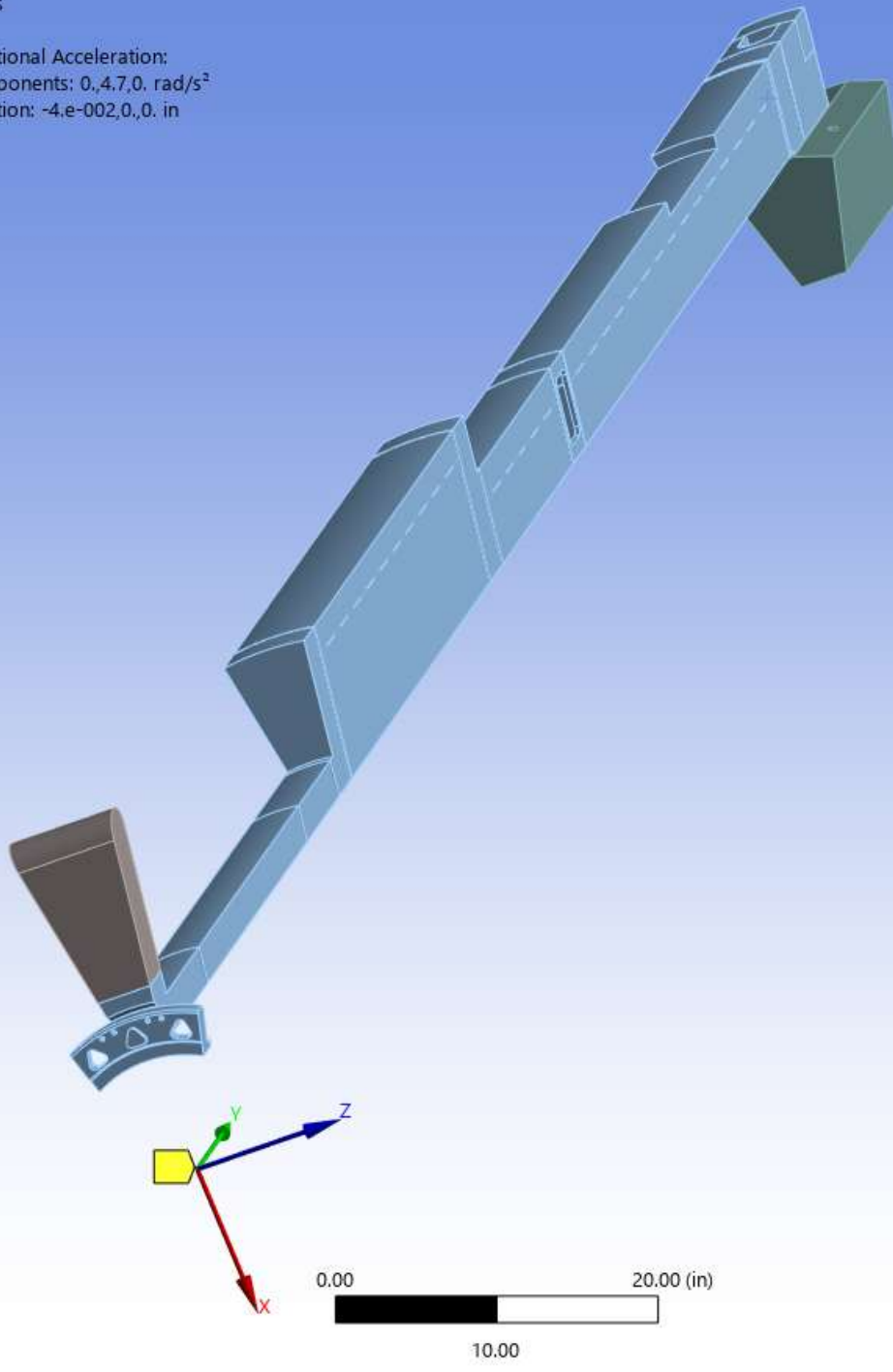


Figure 341 Segment, Elastic Plastic 1, Rotational Acceleration

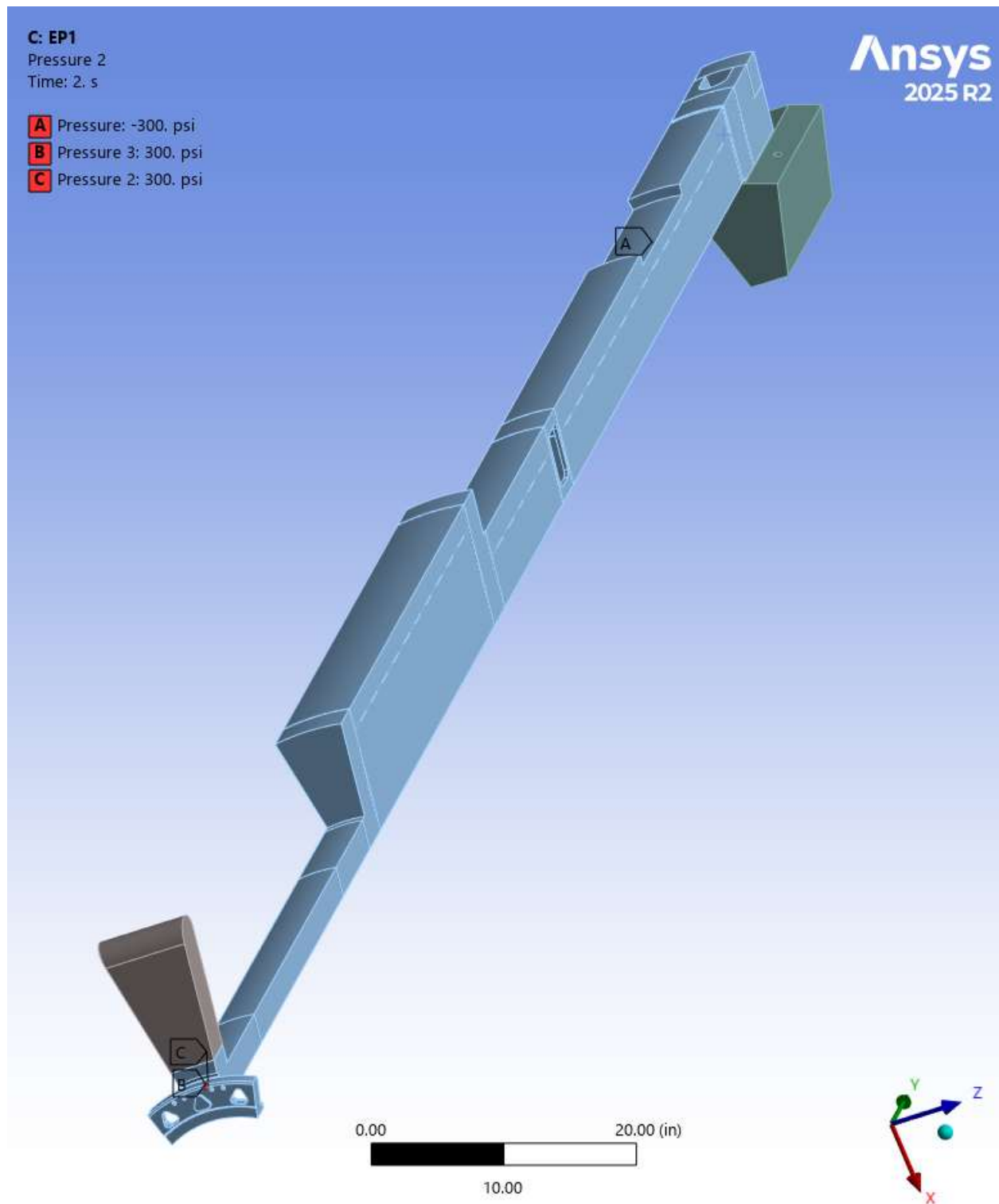


Figure 342 Segment, Elastic Plastic 1, Pressure

4.6.2.5 Elastic Plastic Case 2

Table 21 Segment, EP Case 2

Load Case	Time	P	D	L	L	T	E	Preload	Density Factor
EP 2	1		.8g			Imported		24000 lbf	2.7X
	2	264 psi	.8g	4.7 rad/s ²	45 rpm	Imported		Locked	2.7X

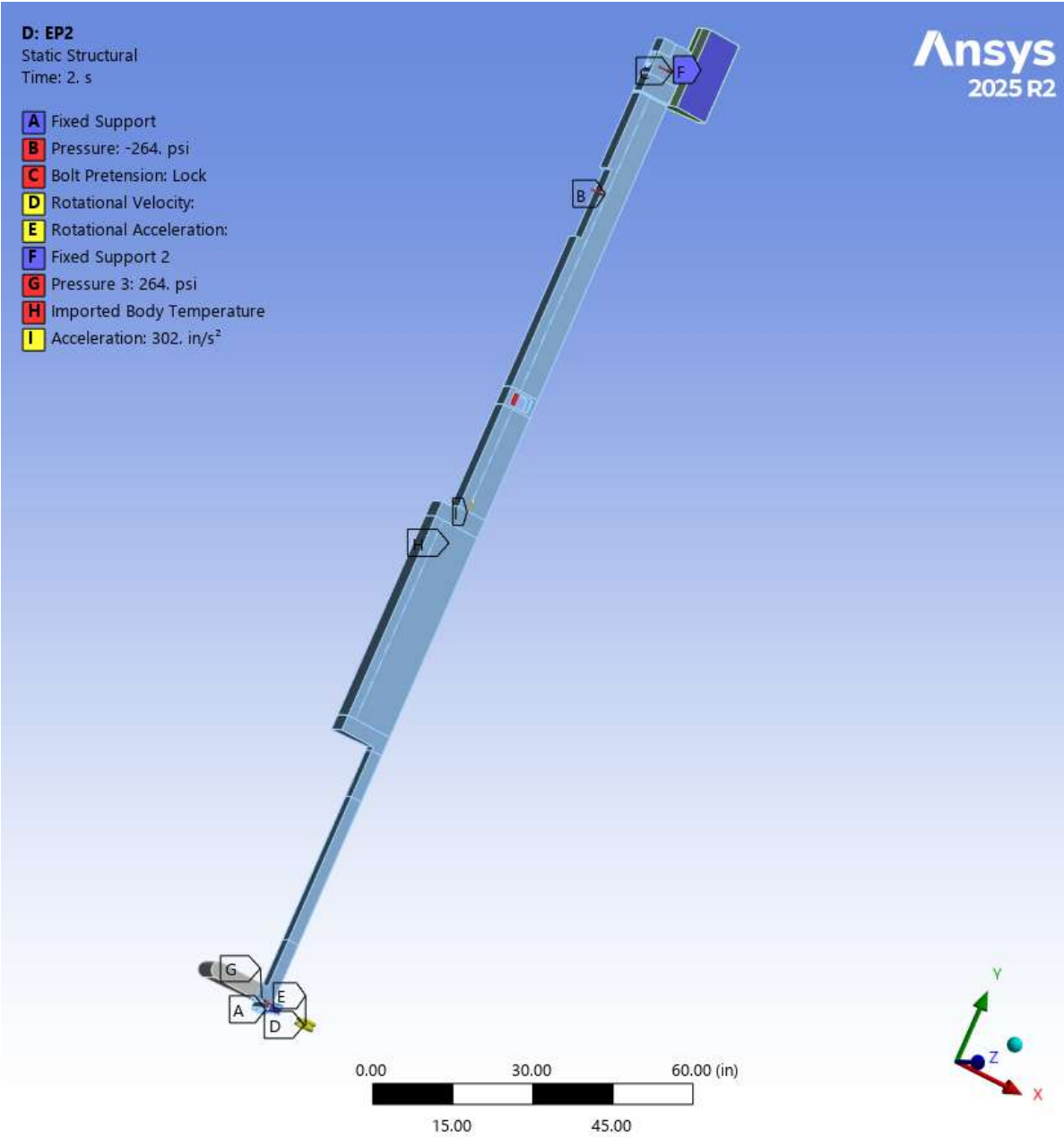


Figure 343 Segment, Elastic Plastic Load Case 2

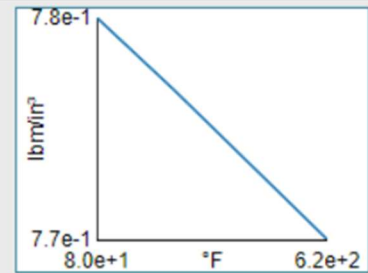


316 Plastic 2.7



Sample data representative of 316 Stainless Steel

Density

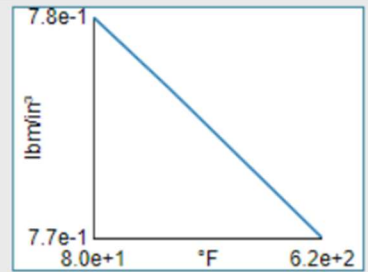


316 2.7



Sample data representative of 316 Stainless Steel

Density

*Figure 344 Segment, Elastic Plastic 2 Density Factor*

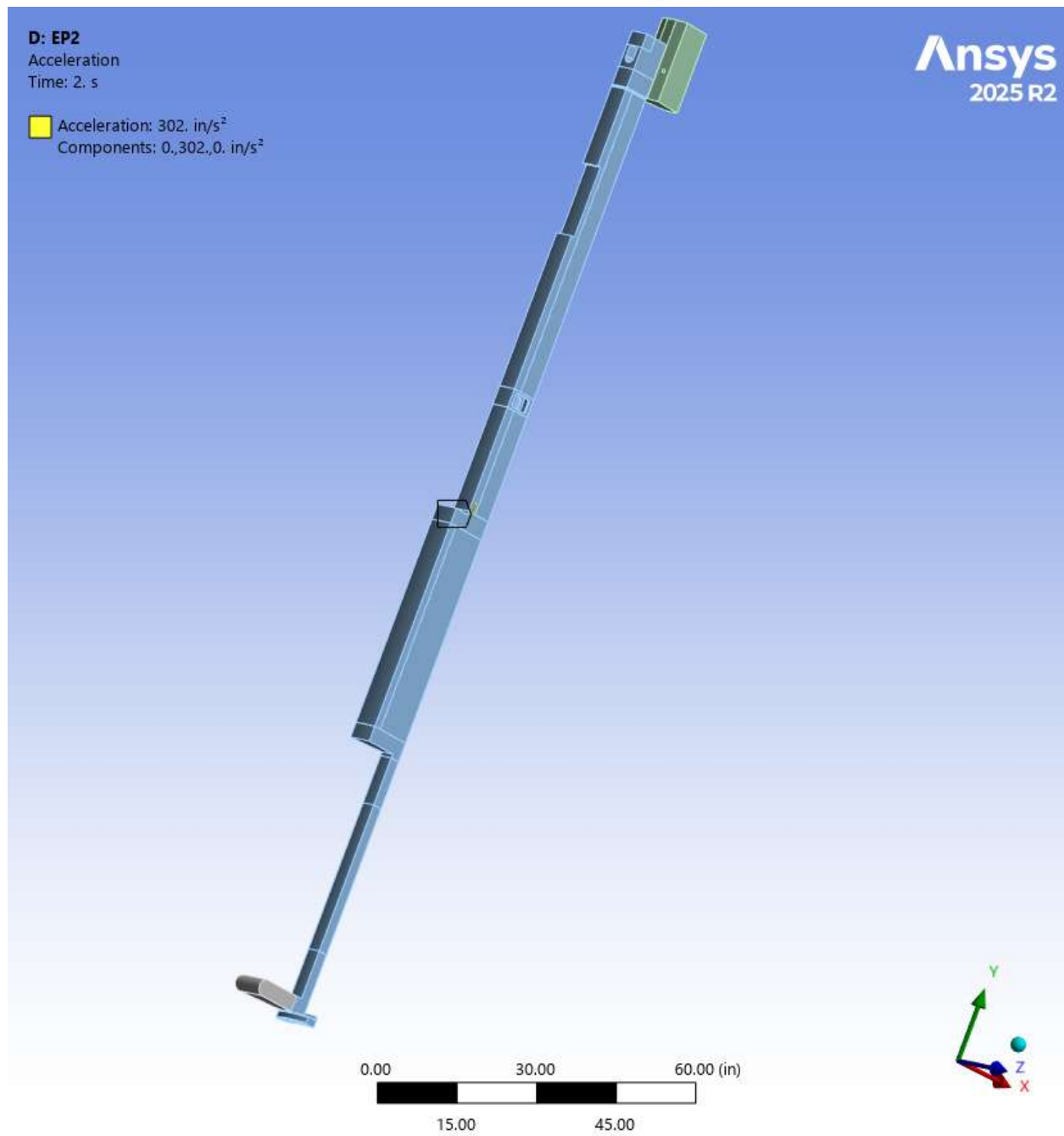


Figure 345 Segment, Elastic Plastic 2 Acceleration

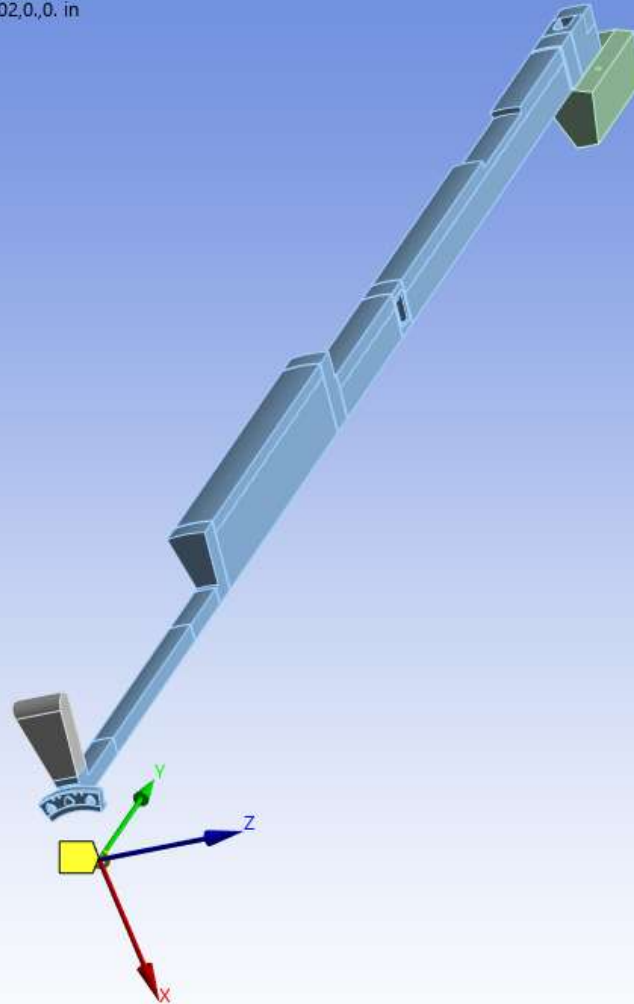
D: EP2

Rotational Velocity

Time: 2. s

Ansys
2025 R2

Rotational Velocity:
Components: 0,45,0. RPM
Location: -4.e-002,0,0. in



0.00 25.00 50.00 (in)
12.50 37.50

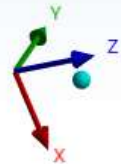


Figure 346 Segment, Elastic Plastic 2 Rotational Velocity

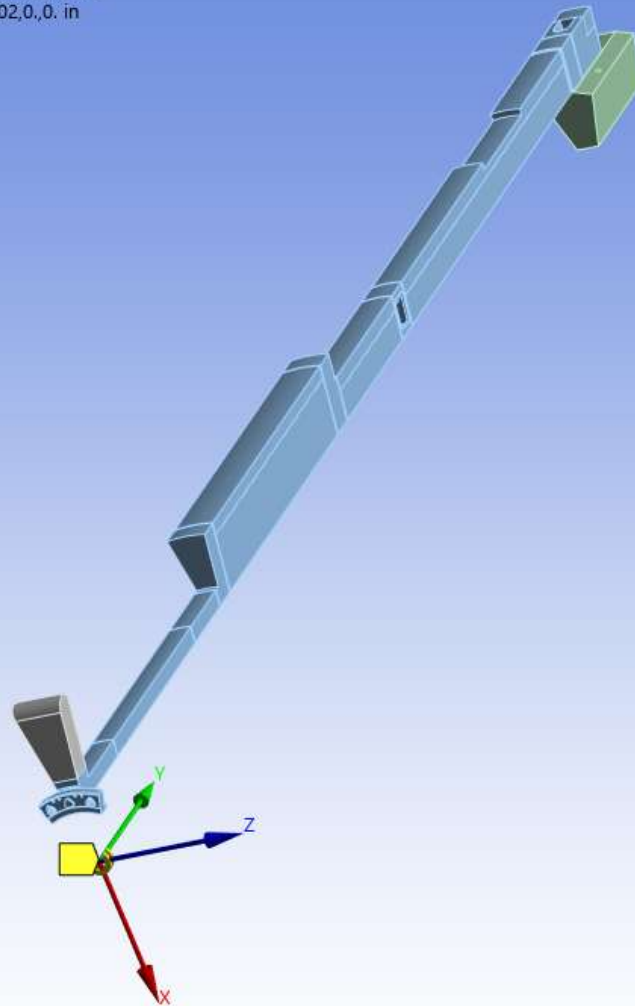
D: EP2

Rotational Acceleration

Time: 2. s

Ansys
2025 R2

Rotational Acceleration:
Components: 0, 4.7, 0. rad/s^2
Location: -4.e-002, 0, 0. in



0.00 25.00 50.00 (in)
12.50 37.50

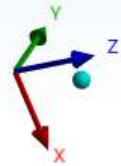


Figure 347 Segment, Elastic Plastic 2 Rotational Acceleration

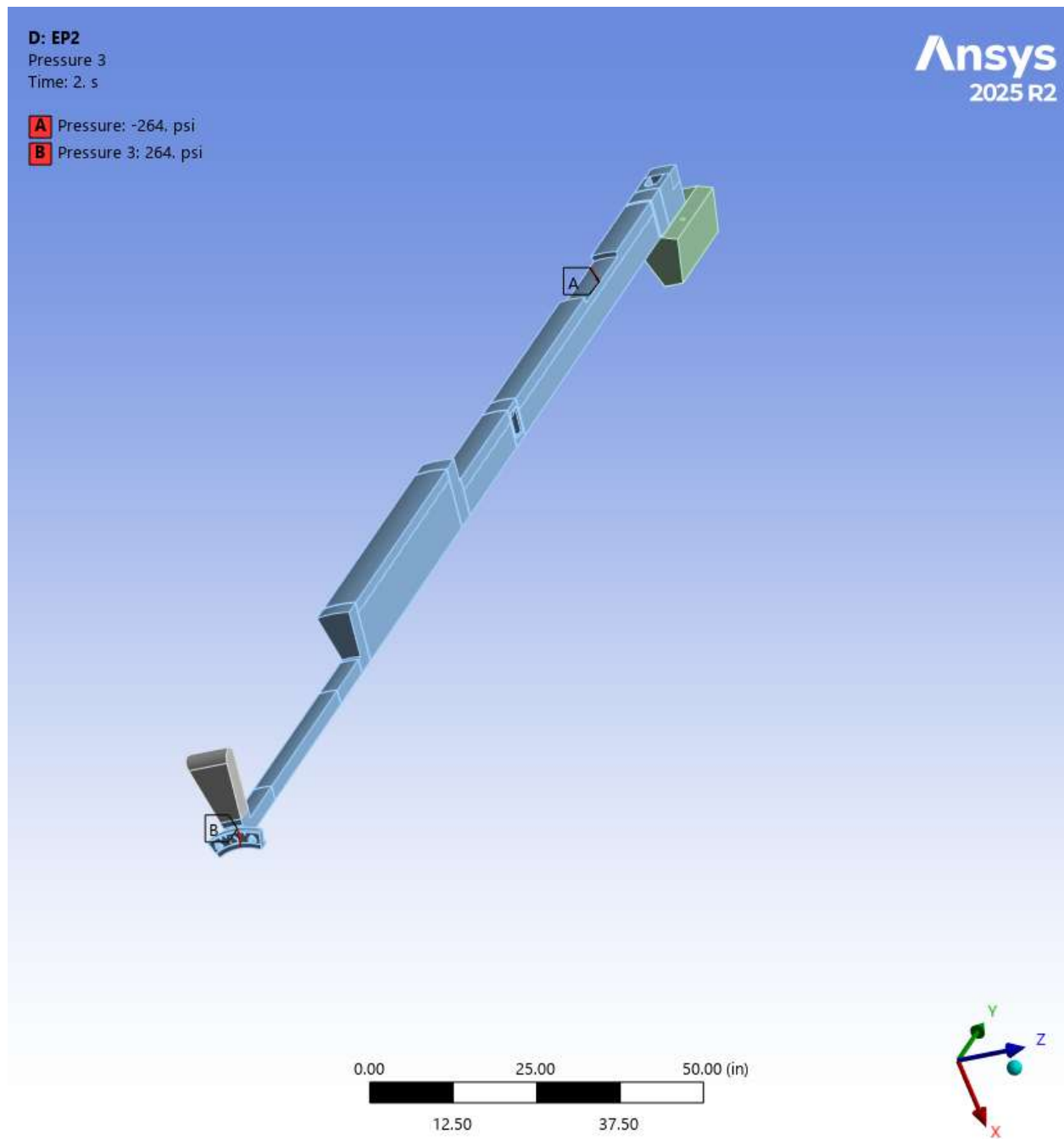


Figure 348 Segment, Elastic Plastic 2 Pressure

4.6.2.6 Elastic Plastic Case 5

Table 22 Segment, EP Case 5

Load Case	Time	P	D	L	L	T	E	Preload	Density Factor
EP5	1		480 in/s ²			Imported		24000 lbf	1.7X
	2	264 psi	480 in/s ²	4.7 rad/s ²	45 rpm	Imported	+X 411 in/s ²	Locked	1.7X

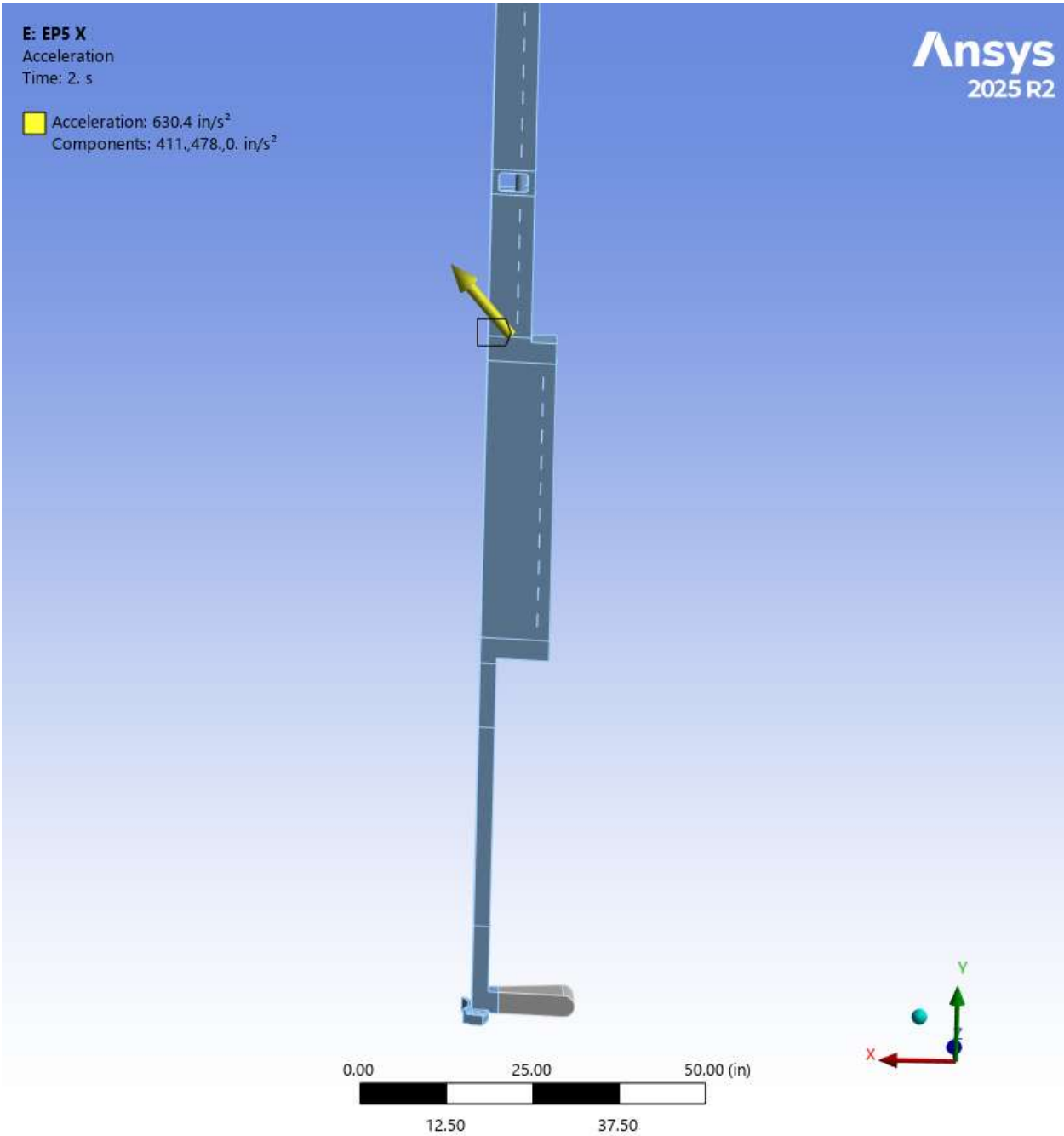


Figure 349 Segment, EP5 X Acceleration

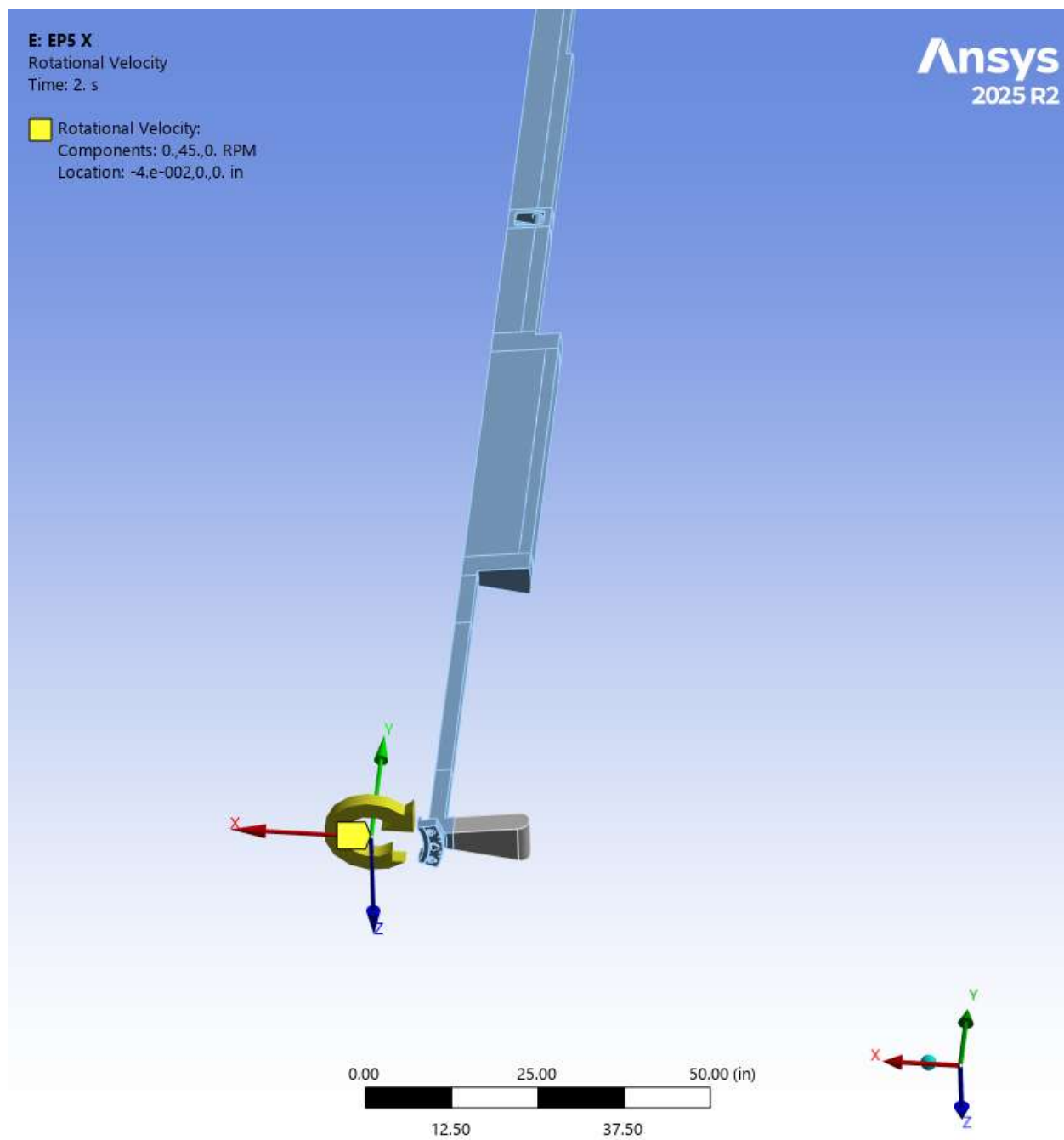


Figure 350 Segment, EP5 X Rotational Velocity

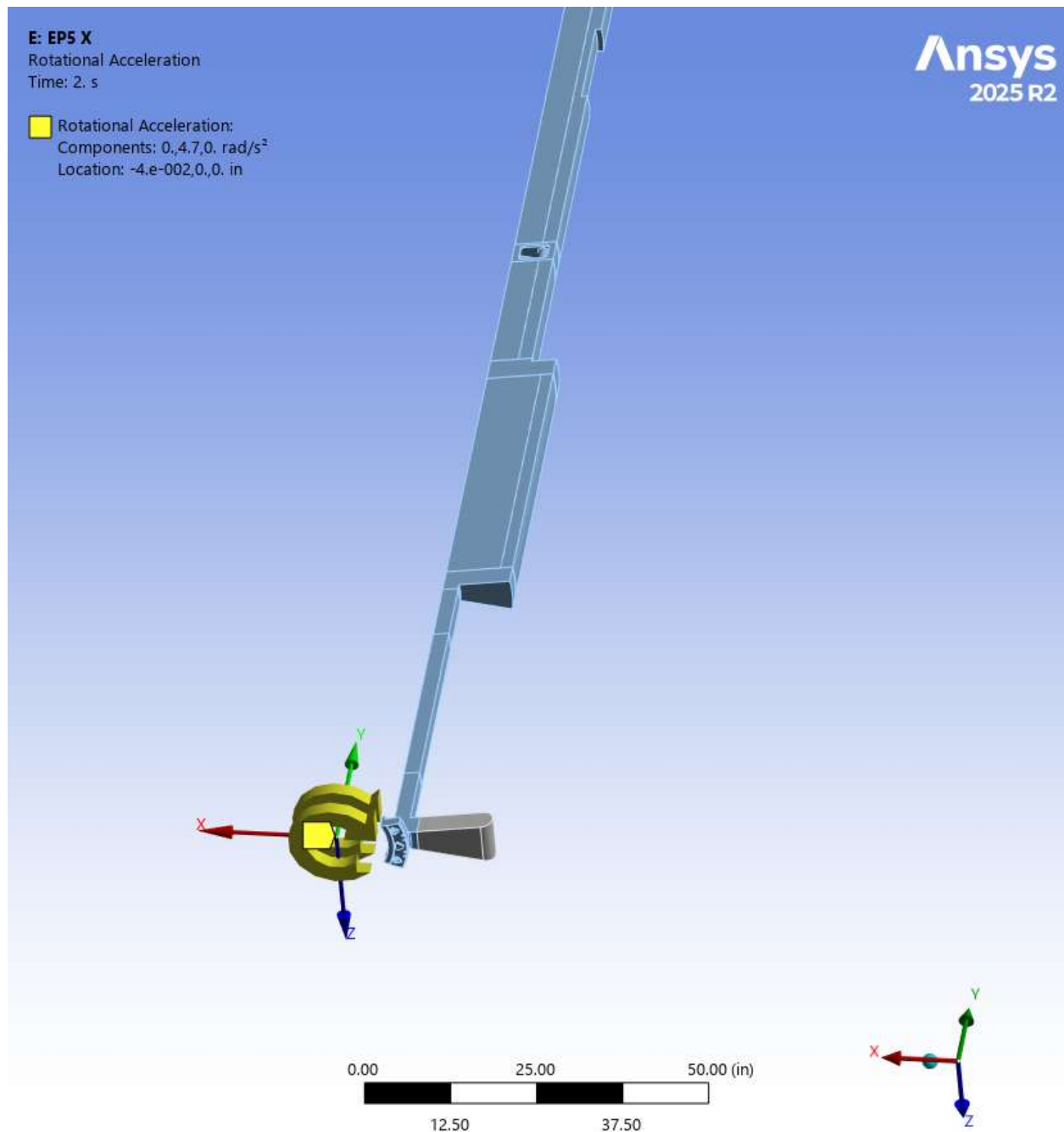


Figure 351 Segment, EP5 X Rotational Acceleration

Table 23 Segment, EP Case 5

Load Case	Time	P	D	L	L	T	E	Preload	Density Factor
EP5	1		480 in/s ²			Imported		24000 lbf	1.7X
	2	264 psi	480 in/s ²	4.7 rad/s ²	45 rpm	Imported	+Z 411 in/s ²	Locked	1.7X

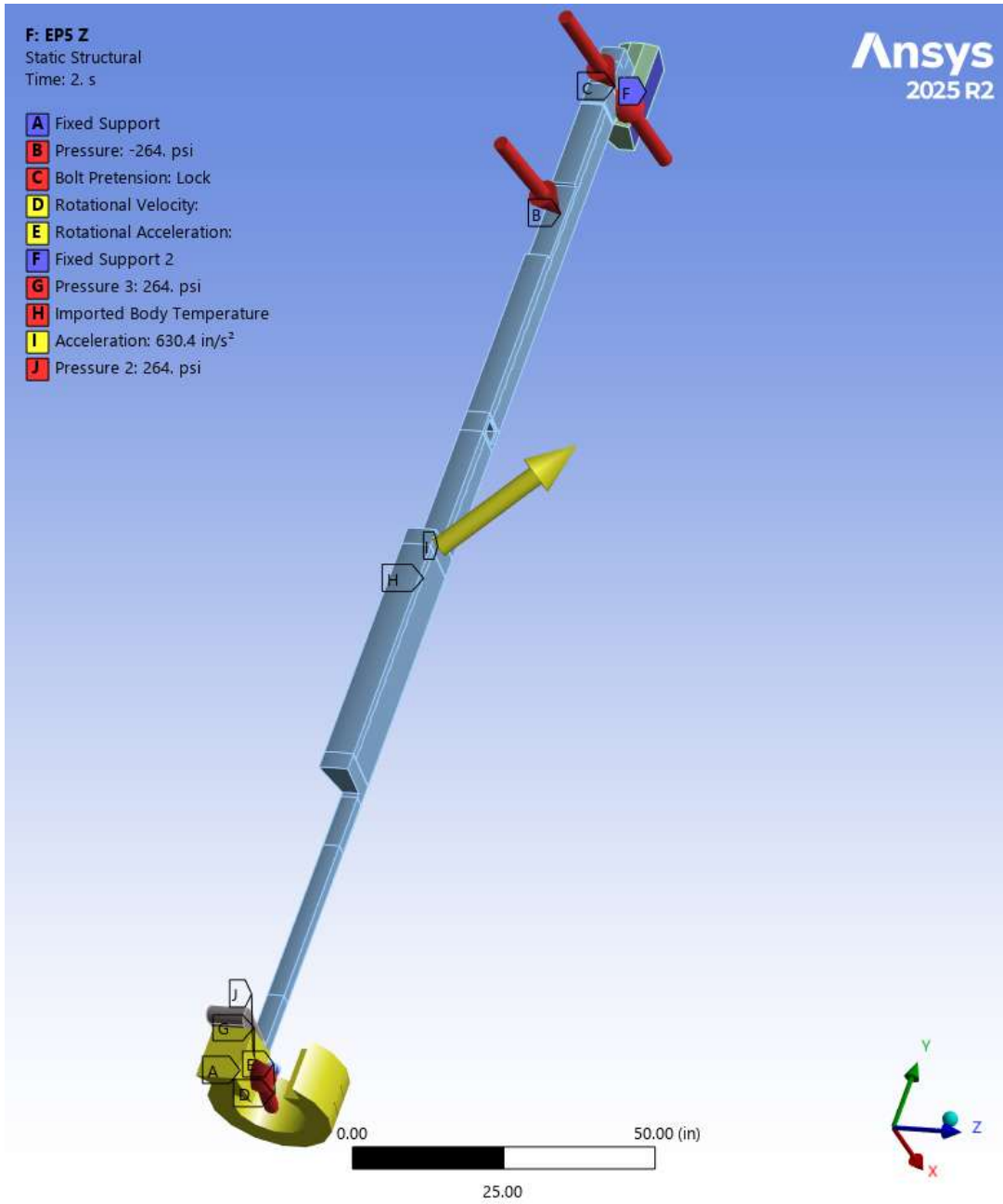


Figure 352 Segment, EP5 Z Acceleration

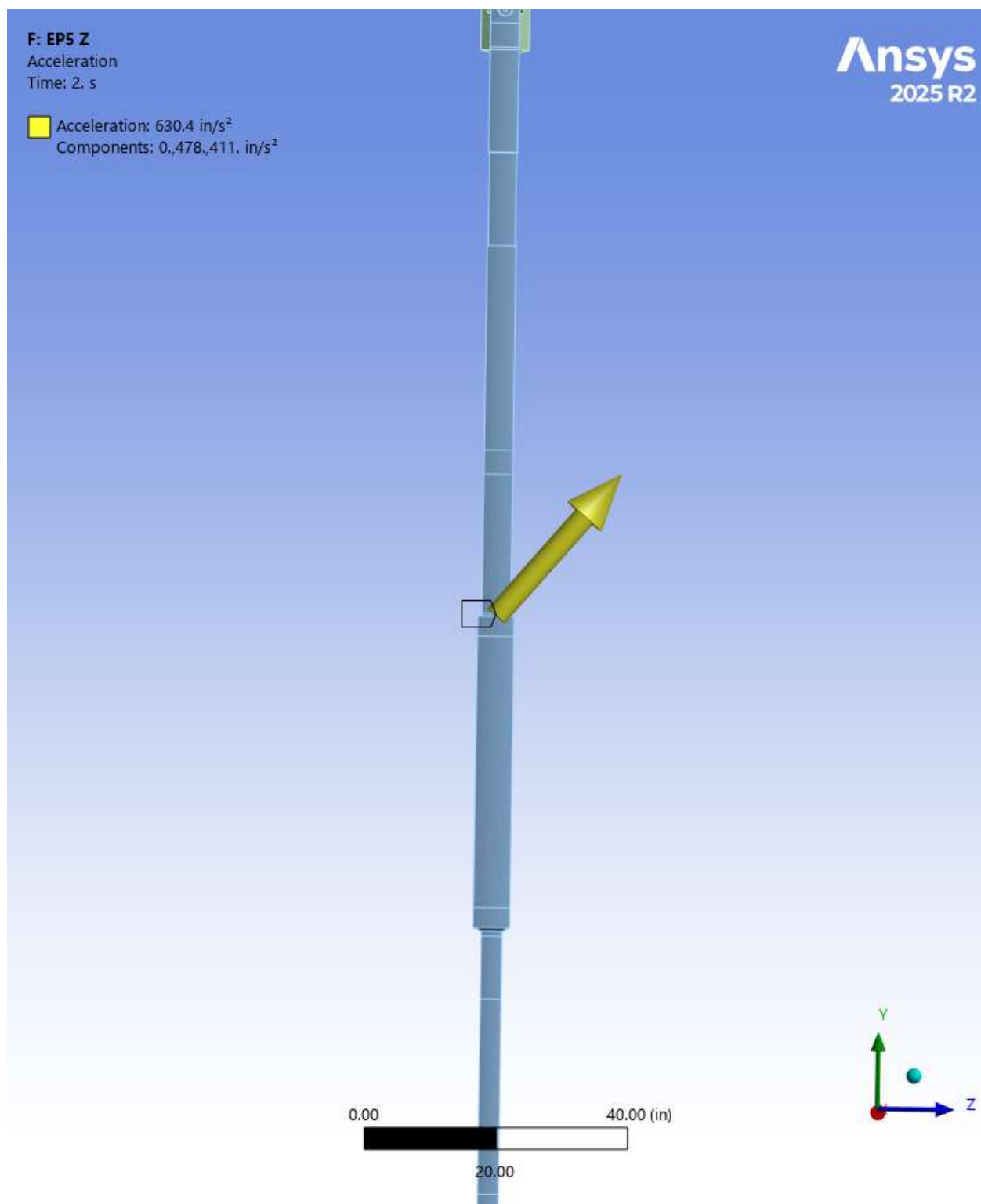


Figure 353 Segment, EP5 Acceleration

4.6.3 Target Shaft Load Cases

The Target Shaft model incorporates the same Elastic load combinations and Elastic Plastic load combinations. Also similar to the Segment model the Shaft model includes bolt preload on the Tie Rods. The Tie Rods use a pretension force and are set up in the same method as the Segment model, pretension is applied on step 1 and locked for step 2. Step 2 has the appropriate loads then applied for each case. Note for the temperature load, it is external data mapped to the model, the temperatures are the same for each load case.

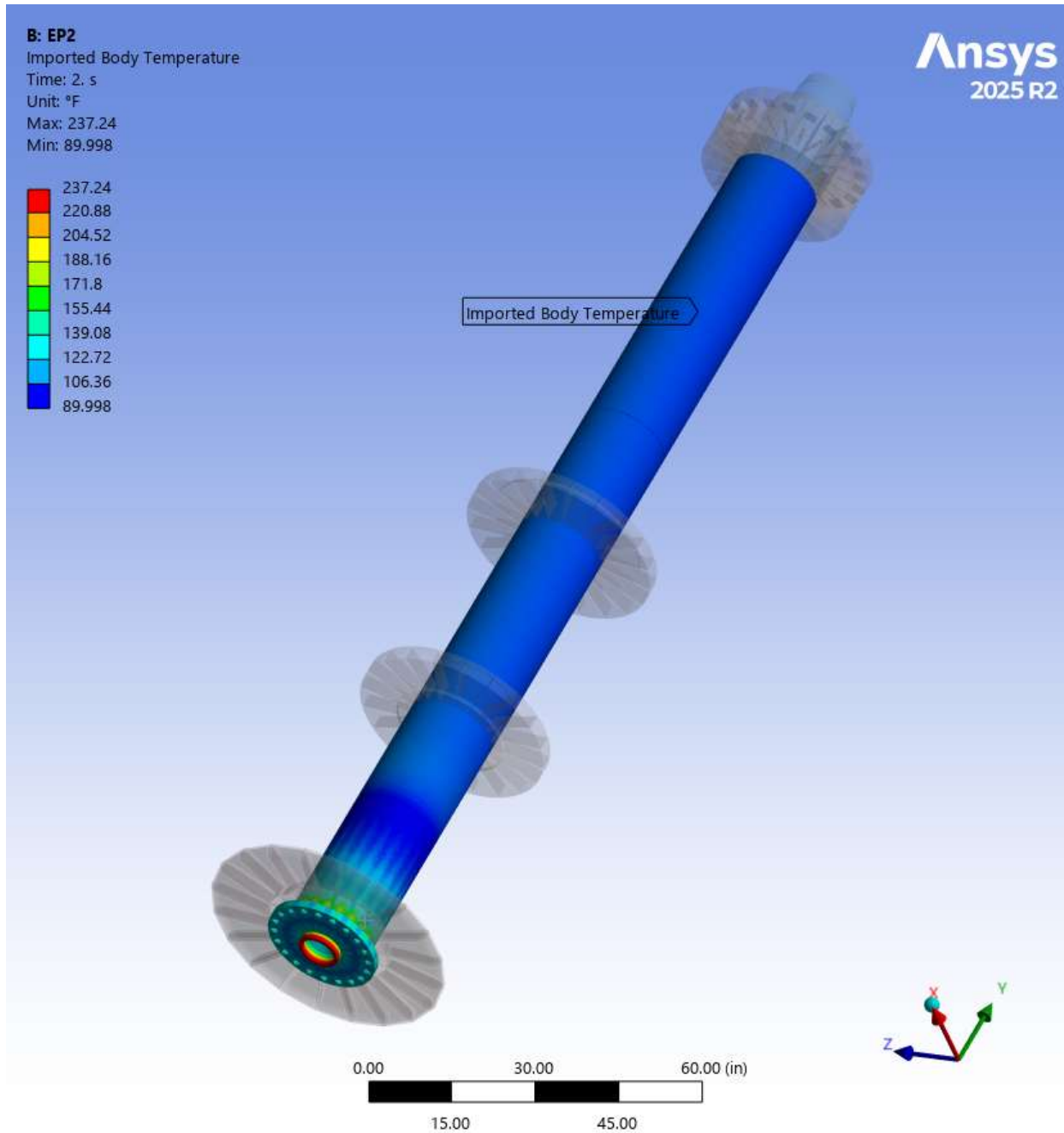


Figure 354 Shaft Analysis Temperature Data

The same is true for the Tie Rod preload, each analysis has an initial pretention step then all remaining steps are 'locked'. To reduce redundancy the temperature and pretention loads are only shown once.

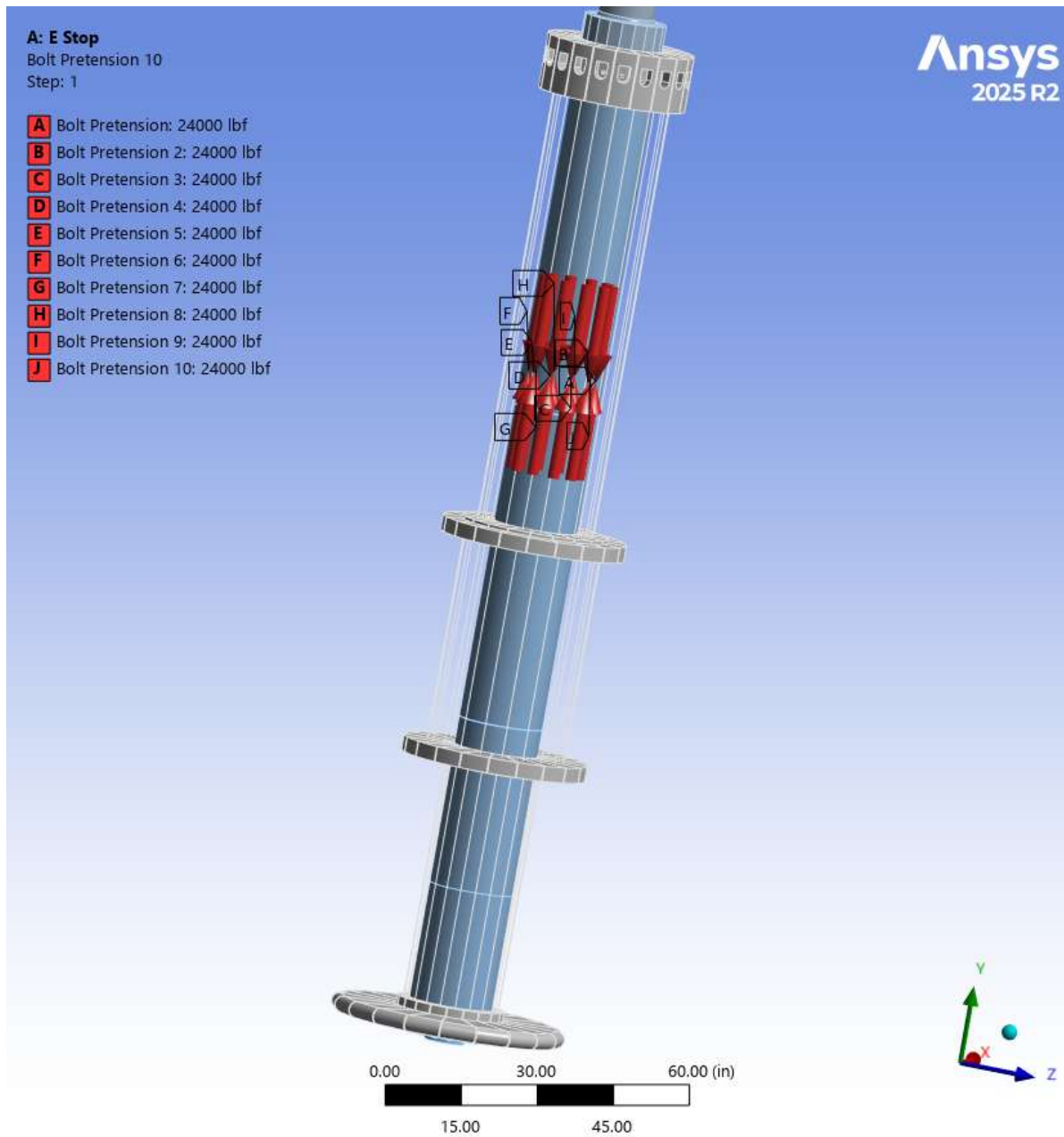


Figure 355 Tie Rod Pretension

4.6.3.1 Elastic Case 3, E Stop

Table 24 Shaft, Elastic Case 3

Load Case	Time	P	D	L	L	T	E	Preload
3	1		1g			Imported		24000 lbf
	2		1g	4.7 rad/s ²	45 rpm	Imported		Locked

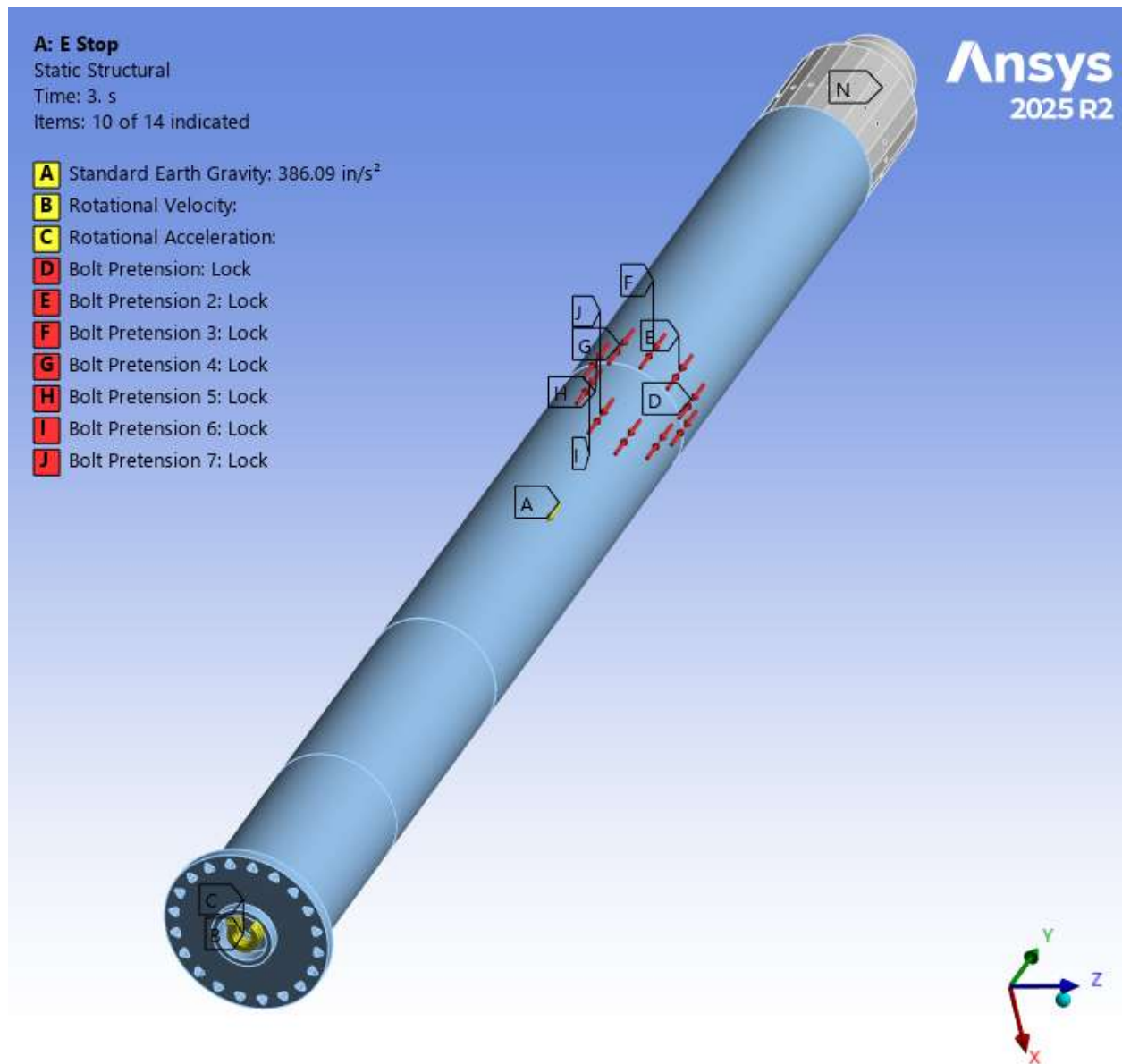


Figure 356 Shaft, E Stop Load Summary

Note that ANSYS will only show ten of the load cases, not all the pretension loads are listed above.

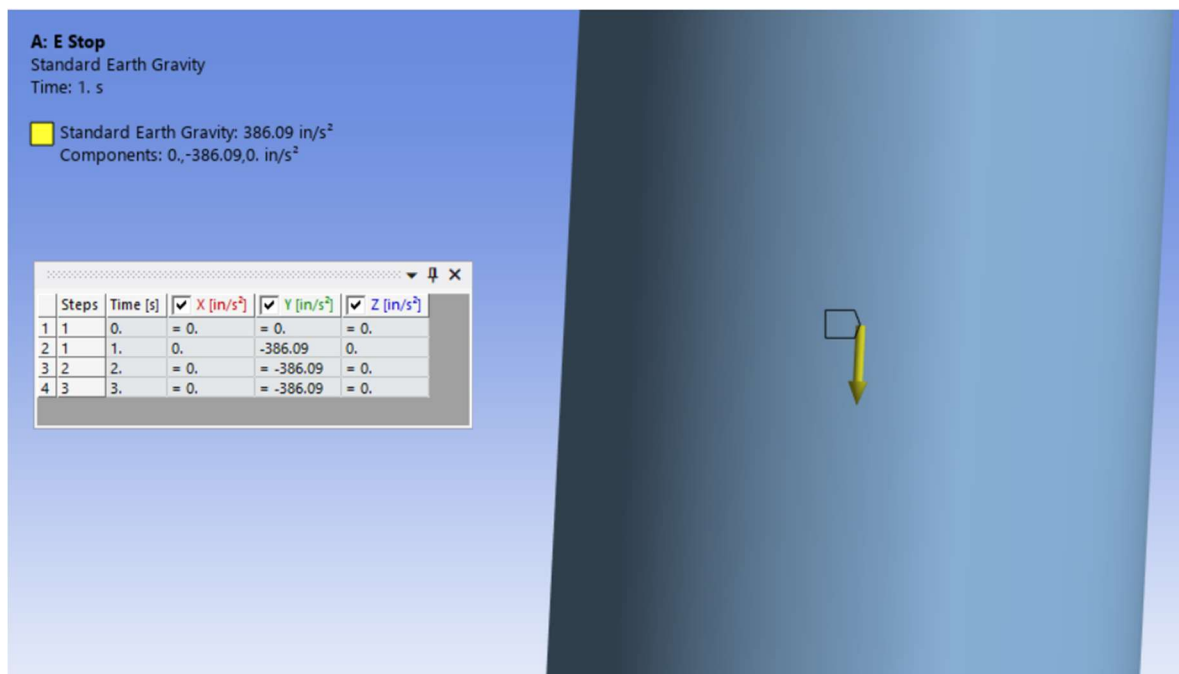


Figure 357 Shaft, E Stop Standard Gravity

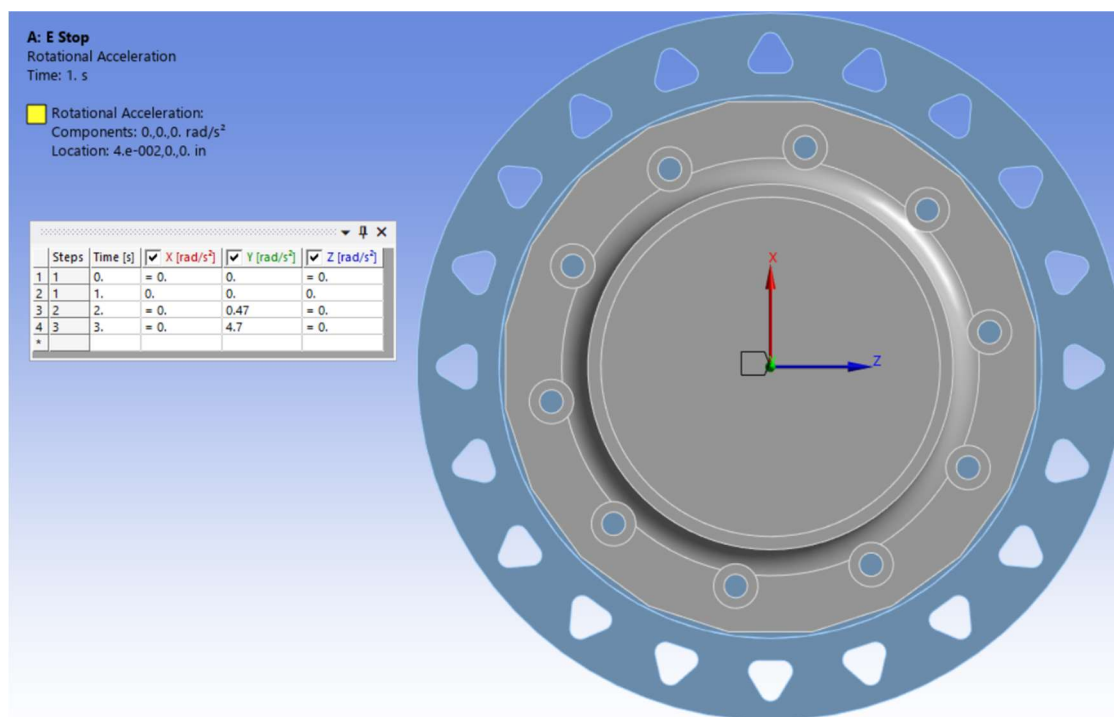


Figure 358 Shaft, E Stop Rotational Acceleration

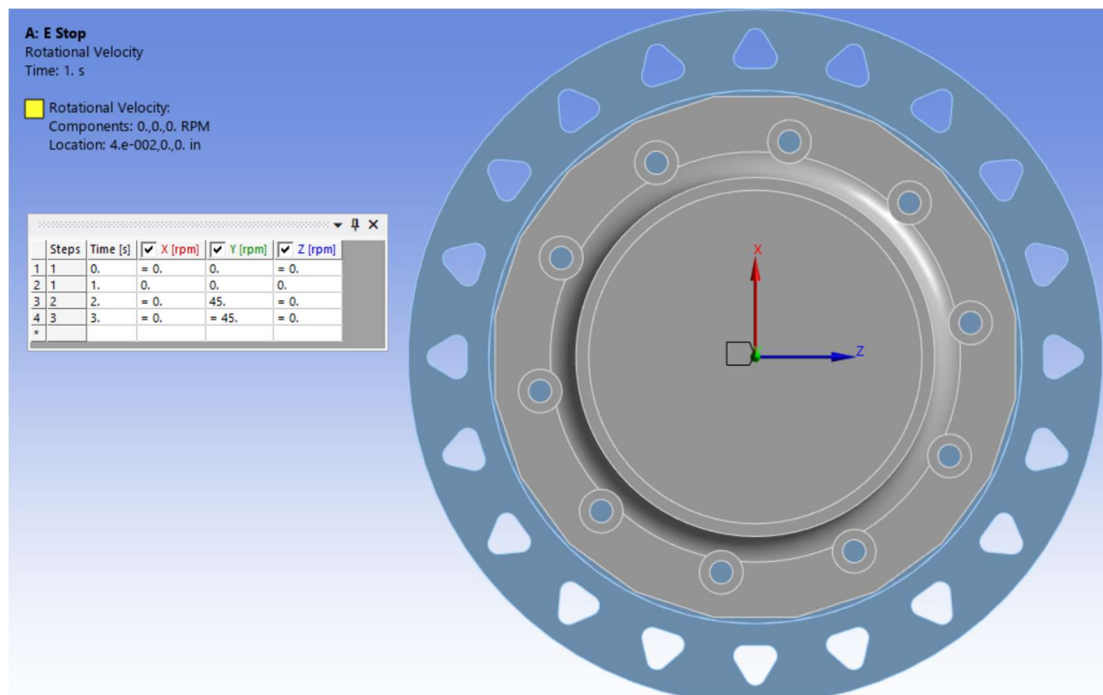


Figure 359 Shaft, E Stop Rotational Velocity

4.6.3.2 Elastic Case 6, Seismic

Table 25 Shaft, Elastic Case 6

Load Case	Time	P	D	L	L	T	E	Preload
6	1		1g			Imported		24000 lbf
	2		1g			Imported	169 in/s ²	Locked

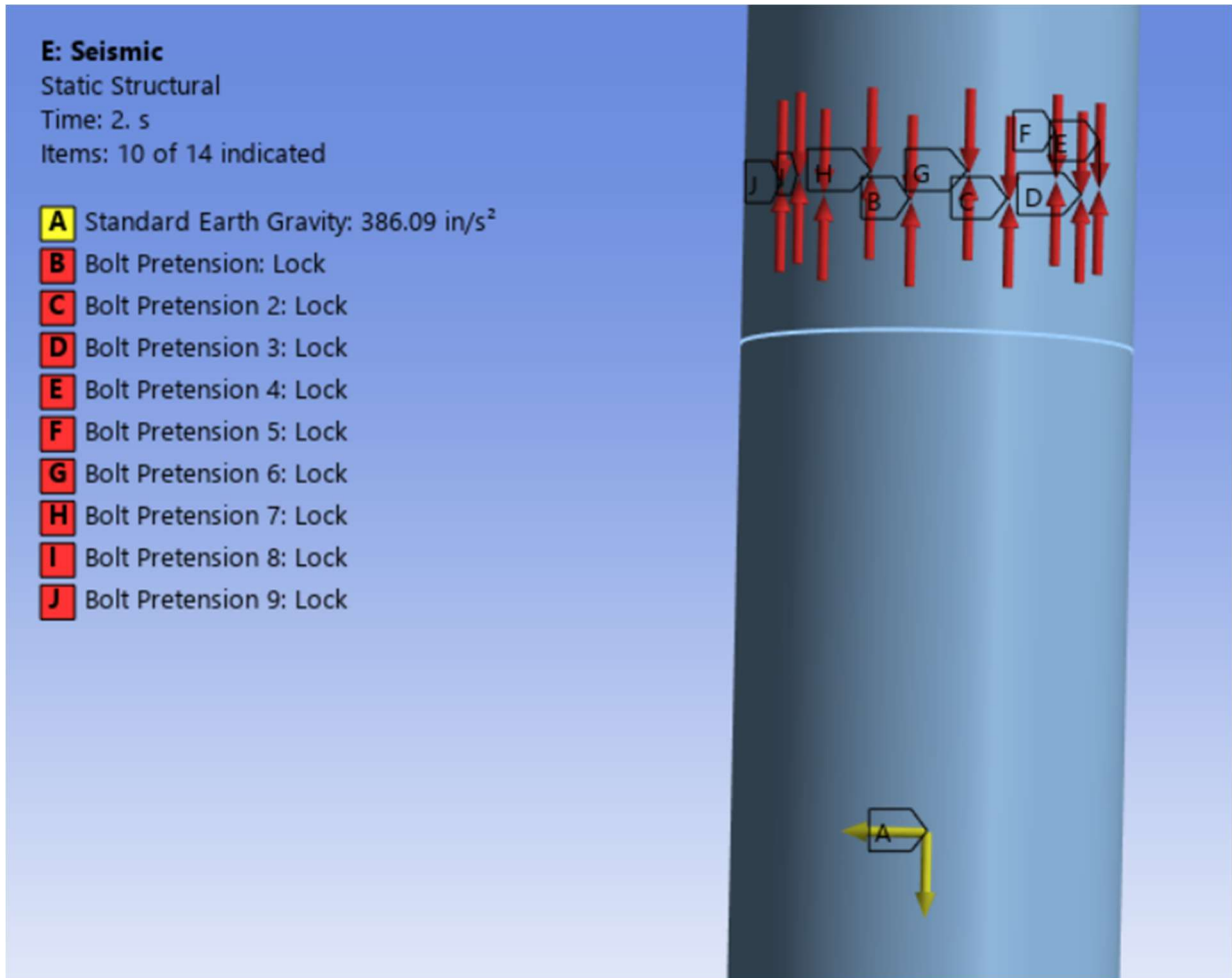


Figure 360 Shaft, Seismic Load Cases

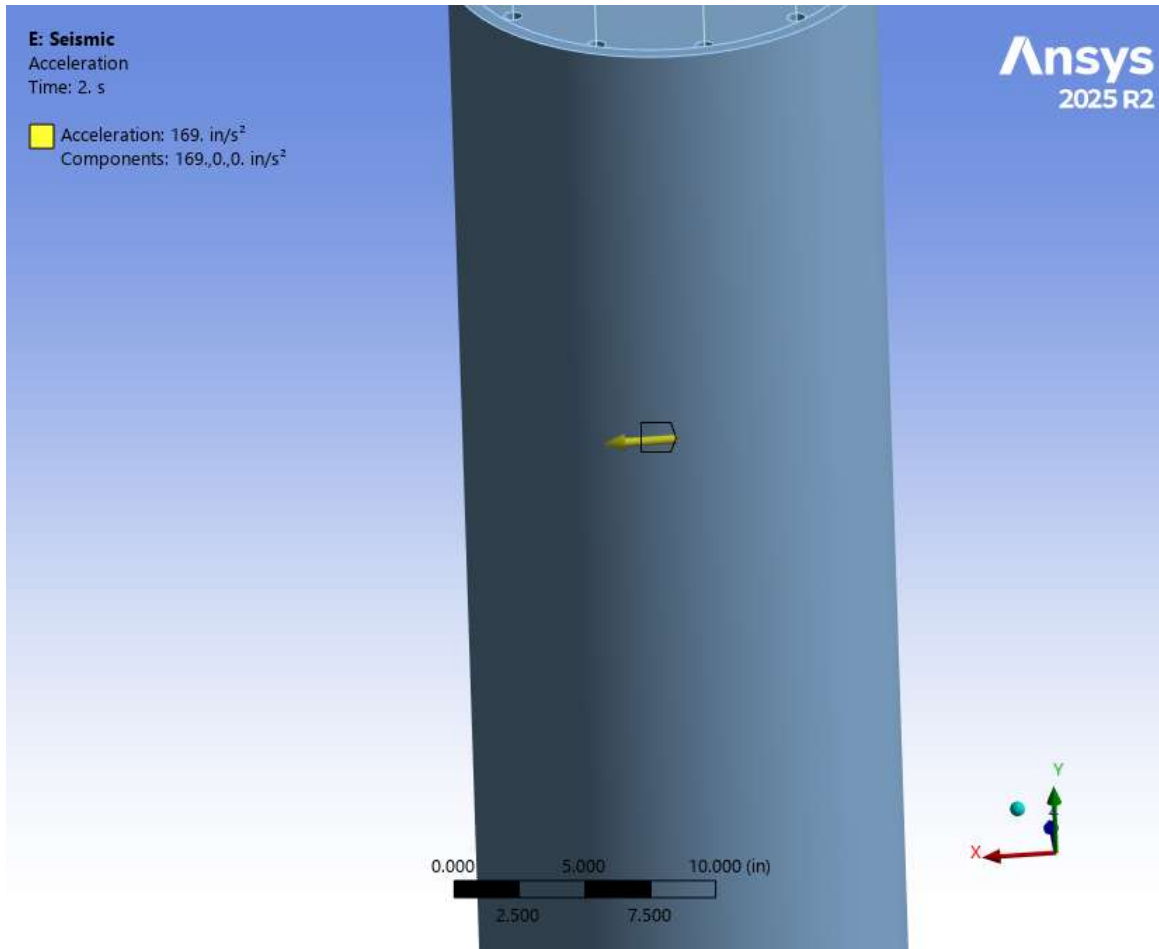


Figure 361 Shaft, Seismic Acceleration

4.6.3.3 Elastic Case 8, Seismic + Stop

Table 26 Shaft, Elastic Case 8

Load Case	Time	P	D	L	L	T	E	Preload
8	1		1g			Imported		24000 lbf
	2		1g	3.5 rad/s ²	34 rpm	Imported	127 in/s ²	Locked

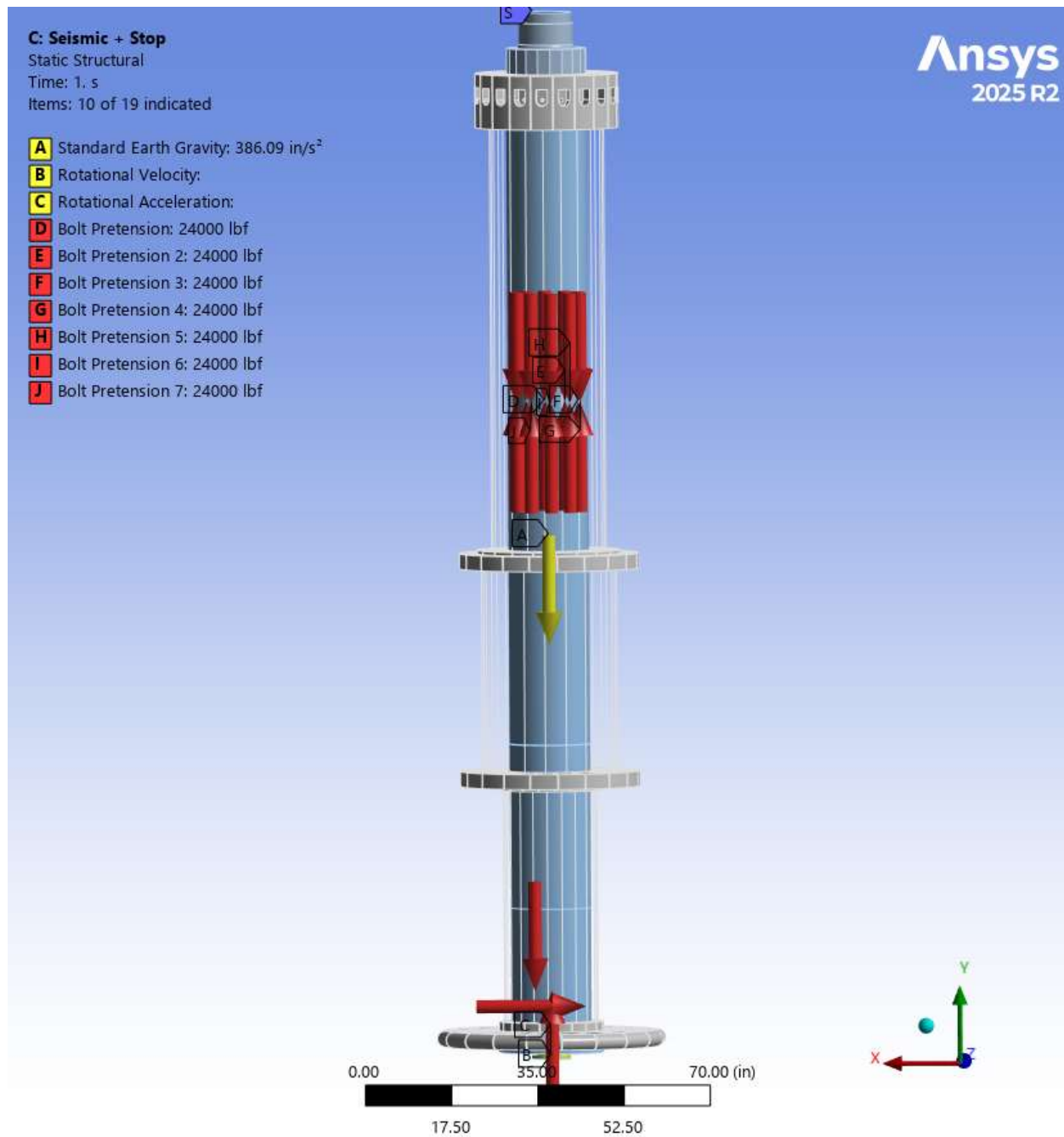


Figure 362 Shaft, Seismic + Stop Load Summary

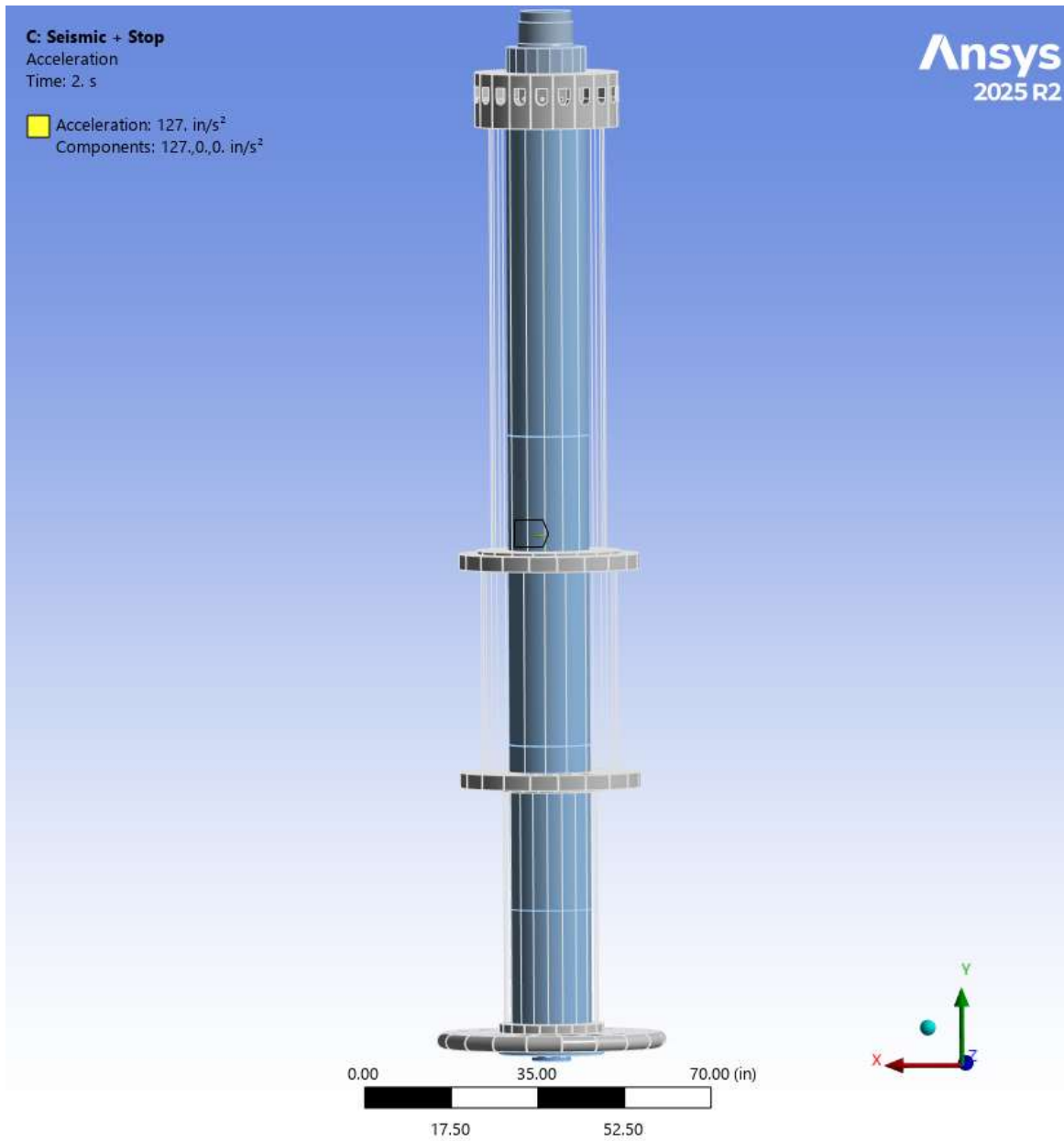
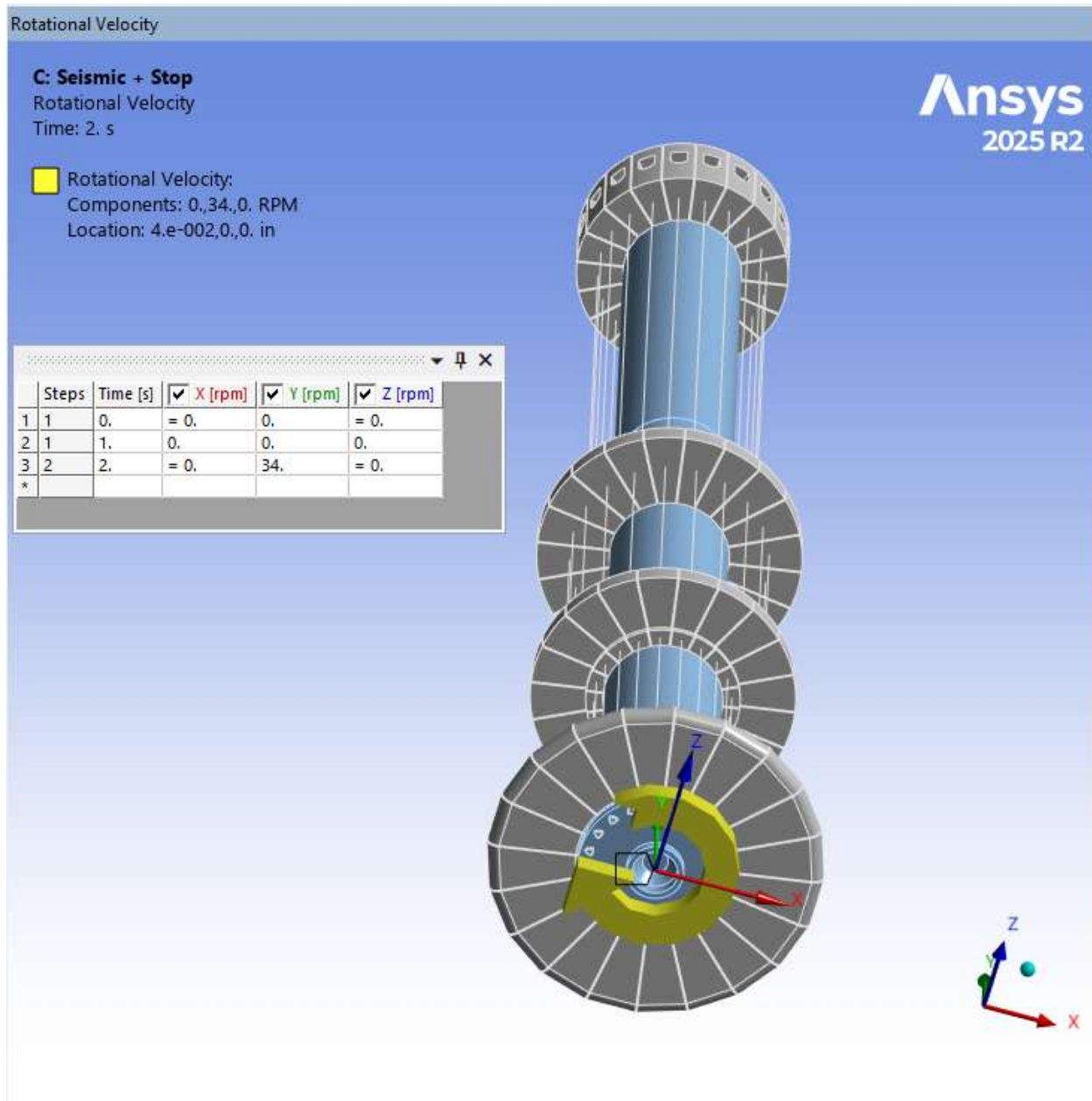


Figure 363 Shaft, Seismic + Stop Acceleration



C: Seismic + Stop

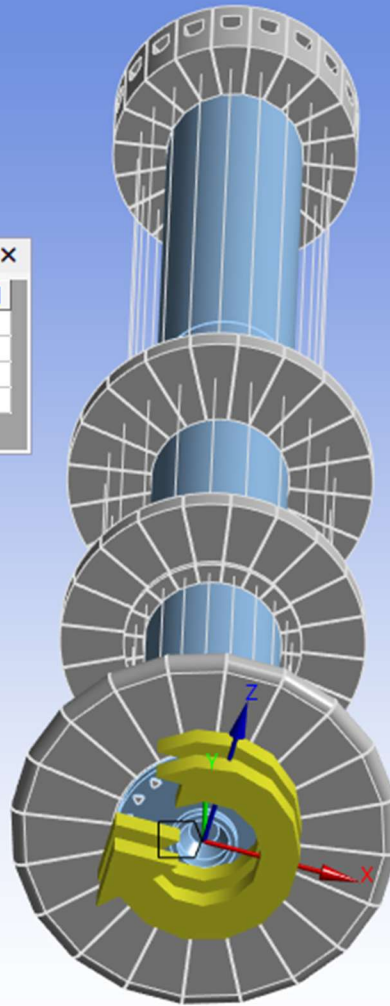
Rotational Acceleration

Time: 2. s

 Rotational Acceleration:
Components: 0., 3.5, 0. rad/s²
Location: 4.e-002, 0., 0. in

Ansys
2025 R2

	Steps	Time [s]	☒ X [rad/s ²]	☒ Y [rad/s ²]	☒ Z [rad/s ²]
1	1	0.	= 0.	0.	= 0.
2	1	1.	0.	0.	0.
3	2	2.	= 0.	3.5	= 0.
*					

*Figure 365 Shaft, Seismic + Stop Rotational Acceleration*

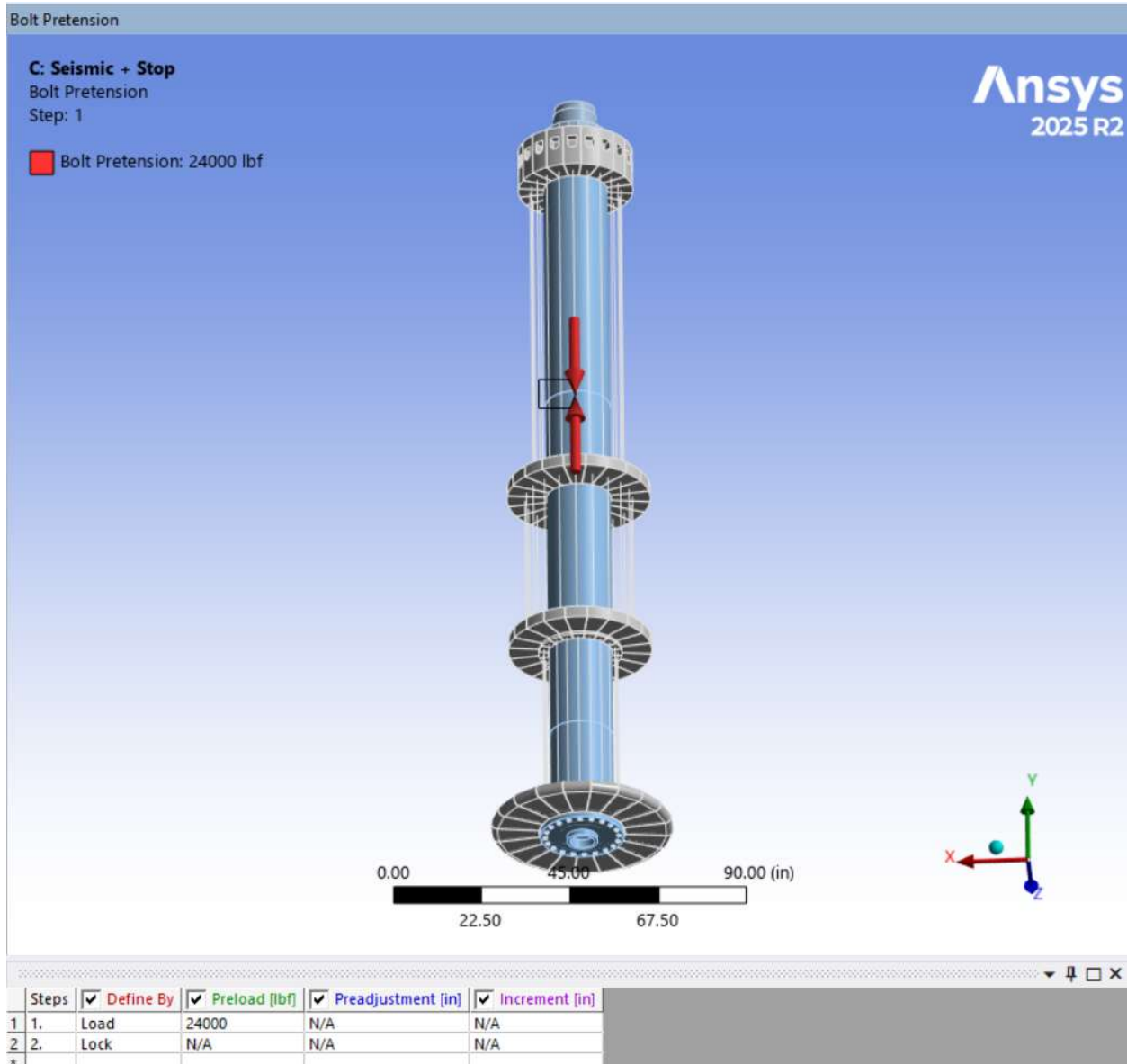


Figure 366 Shaft, Seismic + Stop Bolt Pretension

4.6.3.4 Elastic Plastic Case 1

Table 27 Shaft, EP Case 1

Load Case	Time	P	D	L	L	T	Preload	Density
EP 1	1		386 in/s ²			Imported	24000 lbf	2.4X
	2	300 psi	386 in/s ²	4.7 rad/s ²	45 rpm	Imported	Locked	2.4X

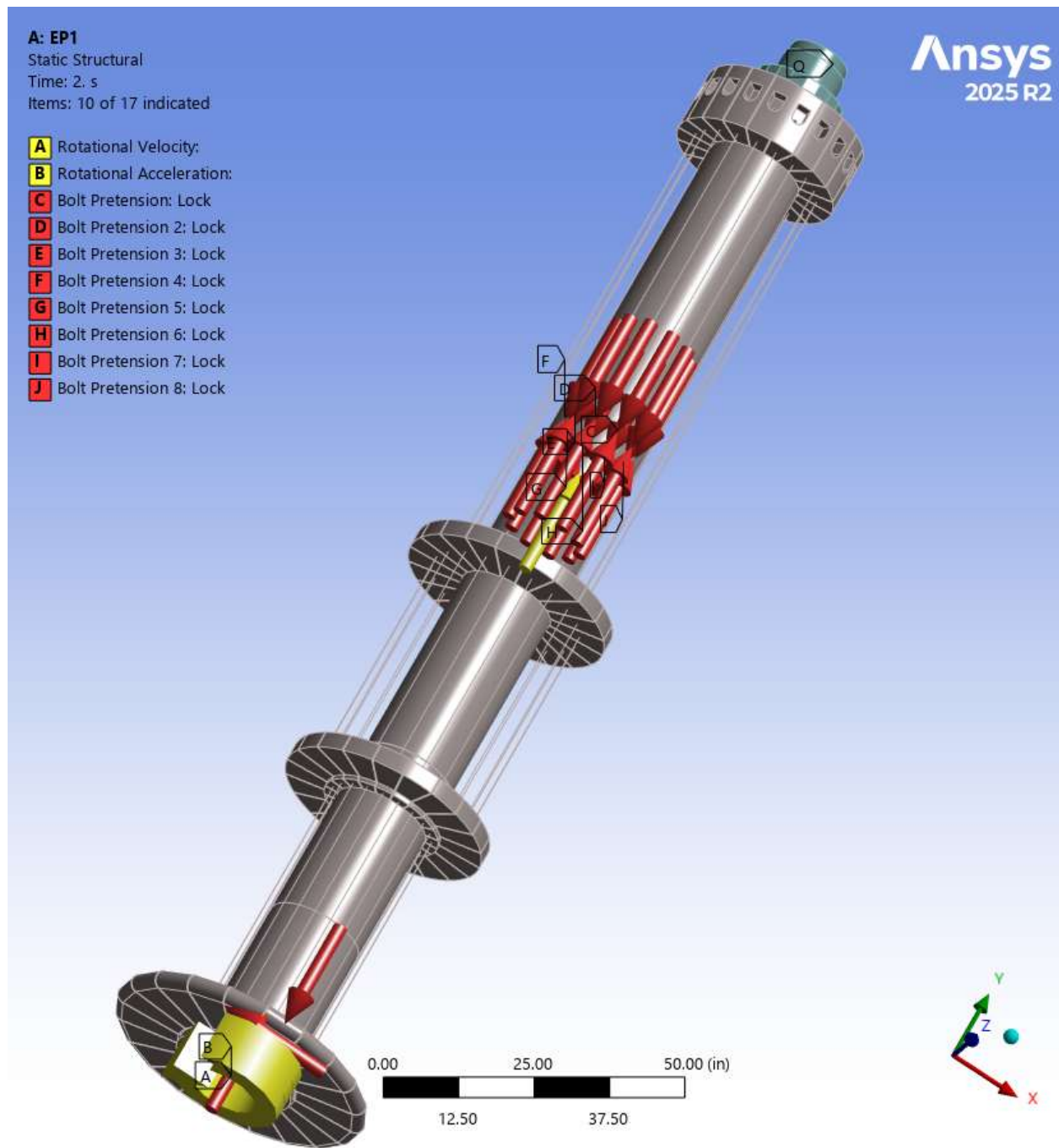


Figure 367 Shaft Elastic Plastic Case 1

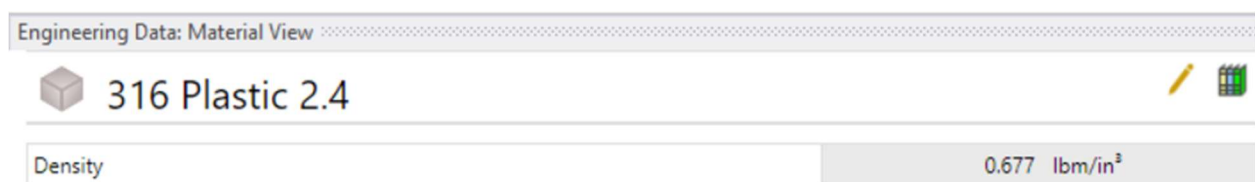


Figure 368 Shaft, Elastic Plastic 1 Density Factor

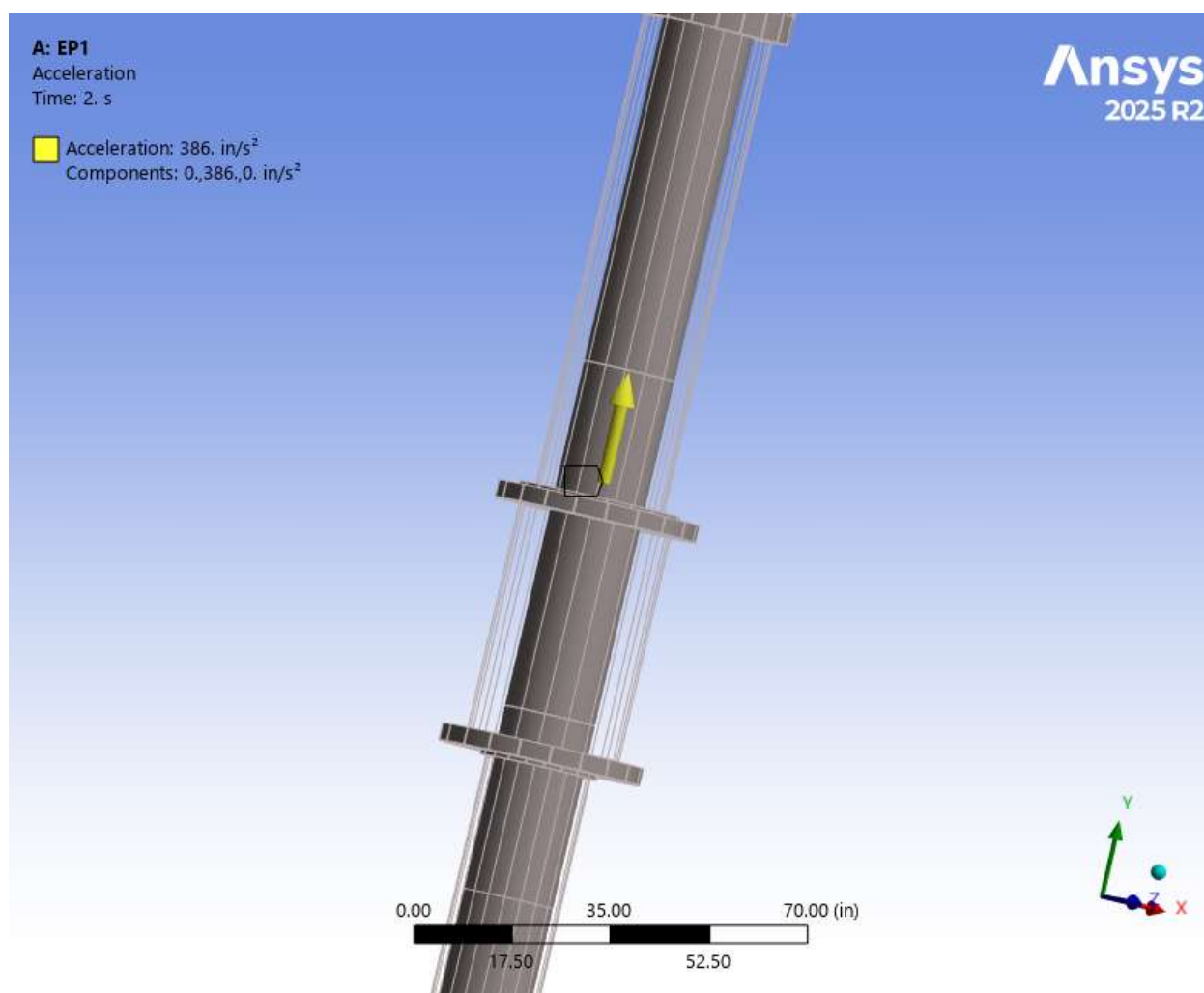


Figure 369 Shaft, Elastic Plastic 1 Acceleration

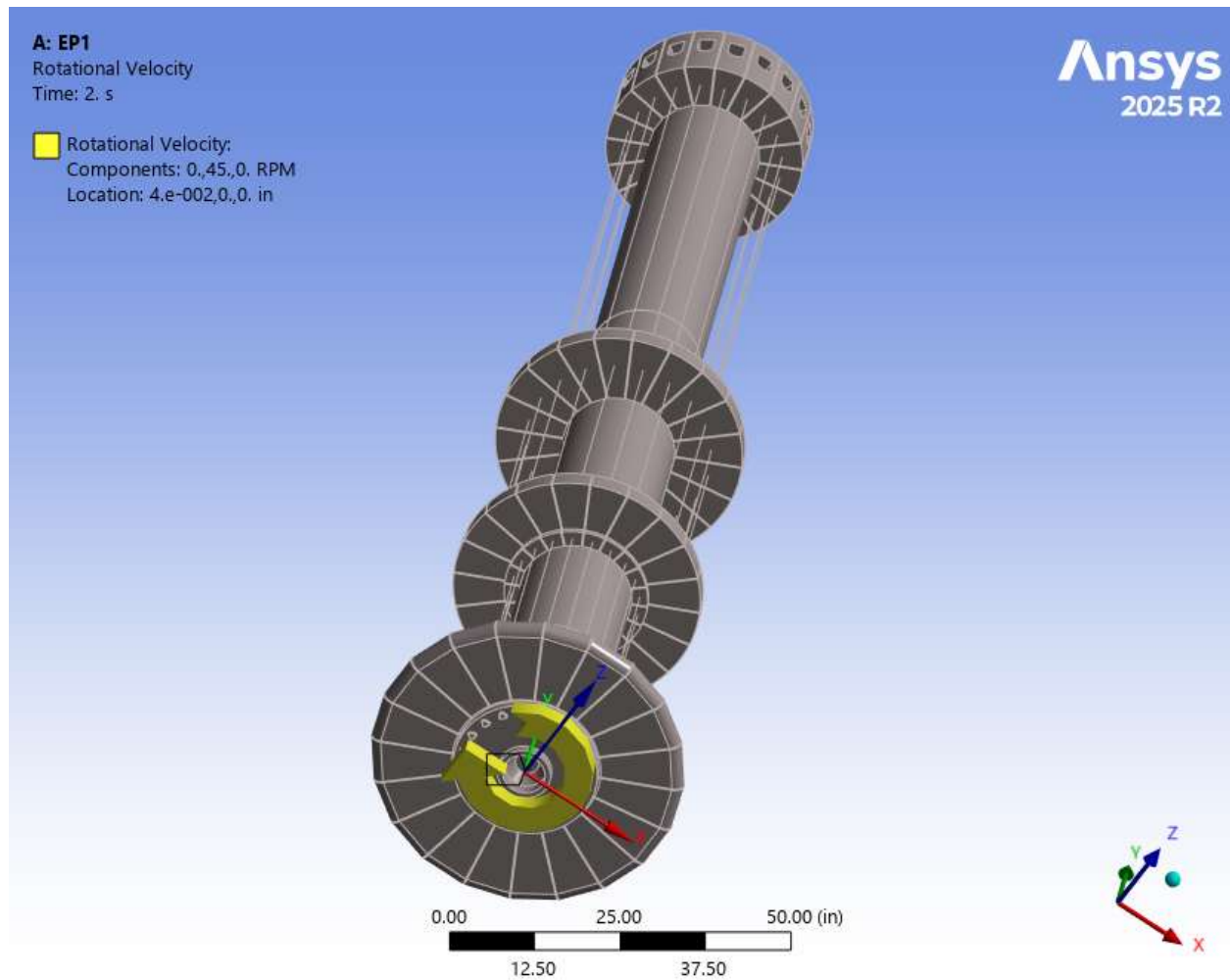


Figure 370 Shaft, Elastic Plastic 1 Rotational Velocity

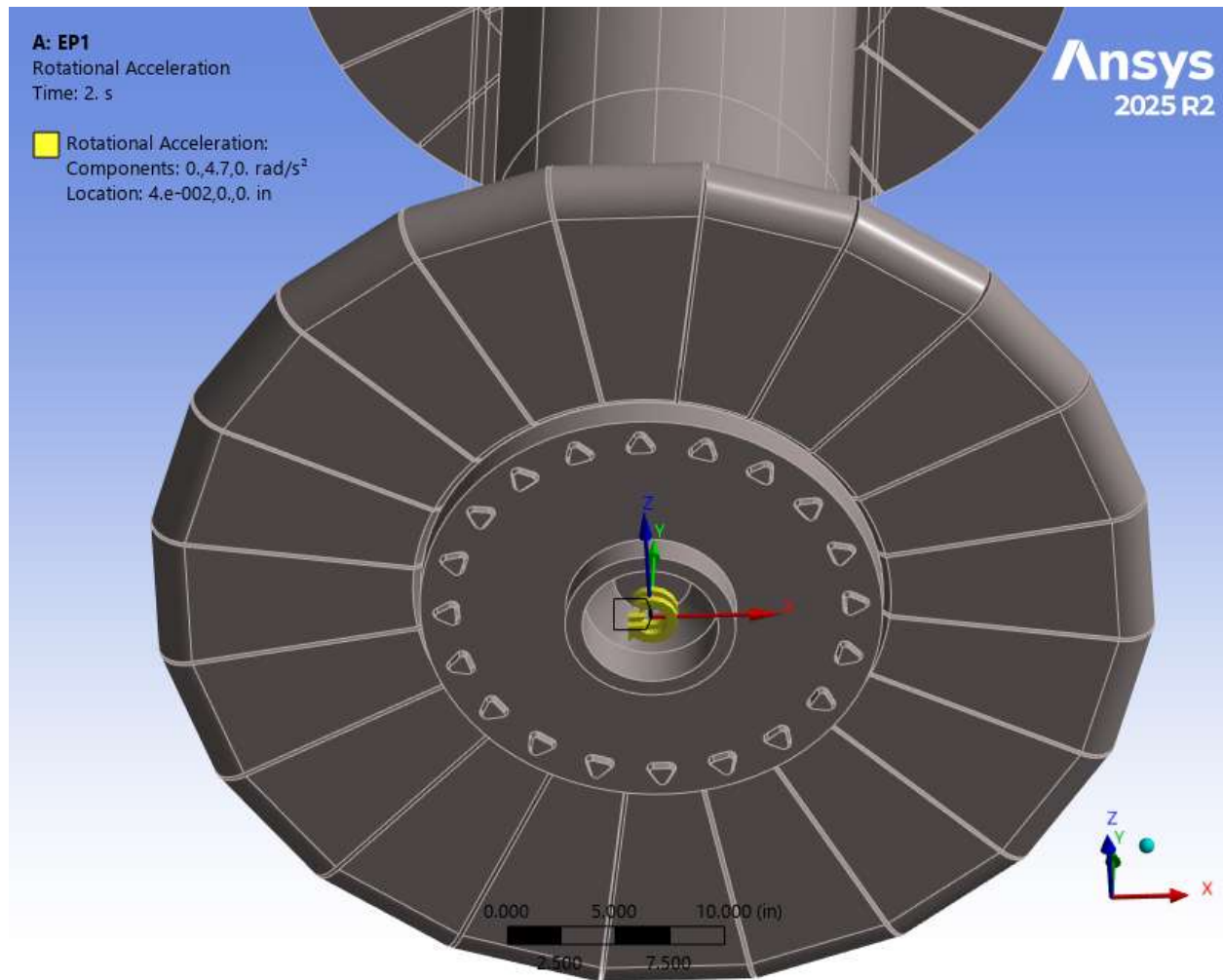


Figure 371 Shaft, Elastic Plastic 1 Rotational Acceleration

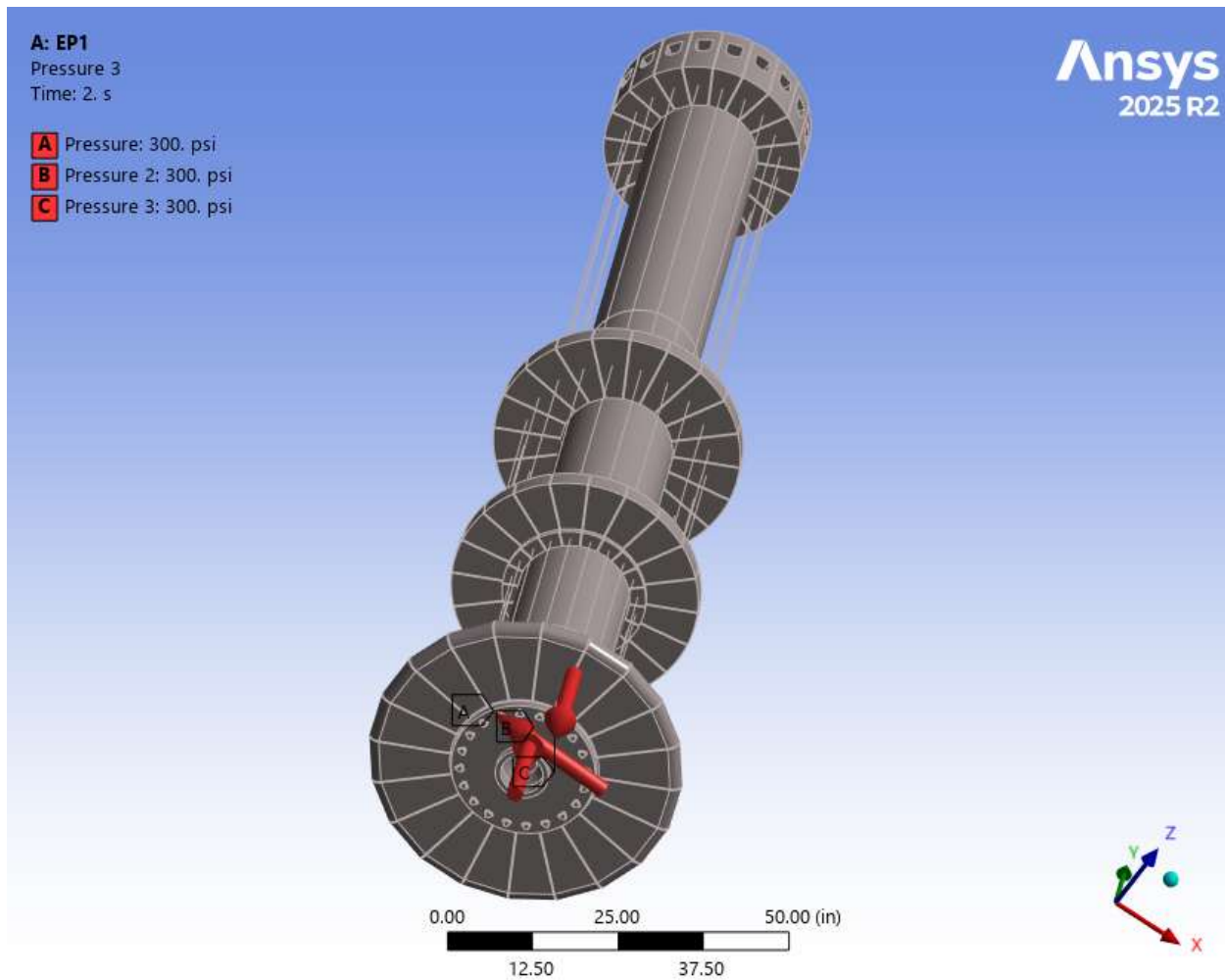


Figure 372 Shaft, Elastic Plastic 1 Pressure

4.6.3.5 Elastic Plastic Case 2

Table 28 Shaft, EP Case 2

Load Case	Time	P	D	L	L	T	Preload	Density Factor
EP 2	1		302 in/s ²			Imported	24000 lbf	2.7X
	2	264 psi	302 in/s ²	4.7 rad/s ²	45 rpm	Imported	Locked	2.7X

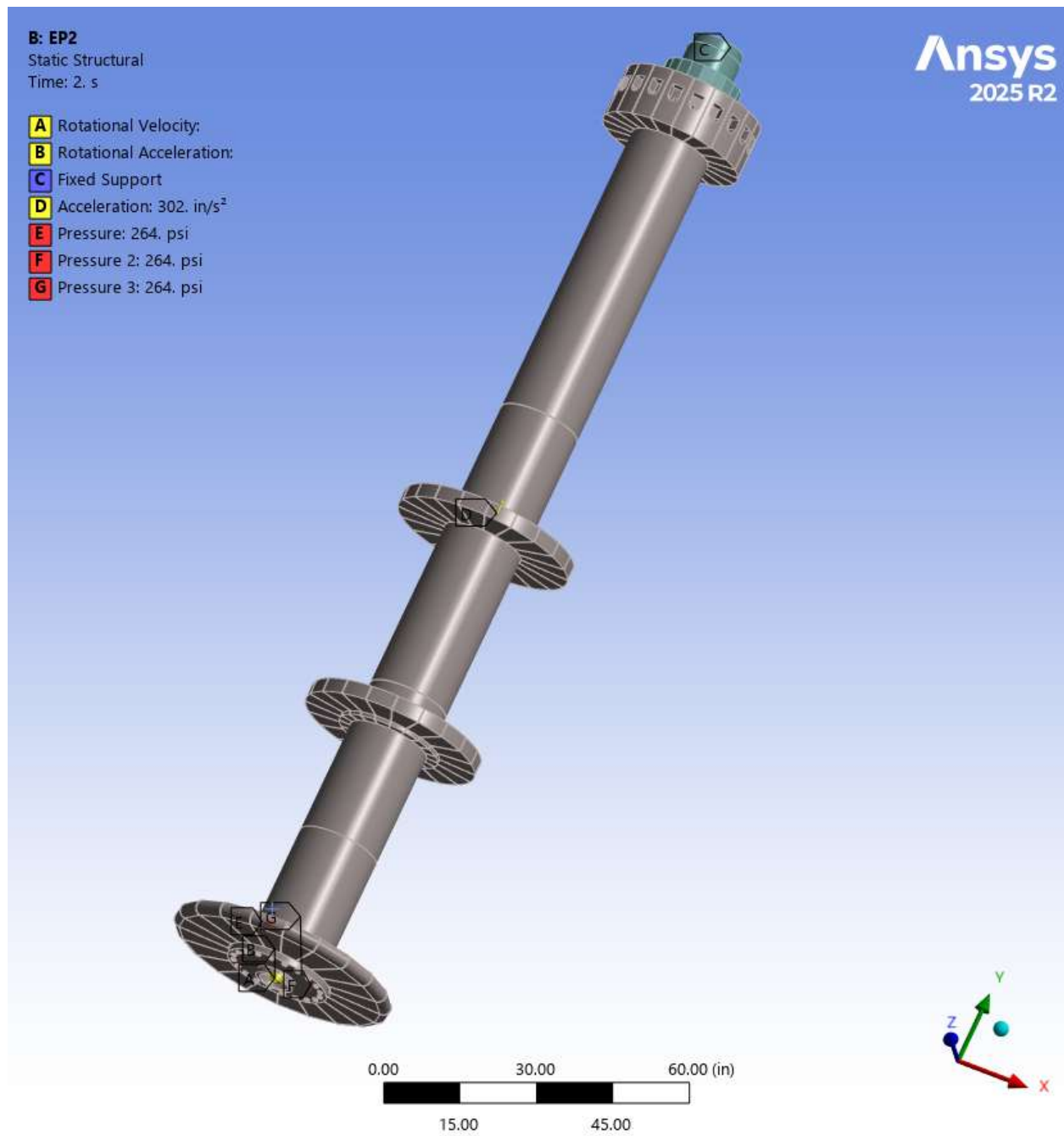


Figure 373 Shaft, Elastic Plastic Load Case 2

Engineering Data: Material View	
 316 Plastic 2.7  	
Density	0.7614 lbm/in ³

Figure 374 Shaft, Elastic Plastic 2 Density Factor

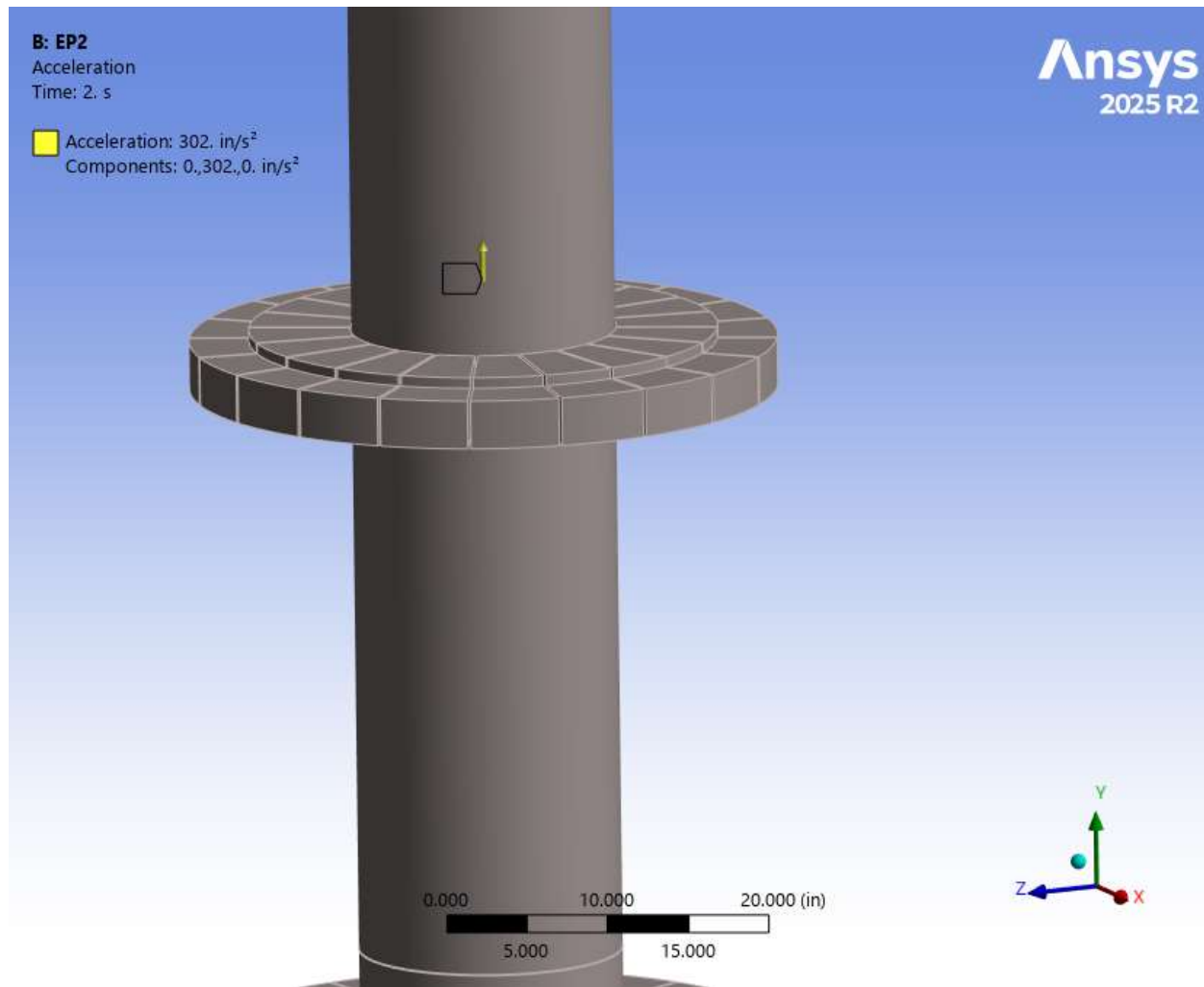


Figure 375 Shaft, Elastic Plastic 2 Acceleration

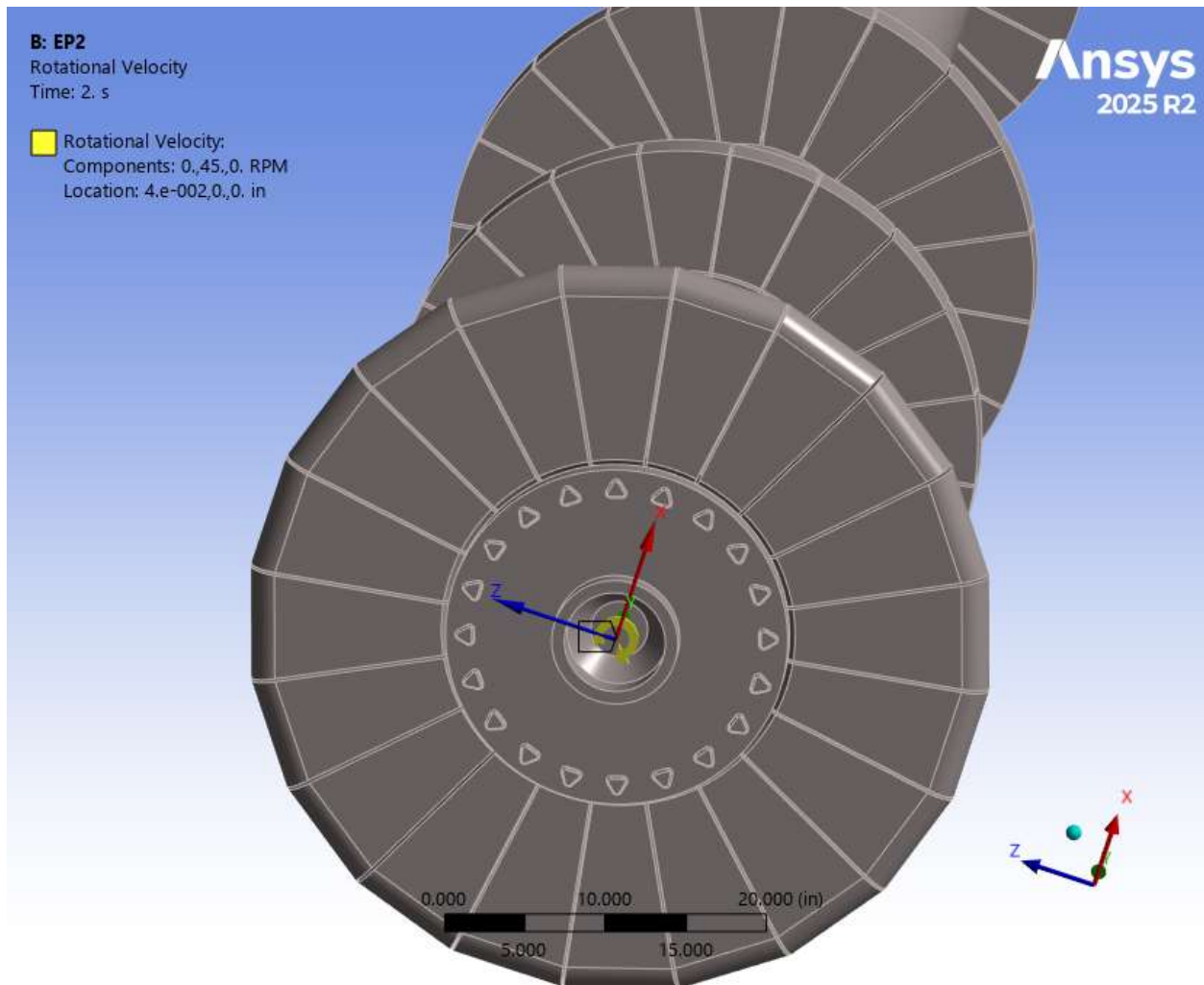


Figure 376 Shaft, Elastic Plastic 2 Rotational Velocity

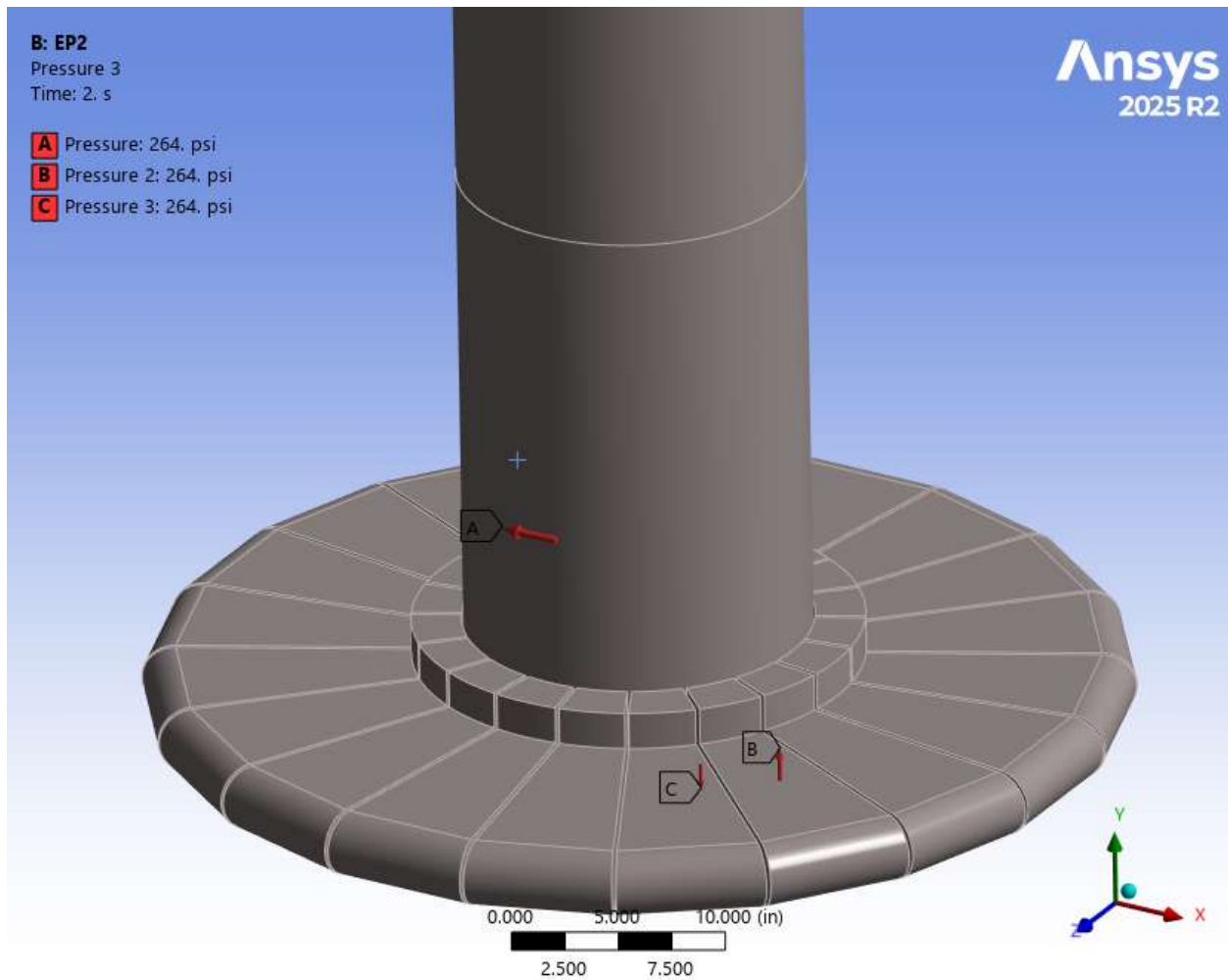


Figure 377 Shaft, Elastic Plastic 2 Pressure

4.6.3.6 Elastic Plastic Case 5

Table 29 Shaft, EP 5

Load Case	Time	P	D	L	L	T	E	Preload	Density Factor
EP5	1		480 in/s ²			Imported		24000 lbf	1.7X
	2	264 psi	480 in/s ²	4.7 rad/s ²	45 rpm	Imported	411 in/s ²	Locked	1.7X

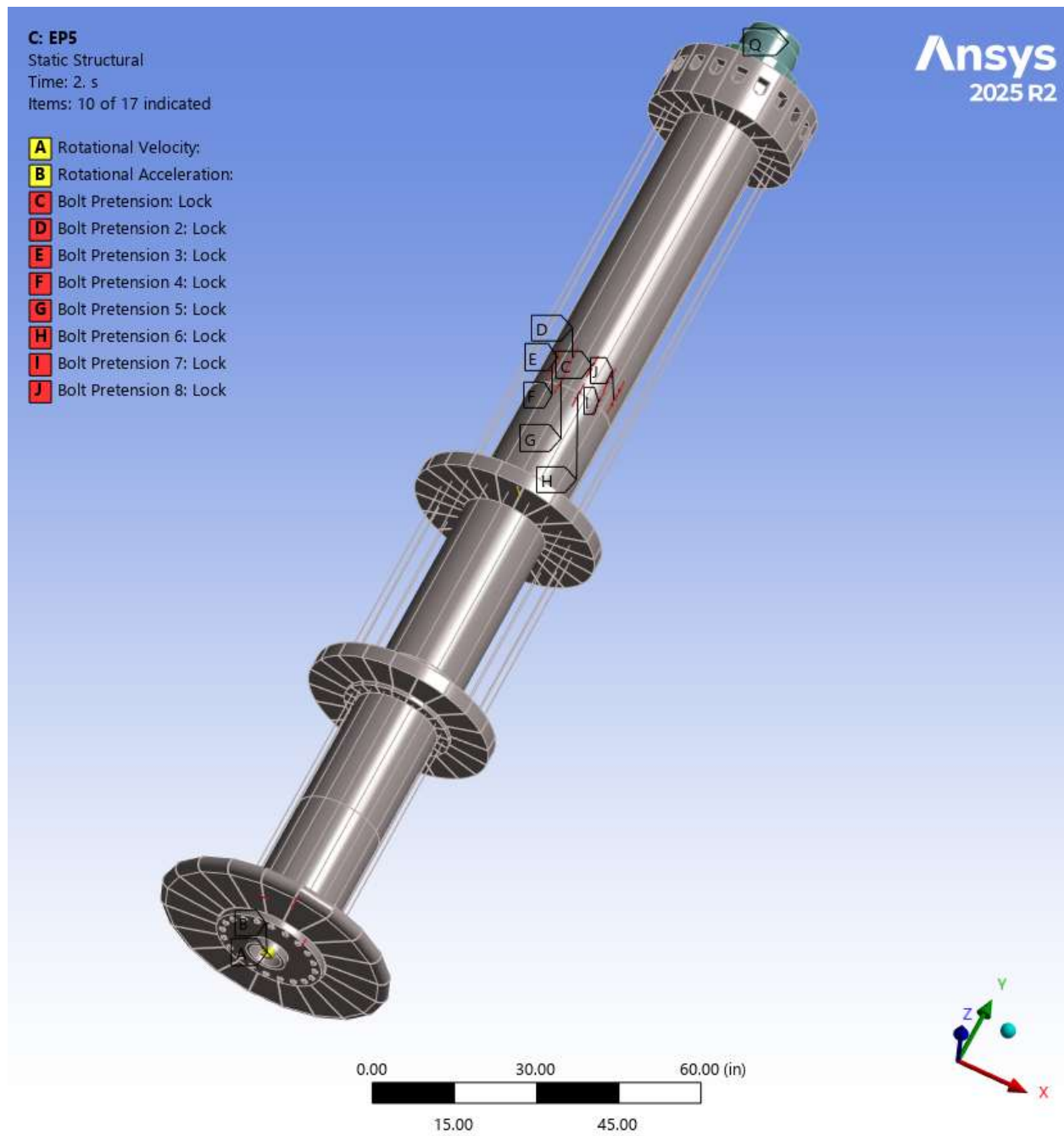


Figure 378 Shaft, Elastic Plastic Load Case 5

Engineering Data: Material View	
316 1.7	
Density	0.479 lbm/in ³
Structural	
Isotropic Elasticity	
Isotropic Secant Coefficient of Thermal Expansion	8.5e-06 1/°F
Tensile Ultimate Strength	70000 psi
Tensile Yield Strength	25000 psi

Figure 379 Shaft, EP5 Density Factor

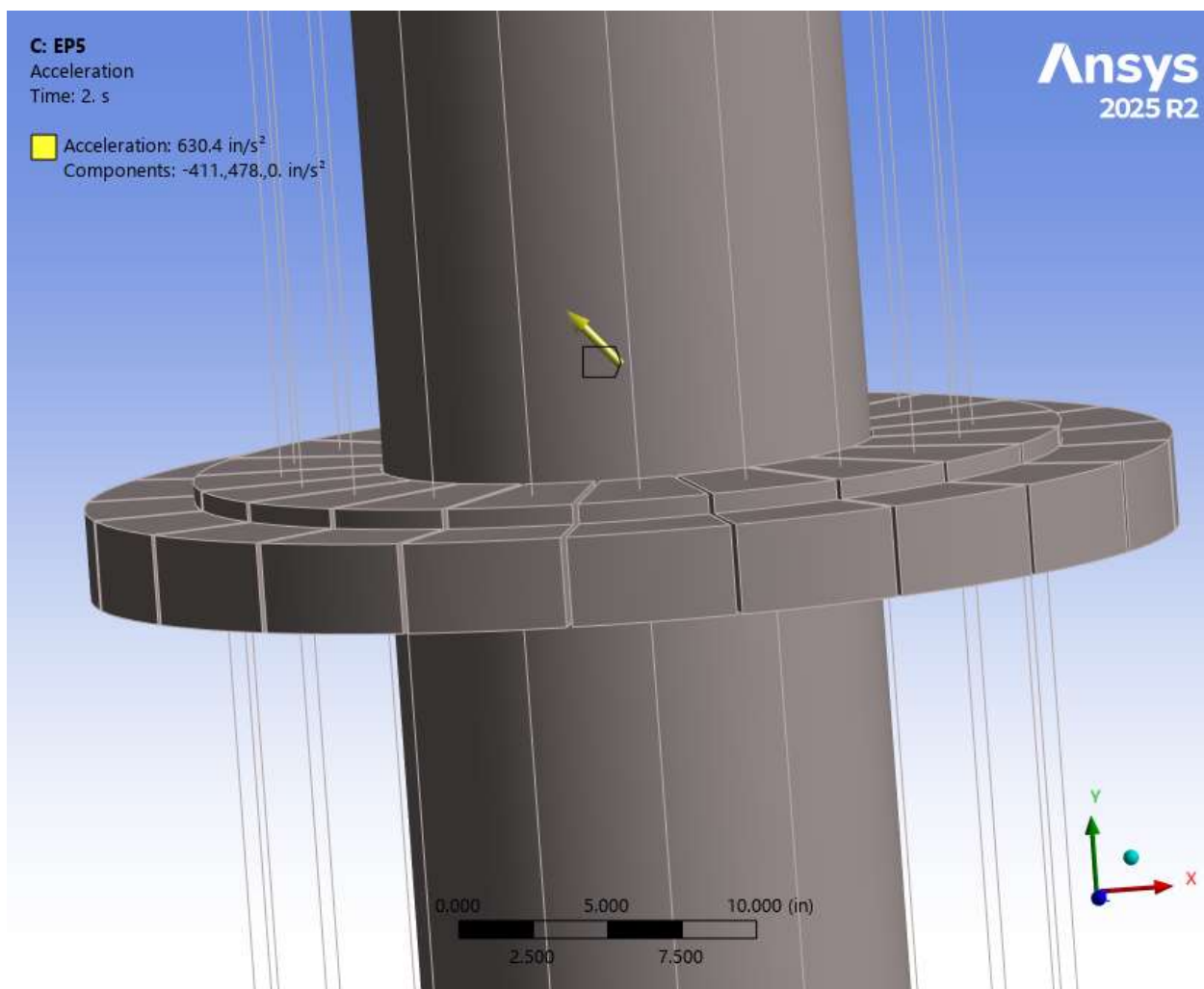


Figure 380 Shaft, EP5 Acceleration

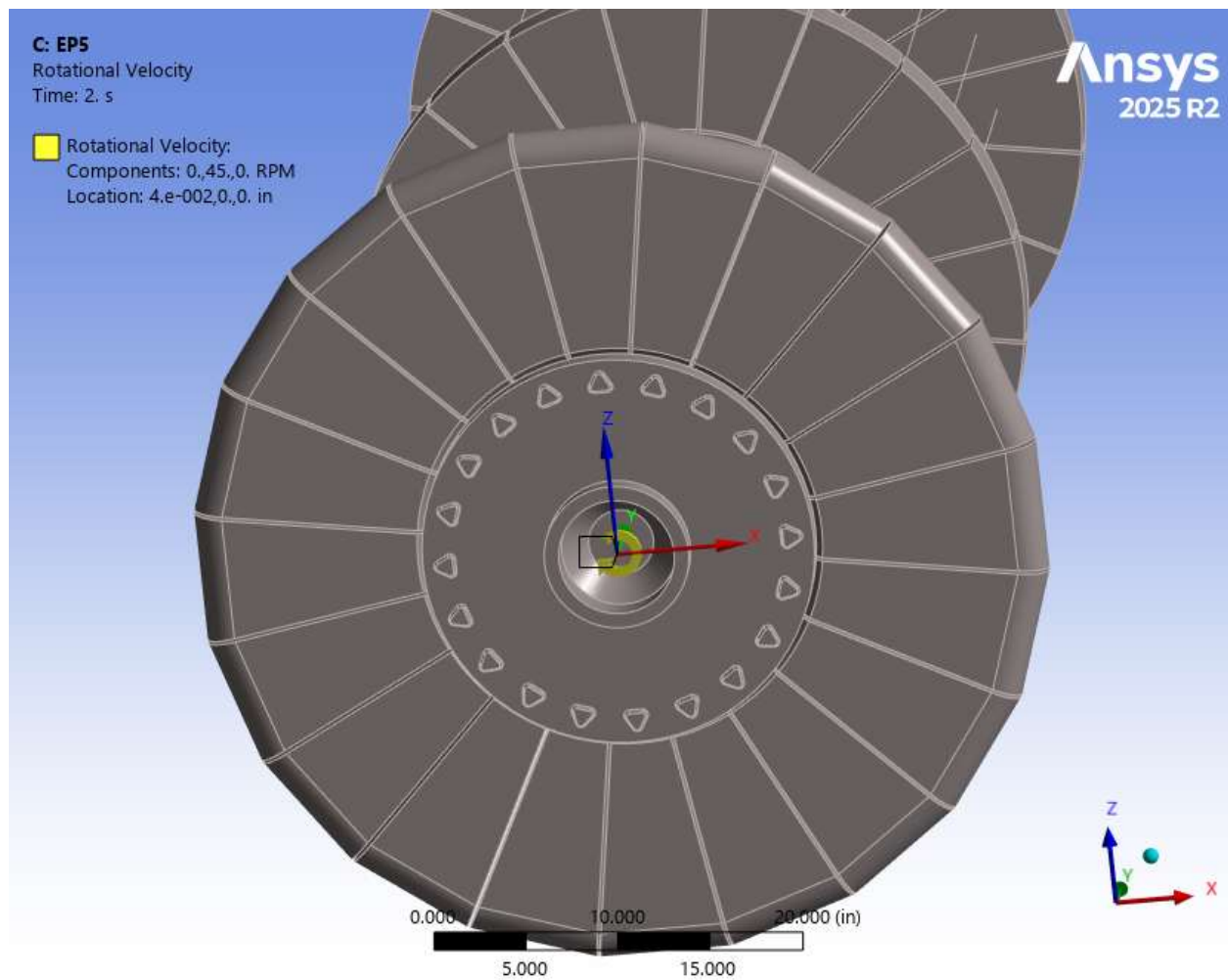


Figure 381 Shaft, EP5 Rotational Velocity

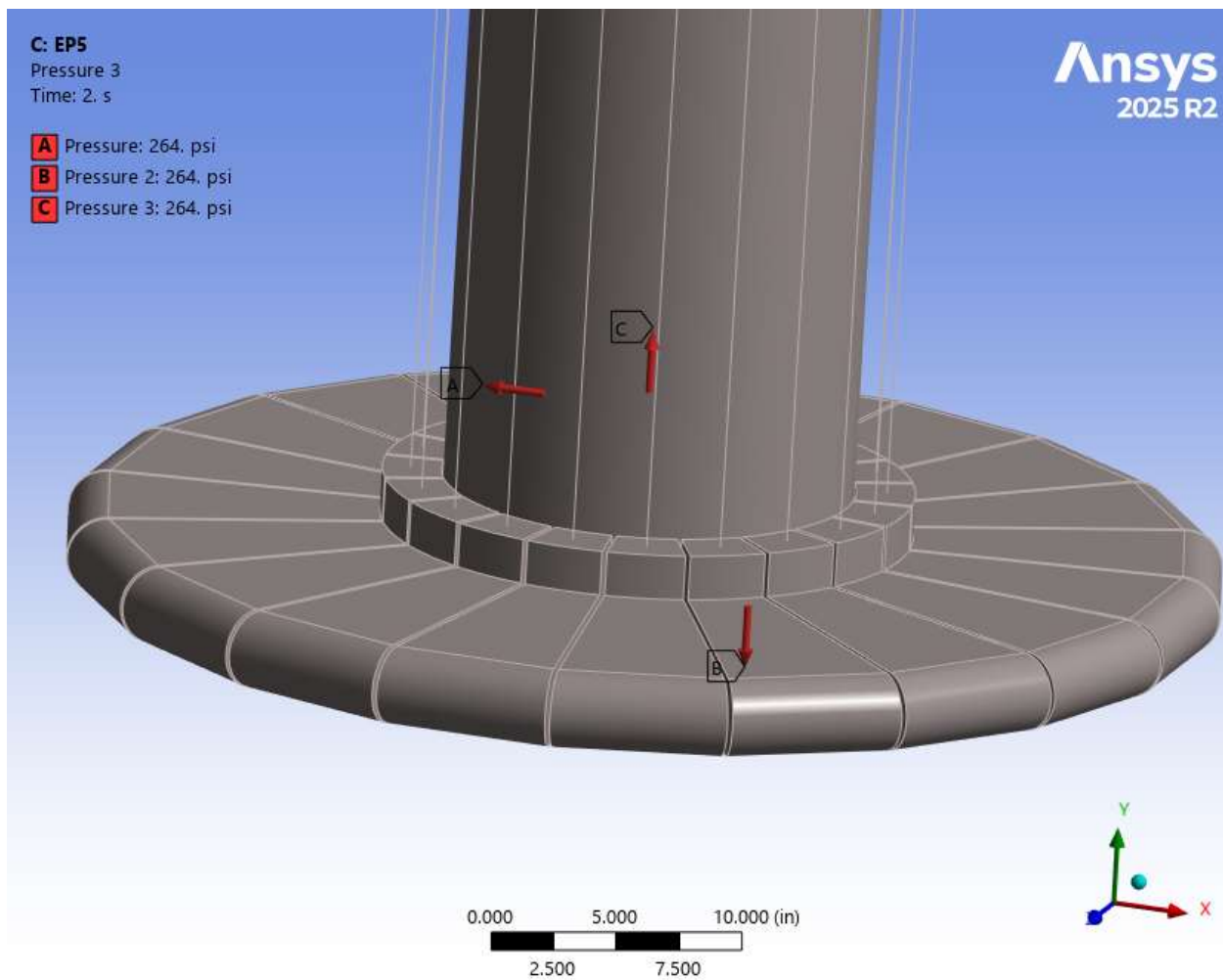


Figure 382 Shaft, EP5 Pressure

4.6.4 Crown and Drive

As with the Segment and Shaft models all load combinations are the same. This model also includes most of the fasteners, however these fasteners are not preloaded as the RCSC method does not use preload in the assessment of the bolts. Temperature loads are not applied to these models, the crown area has a

4.6.4.1 Elastic Case 3, E Stop

Table 30 Drive, Elastic 3

Load Case	Time	P	D	L	L	T	E
3	1	125 psi	1g	4.7 rad/s ²	45 rpm		

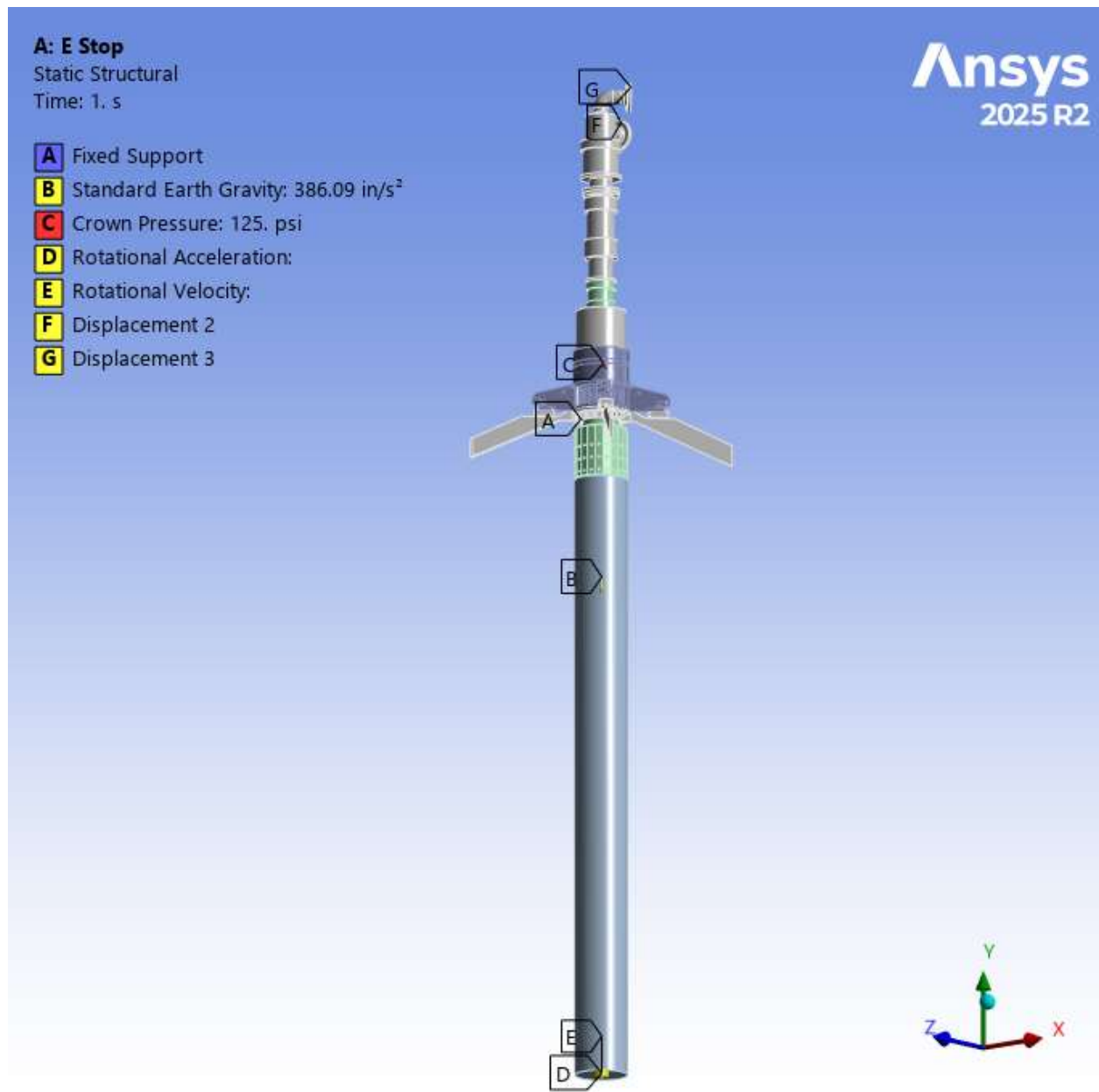


Figure 383 Crown and Drive, E Stop Load Summary

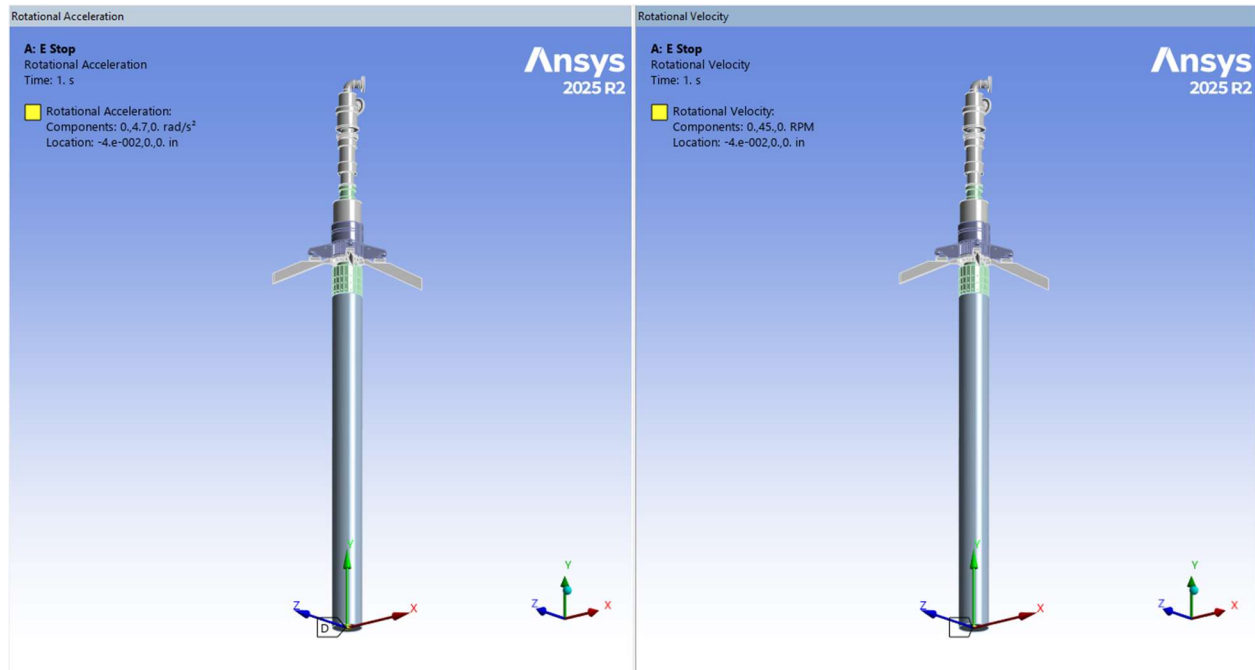


Figure 384 Crown and Drive, E Stop Rotational Acceleration and Velocity

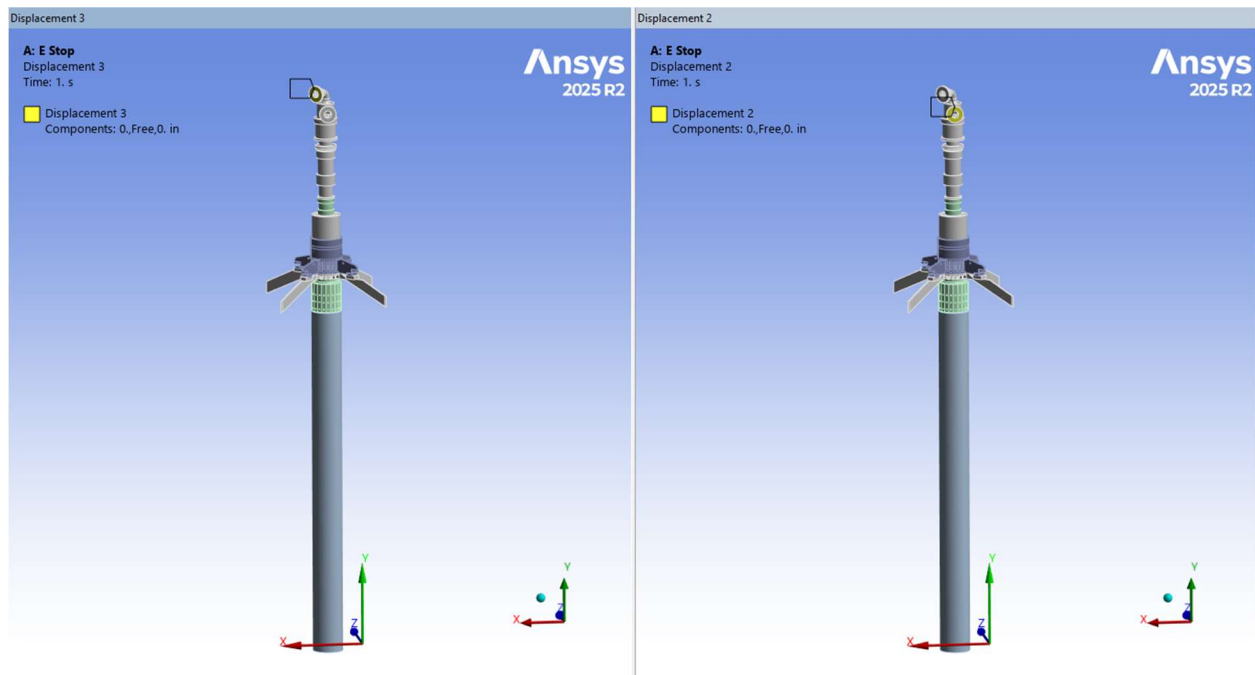


Figure 385 Crown and Drive, E Stop Displacement Constraints

4.6.4.2 Elastic Case 6, Seismic

Table 31 Drive, Elastic 6

Load Case	Time	P	D	L	L	T	E
6	1	125 psi	1g				169 in/s ²

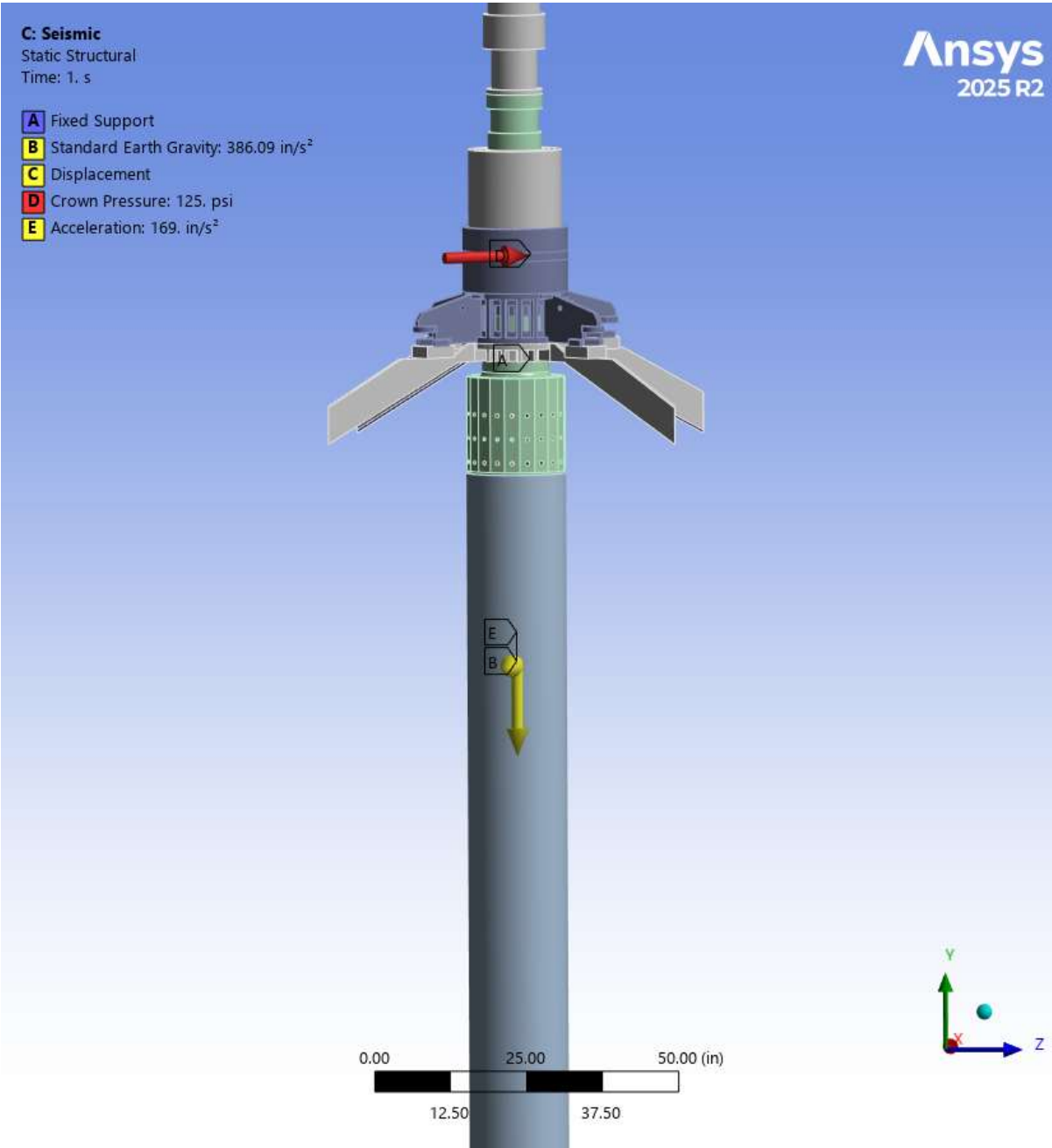


Figure 386 Crown and Drive, Seismic Load Cases

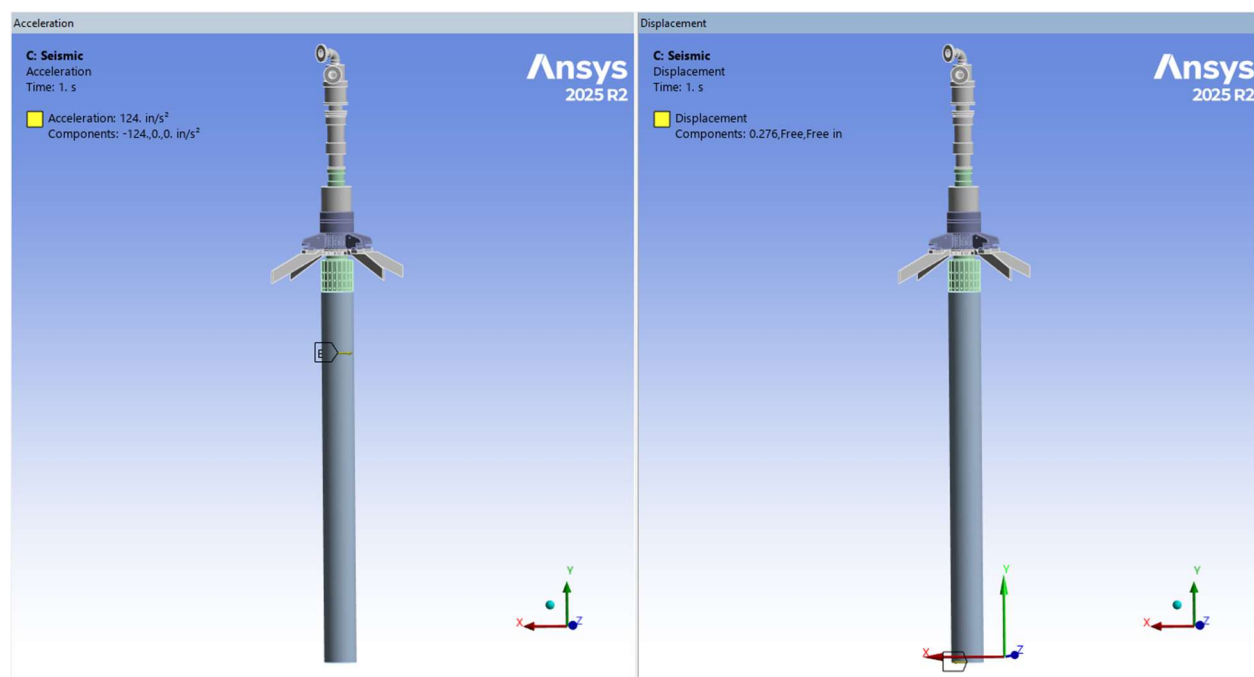


Figure 387 Crown and Drive, Seismic Acceleration and Displacement

4.6.4.3 Elastic Case 8, Seismic + Stop

Table 32 Drive, Elastic 8

Load Case	Time	P	D	L	L	T	E
8	1	125 psi	1g	3.5 rad/s ²	34 rpm		127 in/s ²

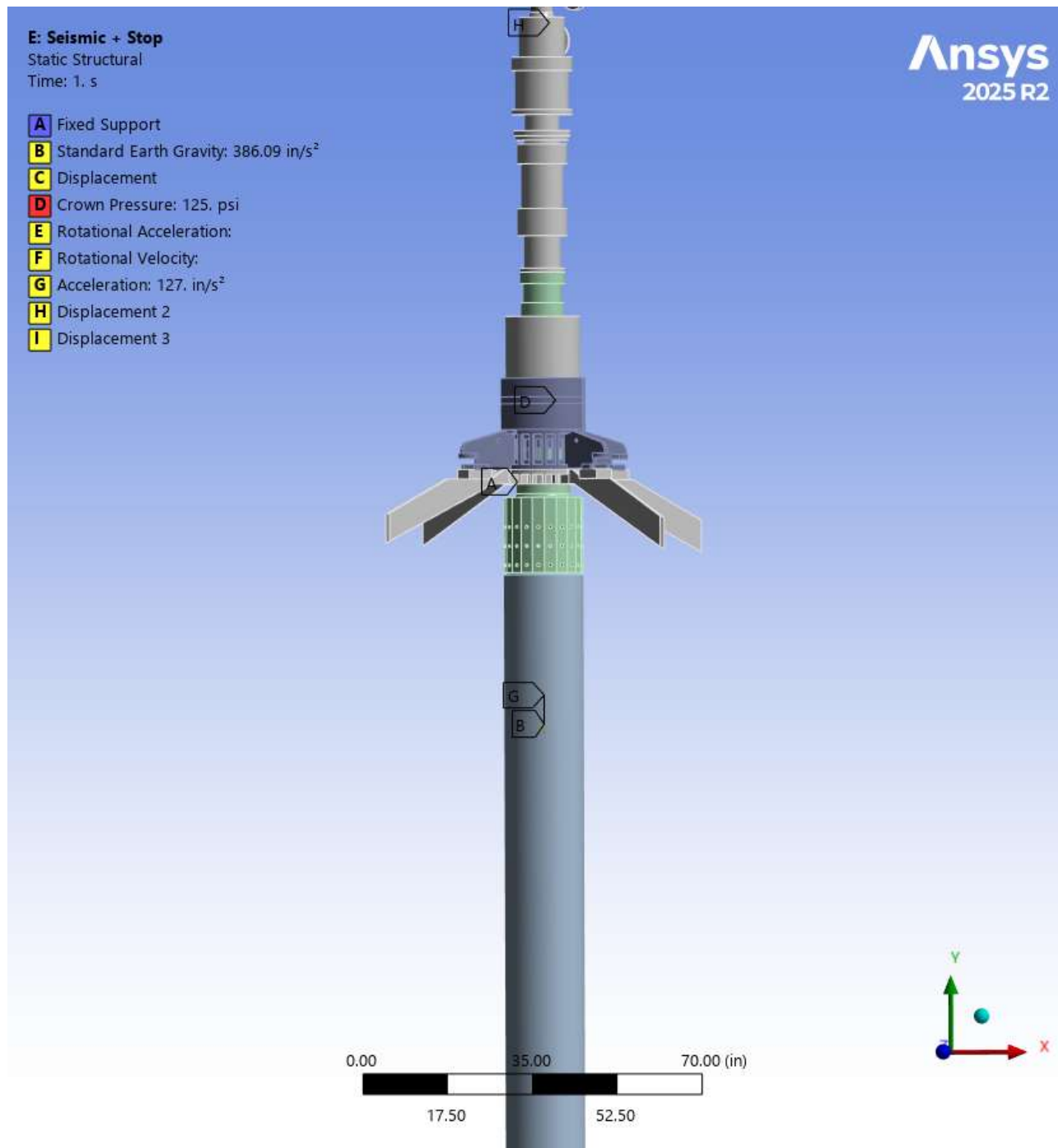


Figure 388 Crown and Drive, Seismic + Stop Load Cases

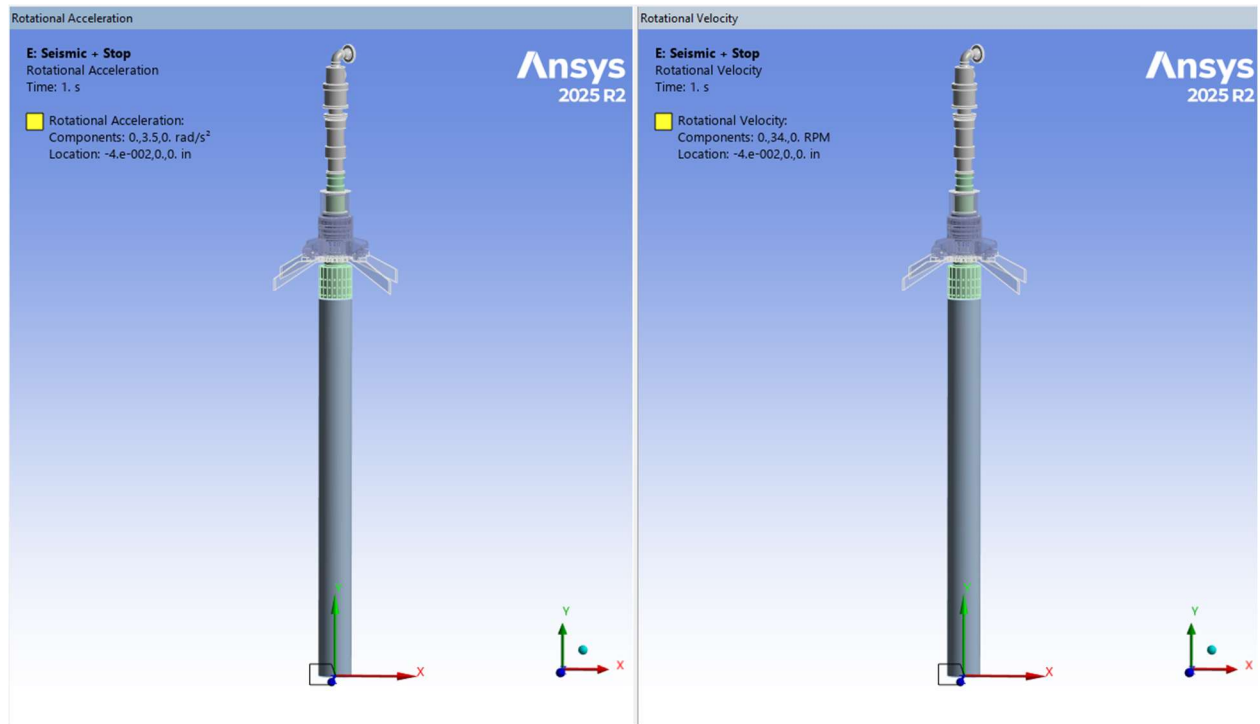


Figure 389 Crown and Drive, Seismic + Stop Rotational Acceleration and Velocity

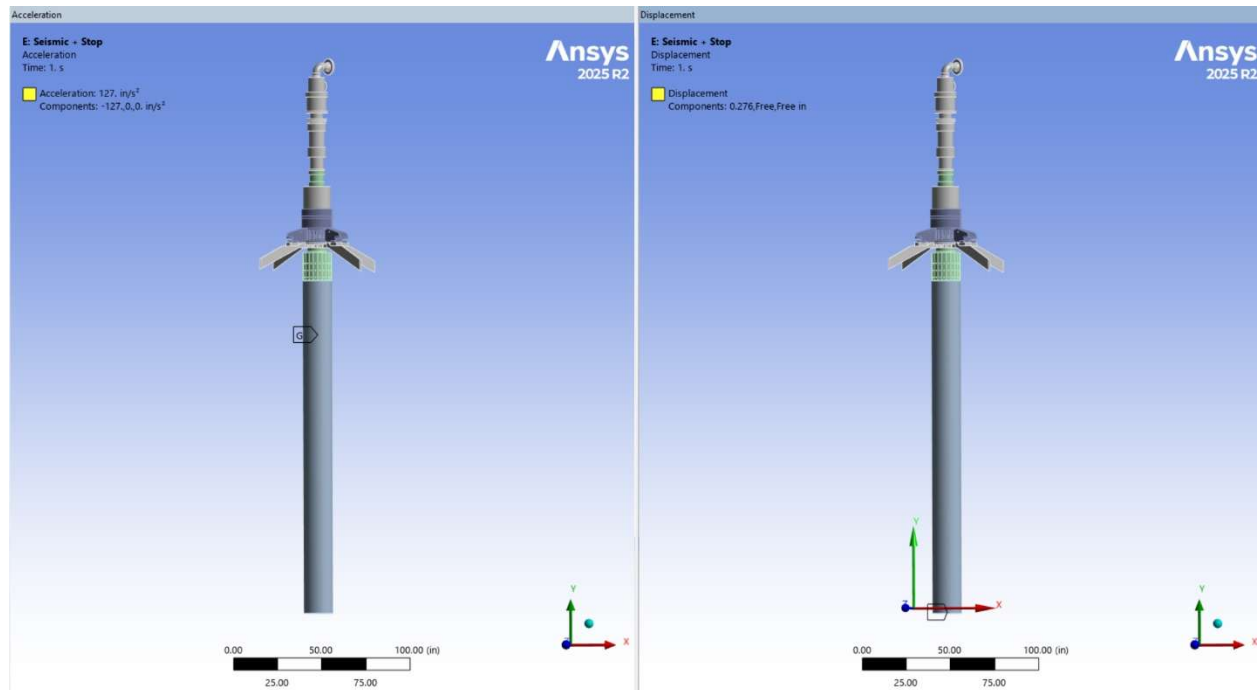


Figure 390 Crown and Drive, Seismic + Stop Acceleration and Displacement

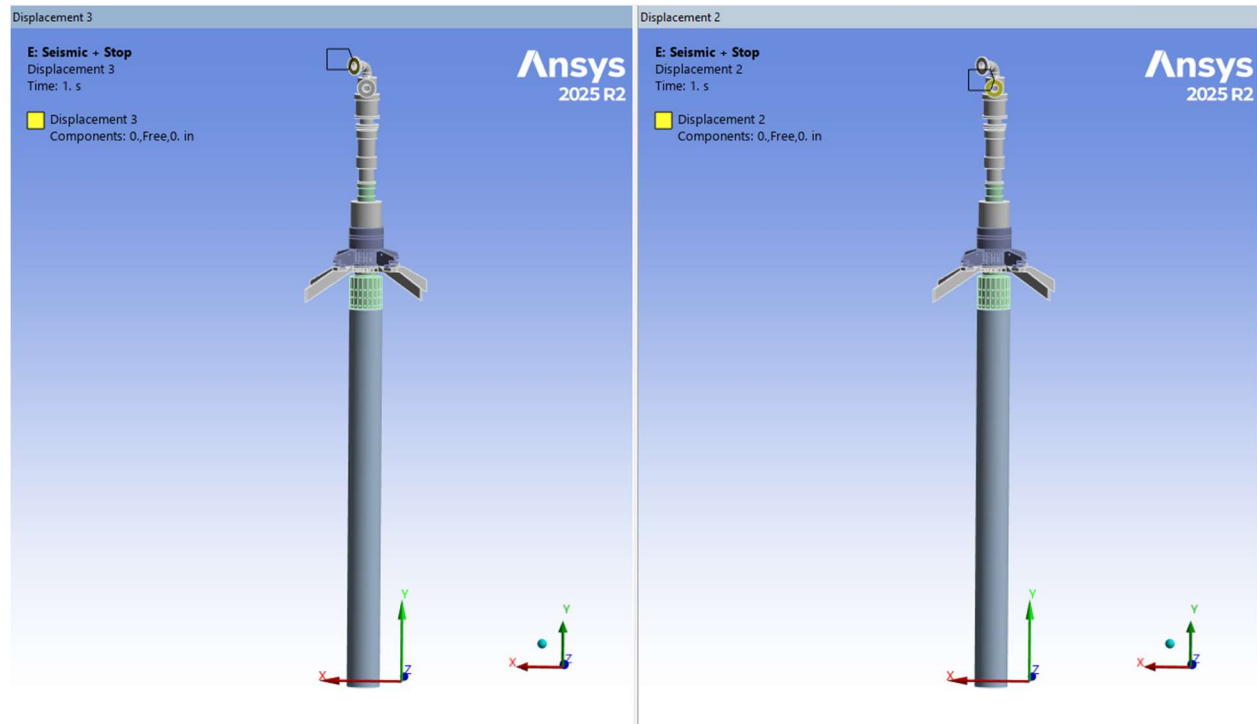


Figure 391 Crown and Drive, Seismic + Stop Displacement Constraints

4.6.4.4 Elastic Plastic Case 1

Table 33 Drive, EP 1

Load Case	Time	P	D	L	L	T	E	Density Factor
EP 1	1	300 psi	386 in/s ²	4.7 rad/s ²	45 rpm			2.4X

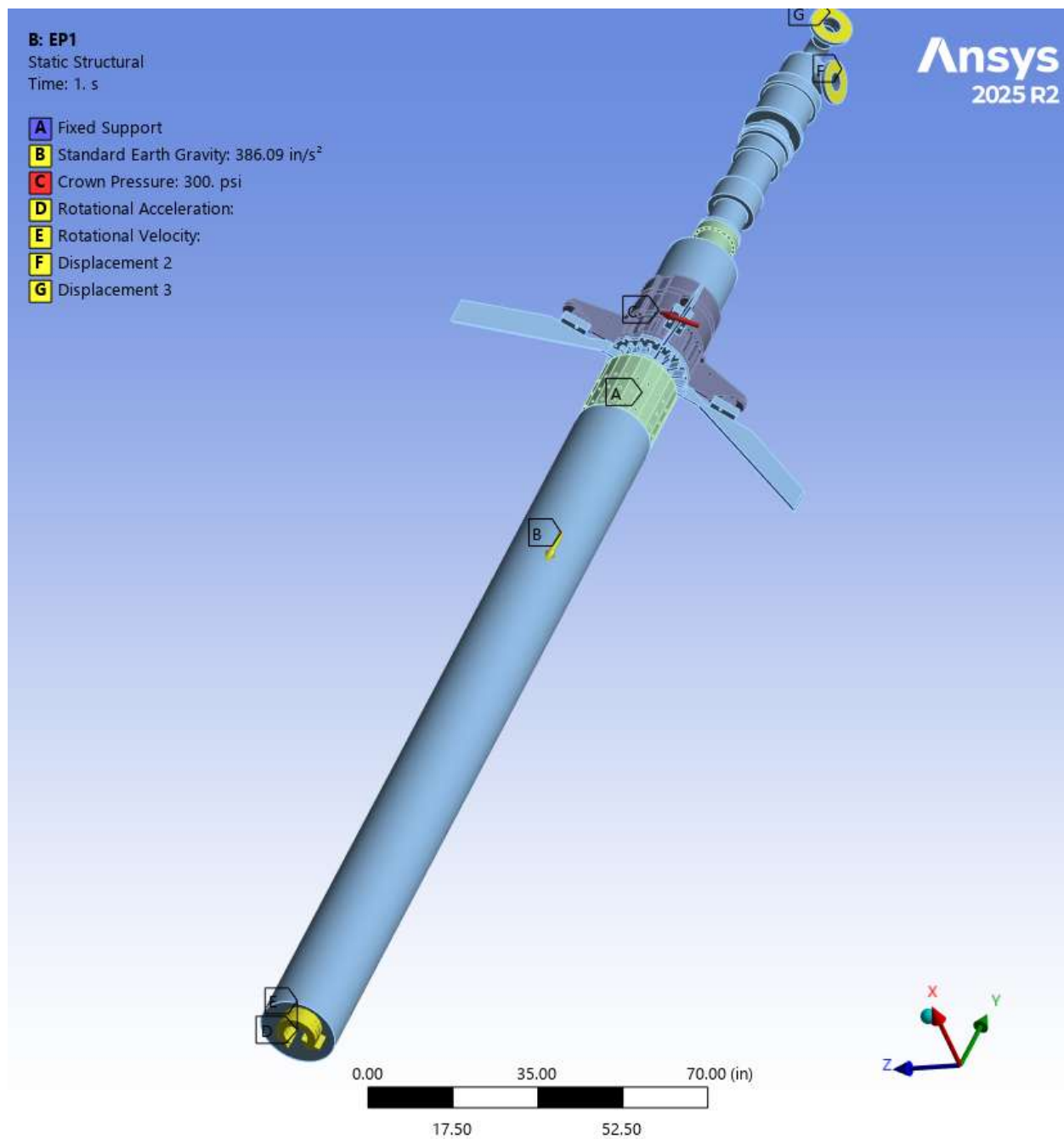


Figure 392 Crown and Drive, Elastic Plastic Load Case 1

Engineering Data: Material View	
 LC Steel Elastic Plastic 2.4	 
Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1	
Density	0.68064 lbm/in ³
Engineering Data: Material View	
 625 Elastic Plastic 2.4	 
Density	0.73198 lbm/in ³
Engineering Data: Material View	
 316 2.4	 
Sample data representative of 316 Stainless Steel	
Density	0.68967 lbm/in ³
Engineering Data: Material View	
 Shaft 2.4	 
Sample data representative of 316 Stainless Steel	
Density	2.167 lbm/in ³

Figure 393 Crown and Drive, EP1 Density Factor

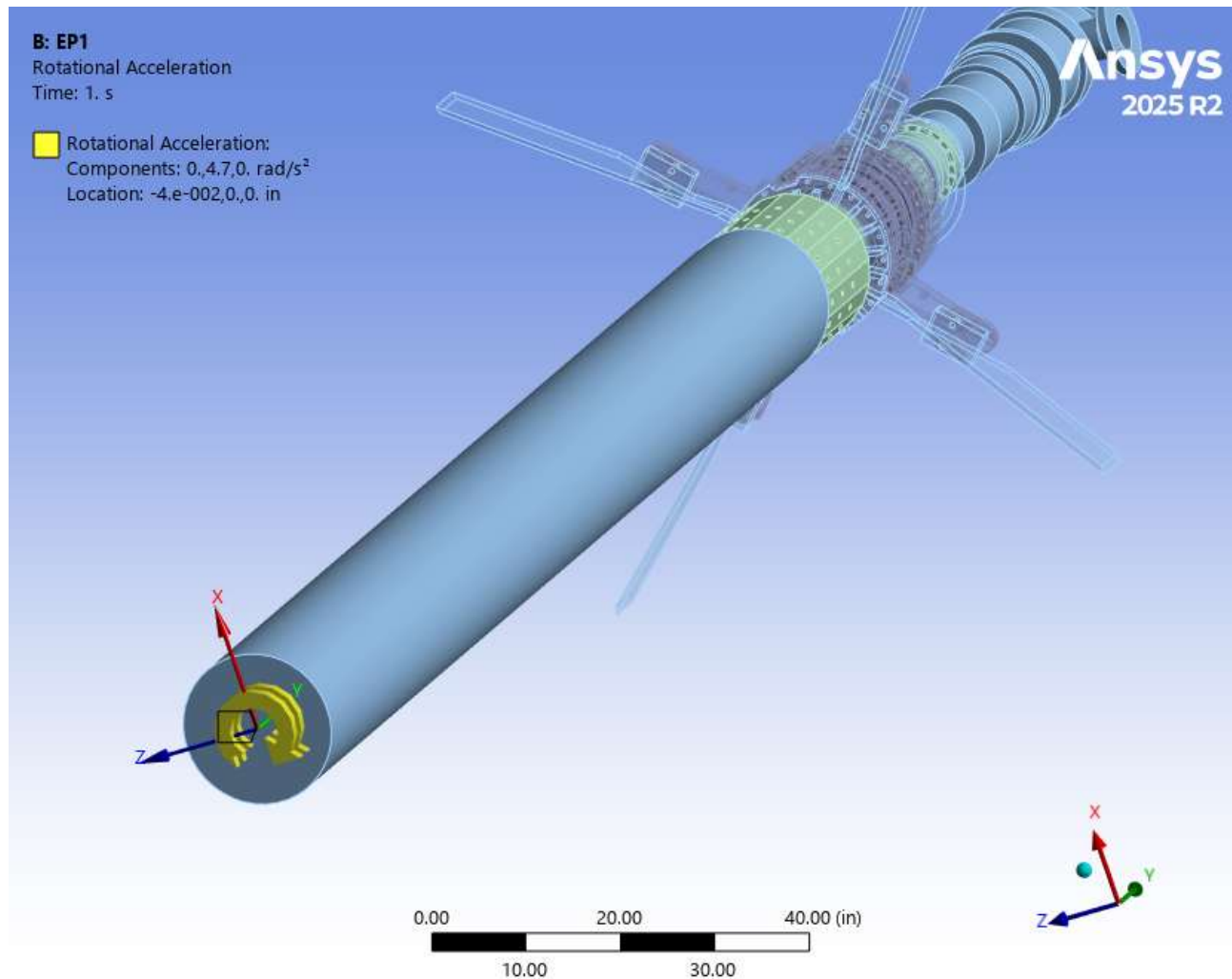


Figure 394 Crown and Drive, EP1 Rotational Acceleration

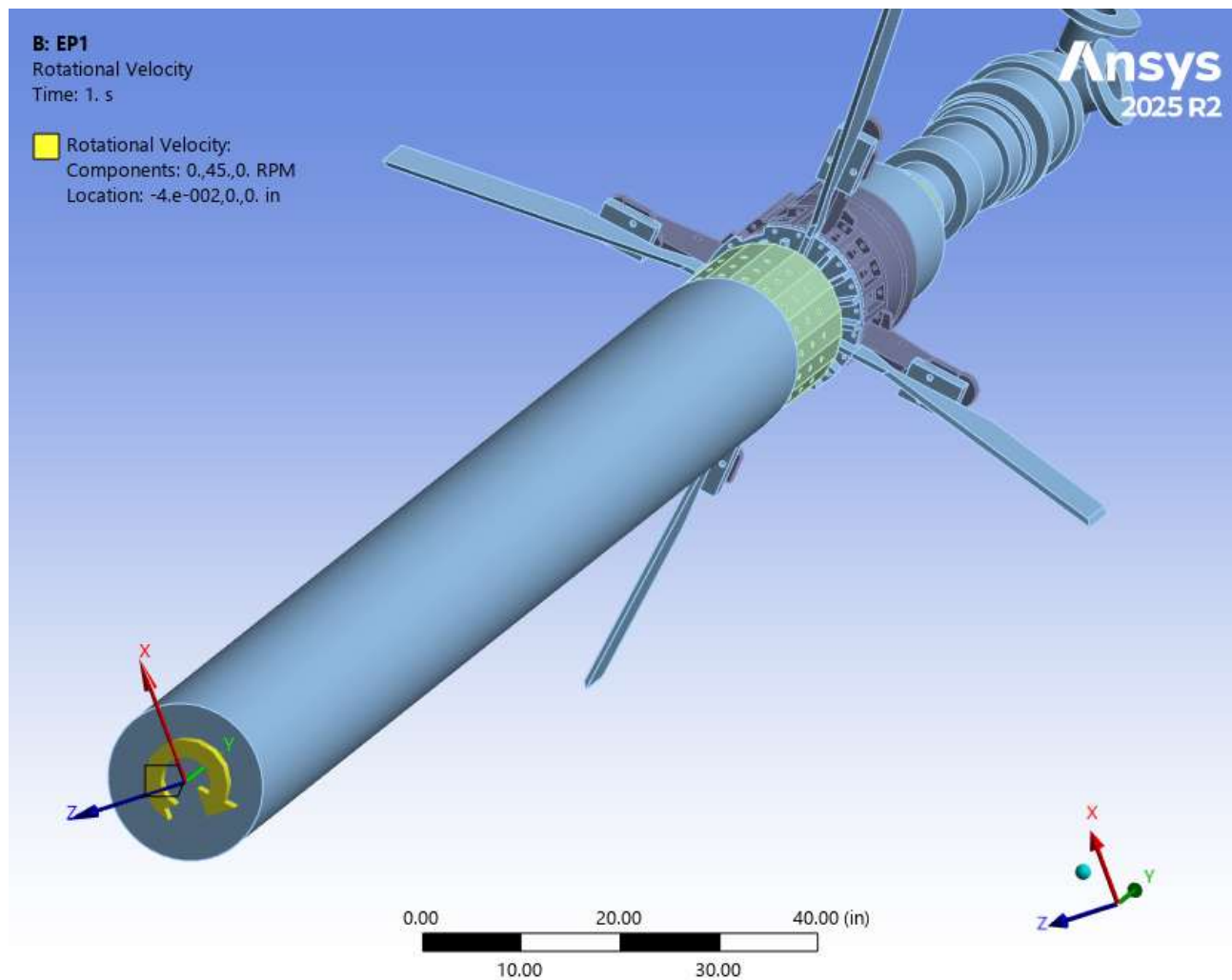


Figure 395 Crown and Drive, EP1 Rotational Velocity

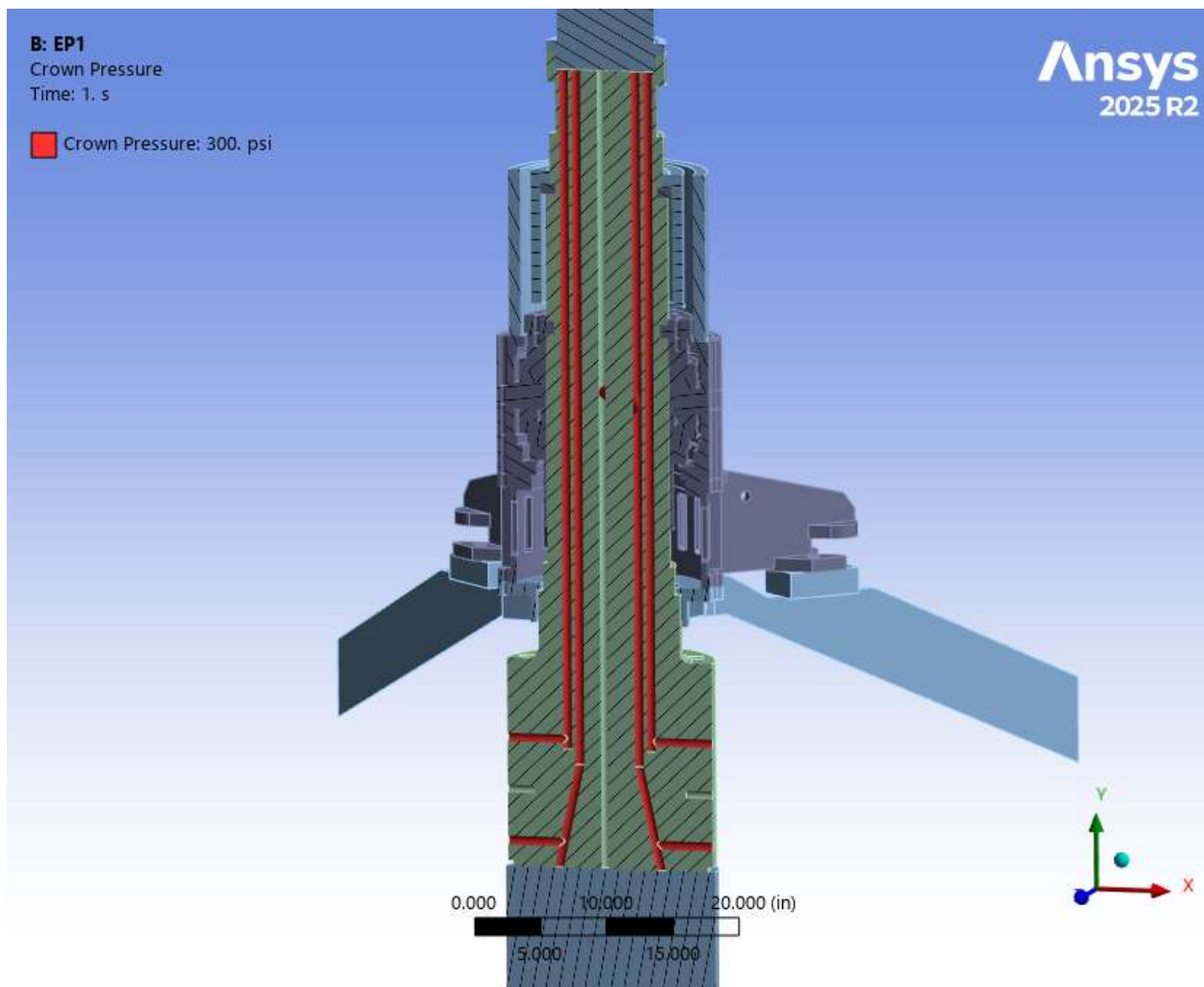


Figure 396 Crown and Drive, EP1 Pressure

4.6.4.5 Elastic Plastic Case 2

Table 34 Drive, EP2

Load Case	Time	P	D	L	L	T	E	Density Factor
EP 2	1	264 psi	302 in/s ²	4.7 rad/s ²	45 rpm	Imported		2.7X

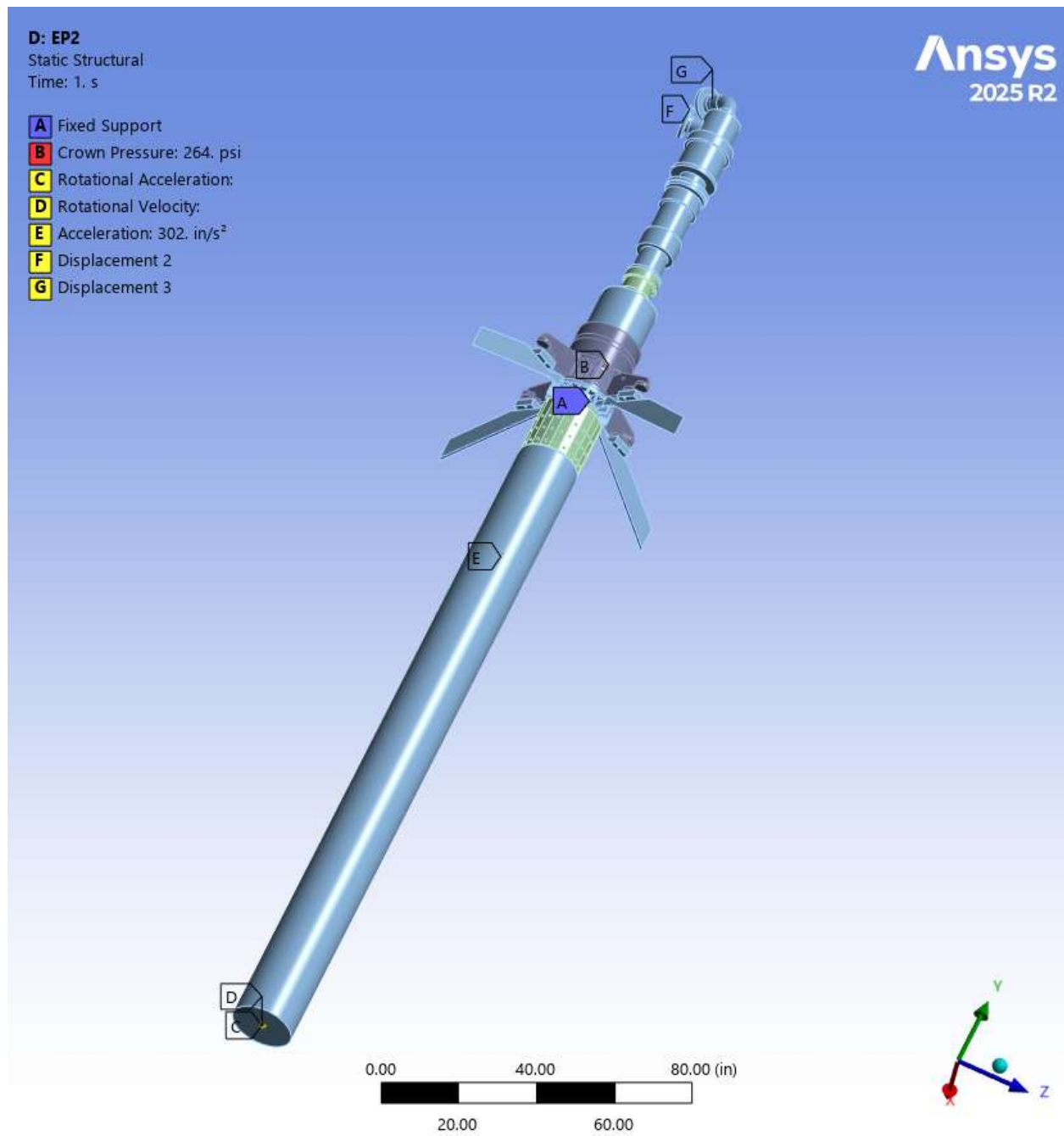


Figure 397 Crown and Drive, Elastic Plastic Load Case 2

Engineering Data: Material View	
 LC Steel Elastic Plastic 2.7	 
Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1	
Density	0.7659 lbm/in ³
Engineering Data: Material View	
 316 2.7	 
Sample data representative of 316 Stainless Steel	
Density	0.77601 lbm/in ³
Engineering Data: Material View	
 625 Elastic Plastic 2.7	 
Density	0.8237 lbm/in ³
Engineering Data: Material View	
 Shaft 2.7	 
Sample data representative of 316 Stainless Steel	
Density	2.44 lbm/in ³

Figure 398 Crown and Drive, EP2 Density Factors

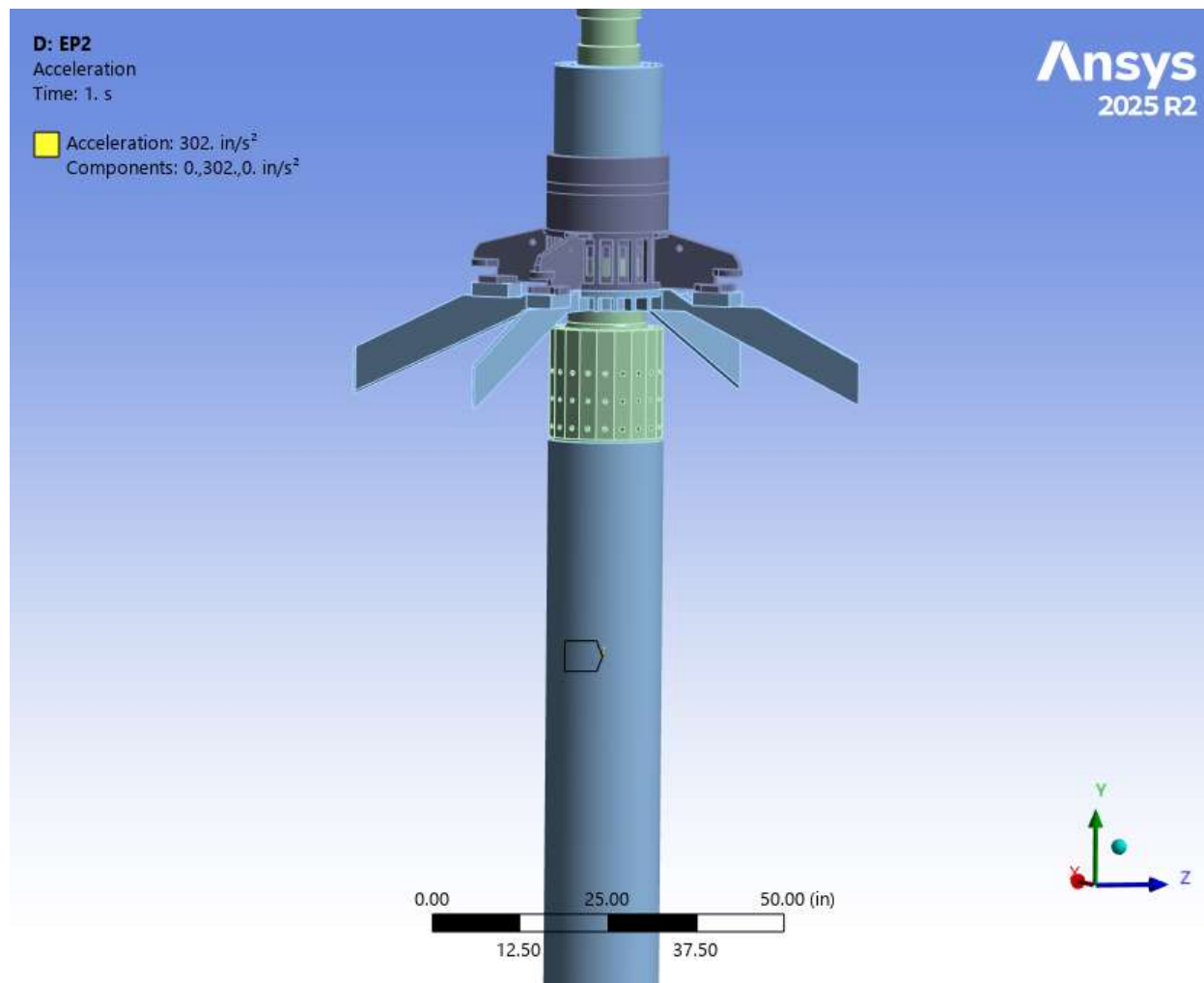


Figure 399 Crown and Drive, EP2 Acceleration

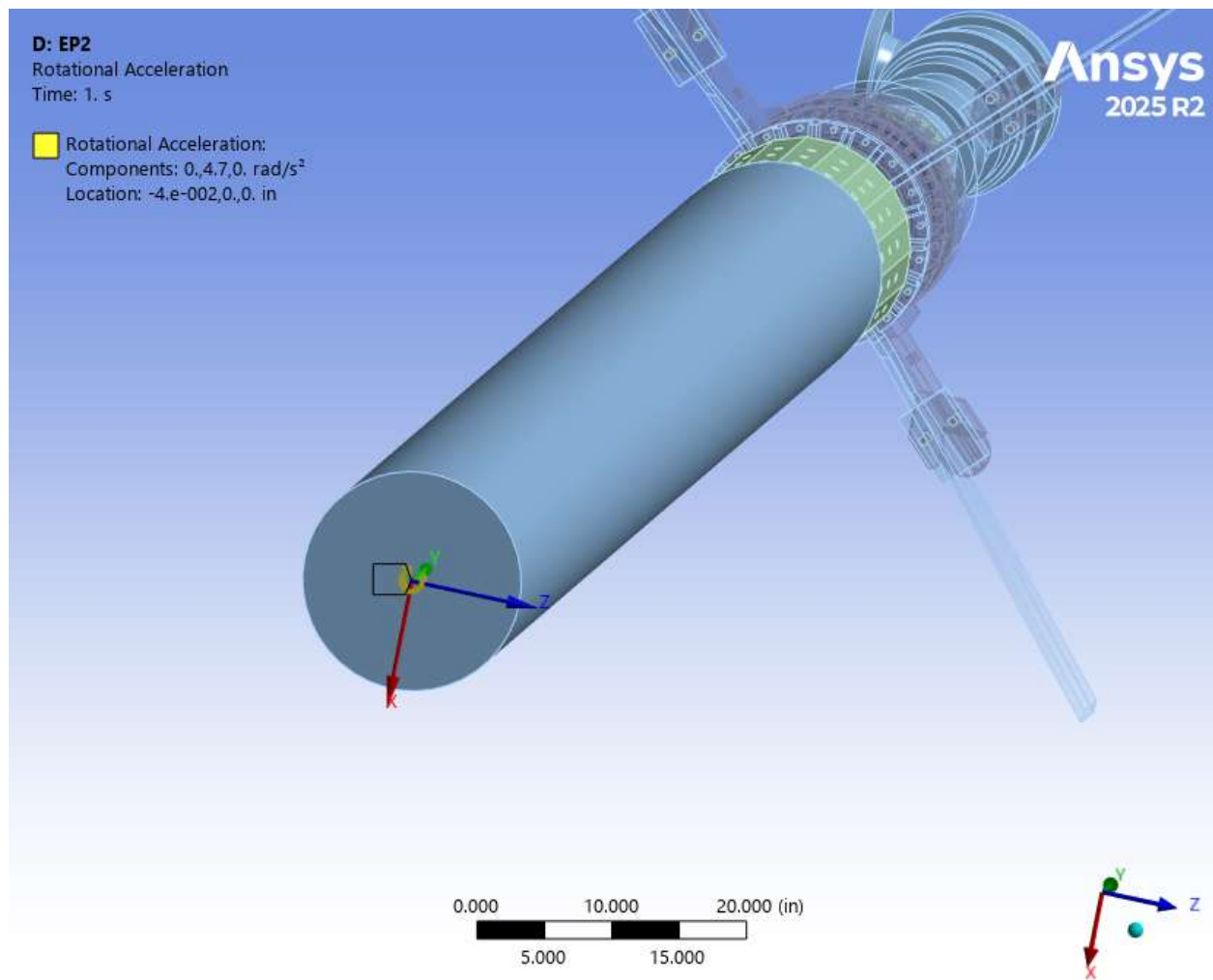


Figure 400 Crown and Drive, EP2 Rotational Acceleration

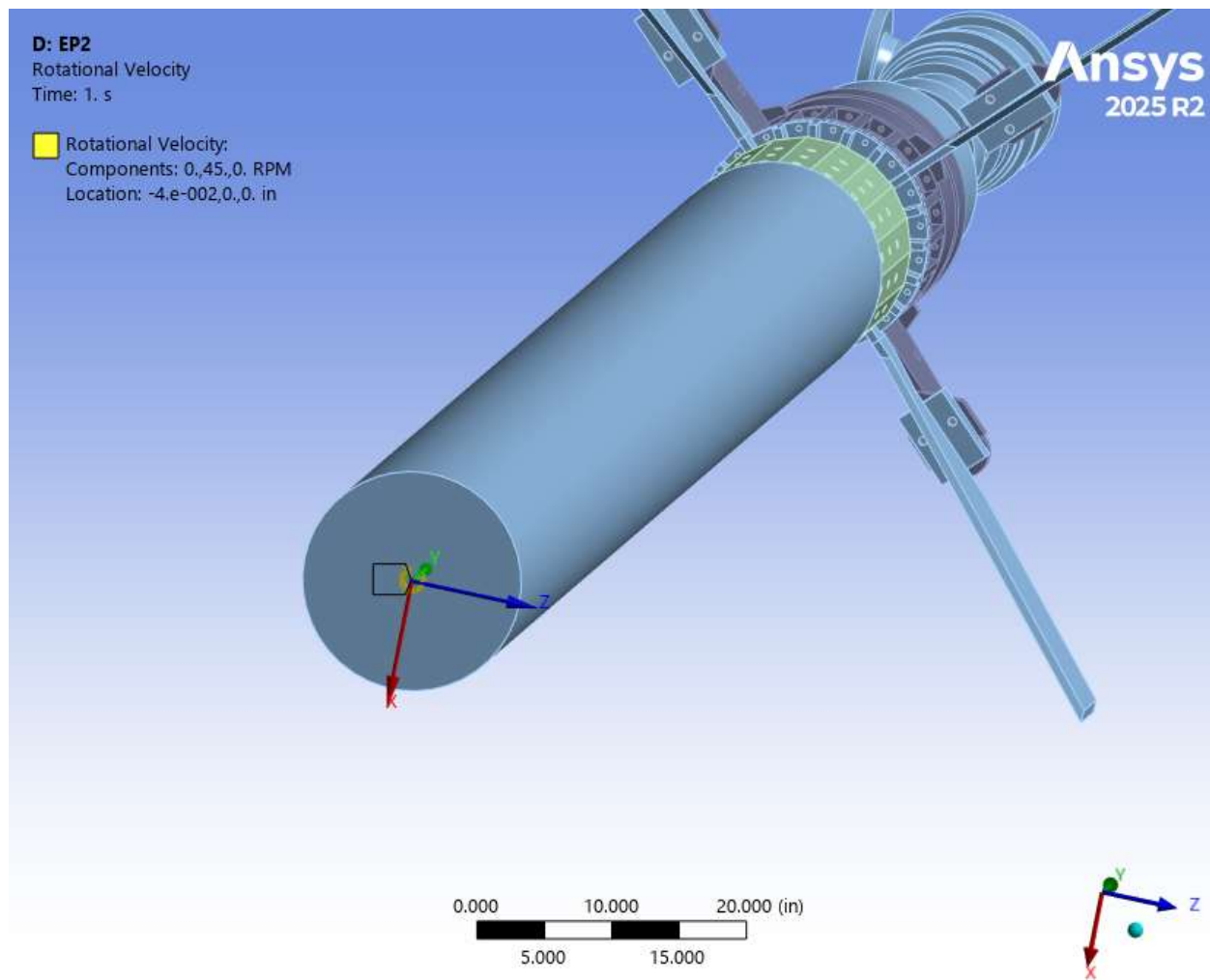


Figure 401 Crown and Drive, EP2 Rotational Velocity

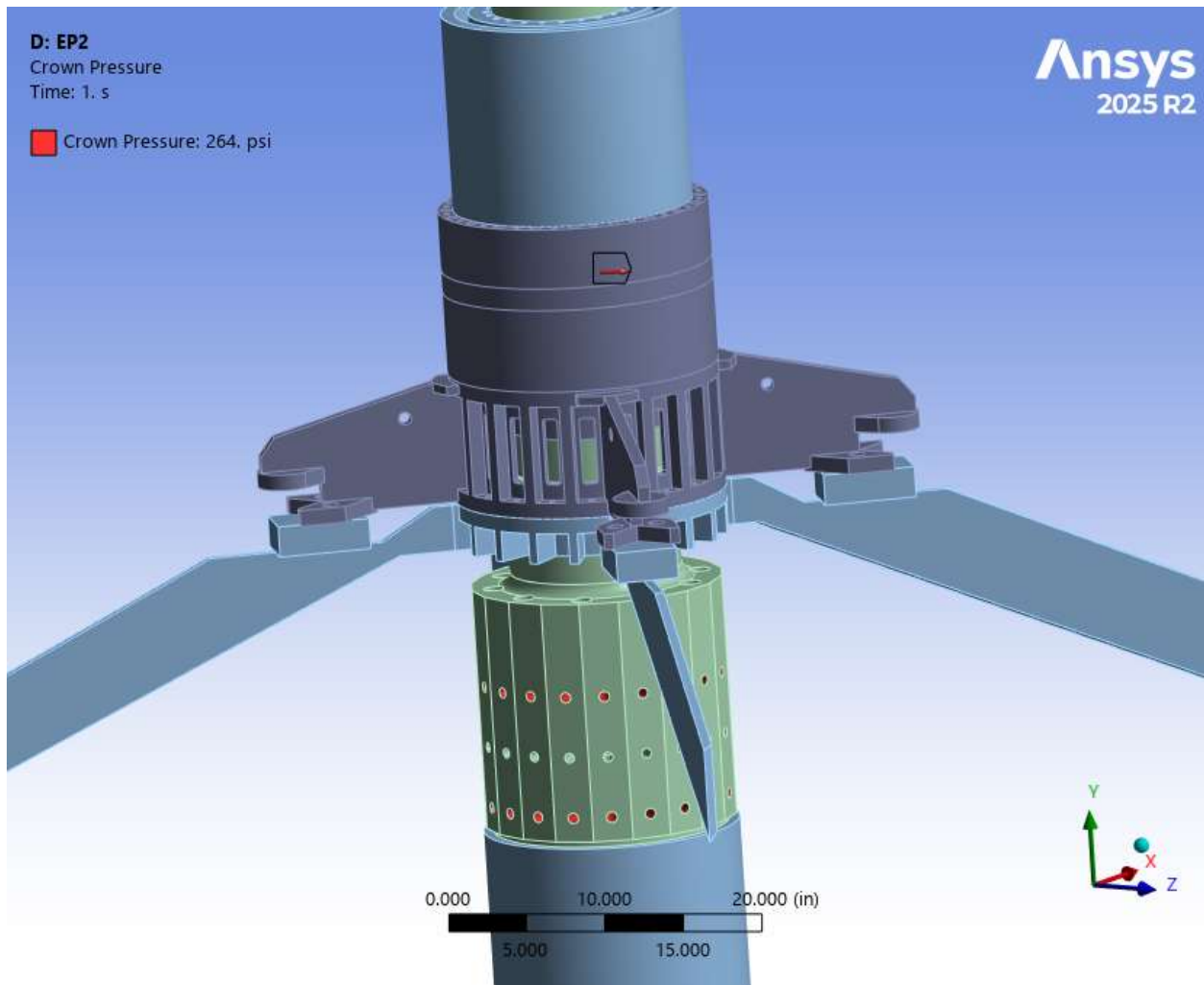


Figure 402 Crown and Drive, EP2 Pressure

4.6.4.6 Elastic Plastic Case 5

Table 35 Drive, EP 5

Load Case	Time	P	D	L	L	T	E	Density Factor
EP5	1	264 psi	480 in/s ²	4.7 rad/s ²	45 rpm	Imported	411 in/s ²	1.7X

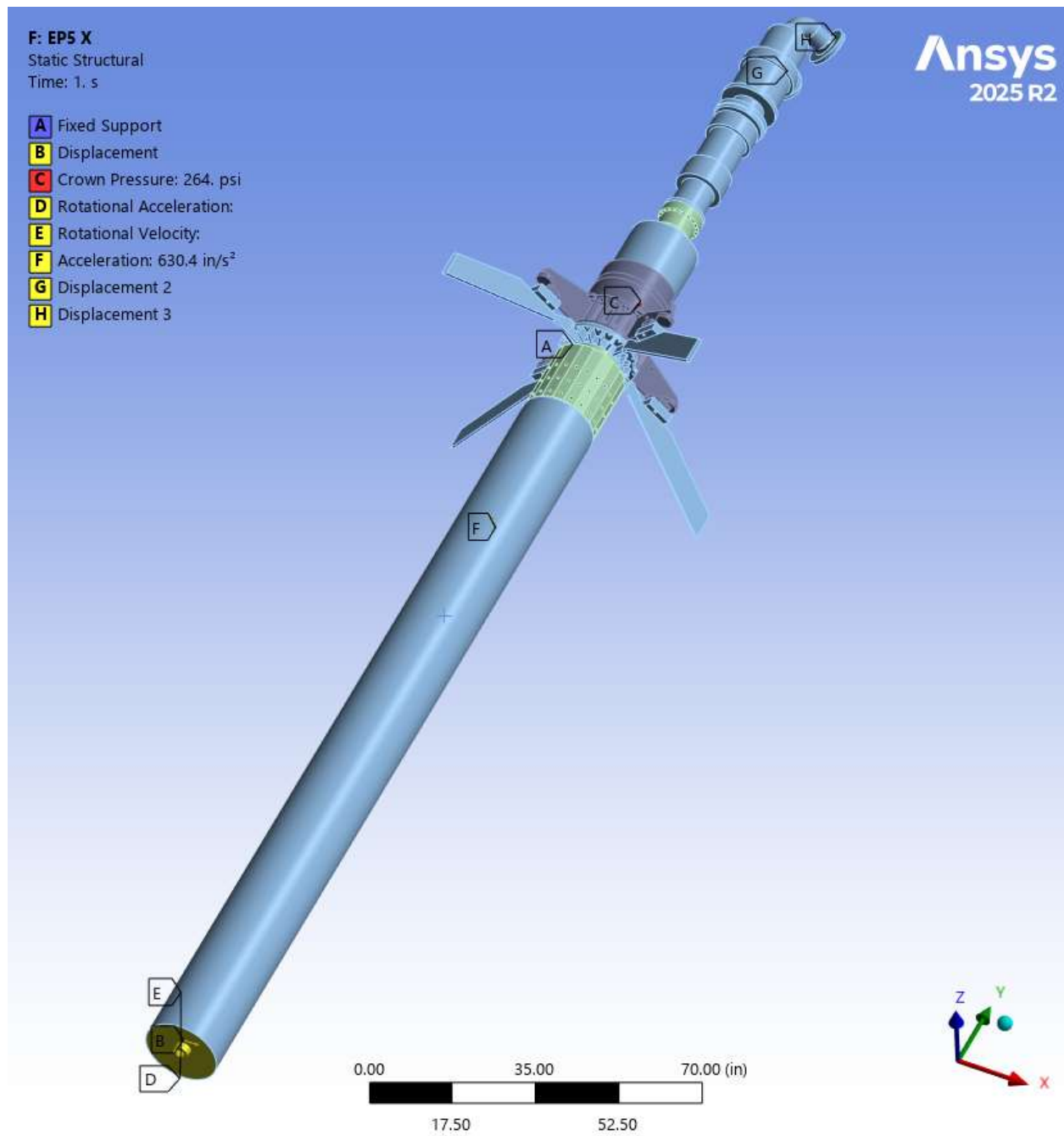


Figure 403 Crown and Drive, Elastic Plastic Load Case 5

Engineering Data: Material View	
 LC Steel Elastic Plastic 1.7	 
Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1	
Density	0.48212 lbm/in ³
Engineering Data: Material View	
 316 1.7	 
Sample data representative of 316 Stainless Steel	
Density	0.48851 lbm/in ³
Engineering Data: Material View	
 625 Elastic Plastic 1.7	 
Density	0.51846 lbm/in ³
Engineering Data: Material View	
 Shaft 1.7	 
Sample data representative of 316 Stainless Steel	
Density	1.535 lbm/in ³

Figure 404 Crown and Drive, EP5 Density Factor

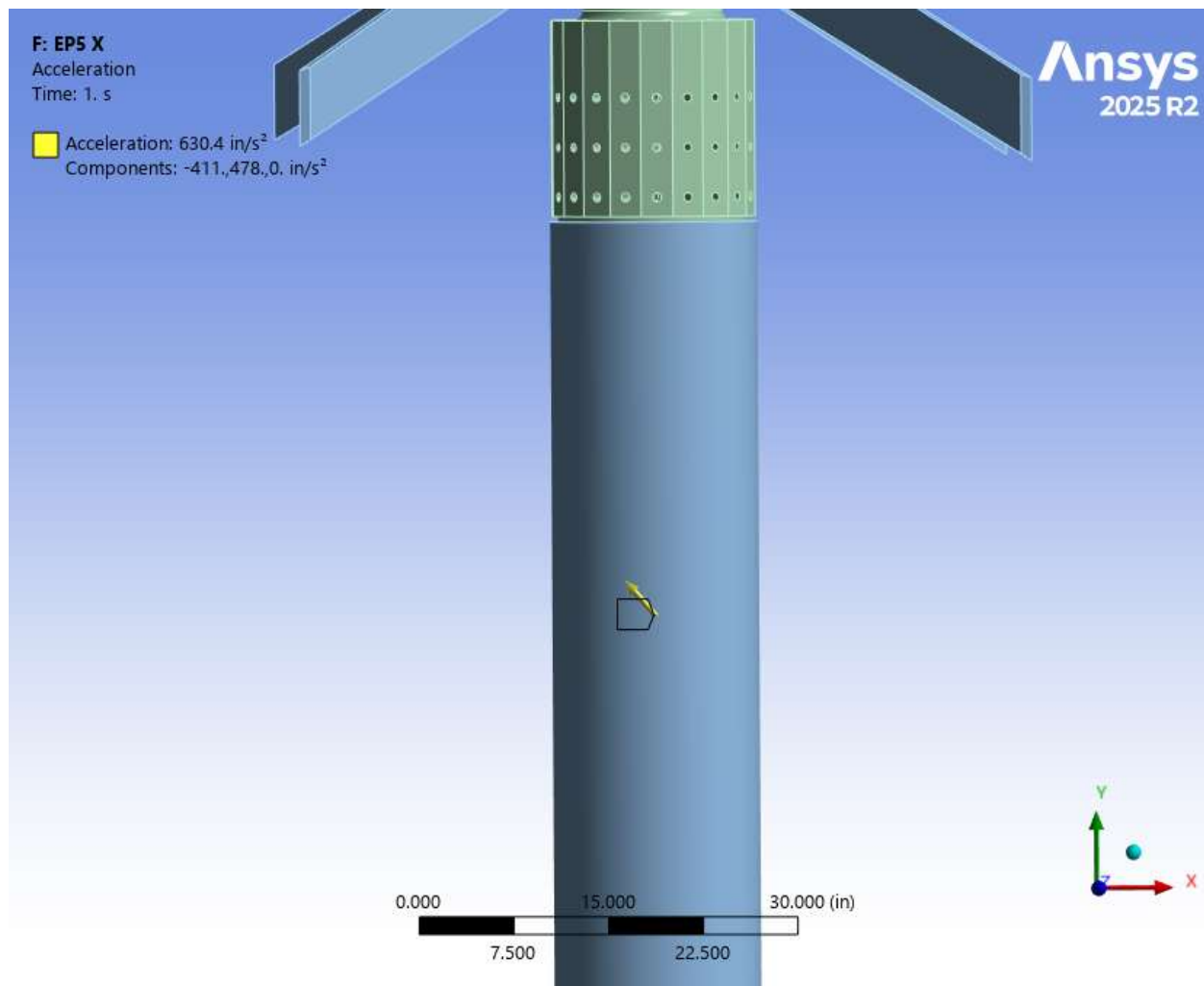


Figure 405 Crown and Drive, EP5 Accelerations

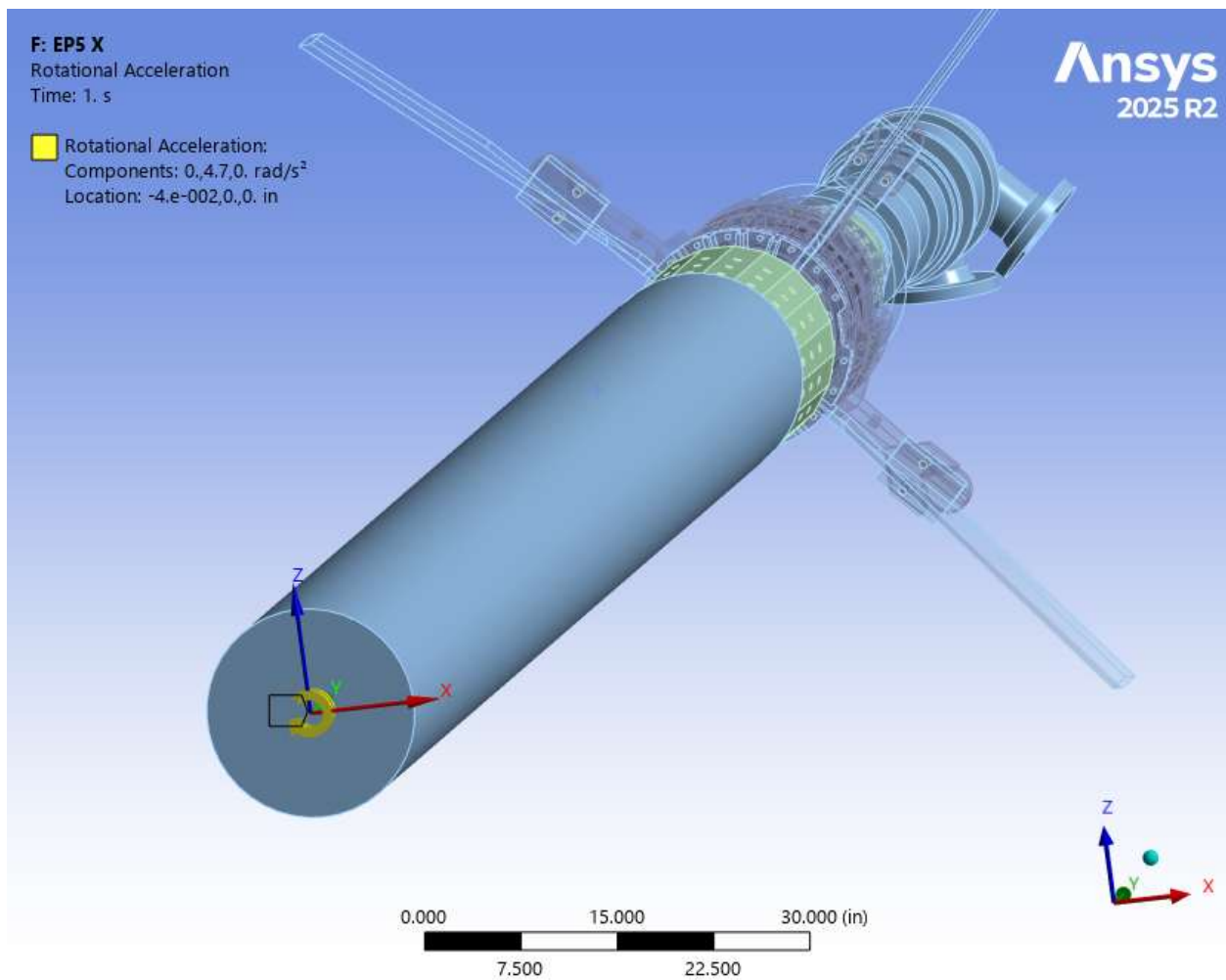


Figure 406 Crown and Drive, EP5 Rotational Acceleration

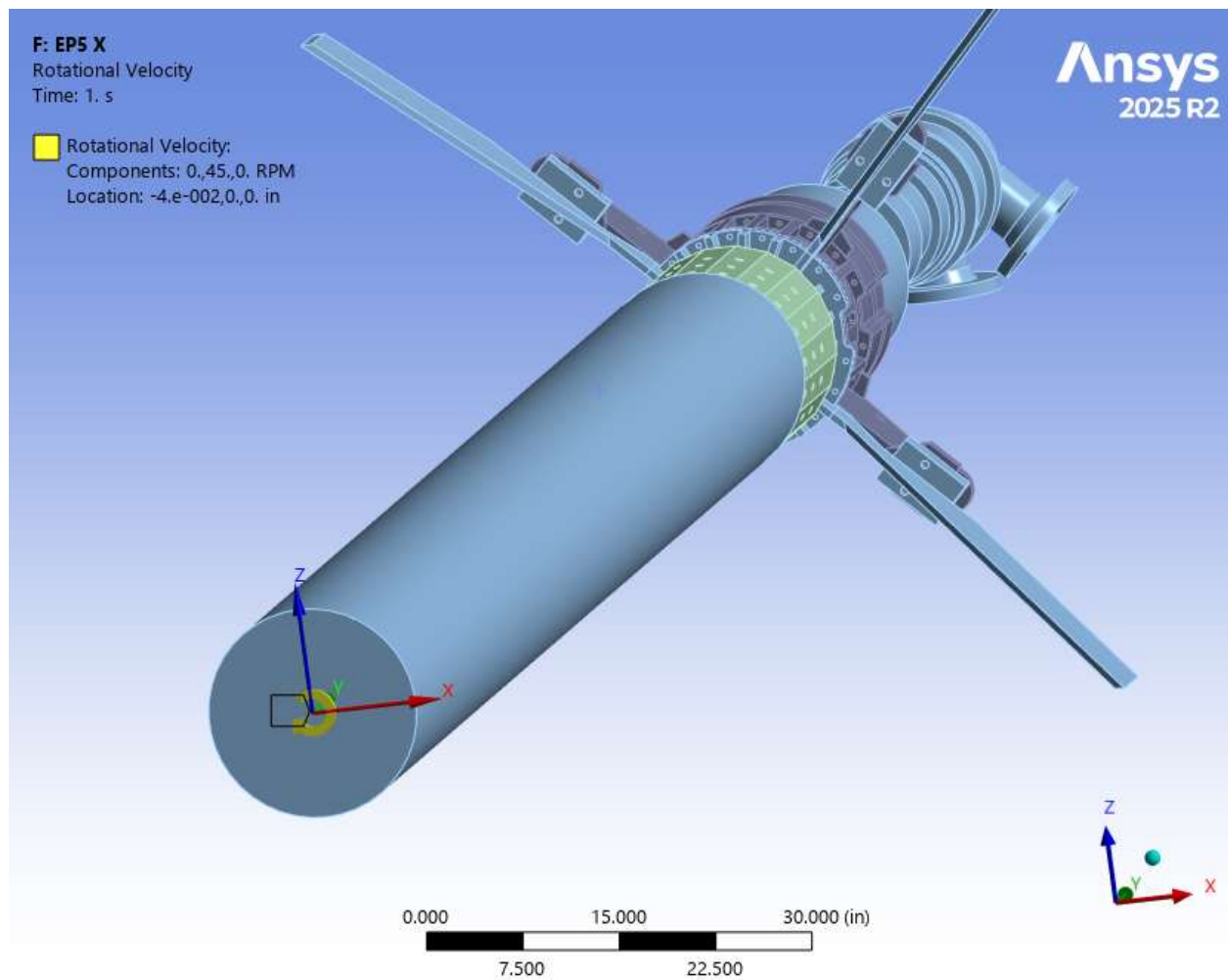


Figure 407 Crown and Drive, EP5 Rotational Velocity

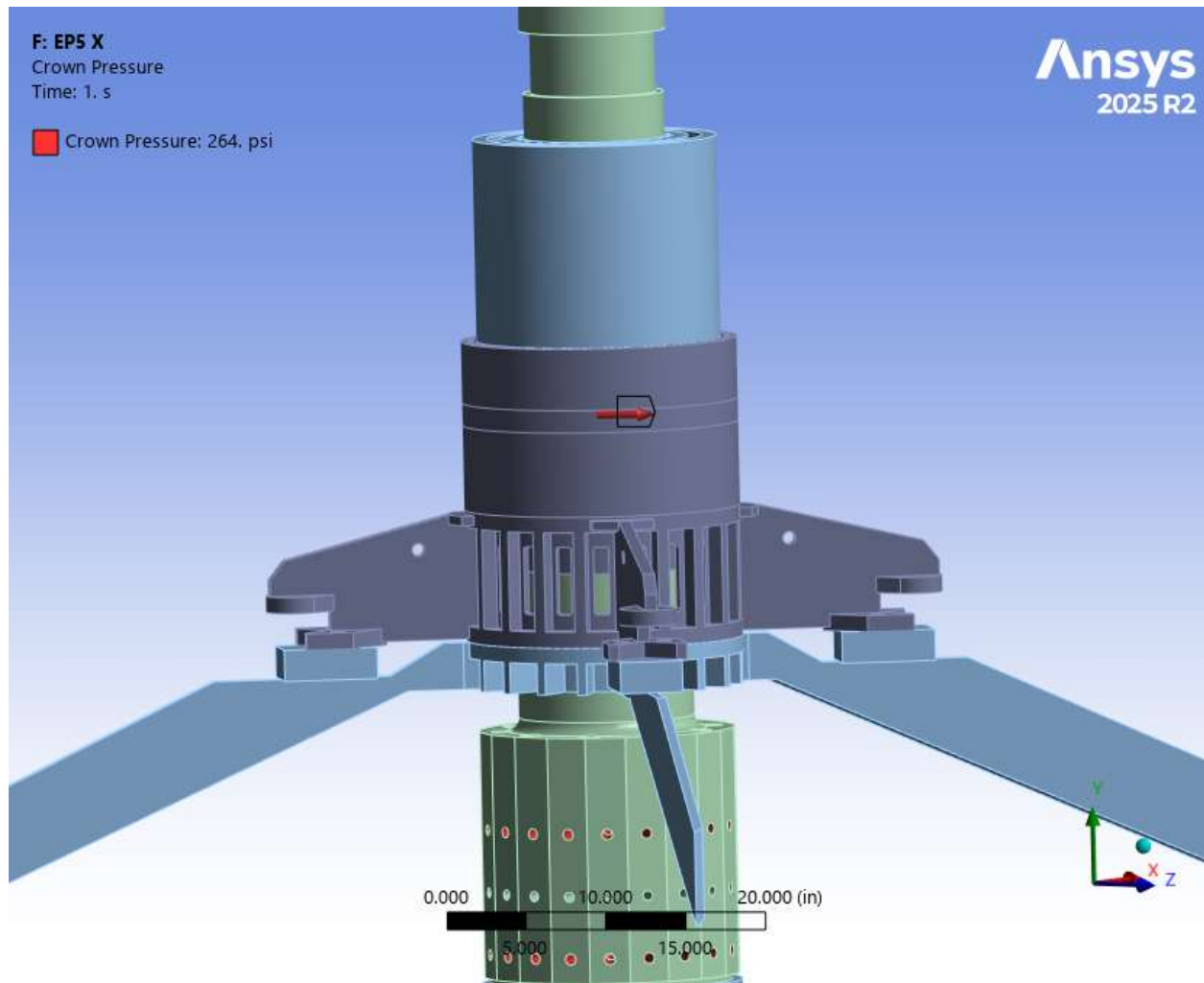


Figure 408 Crown and Drive, EP5 Pressure

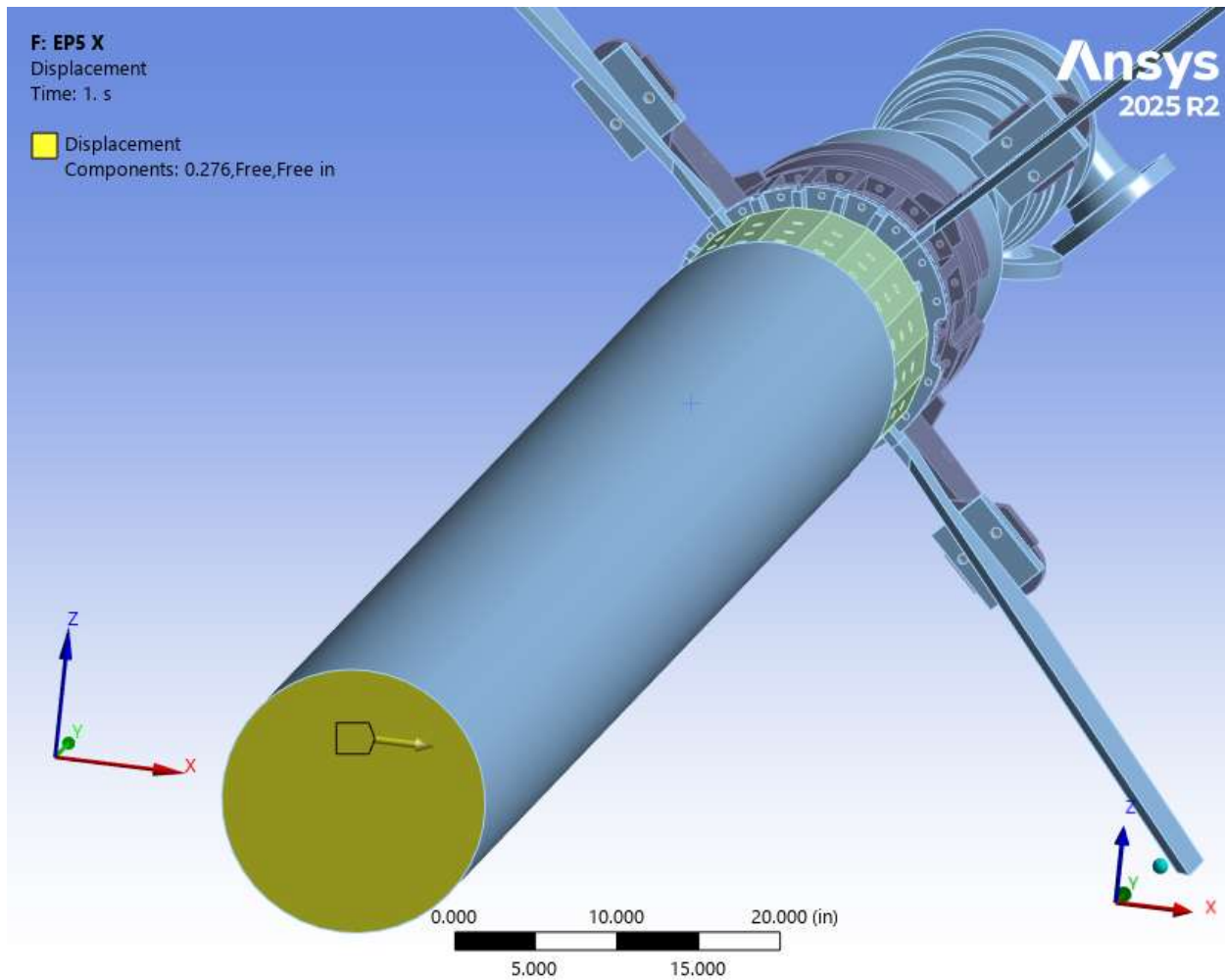


Figure 409 Crown and Drive, EP5 Displacement

4.7 SOLUTION METHODOLOGY

4.7.1 Target Assembly Analysis Settings

The Target Assembly model is a linear static structural analysis, this model is mainly used to satisfy the deflection requirements.

Details of "Analysis Settings" ▾ 🔍 ✕	
[-] Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
[-] Solver Controls	
Solver Type	Iterative
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Quasi-Static Solution	Off
[-] Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Combine Restart Files	Program Controlled
[-] Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Energy Convergence (Beta)	Program Controlled
Line Search	Program Controlled
Stabilization	Program Controlled
[-] Advanced	
Inverse Option	No
Contact Split (DMP)	Program Controlled
Semi Implicit (Beta)	Off
[-] Output Controls	
Output Selection	None
Stress	Yes
Back Stress	No
Strain	Yes
Contact Data	Yes
Nonlinear Data	No
Nodal Forces	Yes
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Cache Results in Memory (Beta)	Never
Combine Distributed Result Fil...	Program Controlled
Result File Compression	Program Controlled
[-] Analysis Data Management	
Solver Files Directory	C:\Users\qys\Desktop\TA\Target_Assembly_file...
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	No
Solver Units	Active System
Solver Unit System	Bin
[+] Visibility	

Figure 410 Target Assembly Analysis Settings

```

Time at end of element matrix formulation CP = 989.0625.
Iteration=      5 Ratio= 0.262318 Limit= 1.000000E-08 Wall=      3.0
Iteration=     65 Ratio= 3.361048E-02 Limit= 1.000000E-08 Wall=     63.8
Iteration=    140 Ratio= 8.786988E-03 Limit= 1.000000E-08 Wall=    141.4
Iteration=    285 Ratio= 2.297694E-02 Limit= 1.000000E-08 Wall=    303.5
Iteration=    525 Ratio= 9.621235E-04 Limit= 1.000000E-08 Wall=    575.9
Iteration=    600 Ratio= 4.754737E-04 Limit= 1.000000E-08 Wall=    665.3
Iteration=    670 Ratio= 4.696125E-04 Limit= 1.000000E-08 Wall=    753.6
Iteration=    725 Ratio= 3.200324E-04 Limit= 1.000000E-08 Wall=    819.8
Iteration=    850 Ratio= 3.948699E-04 Limit= 1.000000E-08 Wall=    970.5
Iteration=    925 Ratio= 2.938854E-04 Limit= 1.000000E-08 Wall=   1048.3
Iteration=   1130 Ratio= 1.312530E-04 Limit= 1.000000E-08 Wall=   1268.2
Iteration=   1240 Ratio= 9.471181E-05 Limit= 1.000000E-08 Wall=   1383.3
Iteration=   1320 Ratio= 9.051992E-05 Limit= 1.000000E-08 Wall=   1468.2
Iteration=   1395 Ratio= 6.206821E-05 Limit= 1.000000E-08 Wall=   1546.3
Iteration=   1460 Ratio= 3.451905E-05 Limit= 1.000000E-08 Wall=   1612.8
Iteration=   1560 Ratio= 1.808168E-05 Limit= 1.000000E-08 Wall=   1714.8
Iteration=   1665 Ratio= 9.548581E-06 Limit= 1.000000E-08 Wall=   1819.9
Iteration=   1730 Ratio= 7.084216E-06 Limit= 1.000000E-08 Wall=   1885.1
Iteration=   1890 Ratio= 4.042431E-06 Limit= 1.000000E-08 Wall=   2059.3
Iteration=   1955 Ratio= 3.152710E-06 Limit= 1.000000E-08 Wall=   2126.2
Iteration=   2045 Ratio= 2.373502E-06 Limit= 1.000000E-08 Wall=   2214.6
Iteration=   2105 Ratio= 1.693392E-06 Limit= 1.000000E-08 Wall=   2275.8
Iteration=   2240 Ratio= 1.271193E-06 Limit= 1.000000E-08 Wall=   2412.9
Iteration=   2320 Ratio= 7.934702E-07 Limit= 1.000000E-08 Wall=   2495.8
Iteration=   2415 Ratio= 4.828879E-07 Limit= 1.000000E-08 Wall=   2589.2
Iteration=   2505 Ratio= 5.667643E-07 Limit= 1.000000E-08 Wall=   2676.2
Iteration=   2575 Ratio= 4.764044E-07 Limit= 1.000000E-08 Wall=   2742.5
Iteration=   2665 Ratio= 5.016260E-07 Limit= 1.000000E-08 Wall=   2825.2
Iteration=   2735 Ratio= 4.451231E-07 Limit= 1.000000E-08 Wall=   2890.1
Iteration=   2825 Ratio= 3.484615E-07 Limit= 1.000000E-08 Wall=   2974.8
Iteration=   2905 Ratio= 3.121899E-07 Limit= 1.000000E-08 Wall=   3051.4
Iteration=   2985 Ratio= 2.432920E-07 Limit= 1.000000E-08 Wall=   3133.9
Iteration=   3095 Ratio= 1.702718E-07 Limit= 1.000000E-08 Wall=   3244.4
Iteration=   3190 Ratio= 1.358114E-07 Limit= 1.000000E-08 Wall=   3338.5
Iteration=   3260 Ratio= 1.453689E-07 Limit= 1.000000E-08 Wall=   3405.9
Iteration=   3340 Ratio= 1.426744E-07 Limit= 1.000000E-08 Wall=   3484.6
Iteration=   3440 Ratio= 1.008001E-07 Limit= 1.000000E-08 Wall=   3584.6
Iteration=   3505 Ratio= 8.556333E-08 Limit= 1.000000E-08 Wall=   3645.2
Iteration=   3615 Ratio= 5.852747E-08 Limit= 1.000000E-08 Wall=   3757.0
Iteration=   3765 Ratio= 3.008049E-08 Limit= 1.000000E-08 Wall=   3916.1
Iteration=   3820 Ratio= 2.604051E-08 Limit= 1.000000E-08 Wall=   3977.2
Iteration=   3910 Ratio= 2.282895E-08 Limit= 1.000000E-08 Wall=   4071.3
Iteration=   4010 Ratio= 1.672385E-08 Limit= 1.000000E-08 Wall=   4194.8
Iteration=   4065 Ratio= 1.416155E-08 Limit= 1.000000E-08 Wall=   4263.1
Iteration=   4180 Ratio= 1.198459E-08 Limit= 1.000000E-08 Wall=   4386.7
Iteration=   4285 Ratio= 1.069138E-08 Limit= 1.000000E-08 Wall=   4495.4

```

DISTRIBUTED PCG SOLVER SOLUTION CONVERGED

DISTRIBUTED PCG SOLVER SOLUTION STATISTICS

```

NUMBER OF ITERATIONS=      4289
NUMBER OF EQUATIONS =    22560078
CALCULATED NORM      = 0.90743E-08
SPECIFIED TOLERANCE = 0.10000E-07
TOTAL CPU TIME (sec)=    4406.56
TOTAL WALL TIME(sec)=    4522.82
TOTAL MEMORY (GB)    =      9.49

```

Figure 411 Target Assembly, E Stop Convergence

Time at end of element matrix formulation CP = 651.296875.

Iteration=	5	Ratio=	0.200034	Limit=	1.000000E-08	Wall=	2.1
Iteration=	70	Ratio=	7.544678E-04	Limit=	1.000000E-08	Wall=	46.7
Iteration=	195	Ratio=	8.102319E-05	Limit=	1.000000E-08	Wall=	134.3
Iteration=	290	Ratio=	2.216822E-05	Limit=	1.000000E-08	Wall=	209.8
Iteration=	360	Ratio=	6.081327E-06	Limit=	1.000000E-08	Wall=	275.4
Iteration=	475	Ratio=	4.644234E-06	Limit=	1.000000E-08	Wall=	370.6
Iteration=	580	Ratio=	3.252703E-06	Limit=	1.000000E-08	Wall=	445.1
Iteration=	590	Ratio=	3.084979E-06	Limit=	1.000000E-08	Wall=	452.2
Iteration=	710	Ratio=	1.128236E-06	Limit=	1.000000E-08	Wall=	536.0
Iteration=	830	Ratio=	8.638101E-07	Limit=	1.000000E-08	Wall=	619.1
Iteration=	950	Ratio=	3.858466E-07	Limit=	1.000000E-08	Wall=	702.4
Iteration=	1145	Ratio=	2.036887E-07	Limit=	1.000000E-08	Wall=	838.9
Iteration=	1240	Ratio=	1.284292E-07	Limit=	1.000000E-08	Wall=	905.3
Iteration=	1360	Ratio=	8.382054E-08	Limit=	1.000000E-08	Wall=	987.7
Iteration=	1460	Ratio=	7.252584E-08	Limit=	1.000000E-08	Wall=	1058.1
Iteration=	1580	Ratio=	6.122840E-08	Limit=	1.000000E-08	Wall=	1140.5
Iteration=	1700	Ratio=	7.266203E-08	Limit=	1.000000E-08	Wall=	1222.7
Iteration=	1820	Ratio=	5.086864E-08	Limit=	1.000000E-08	Wall=	1304.4
Iteration=	1940	Ratio=	3.635110E-08	Limit=	1.000000E-08	Wall=	1386.8
Iteration=	2015	Ratio=	2.181013E-08	Limit=	1.000000E-08	Wall=	1449.5
Iteration=	2150	Ratio=	2.051281E-08	Limit=	1.000000E-08	Wall=	1546.2
Iteration=	2285	Ratio=	2.087931E-08	Limit=	1.000000E-08	Wall=	1640.1
Iteration=	2405	Ratio=	1.264739E-08	Limit=	1.000000E-08	Wall=	1722.6

DISTRIBUTED PCG SOLVER SOLUTION CONVERGED

DISTRIBUTED PCG SOLVER SOLUTION STATISTICS

NUMBER OF ITERATIONS=	2436
NUMBER OF EQUATIONS =	22560078
CALCULATED NORM	= 0.99991E-08
SPECIFIED TOLERANCE =	0.10000E-07
TOTAL CPU TIME (sec)=	1627.56
TOTAL WALL TIME(sec)=	1756.53
TOTAL MEMORY (GB)	= 9.23

Figure 412 Target Assembly, Seismic Convergence

```

Time at end of element matrix formulation CP = 852.671875.
Iteration=    5 Ratio= 0.200969 Limit= 1.000000E-08 Wall=    2.7
Iteration=   65 Ratio= 9.645441E-04 Limit= 1.000000E-08 Wall=   54.7
Iteration=  150 Ratio= 1.225304E-04 Limit= 1.000000E-08 Wall=  133.1
Iteration=  220 Ratio= 5.085549E-05 Limit= 1.000000E-08 Wall=  224.4
Iteration=  285 Ratio= 2.337985E-05 Limit= 1.000000E-08 Wall=  295.1
Iteration=  370 Ratio= 4.254000E-06 Limit= 1.000000E-08 Wall=  369.0
Iteration=  440 Ratio= 4.095896E-06 Limit= 1.000000E-08 Wall=  430.2
Iteration=  475 Ratio= 3.160629E-06 Limit= 1.000000E-08 Wall=  461.7
Iteration=  565 Ratio= 2.446044E-06 Limit= 1.000000E-08 Wall=  541.9
Iteration=  655 Ratio= 1.313376E-06 Limit= 1.000000E-08 Wall=  622.5
Iteration=  740 Ratio= 7.409169E-07 Limit= 1.000000E-08 Wall=  696.5
Iteration=  830 Ratio= 6.098917E-07 Limit= 1.000000E-08 Wall=  777.2
Iteration=  900 Ratio= 3.654865E-07 Limit= 1.000000E-08 Wall=  843.0
Iteration=  990 Ratio= 3.027954E-07 Limit= 1.000000E-08 Wall=  925.9
Iteration= 1080 Ratio= 1.784506E-07 Limit= 1.000000E-08 Wall= 1007.8
Iteration= 1170 Ratio= 1.550793E-07 Limit= 1.000000E-08 Wall= 1089.2
Iteration= 1265 Ratio= 1.353493E-07 Limit= 1.000000E-08 Wall= 1177.1
Iteration= 1355 Ratio= 9.778440E-08 Limit= 1.000000E-08 Wall= 1260.3
Iteration= 1445 Ratio= 1.190467E-07 Limit= 1.000000E-08 Wall= 1341.1
Iteration= 1535 Ratio= 1.060996E-07 Limit= 1.000000E-08 Wall= 1422.2
Iteration= 1625 Ratio= 8.802803E-08 Limit= 1.000000E-08 Wall= 1504.8
Iteration= 1715 Ratio= 6.493482E-08 Limit= 1.000000E-08 Wall= 1584.3
Iteration= 1805 Ratio= 4.459297E-08 Limit= 1.000000E-08 Wall= 1661.7
Iteration= 1900 Ratio= 3.773392E-08 Limit= 1.000000E-08 Wall= 1745.9
Iteration= 1995 Ratio= 2.391331E-08 Limit= 1.000000E-08 Wall= 1836.8
Iteration= 2065 Ratio= 3.245395E-08 Limit= 1.000000E-08 Wall= 1903.0
Iteration= 2135 Ratio= 2.987298E-08 Limit= 1.000000E-08 Wall= 1969.5
Iteration= 2250 Ratio= 2.482363E-08 Limit= 1.000000E-08 Wall= 2085.2
Iteration= 2315 Ratio= 2.100414E-08 Limit= 1.000000E-08 Wall= 2147.6
Iteration= 2400 Ratio= 1.278726E-08 Limit= 1.000000E-08 Wall= 2230.6

```

DISTRIBUTED PCG SOLVER SOLUTION CONVERGED

DISTRIBUTED PCG SOLVER SOLUTION STATISTICS

```

NUMBER OF ITERATIONS=      2415
NUMBER OF EQUATIONS =    22560078
CALCULATED NORM      = 0.99073E-08
SPECIFIED TOLERANCE = 0.10000E-07
TOTAL CPU TIME (sec)=    2194.25
TOTAL WALL TIME(sec)=    2264.02
TOTAL MEMORY (GB)   =      9.23

```

Figure 413 Target Assembly, Seismic + Stop Convergence

4.7.2 Target Segment Analysis Settings

The Target Segment model is a nonlinear analyses including plasticity, pretension, and frictionless interface.

Details of "Analysis Settings" ▾ 🔍 ✕

[-] Restart Analysis	
Restart Type	Program Controlled
Status	Done
[-] Step Controls	
Number Of Steps	2.
Current Step Number	2.
Step End Time	2. s
Auto Time Stepping	Program Controlled
[-] Solver Controls	
Solver Type	Program Controlled
Weak Springs	On
Spring Stiffness	Program Controlled
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Quasi-Static Solution	Off
[+] Rotordynamics Controls	
[-] Restart Controls	
Generate Restart Points	Manual
Load Step	Last
Substep	Last
Retain Files After Full Solve	Yes
Combine Restart Files	Program Controlled
[-] Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Energy Convergence (Beta)	Program Controlled
Line Search	Program Controlled
Stabilization	Program Controlled
[-] Advanced	
Inverse Option	No
Contact Split (DMP)	Program Controlled
Semi Implicit (Beta)	Off
[-] Output Controls	
Output Selection	None
Stress	Yes
Back Stress	No
Strain	Yes
Contact Data	Yes
Nonlinear Data	Yes
Nodal Forces	Yes
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Cache Results in Memory (B...	Never
Combine Distributed Result ...	Program Controlled
Result File Compression	Program Controlled
[-] Analysis Data Management	
Solver Files Directory	C:\Users\qys\Desktop\Segment\Segment_f...
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	Bin
[+] Visibility	

Figure 414 Segment, Analysis Settings

Force Convergence

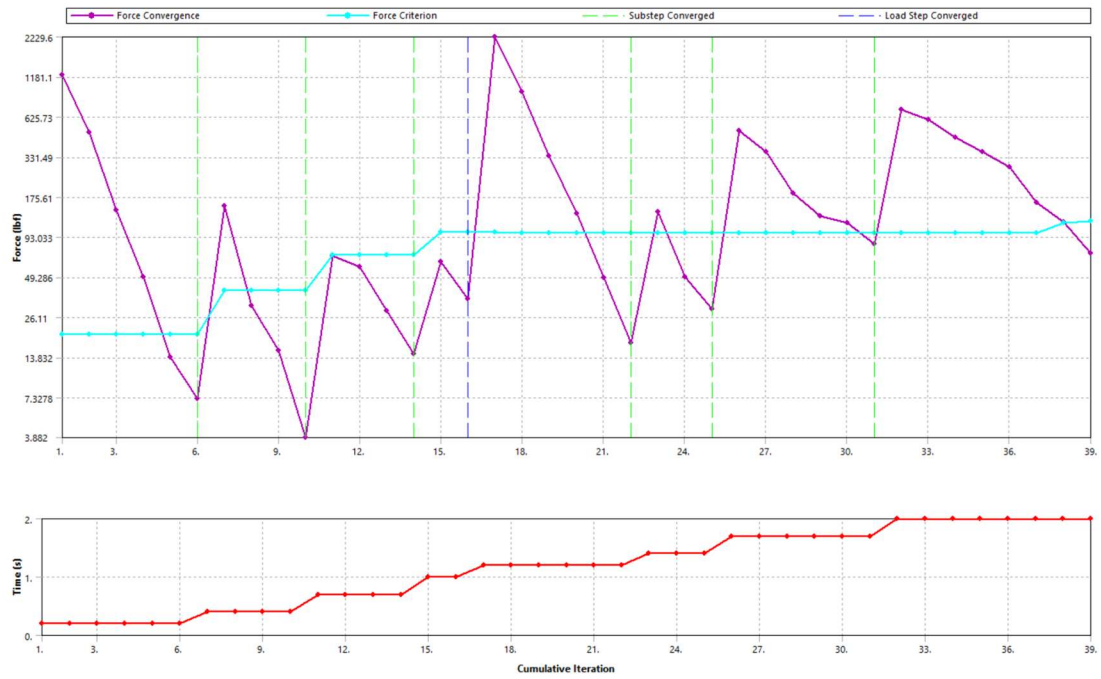


Figure 415 Segment, E Stop Force Convergence

Force Convergence

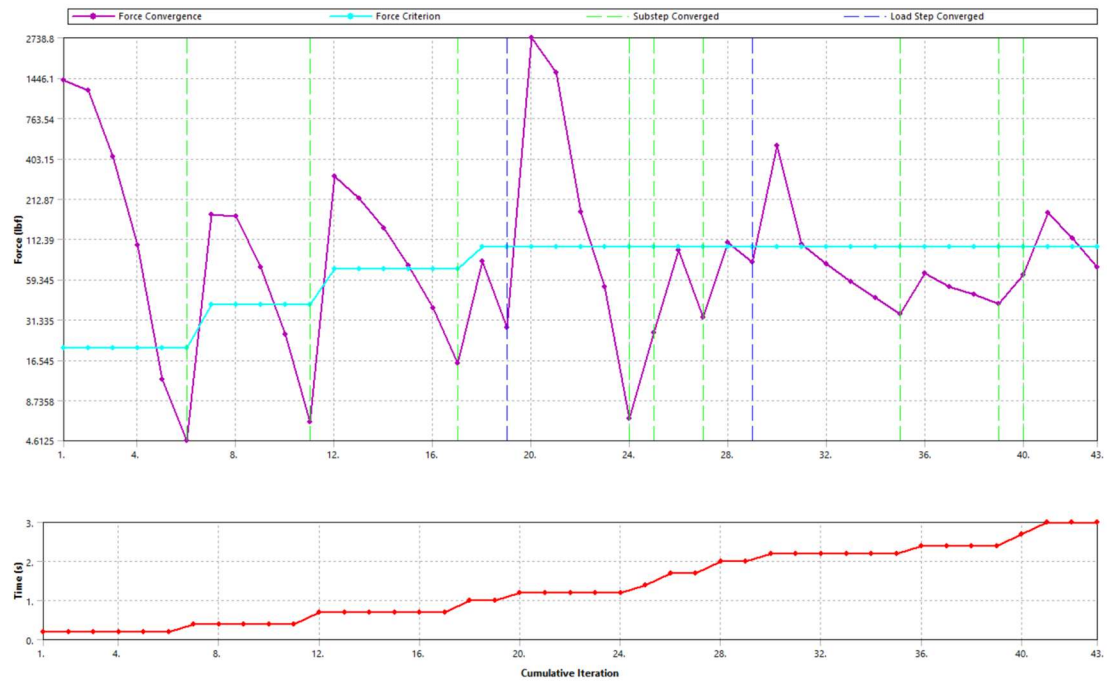


Figure 416 Segment, Seismic Force Convergence

Force Convergence

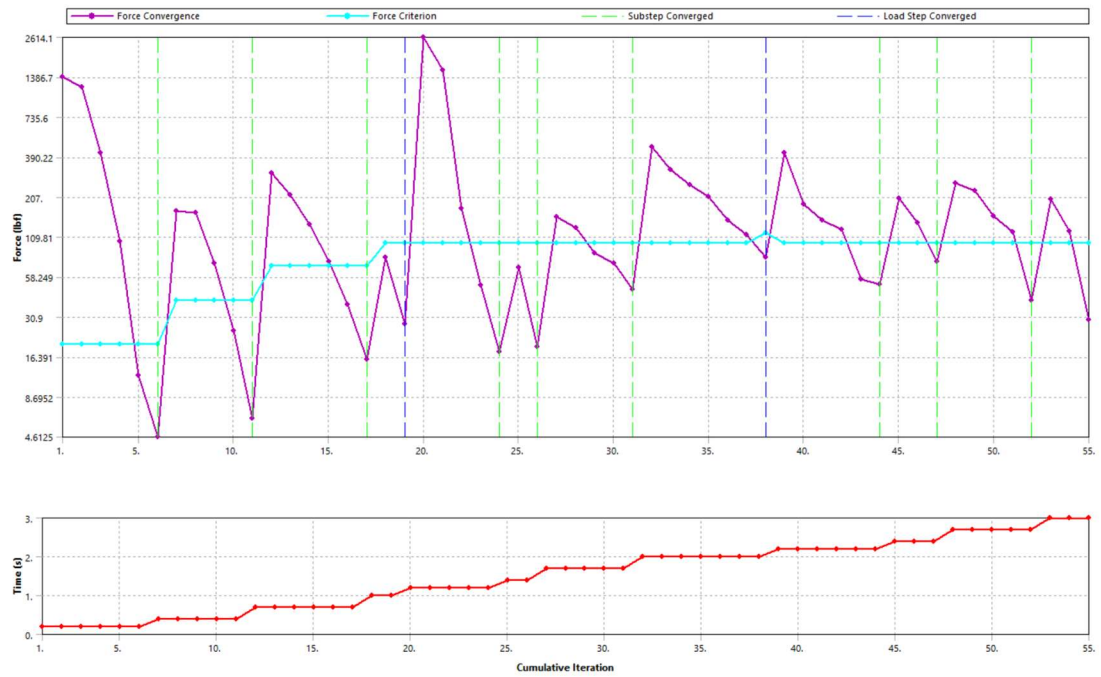


Figure 417 Segment, Seismic + Stop Force Convergence

Force Convergence

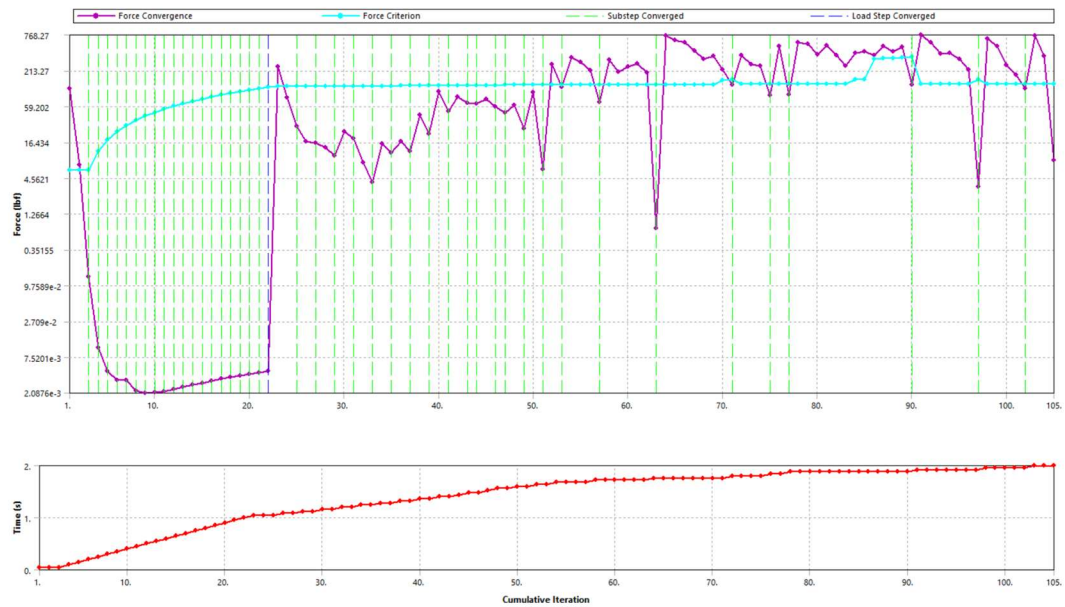


Figure 418 Segment, Elastic Plastic Case 1 Convergence

Force Convergence

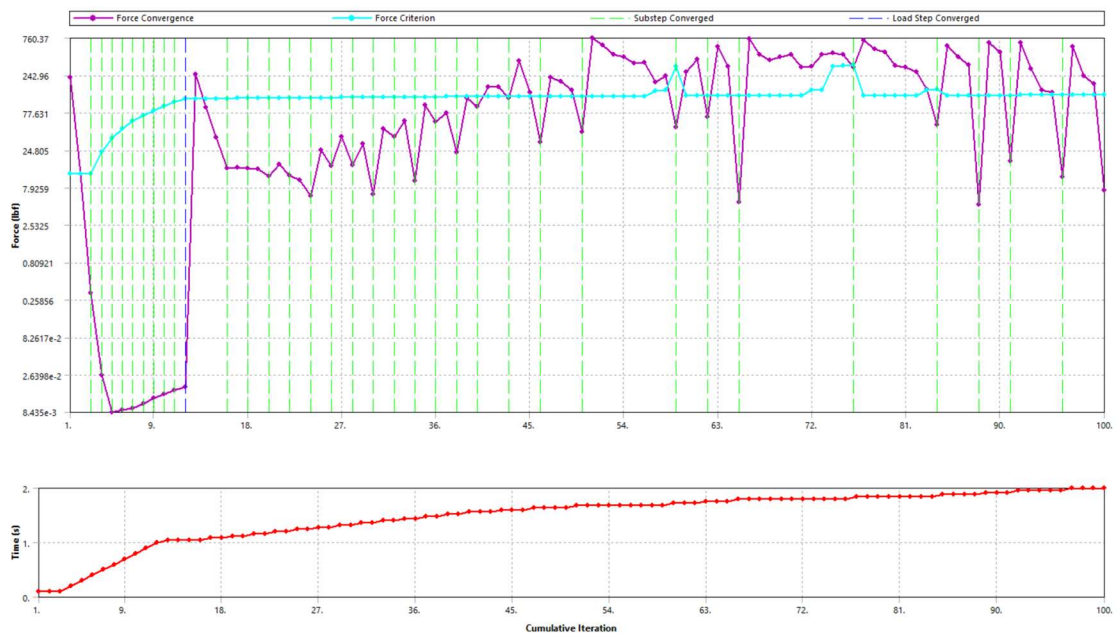


Figure 419 Segment, Elastic Plastic Case 2 Convergence

Force Convergence

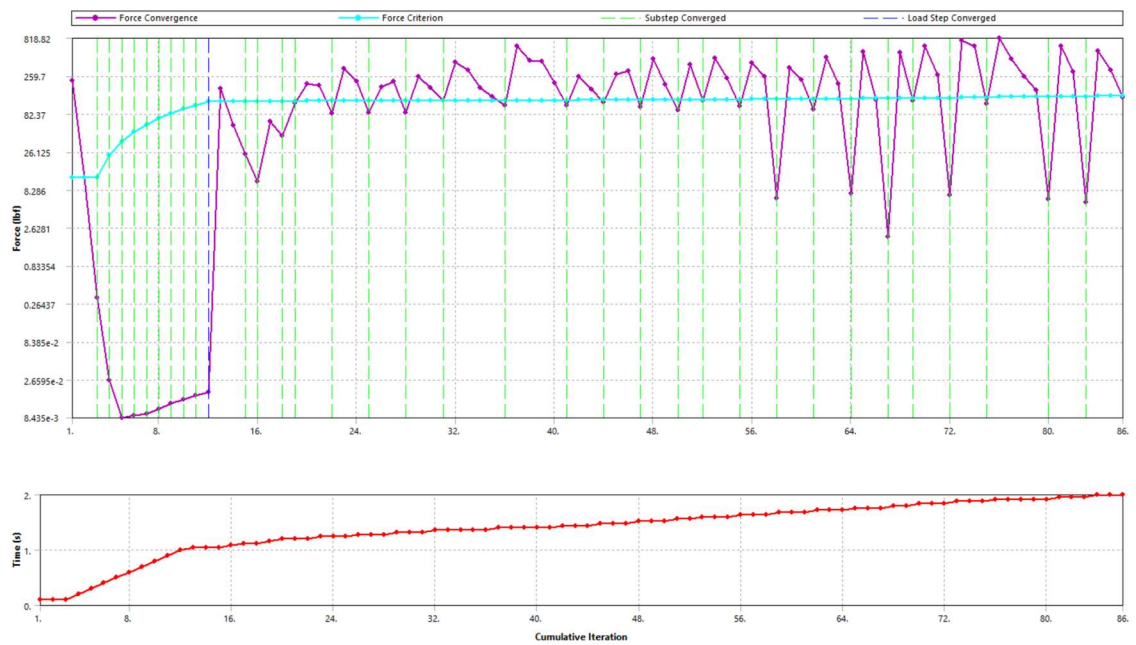


Figure 420 Segment, Elastic Plastic Case 5X Convergence

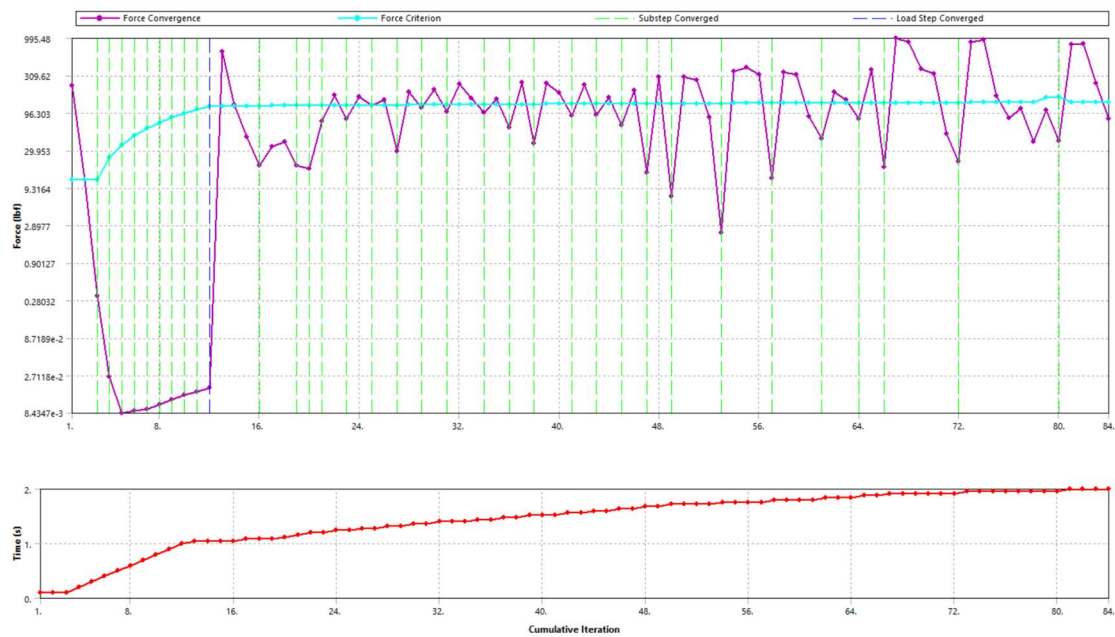


Figure 421 Segment, Elastic Plastic Case 5Z Convergence

4.7.3 Target Shaft Analysis Settings

The Target Shaft model is a nonlinear analyses including plasticity, pretension, and 'rough' interfaces.

Details of "Analysis Settings" ▾ ⚙ ✕	
[-] Step Controls	
Number Of Steps	3.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
[-] Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Quasi-Static Solution	Off
[+] Rotordynamics Controls	
[-] Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Combine Restart Files	Program Controlled
[-] Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Energy Convergence (Beta)	Program Controlled
Line Search	Program Controlled
Stabilization	Program Controlled
[-] Advanced	
Inverse Option	No
Contact Split (DMP)	Program Controlled
Semi Implicit (Beta)	Off
[-] Output Controls	
Output Selection	None
Stress	Yes
Back Stress	No
Strain	Yes
Contact Data	Yes
Nonlinear Data	Yes
Nodal Forces	Yes
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Cache Results in Memory (...)	Never
Combine Distributed Resul...	Program Controlled
Result File Compression	Program Controlled
[-] Analysis Data Management	
Solver Files Directory	C:\Users\qys\Desktop\Shaft\Shaft Tie Rods_...
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	Bin
[+] Visibility	

Figure 422 Shaft, Analysis Settings

Force Convergence

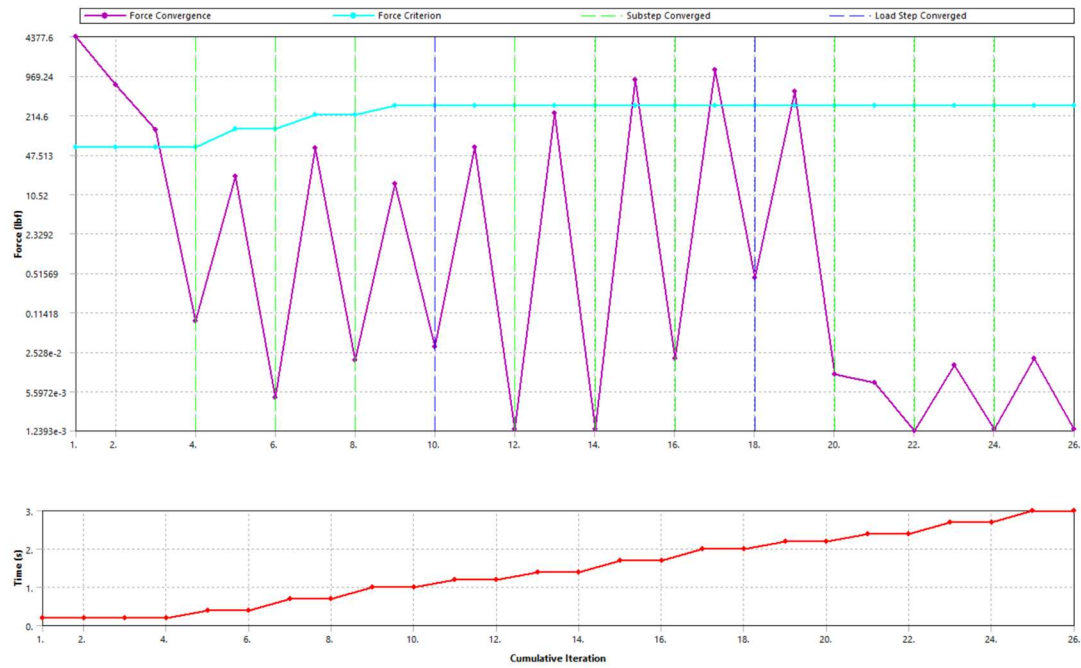


Figure 423 Shaft, E Stop Force Convergence

Force Convergence

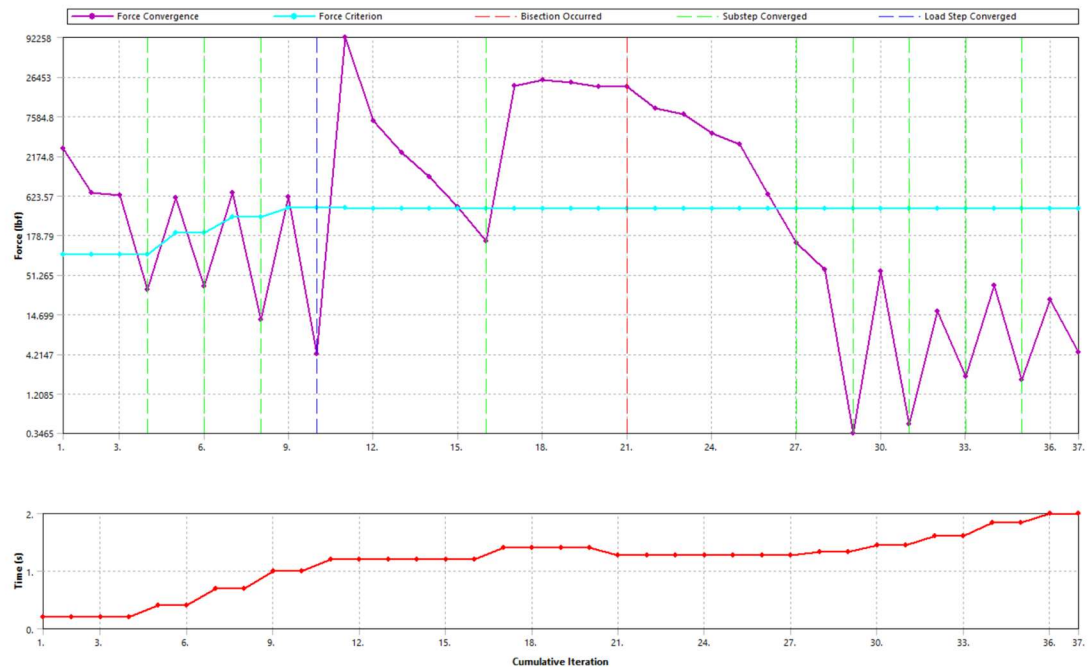


Figure 424 Shaft, Seismic Force Convergence

Force Convergence

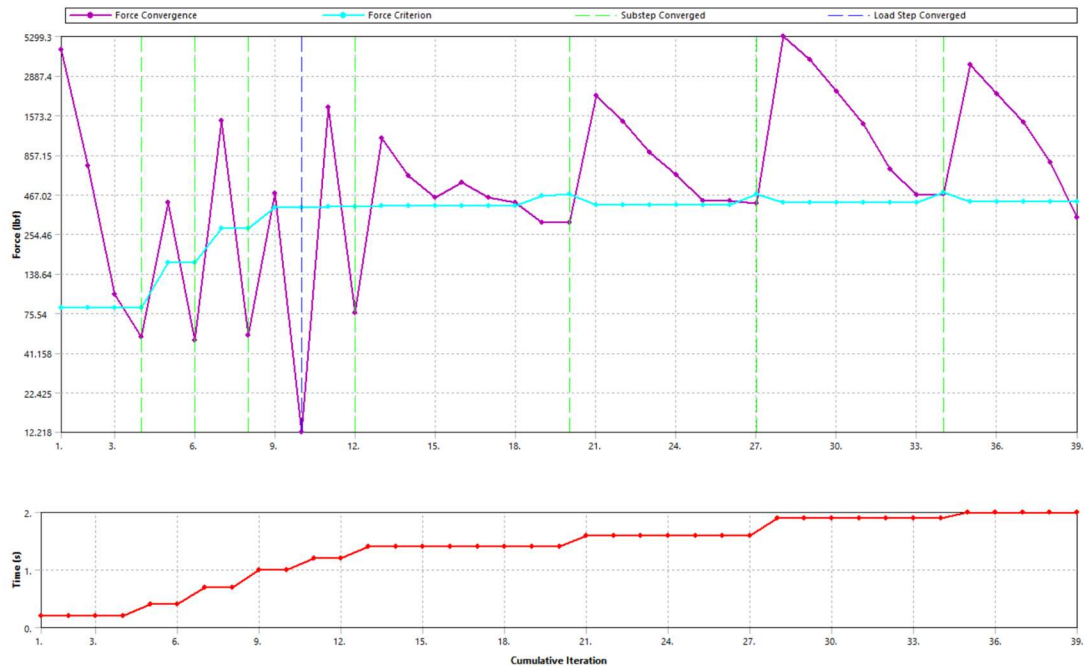


Figure 425 Shaft, Seismic + Stop Force Convergence

Force Convergence

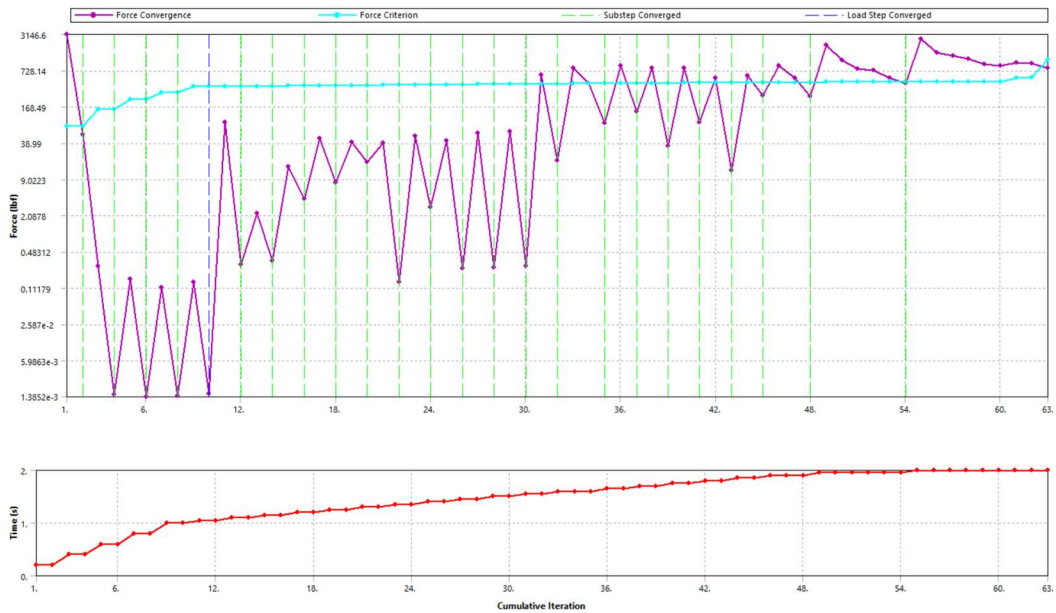


Figure 426 Shaft, Elastic Plastic Case 1 Convergence

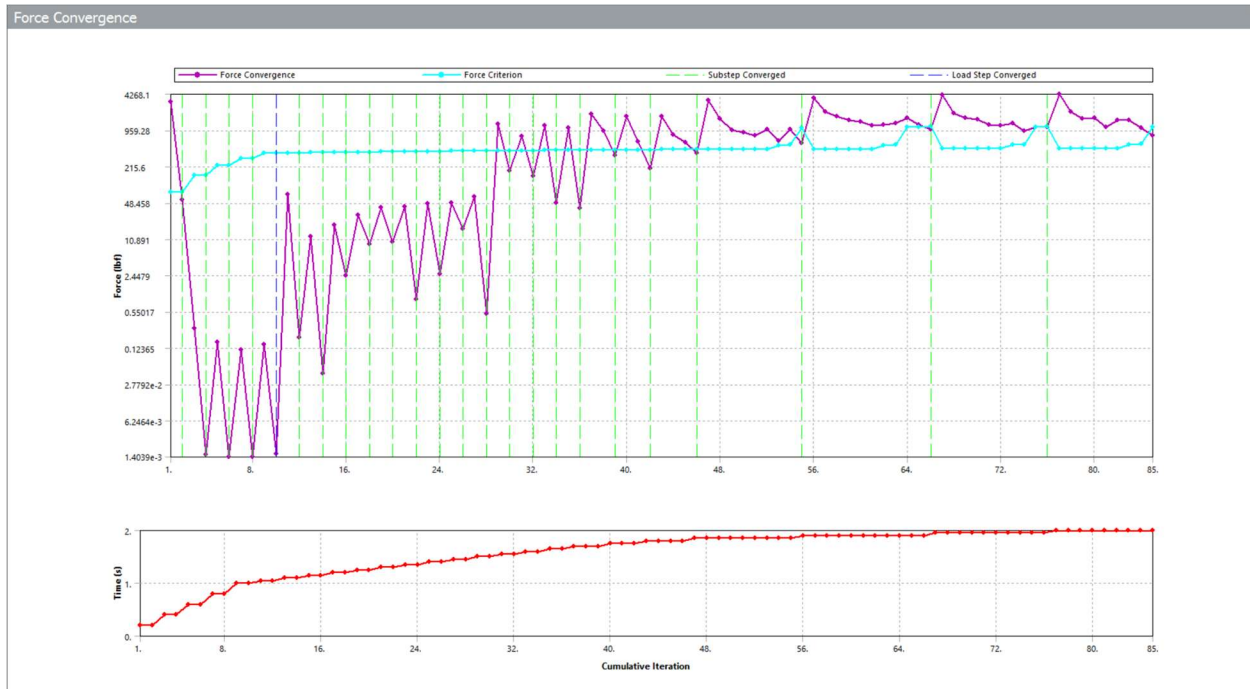


Figure 427 Shaft, Elastic Plastic Case 2 Convergence

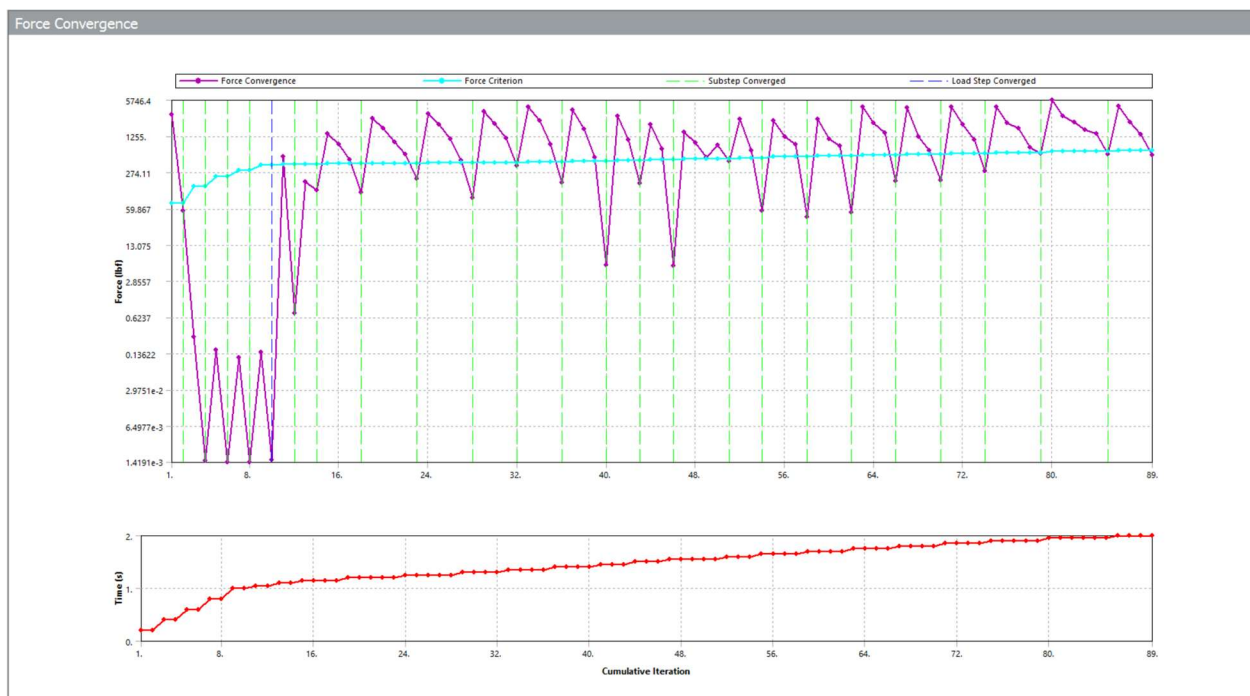


Figure 428 Shaft, Elastic Plastic Case 5 Convergence

4.7.4 Crown and Drive Analysis Settings

Details of "Analysis Settings"	
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Iterative
Weak Springs	On
Spring Stiffness	Program Controlled
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Quasi-Static Solution	Off
Rotordynamics Controls	
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Combine Restart Files	Program Controlled
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Energy Convergence (Beta)	Program Controlled
Line Search	Program Controlled
Stabilization	Program Controlled
Advanced	
Inverse Option	No
Contact Split (DMP)	Program Controlled
Semi Implicit (Beta)	Off
Output Controls	
Output Selection	None
Stress	Yes
Back Stress	No
Strain	Yes
Contact Data	Yes
Nonlinear Data	No
Nodal Forces	Yes
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Cache Results in Memory (Be...	Never
Combine Distributed Result ...	Program Controlled
Result File Compression	Program Controlled
Analysis Data Management	
Solver Files Directory	C:\Users\qys\Desktop\Fasteners\Fastener...
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	Bin
Visibility	

Figure 429 Crown and Drive, Analysis Settings

Force Convergence

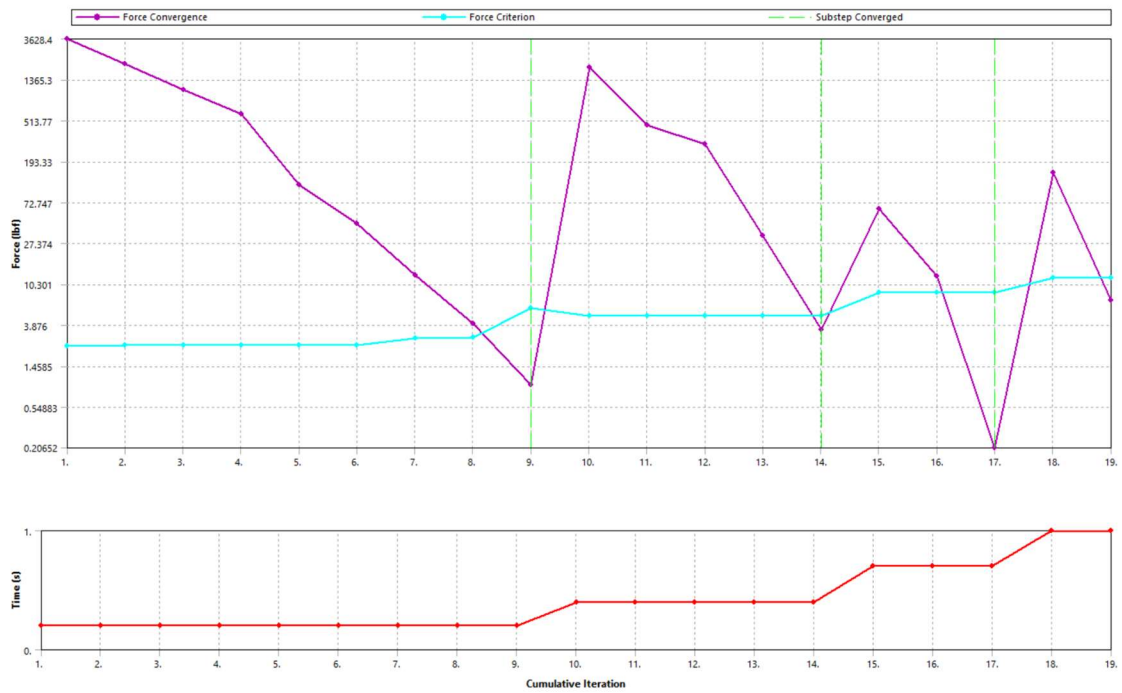


Figure 430 Crown and Drive, E Stop Force Convergence

Force Convergence

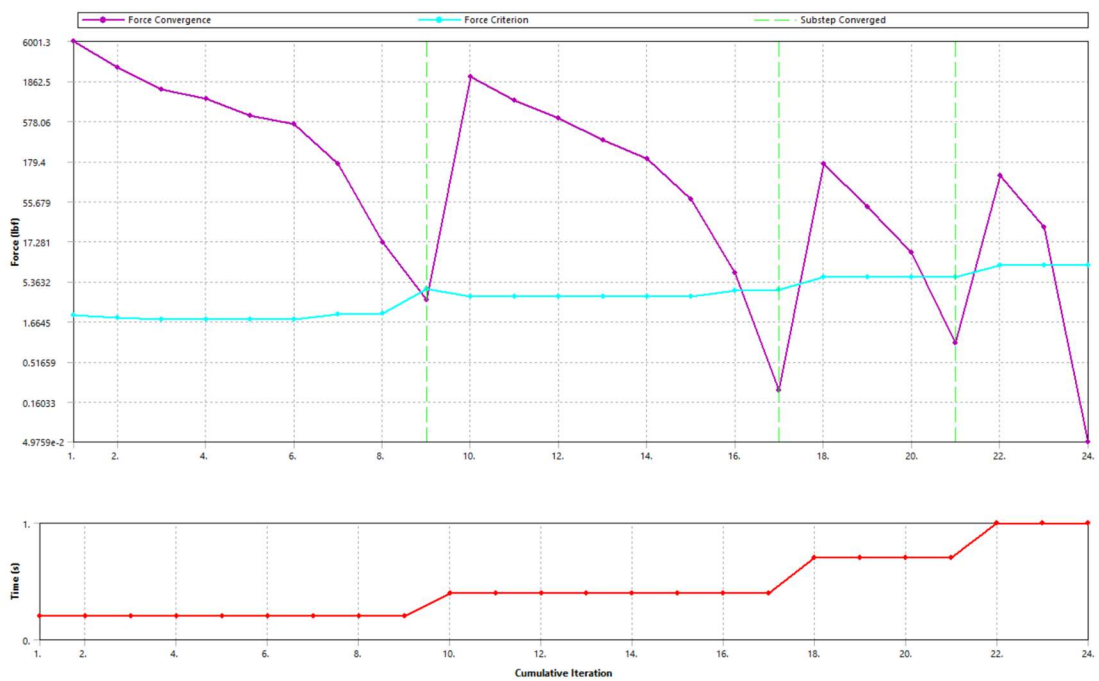


Figure 431 Crown and Drive, Seismic Force Convergence

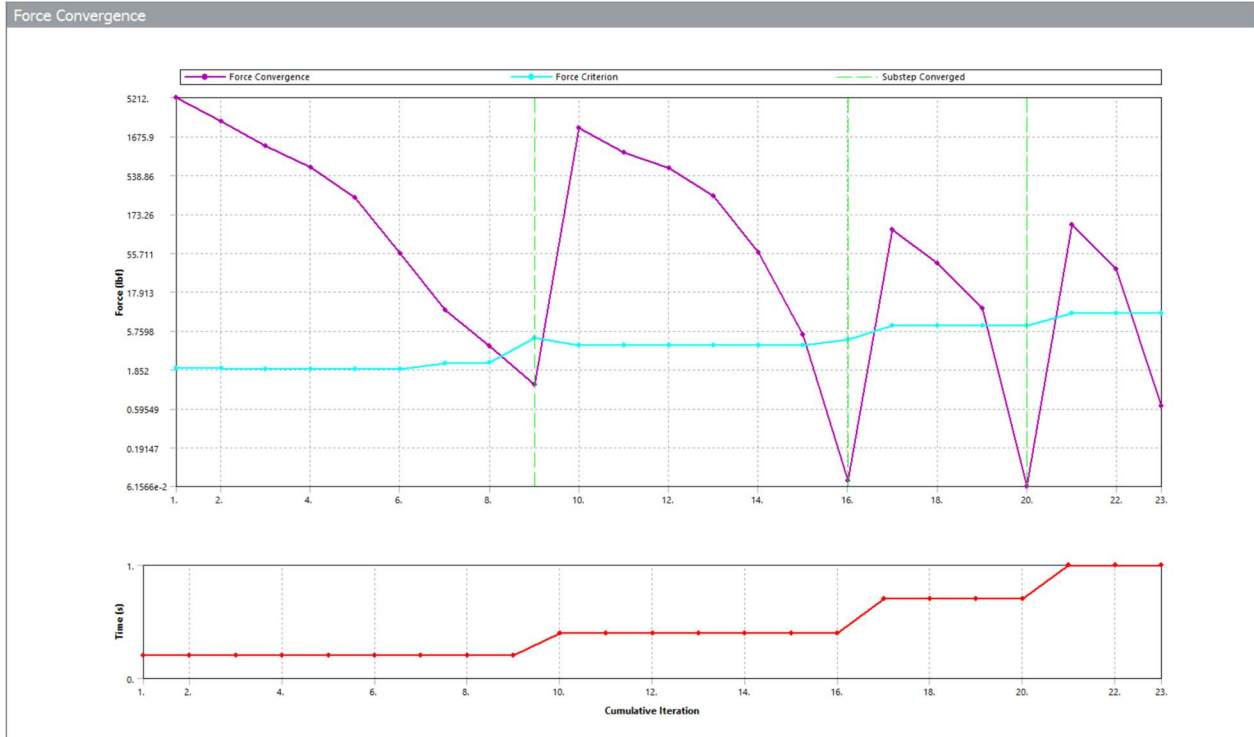


Figure 432 Crown and Drive, Seismic + Stop Force Convergence

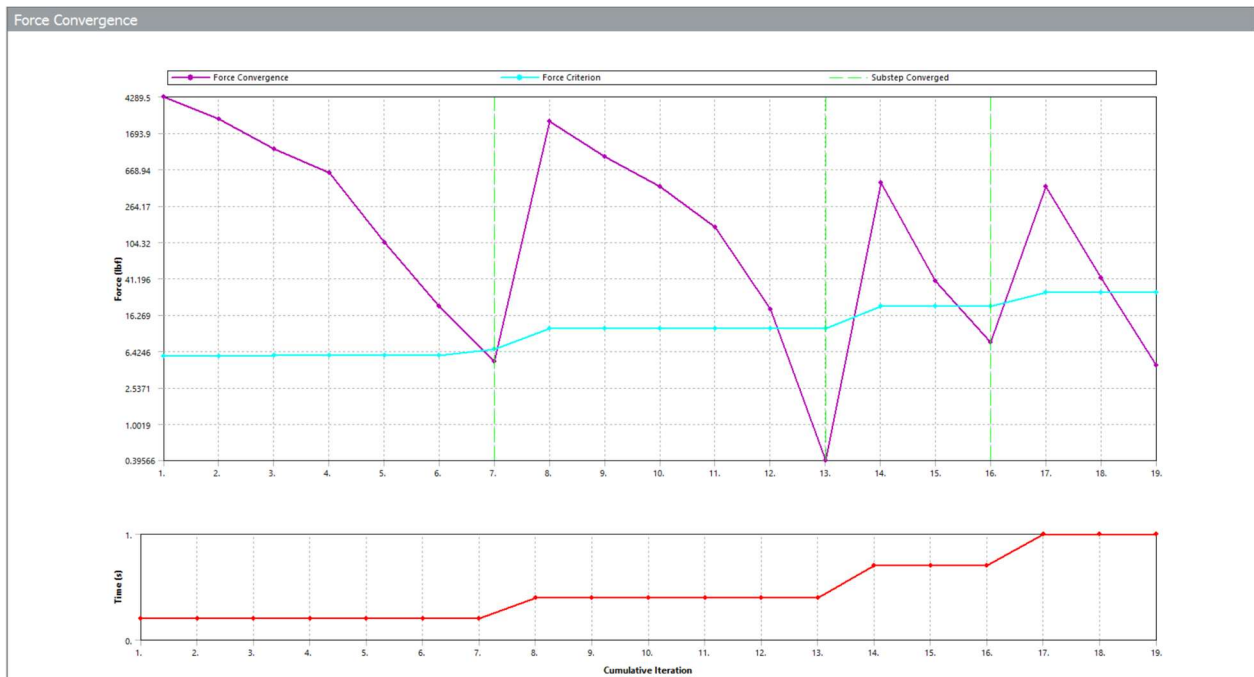
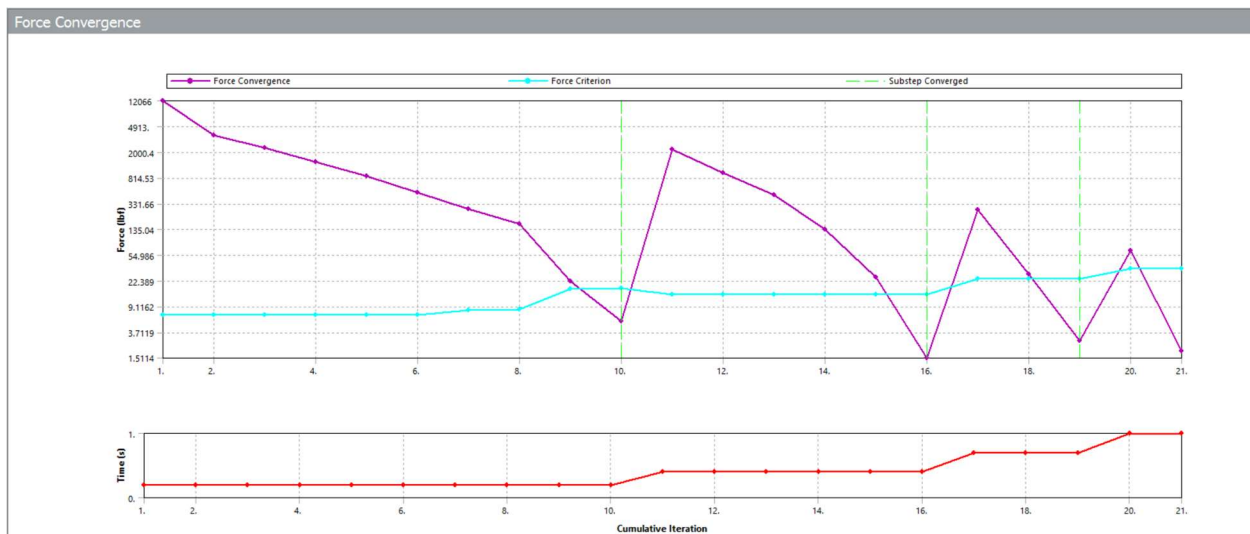
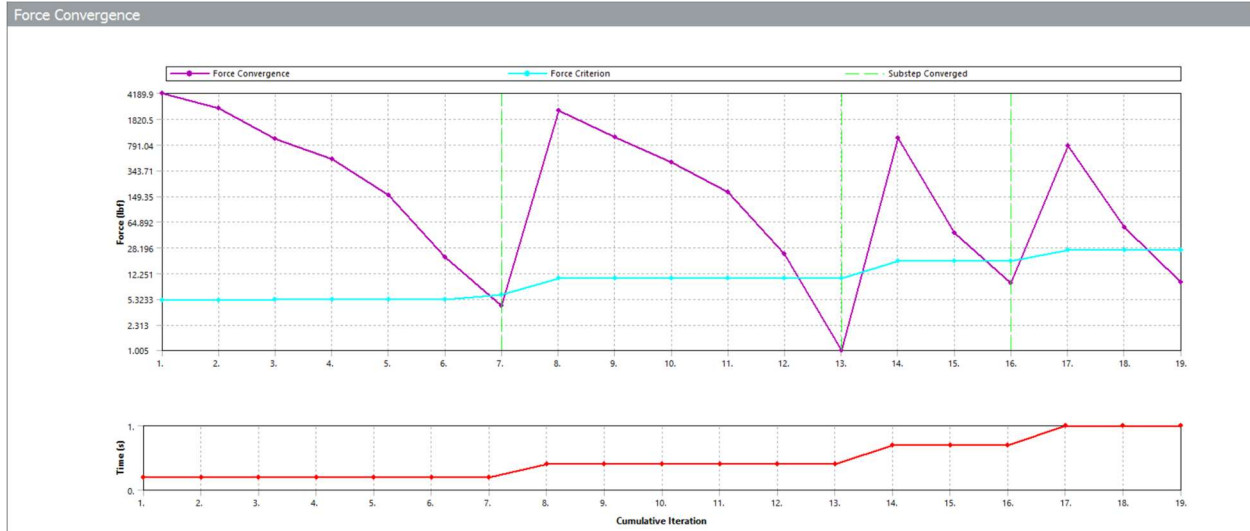


Figure 433 Crown and Drive, Elastic Plastic Case 1 Convergence



5. RESULTS

5.1.1 Target Assembly

5.1.1.1 Target Assembly Deflection

The maximum allowable deflection for the Target Assembly is .315 inches or 8mm.

5.1.1.1.1 E Stop Load Case

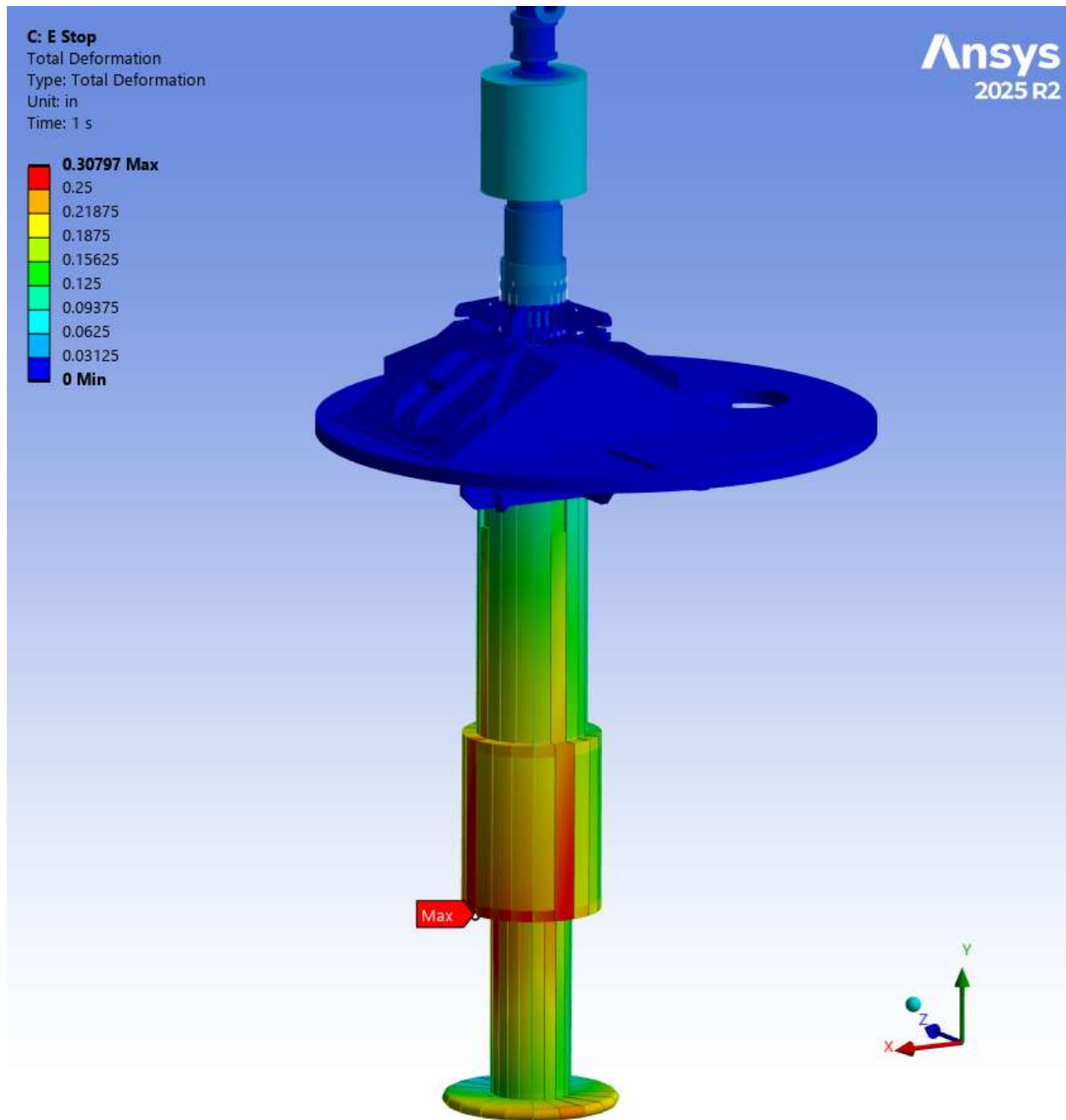


Figure 436 Target Assembly, E Stop Total Deformation

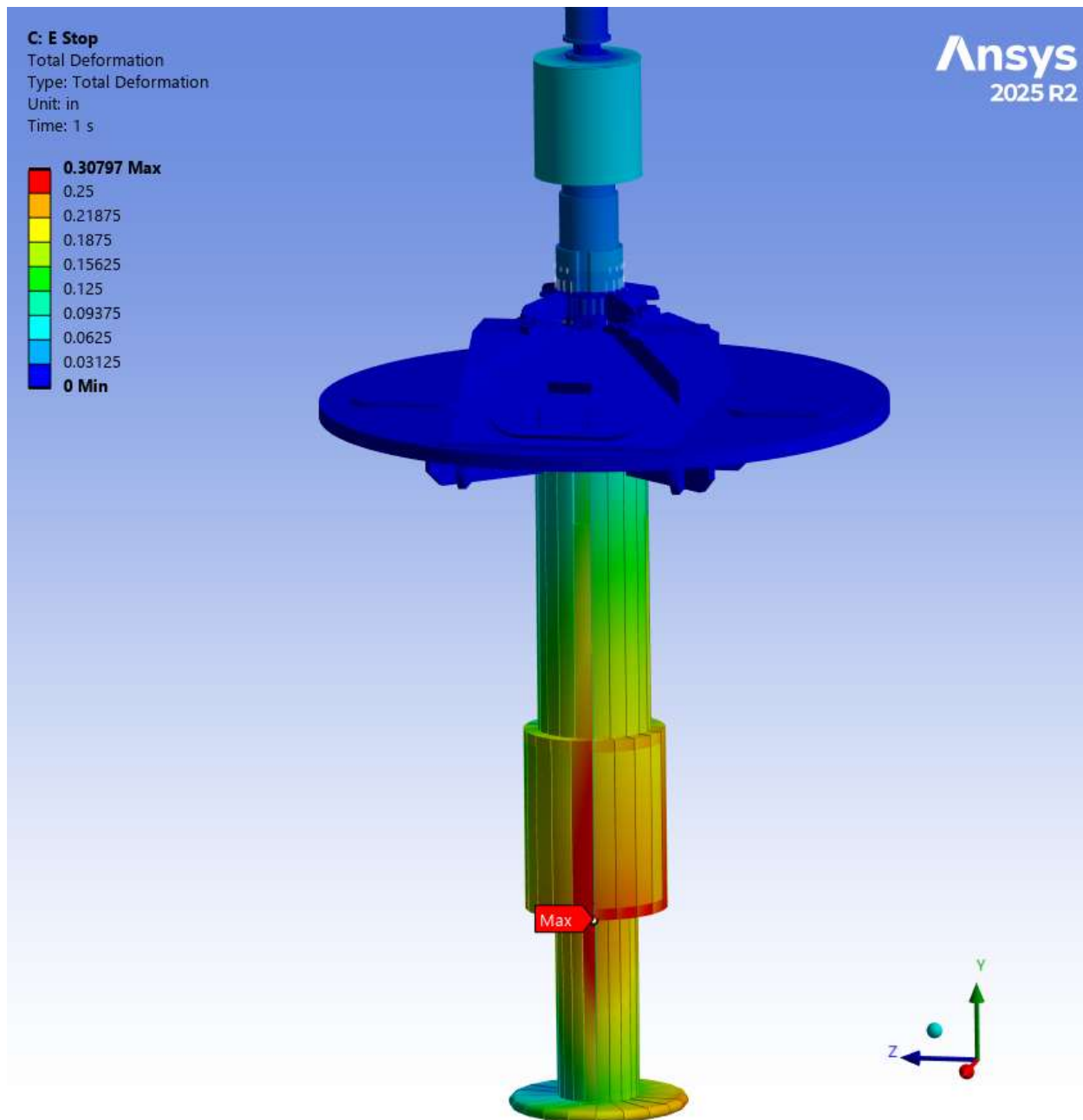


Figure 437 Target Assembly, E Stop Total Deformation

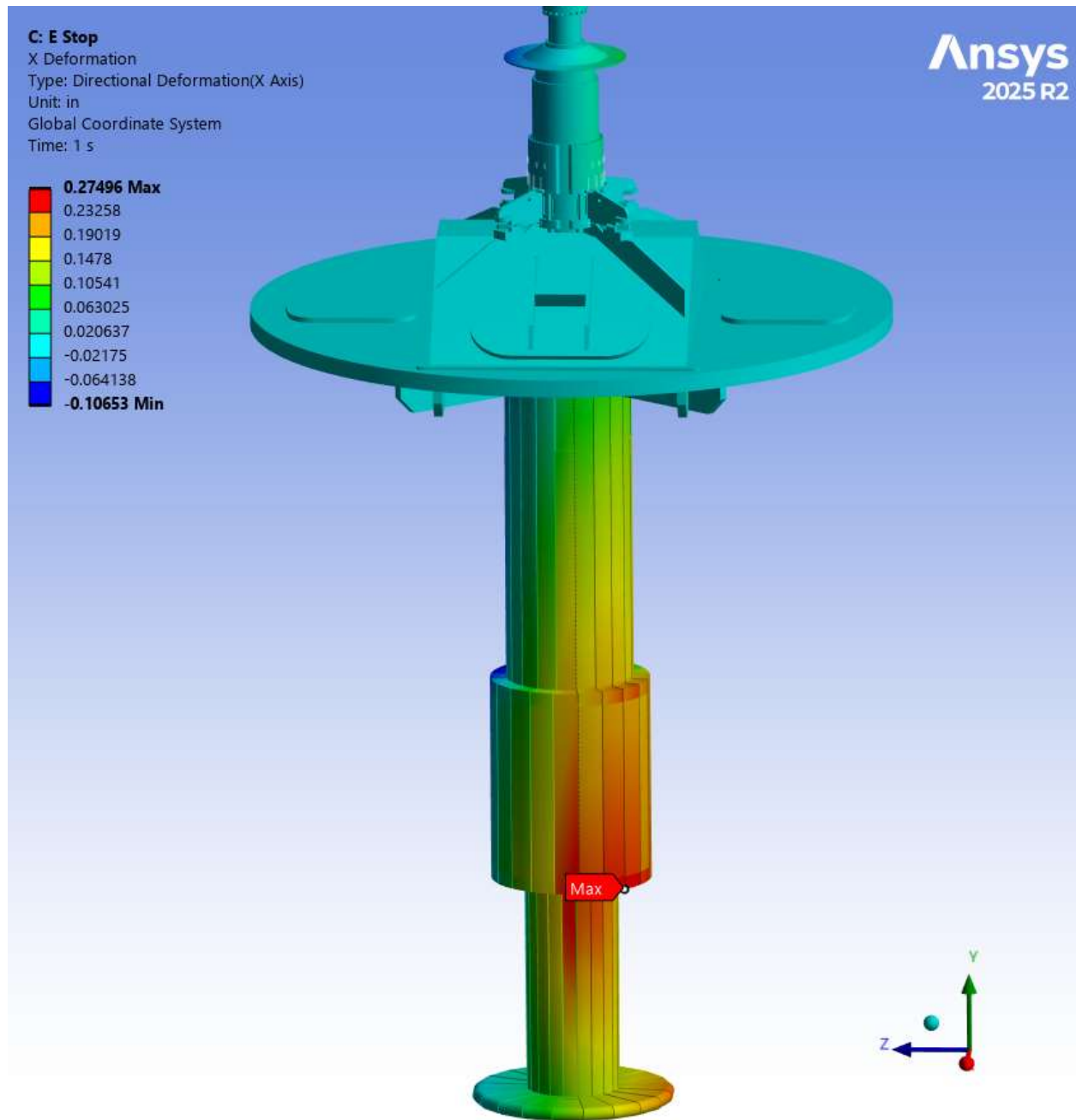


Figure 438 Target Assembly, E Stop X Deformation

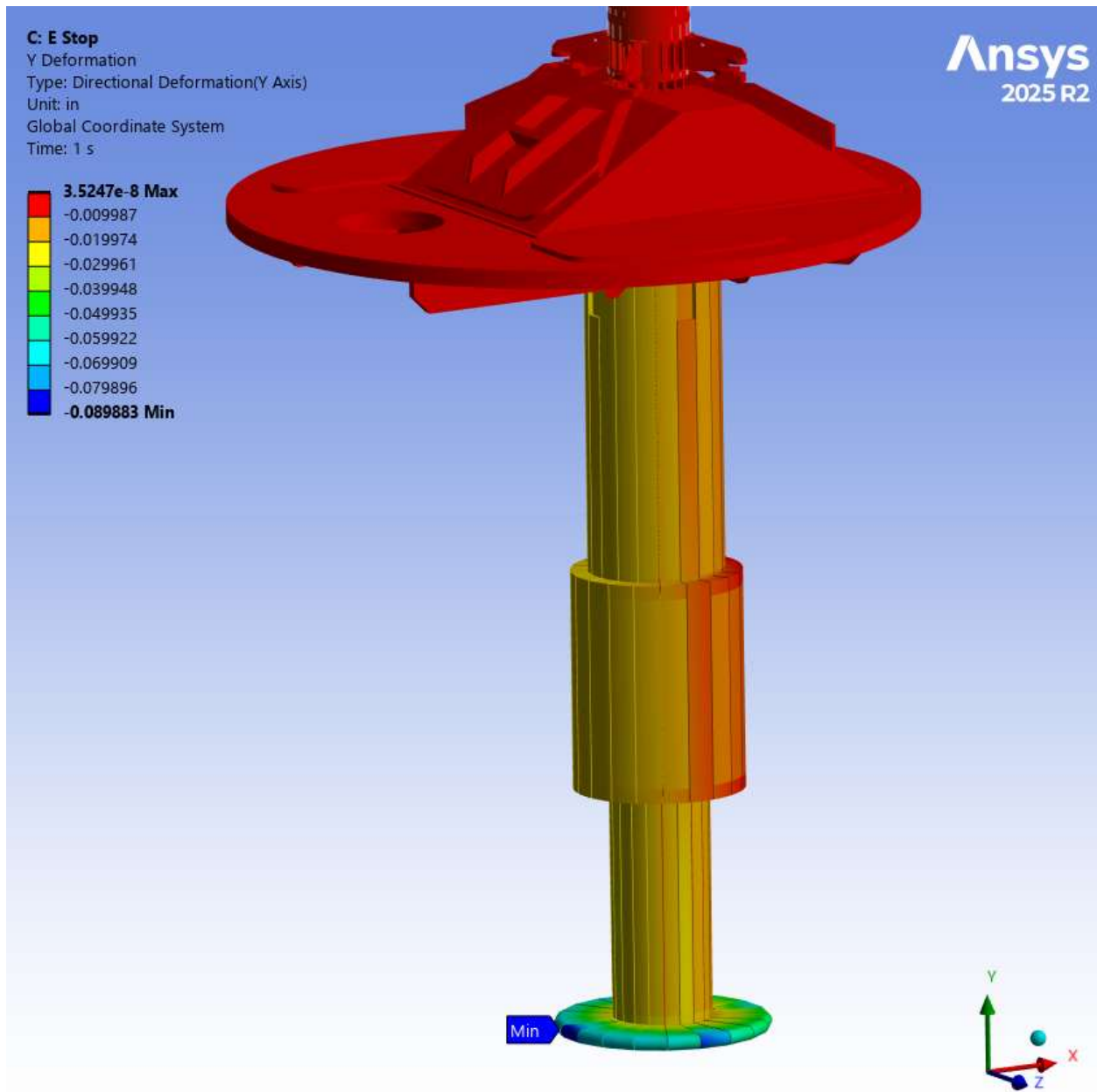


Figure 439 Target Assembly, E Stop Y Deformation

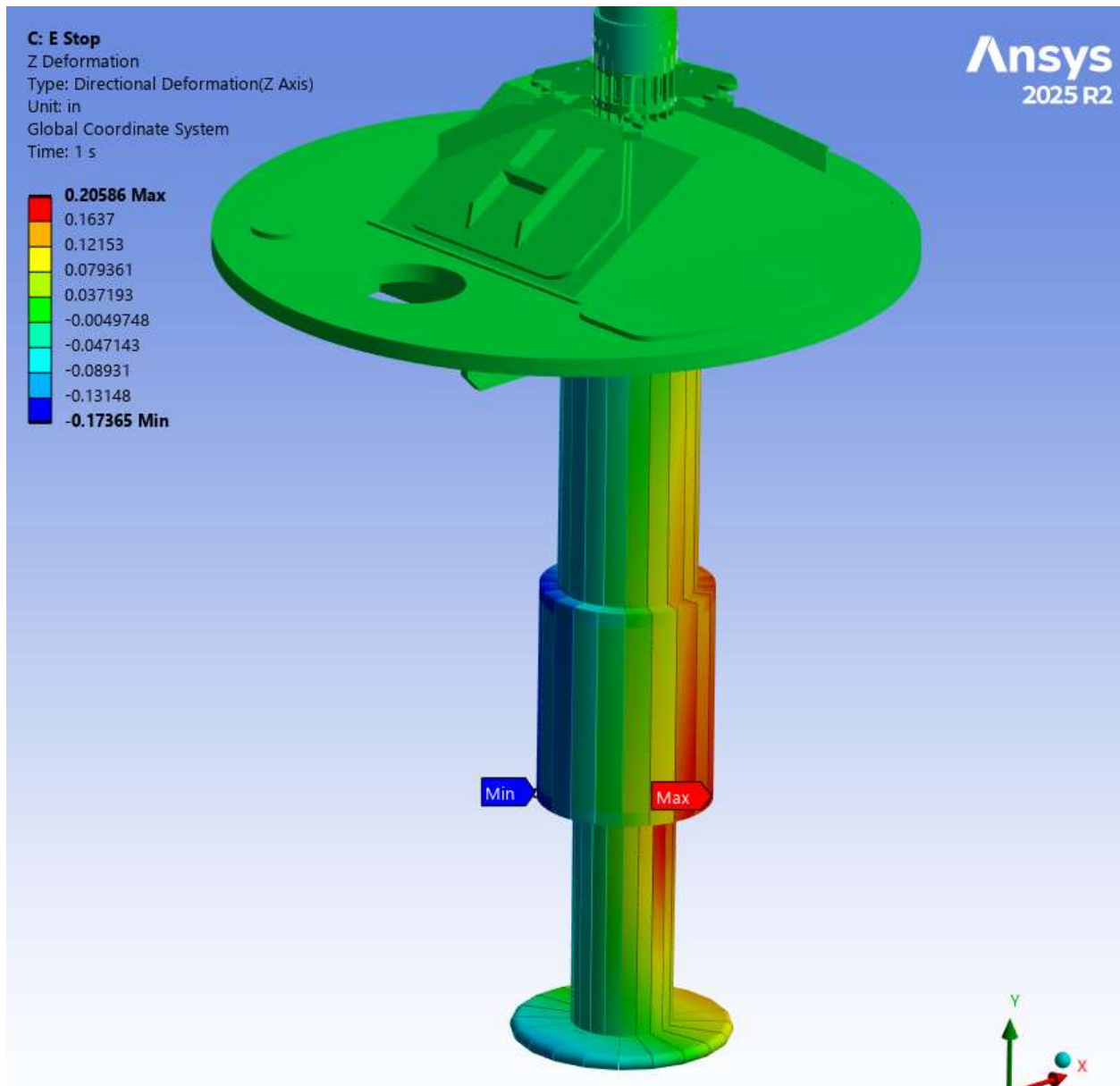


Figure 440 Target Assembly, E Stop Z Deformation

5.1.1.1.2 Seismic Load Case

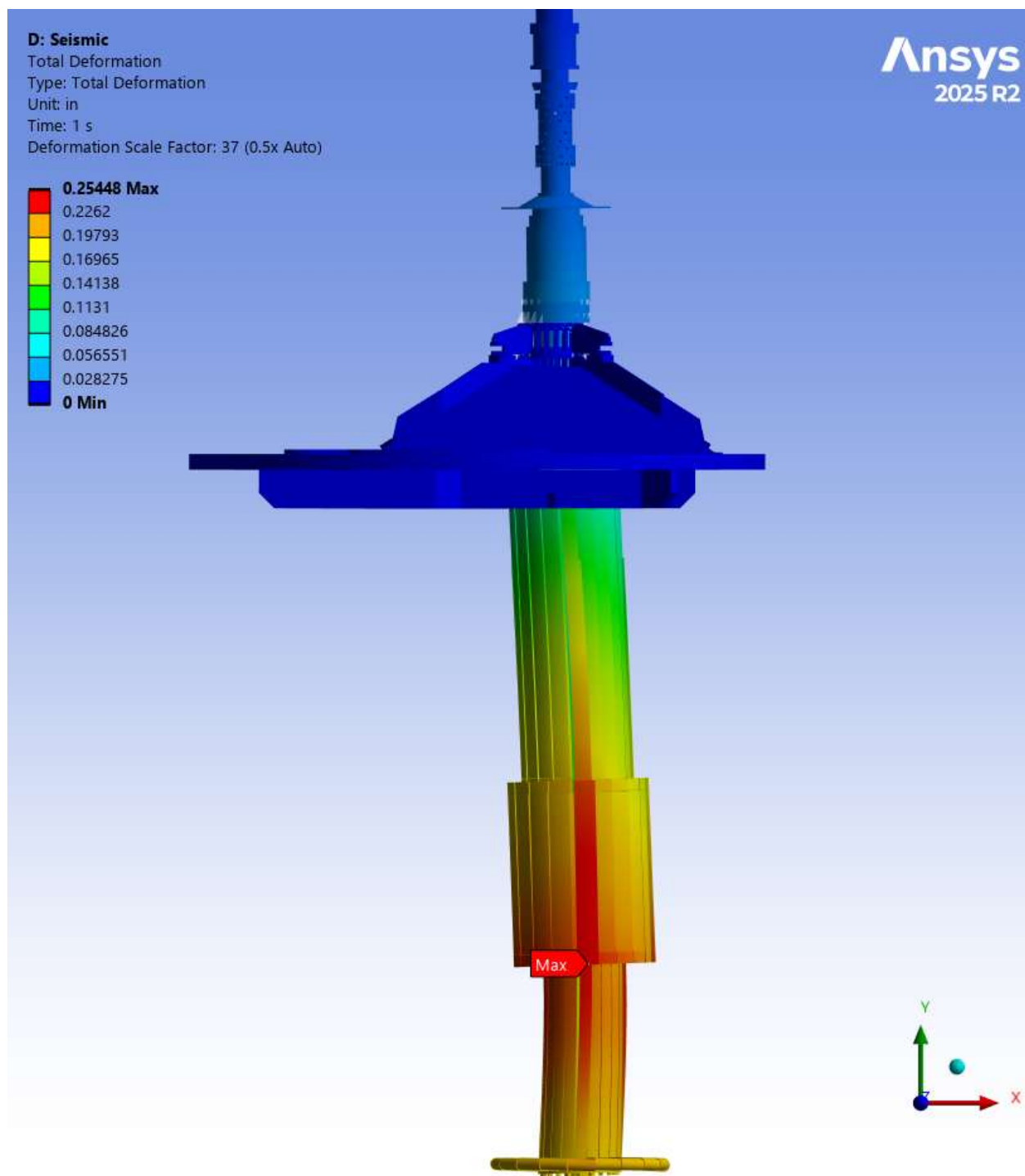


Figure 441 Target Assembly, Seismic Total Deformation

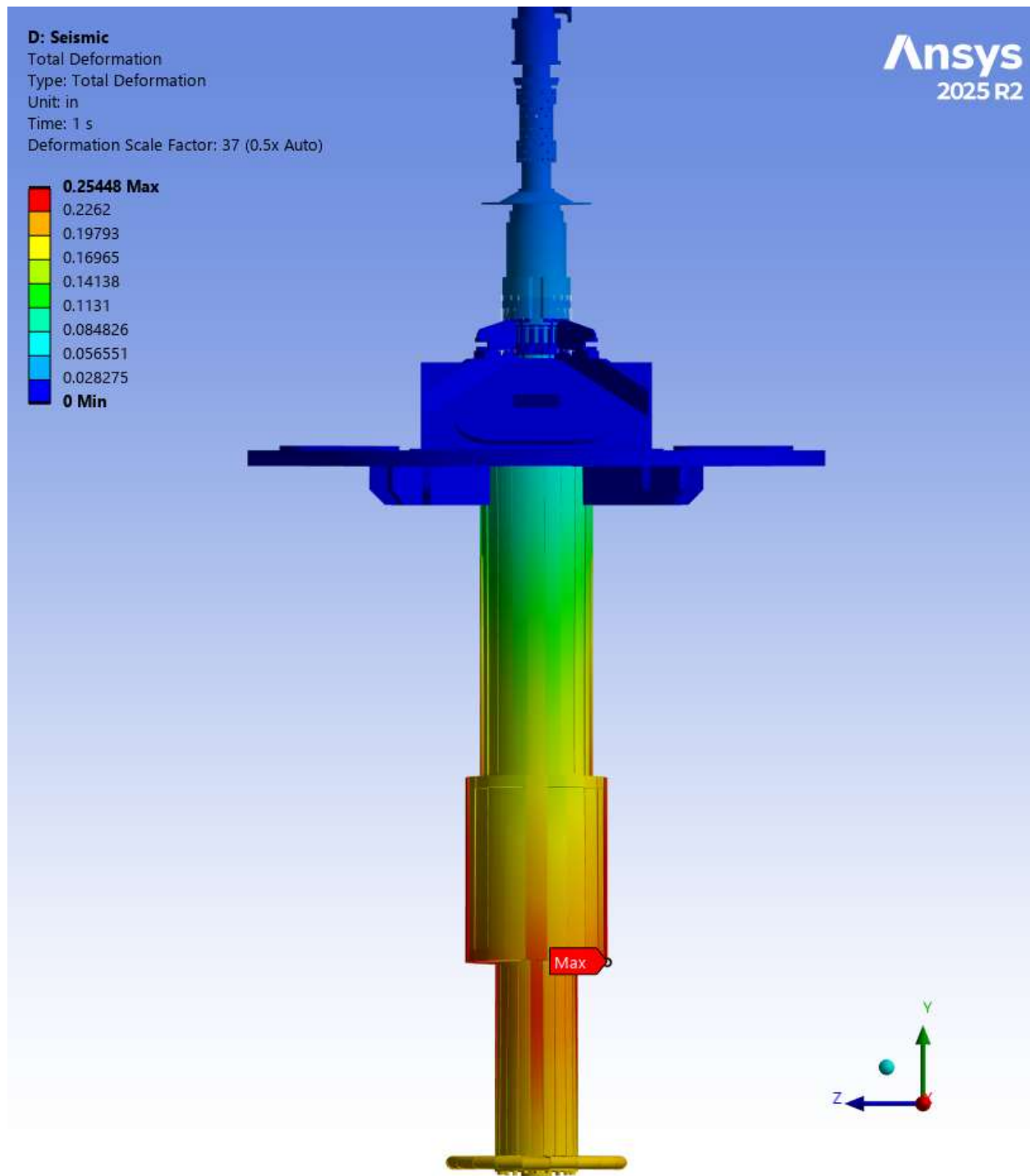


Figure 442 Target Assembly, Seismic Total Deformation

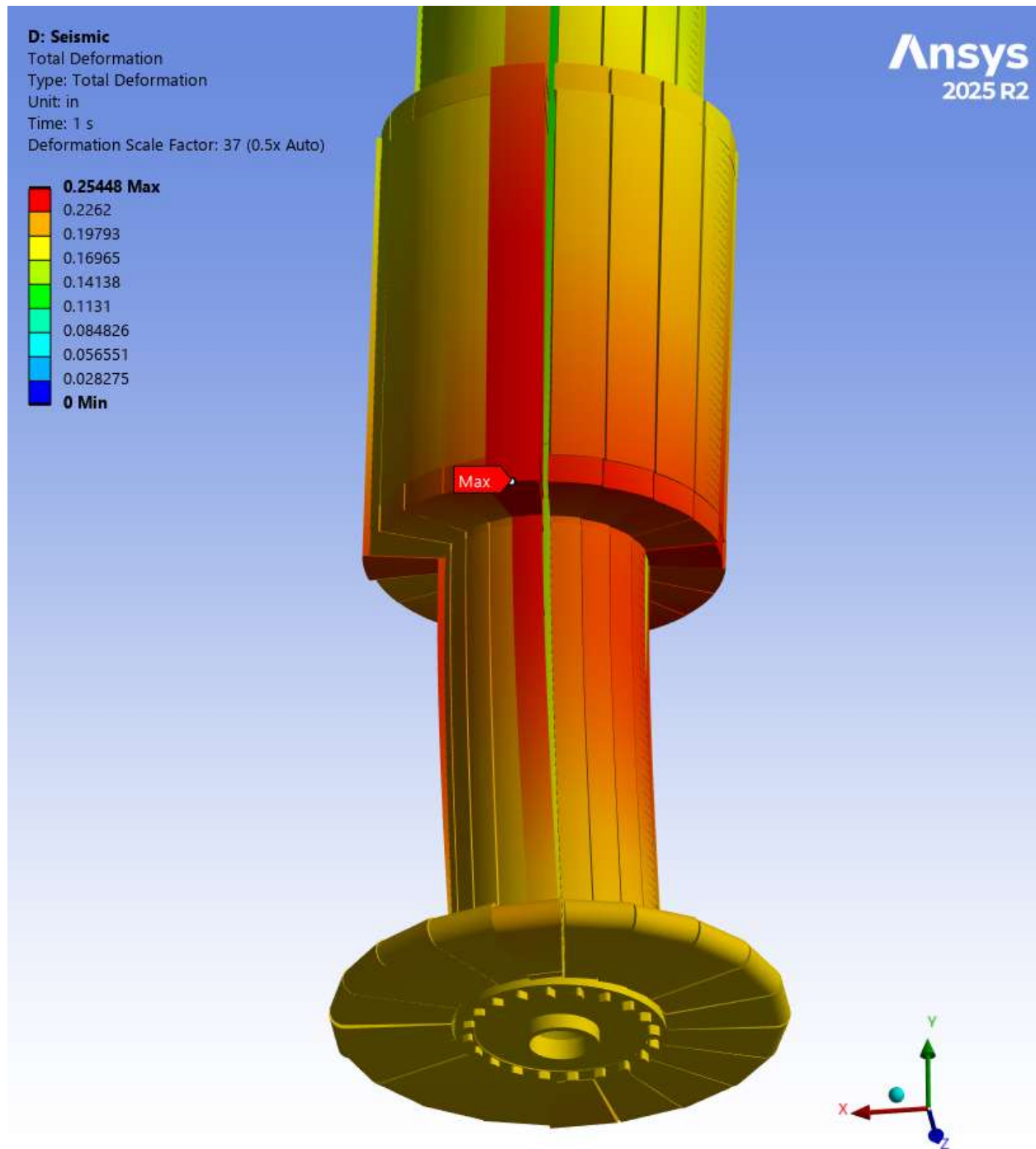


Figure 443 Total Deformation, Seismic Total Deformation

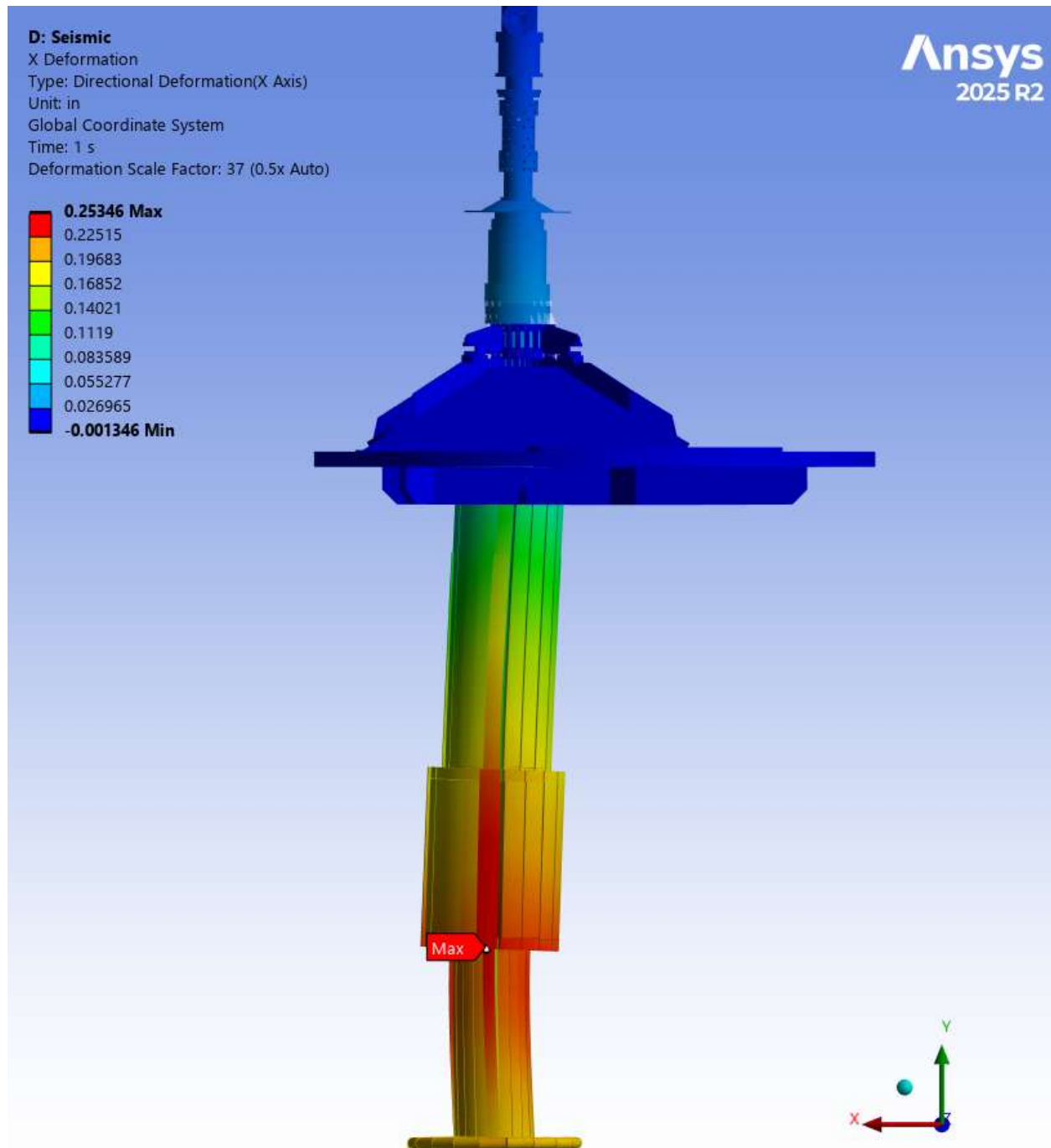


Figure 444 Target Assembly, Seismic X Deformation

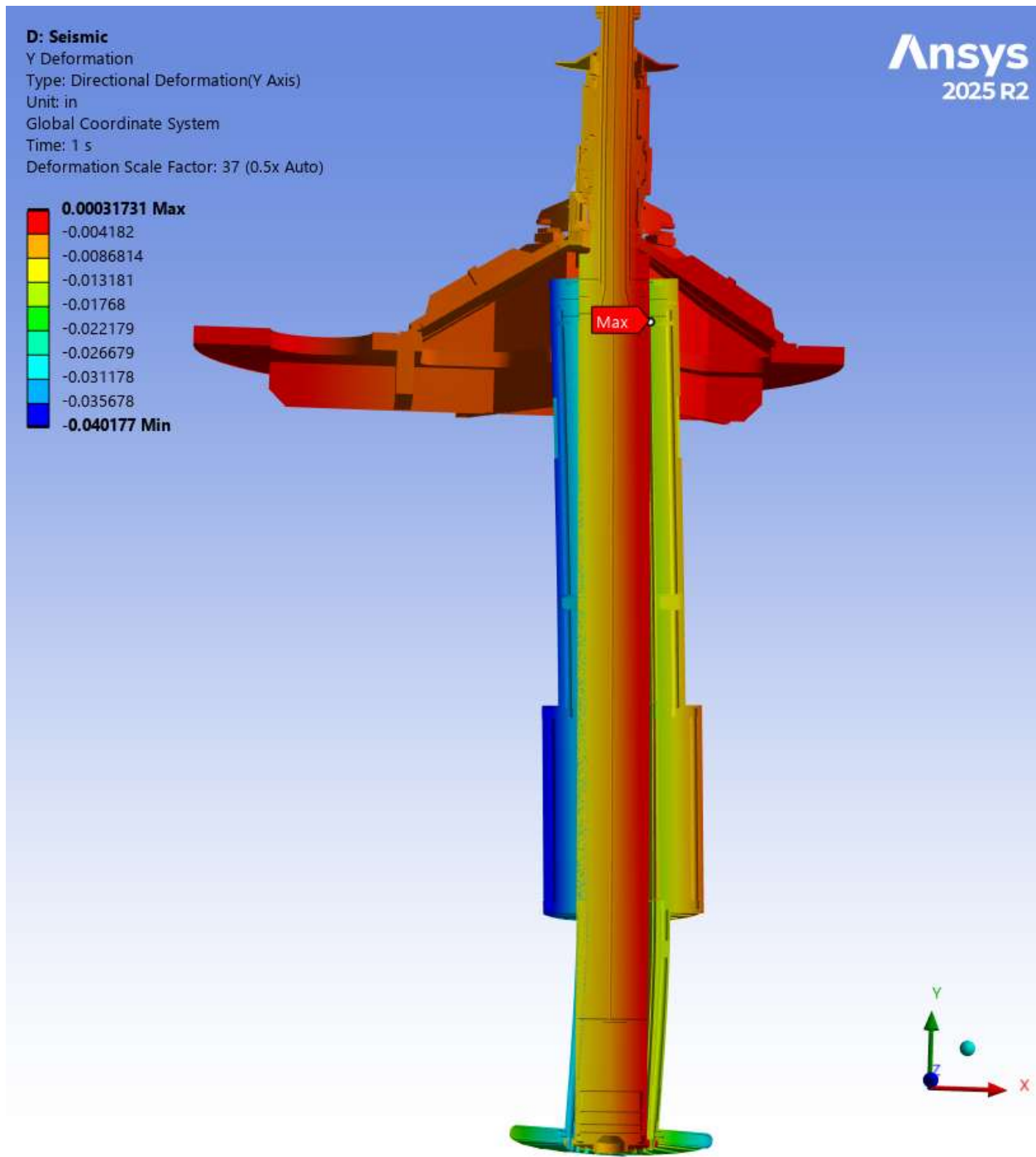


Figure 445 Target Assembly, Seismic Y Deformation

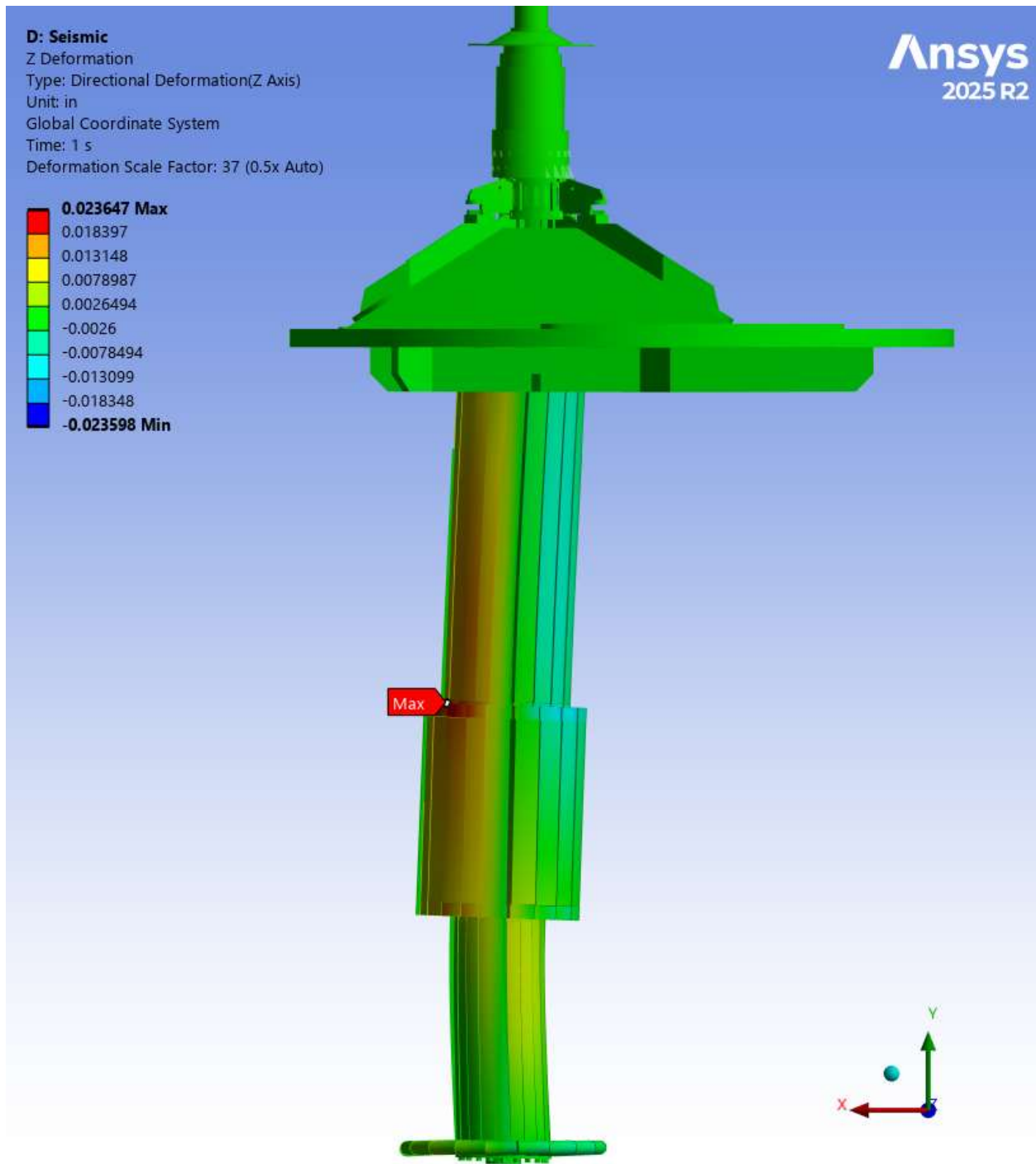


Figure 446 Target Assembly, Seismic Z Deformation

5.1.1.1.3 Seismic + Stop Load Case

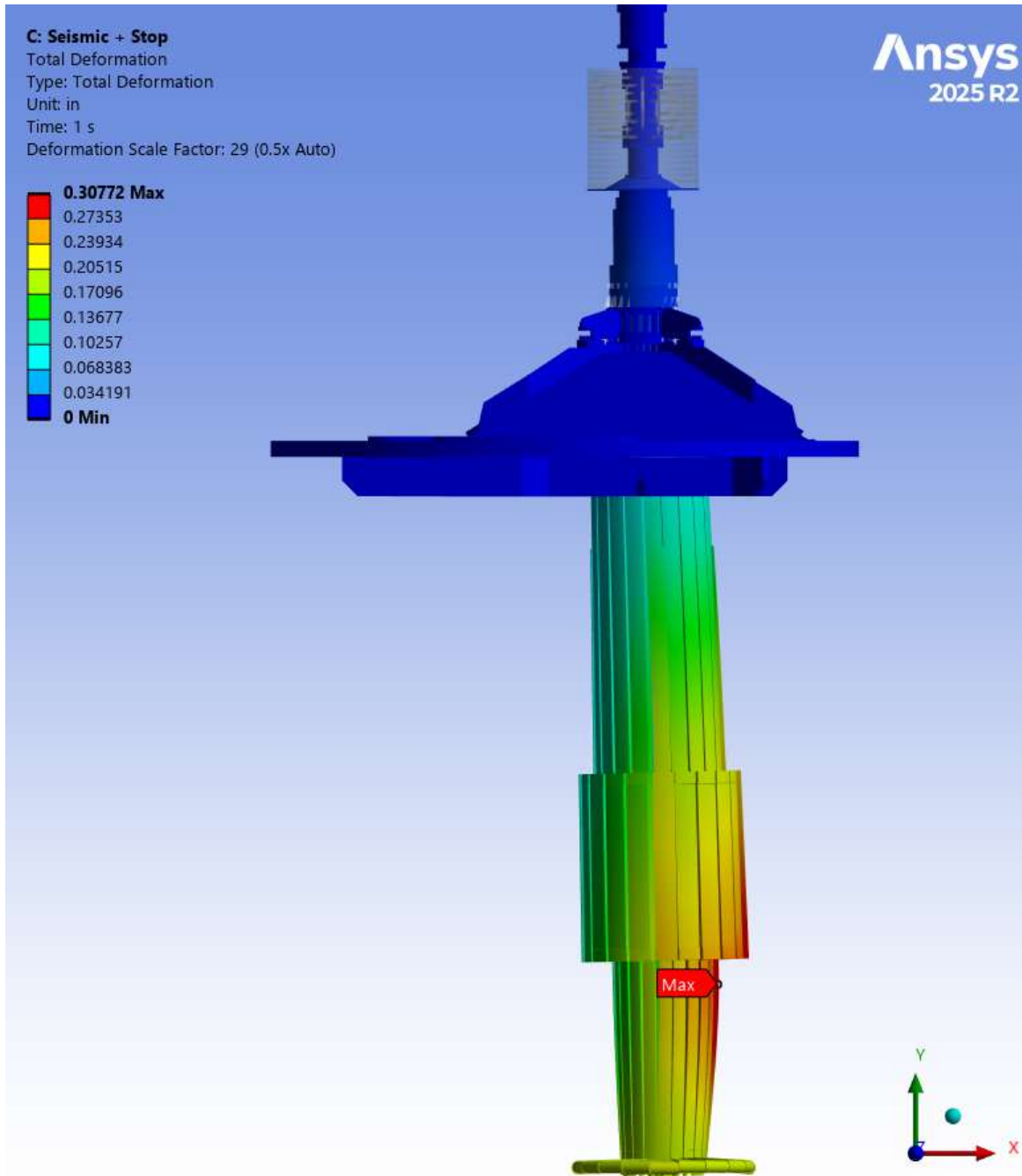


Figure 447 Target Assembly, Seismic + Stop Total Deformation

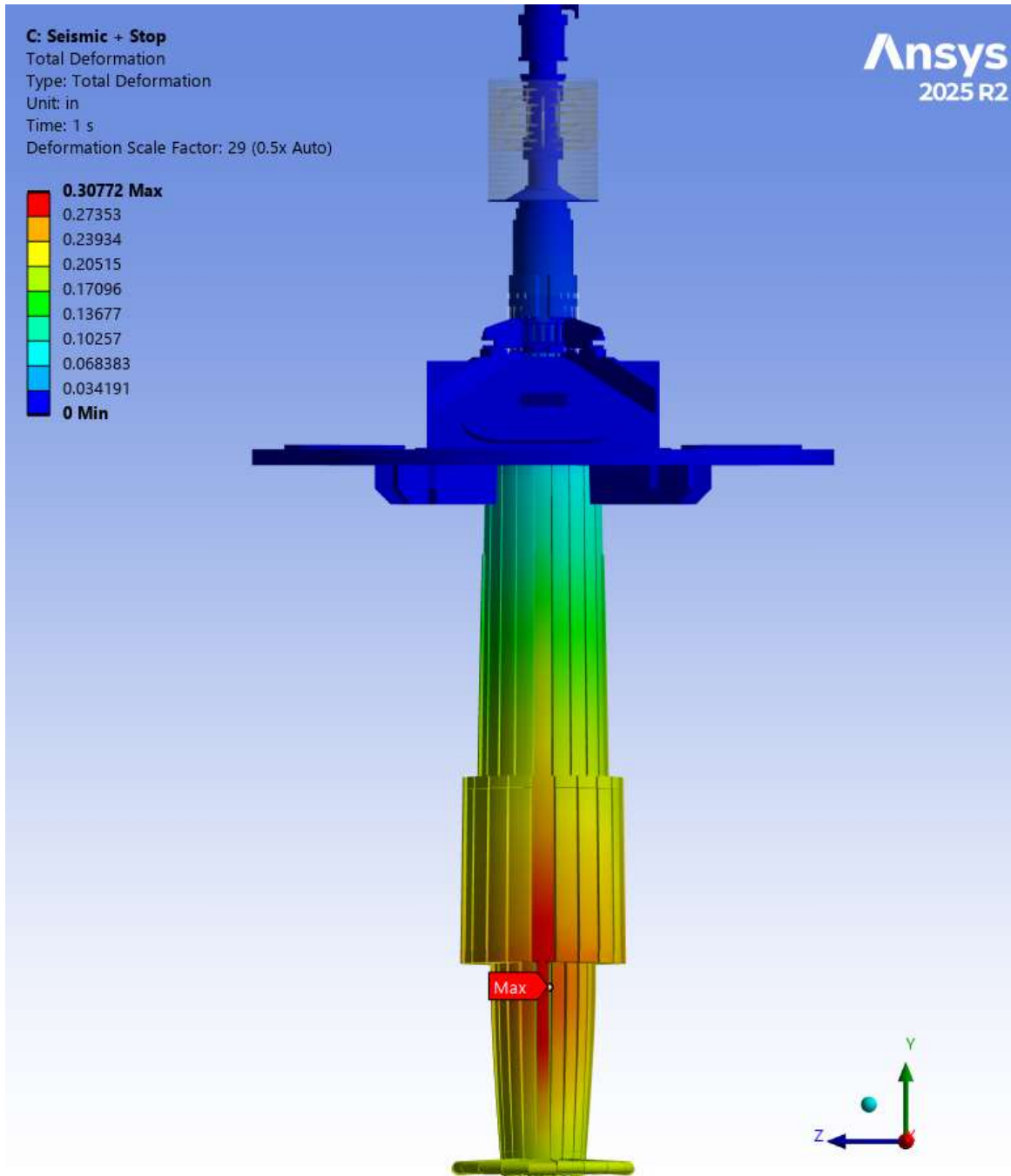


Figure 448 Target Assembly, Seismic + Stop Total Deformation

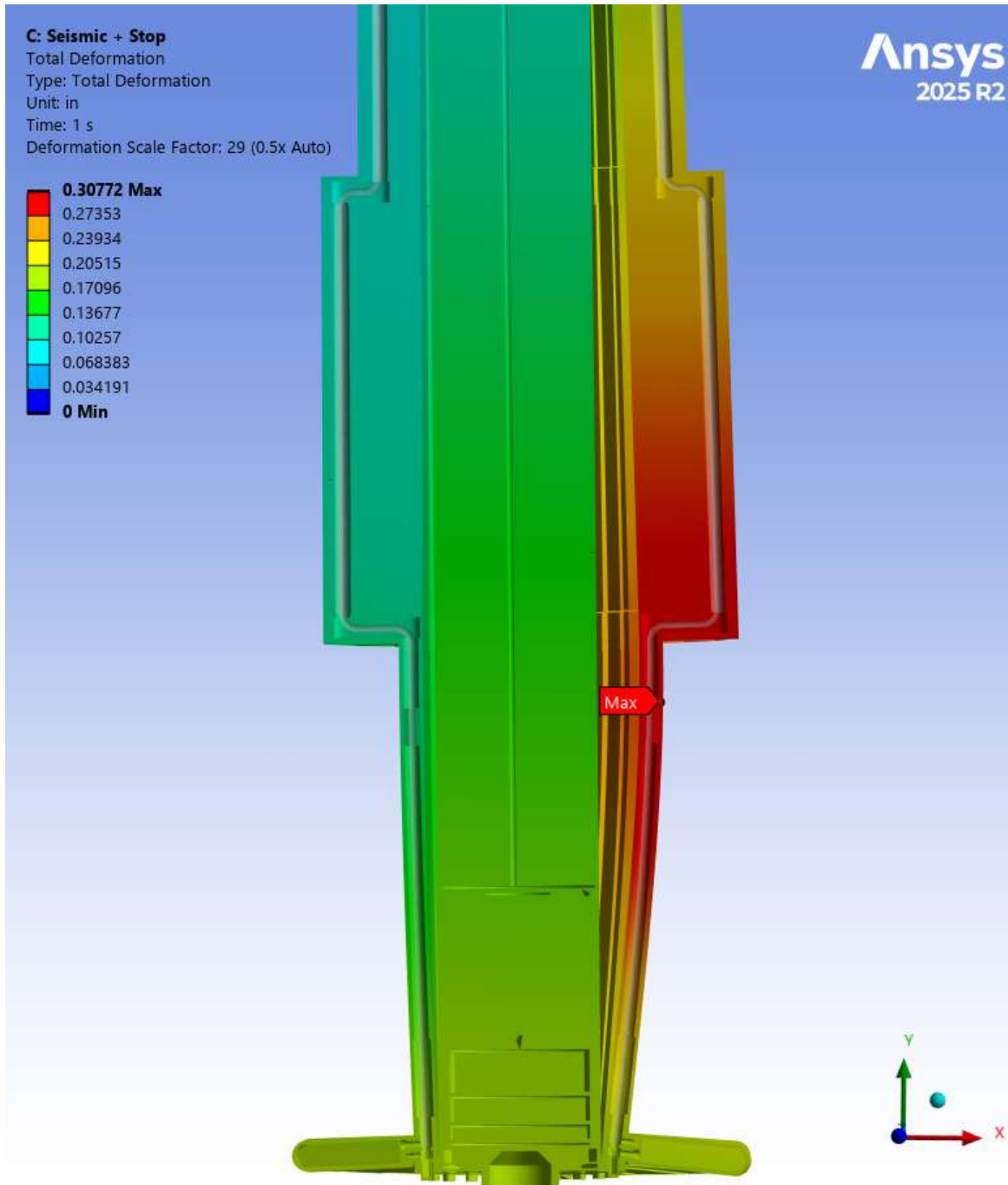


Figure 449 Target Assembly, Seismic + Stop Total Deformation

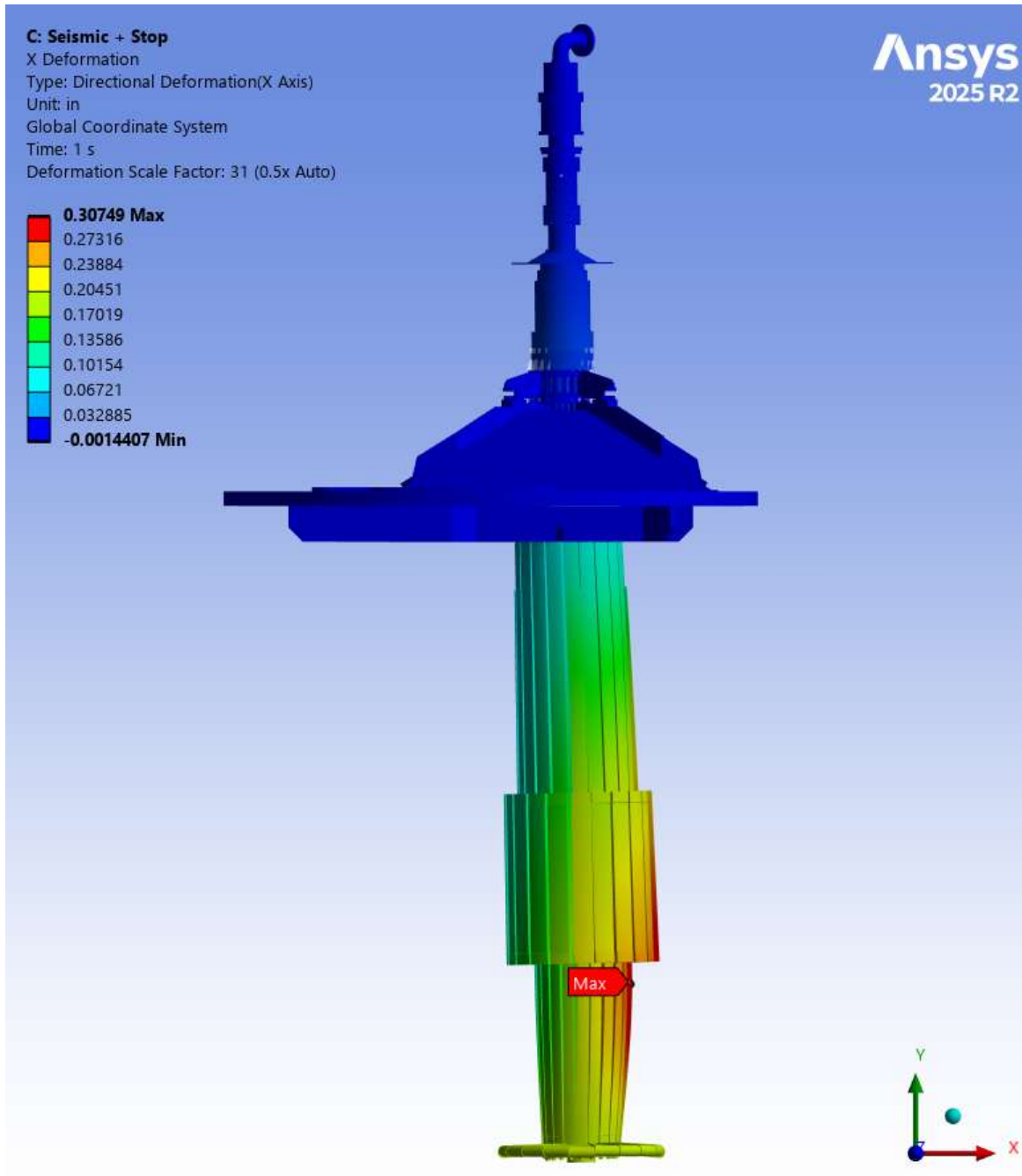


Figure 450 Target Assembly, Seismic + Stop X Deformation

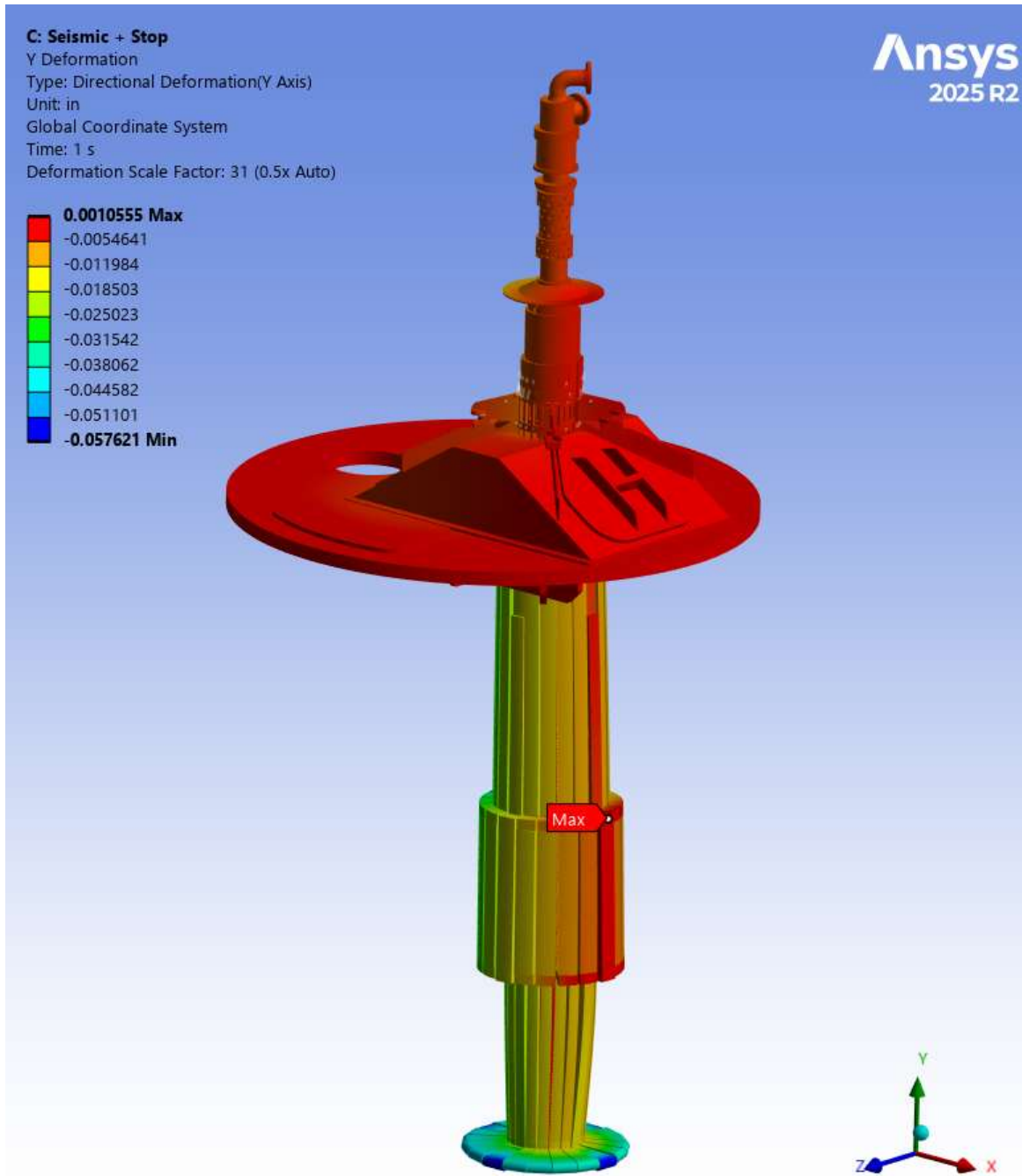


Figure 451 Target Assembly, Seismic + Stop Y Deformation

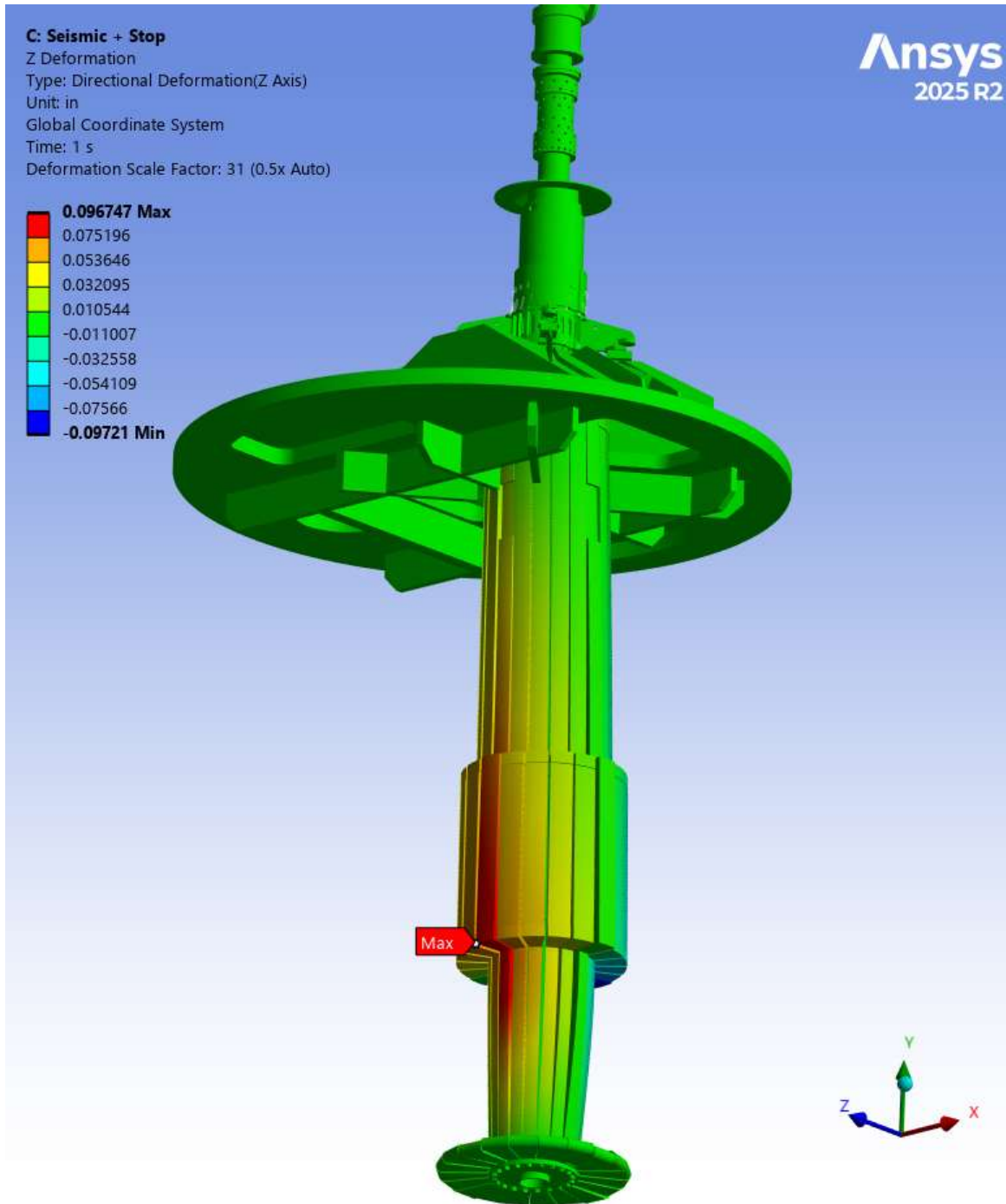


Figure 452 Target Assembly, Seismic + Stop Z Deformation

5.1.2 Target Segment

The Target Segment results go in the order of Plastic Ratcheting then Local Failure. Equivalent stress and contact gap of the water joint are included for reference.

5.1.2.1 Target Segment Plastic Failure

5.1.2.1.1 E Stop Load Case

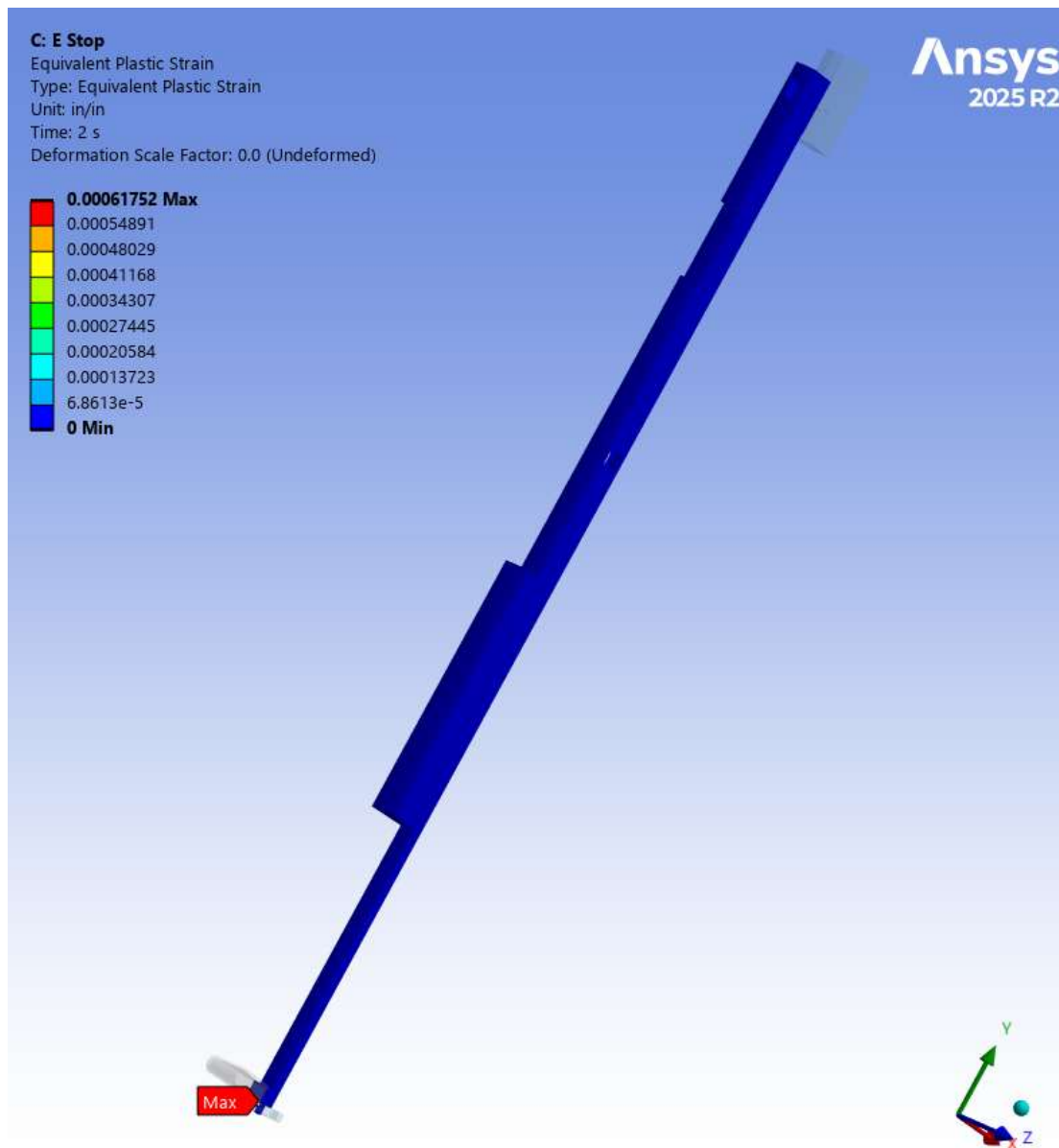


Figure 453 Segment, E Stop Equivalent Plastic Strain

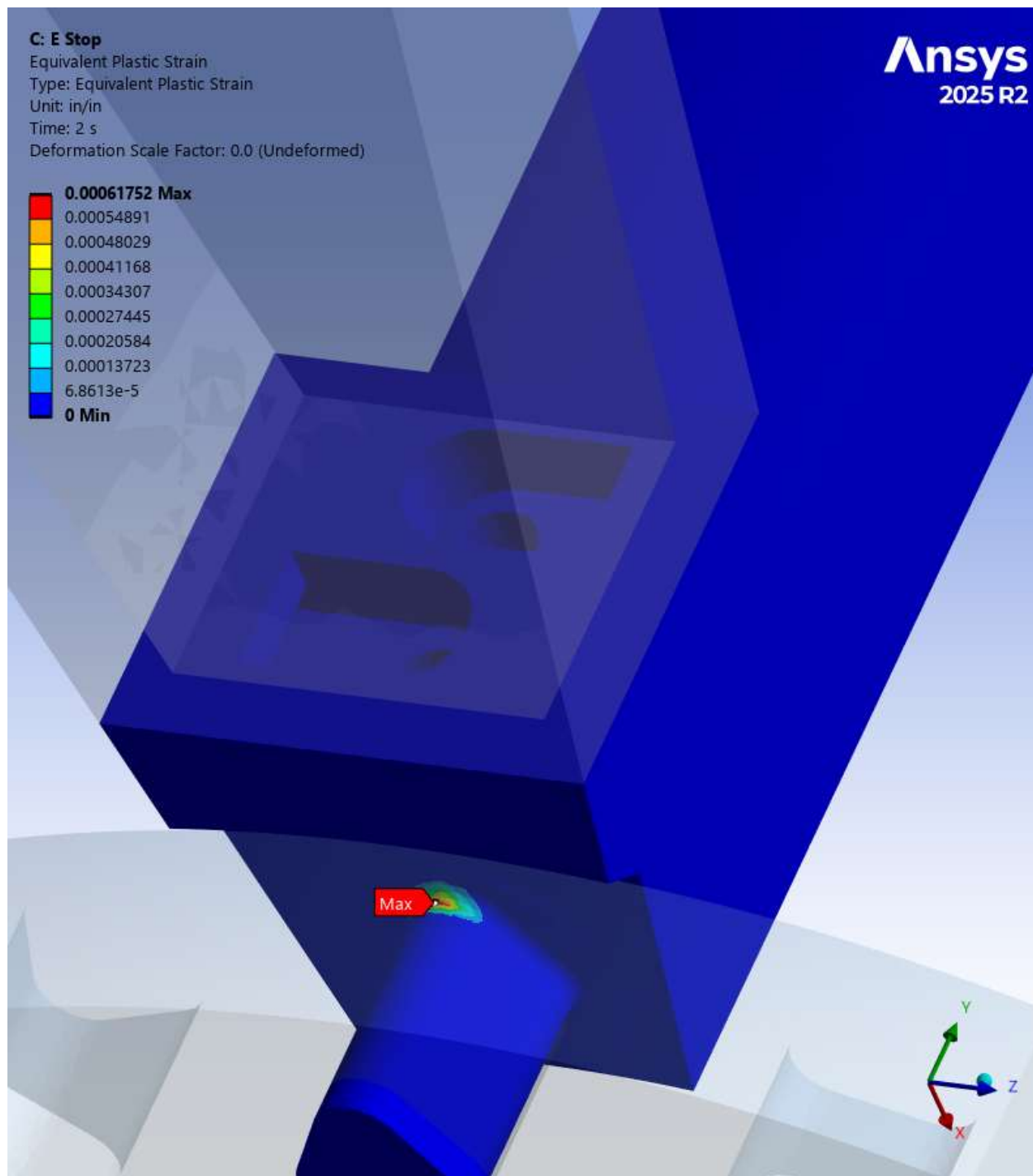


Figure 454 Segment, E Stop Equivalent Plastic Strain

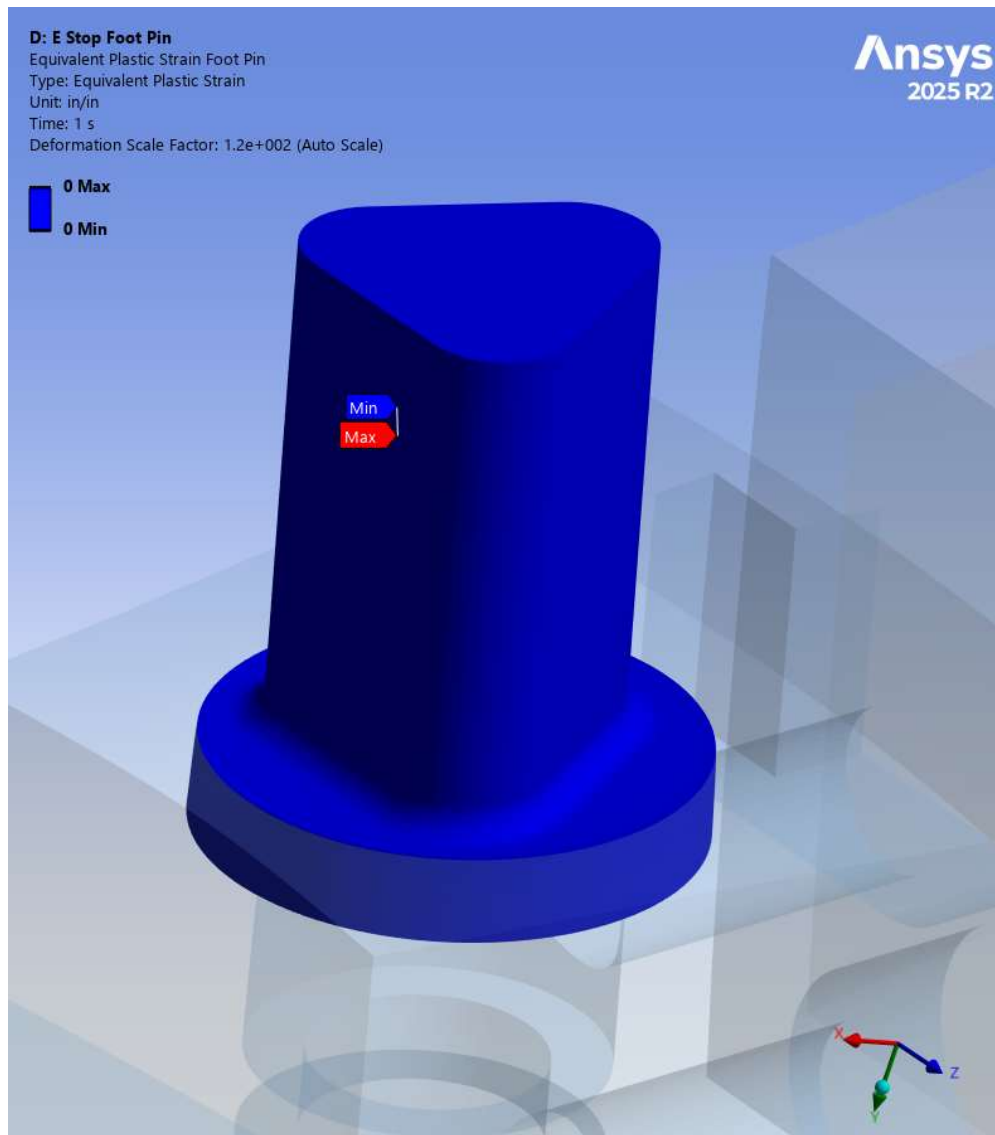


Figure 455 Segment, E Stop Plastic Strain, Foot Pin Focus

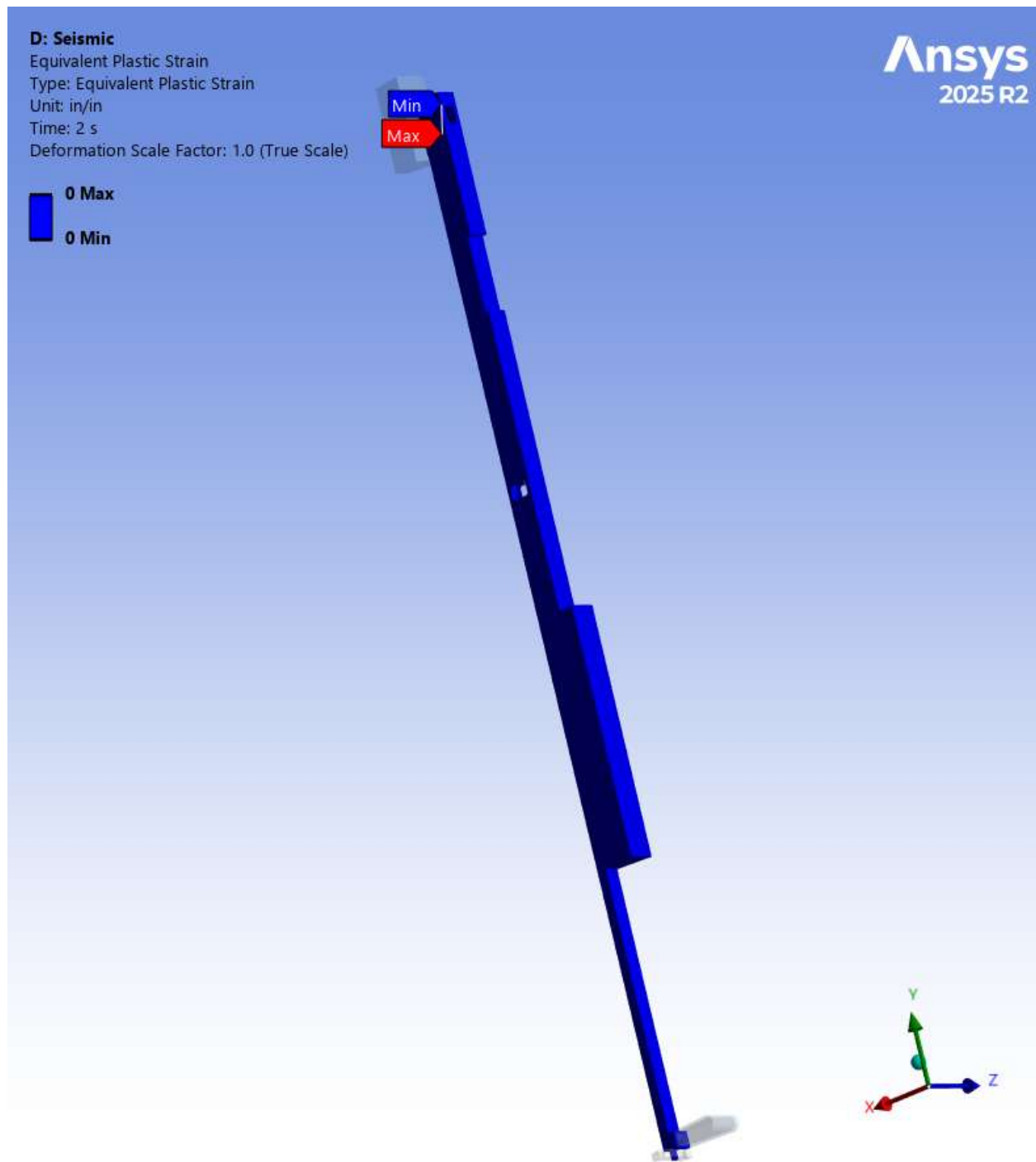


Figure 456 Segment, Seismic Equivalent Plastic Strain, Time 2

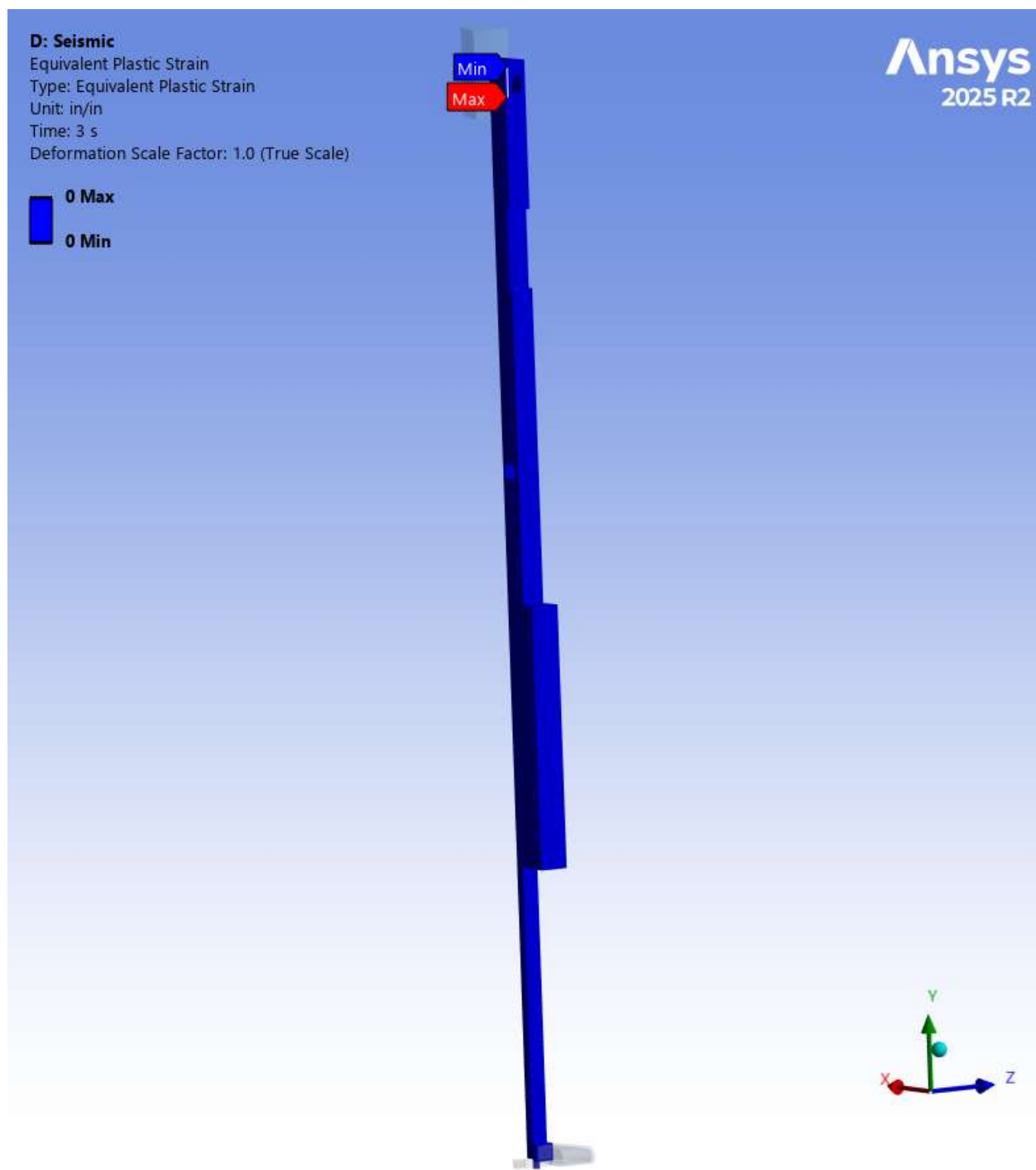


Figure 457 Segment, Seismic Equivalent Plastic Strain, Time 3

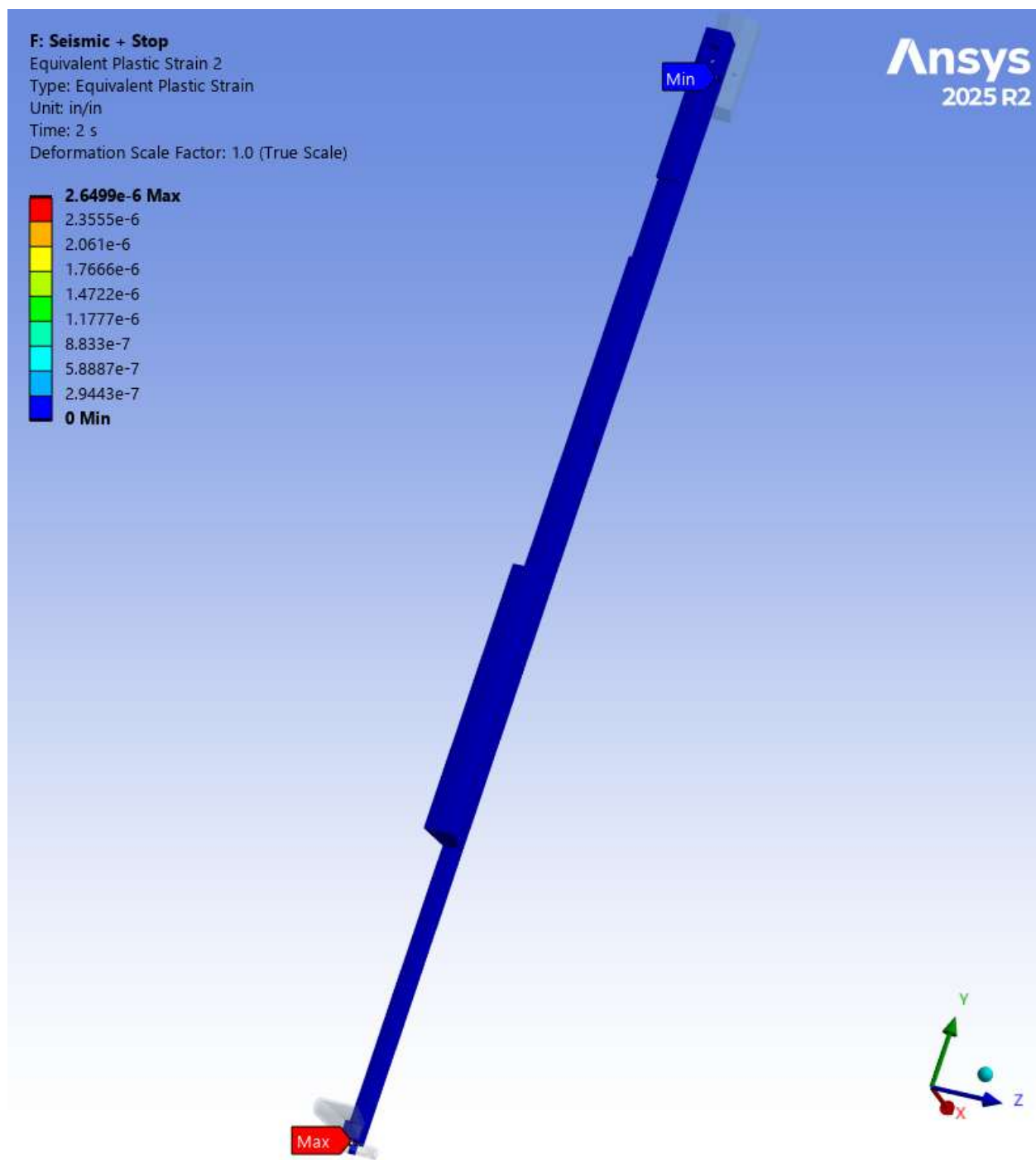


Figure 458 Segment, Seismic + Stop Equivalent Plastic Strain, Time 2

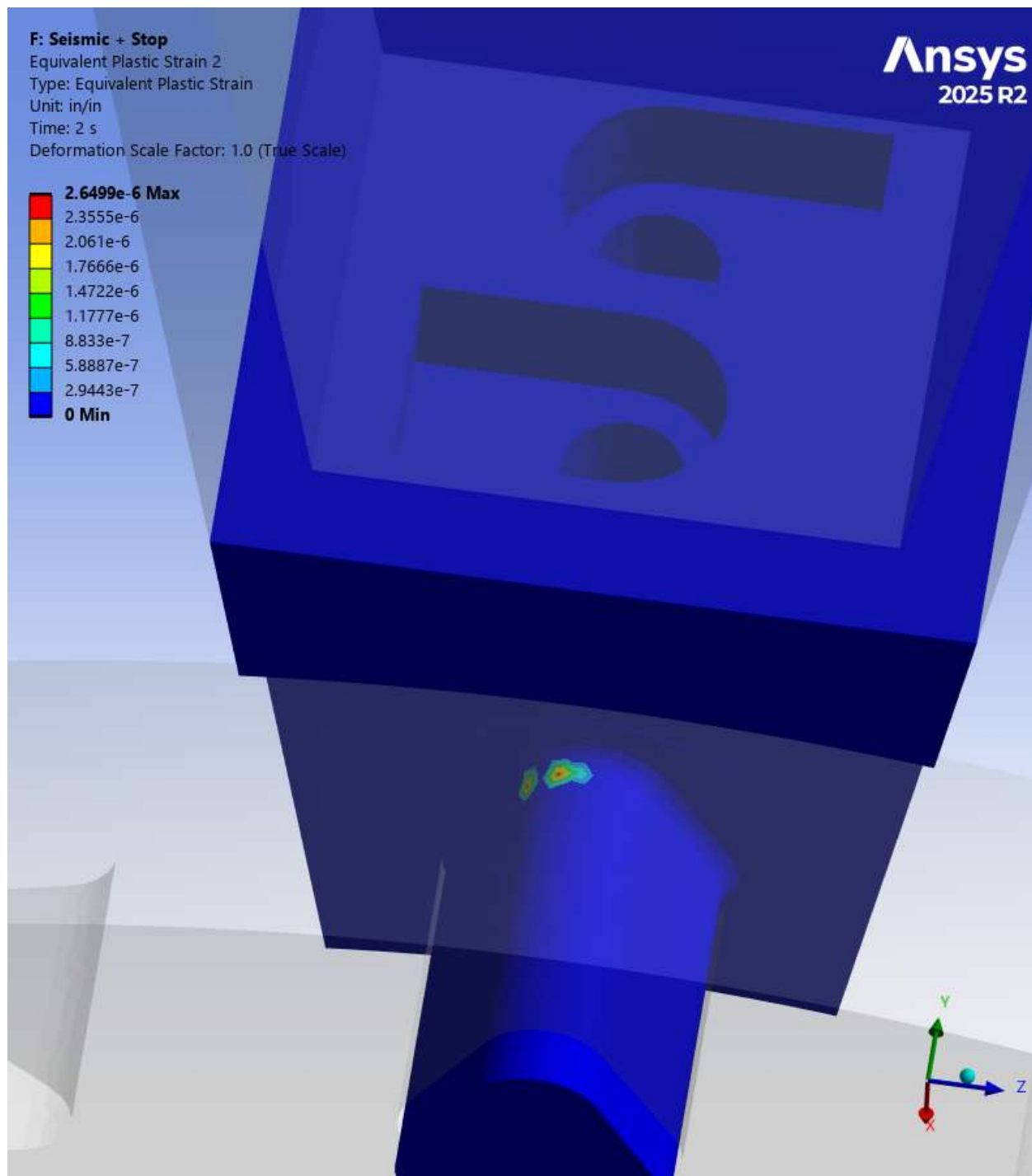


Figure 459 Segment, Seismic + Stop Equivalent Plastic Strain, Time 2

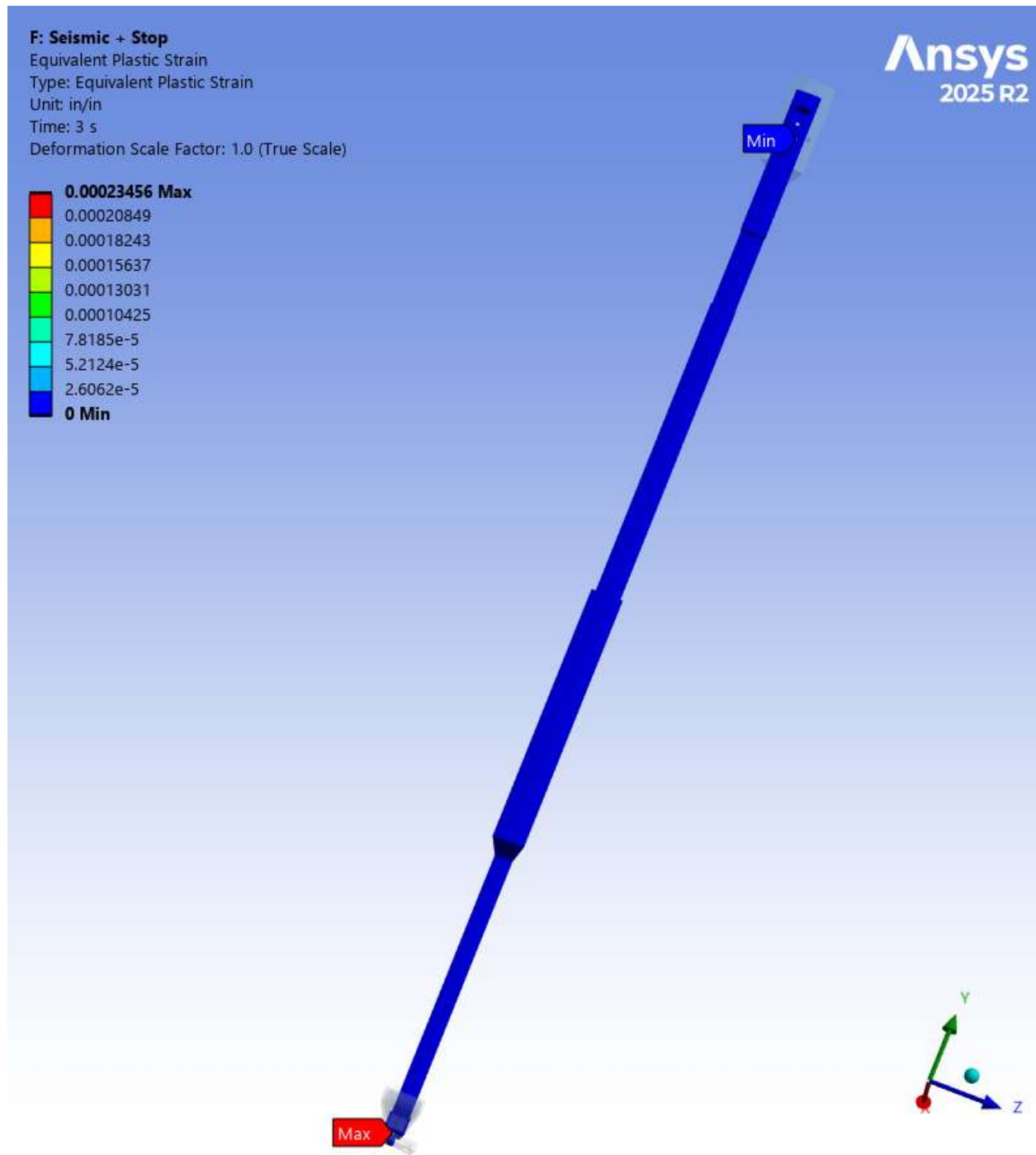


Figure 460 Segment, Seismic + Stop Equivalent Plastic Strain, Time 3

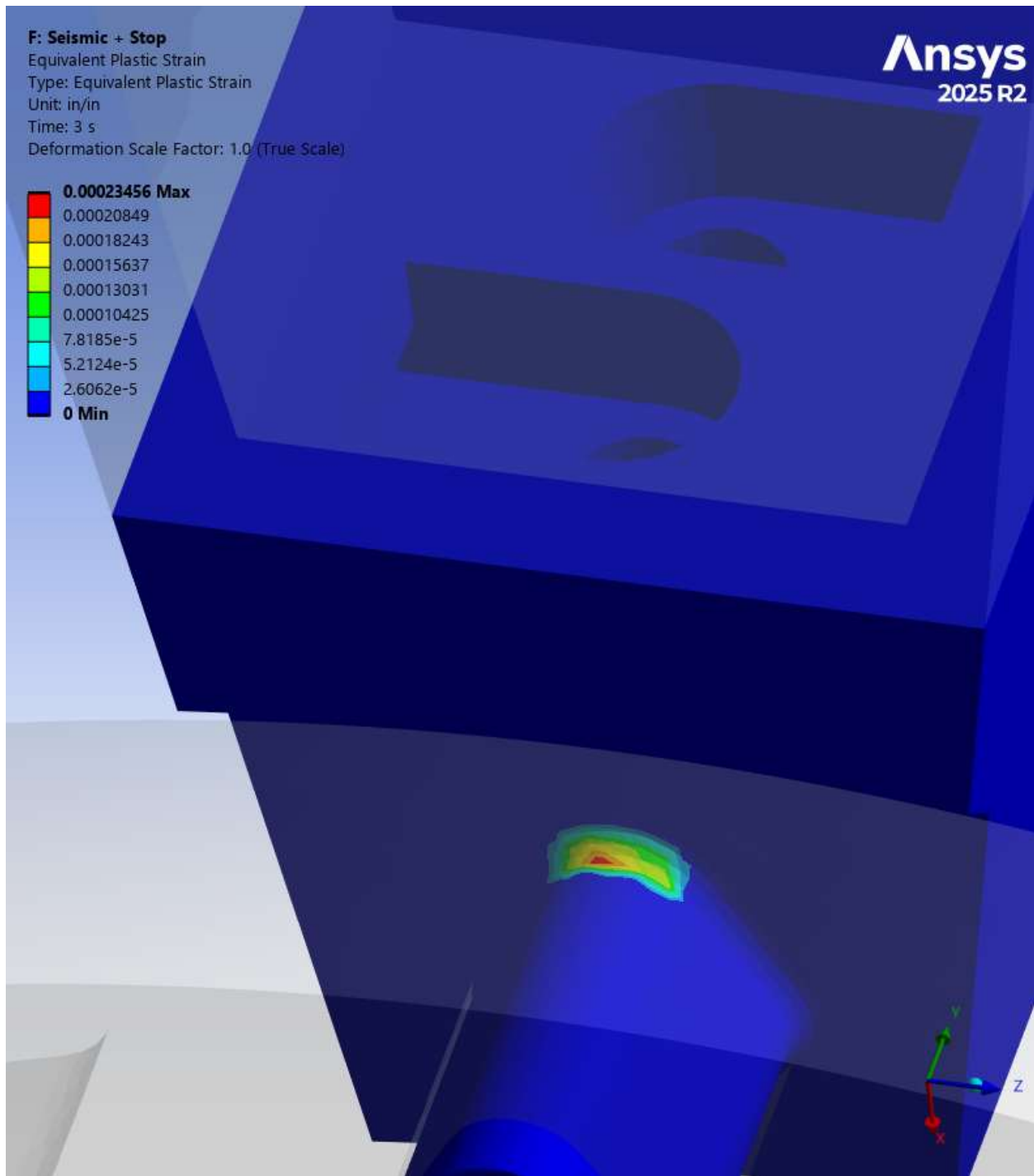


Figure 461 Segment, Seismic + Stop Equivalent Plastic Strain, Time 3

5.1.2.2 Local Failure

5.1.2.2.1 Elastic Plastic Case 1

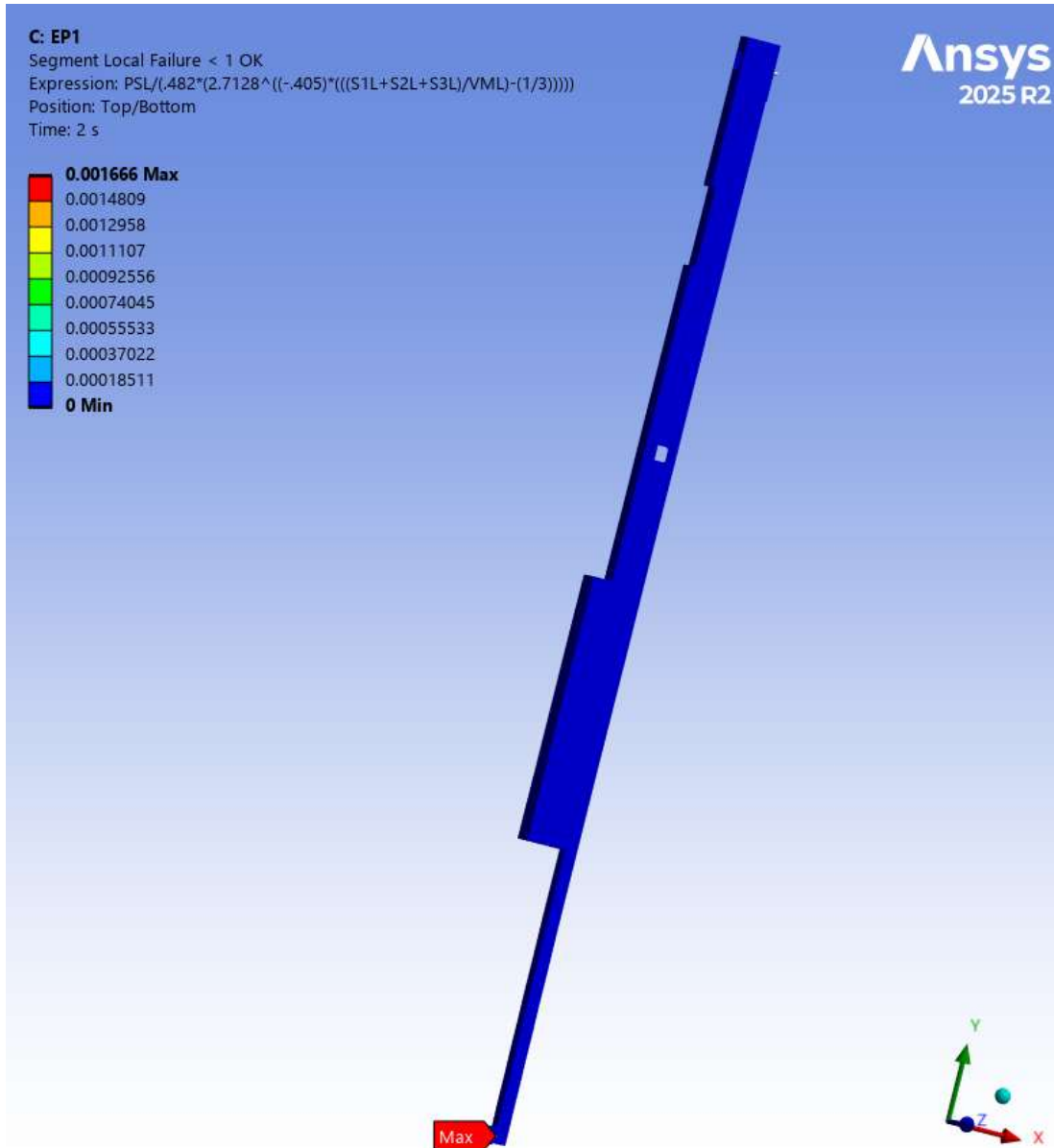


Figure 462 Segment, EP1 Local Failure

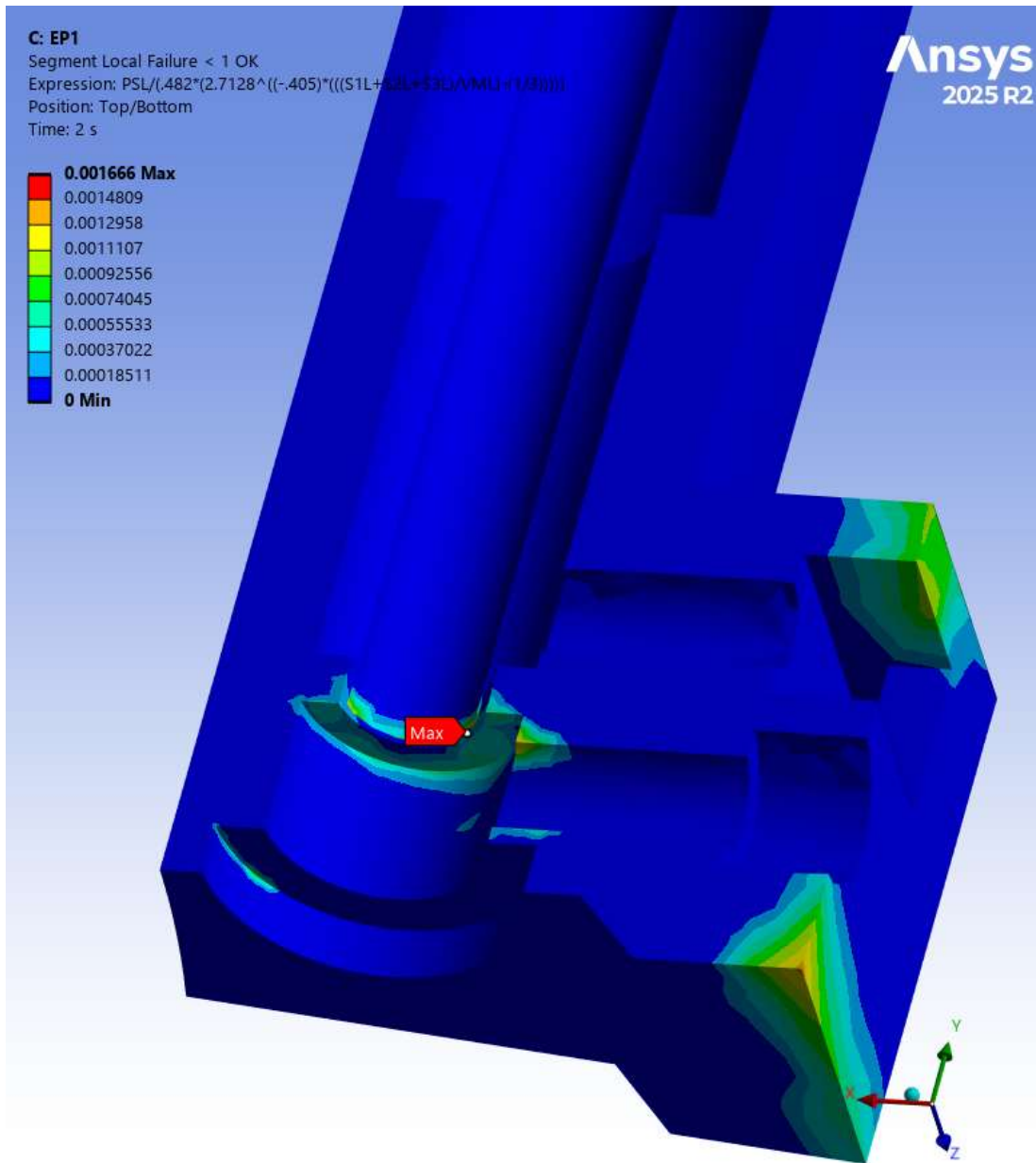


Figure 463 Segment, EP1 Local Failure

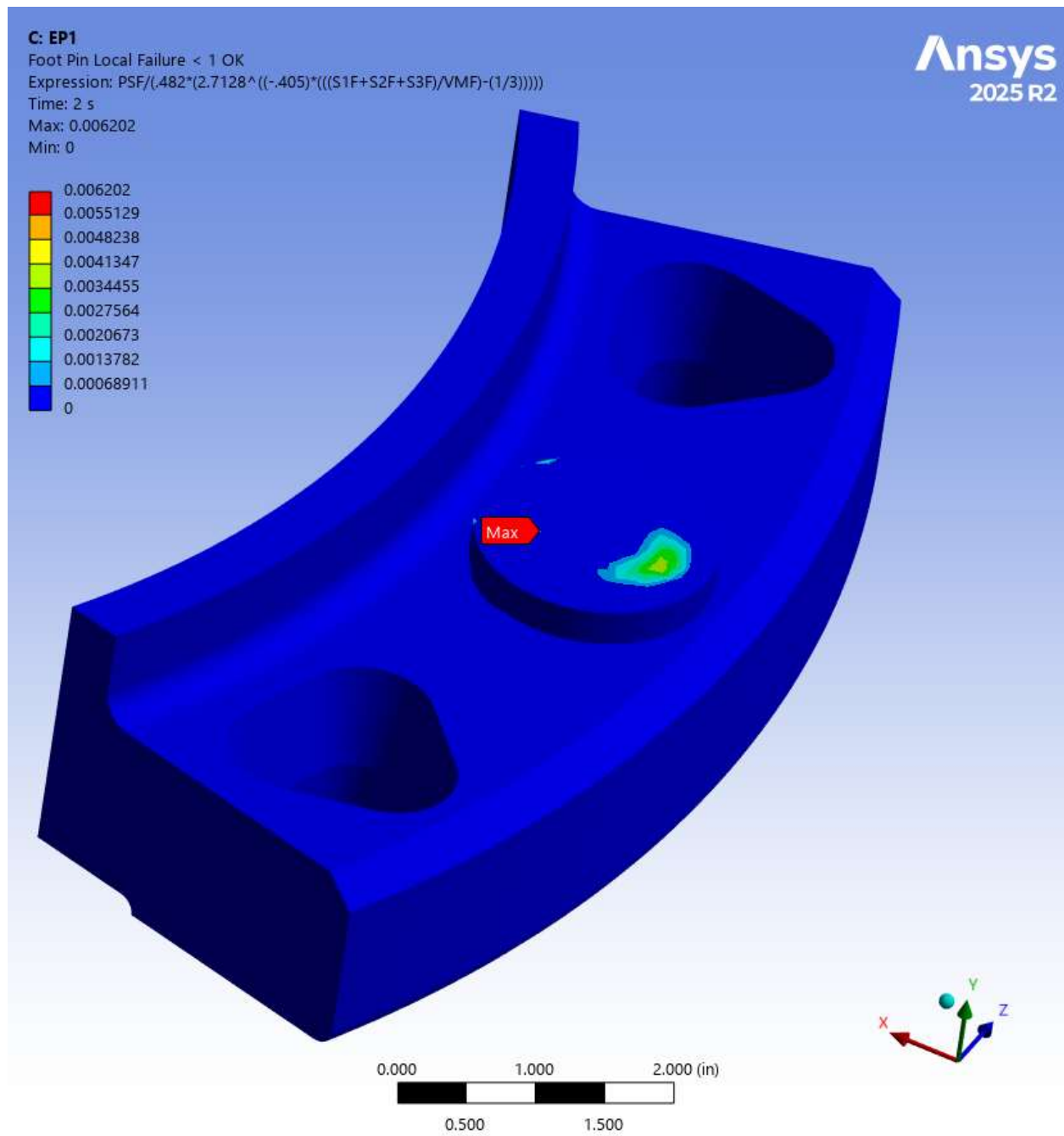


Figure 464 Segment, EP1 Local Failure, Foot Pin

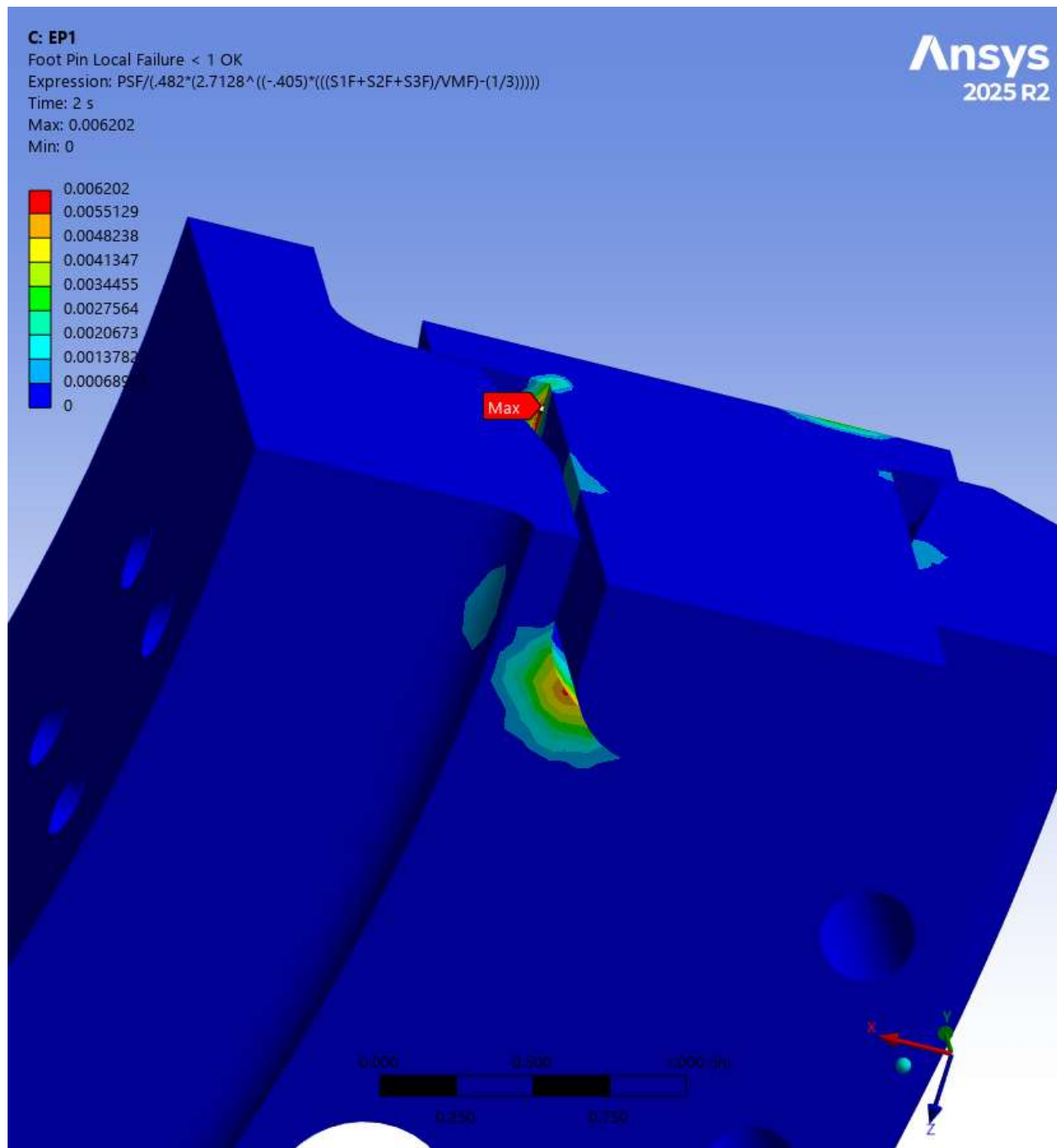


Figure 465 Segment, EP1 Local Failure, Foot Pin

5.1.2.2.2 Elastic Plastic Load Case 2

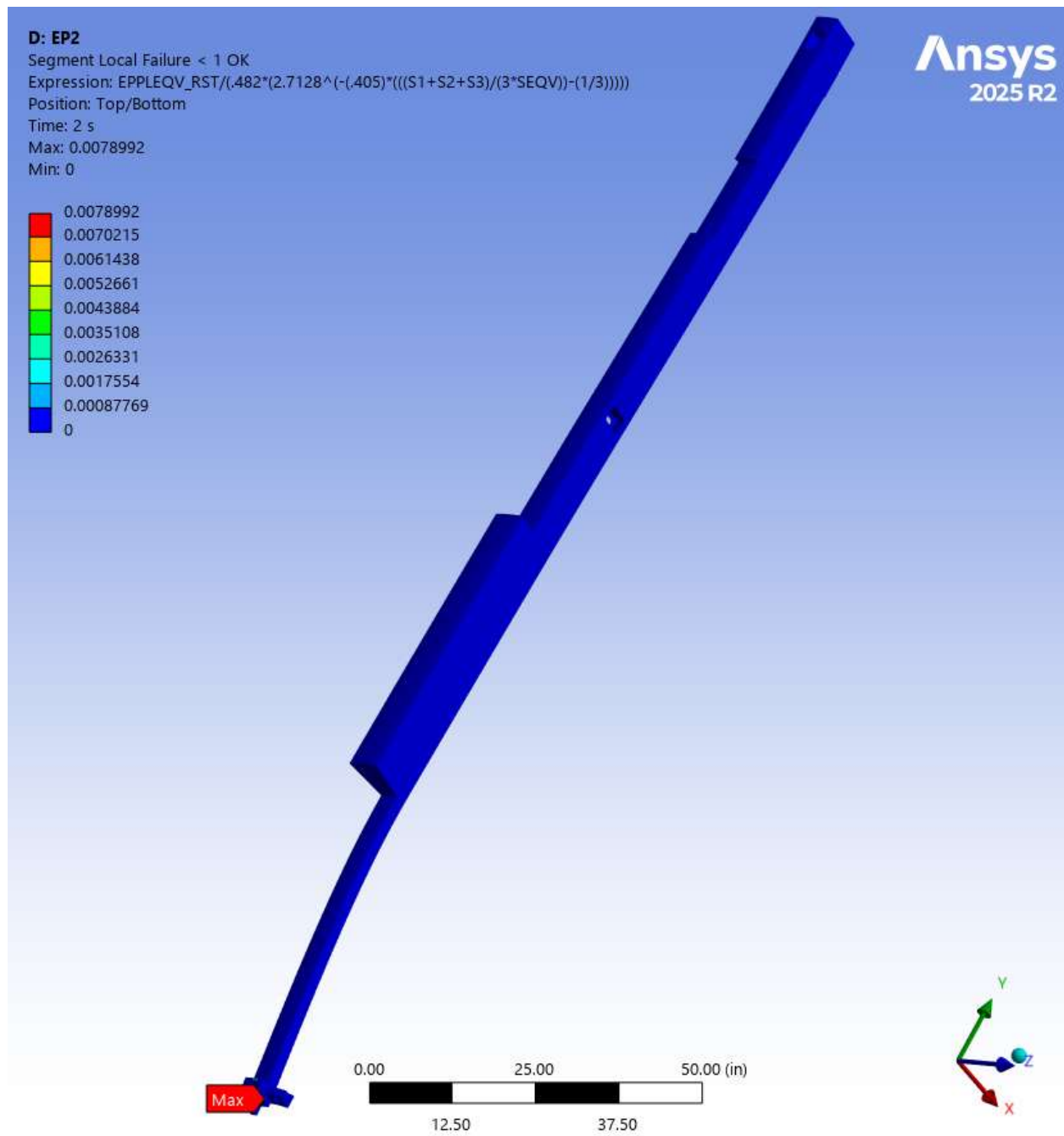


Figure 466 Segment, EP2 Local Failure

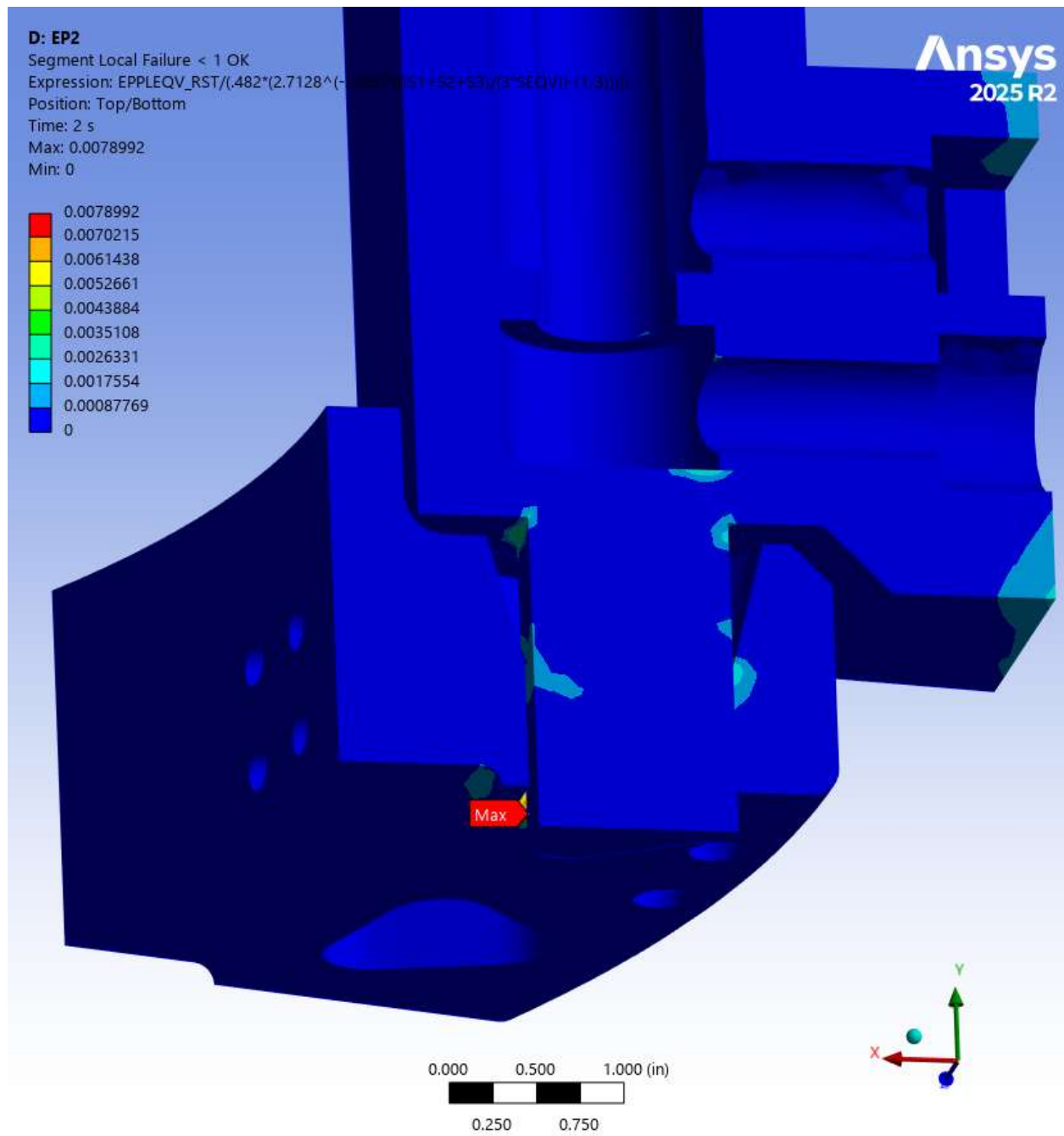


Figure 467 Segment, EP2 Local Failure, Foot Pin

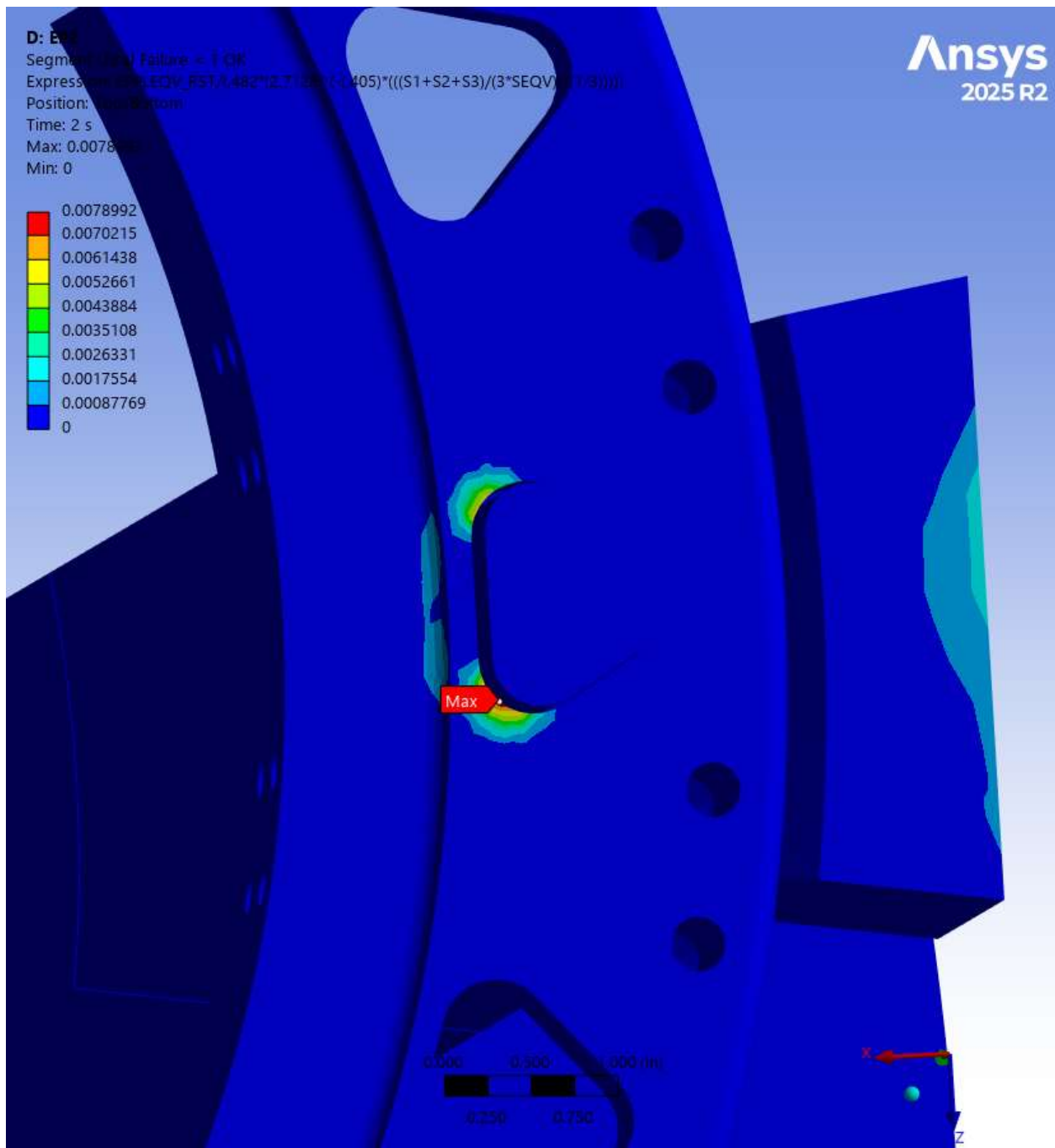


Figure 468 Segment, EP2 Local Failure, Foot Pin

5.1.2.2.3 Elastic Plastic Load Case 5

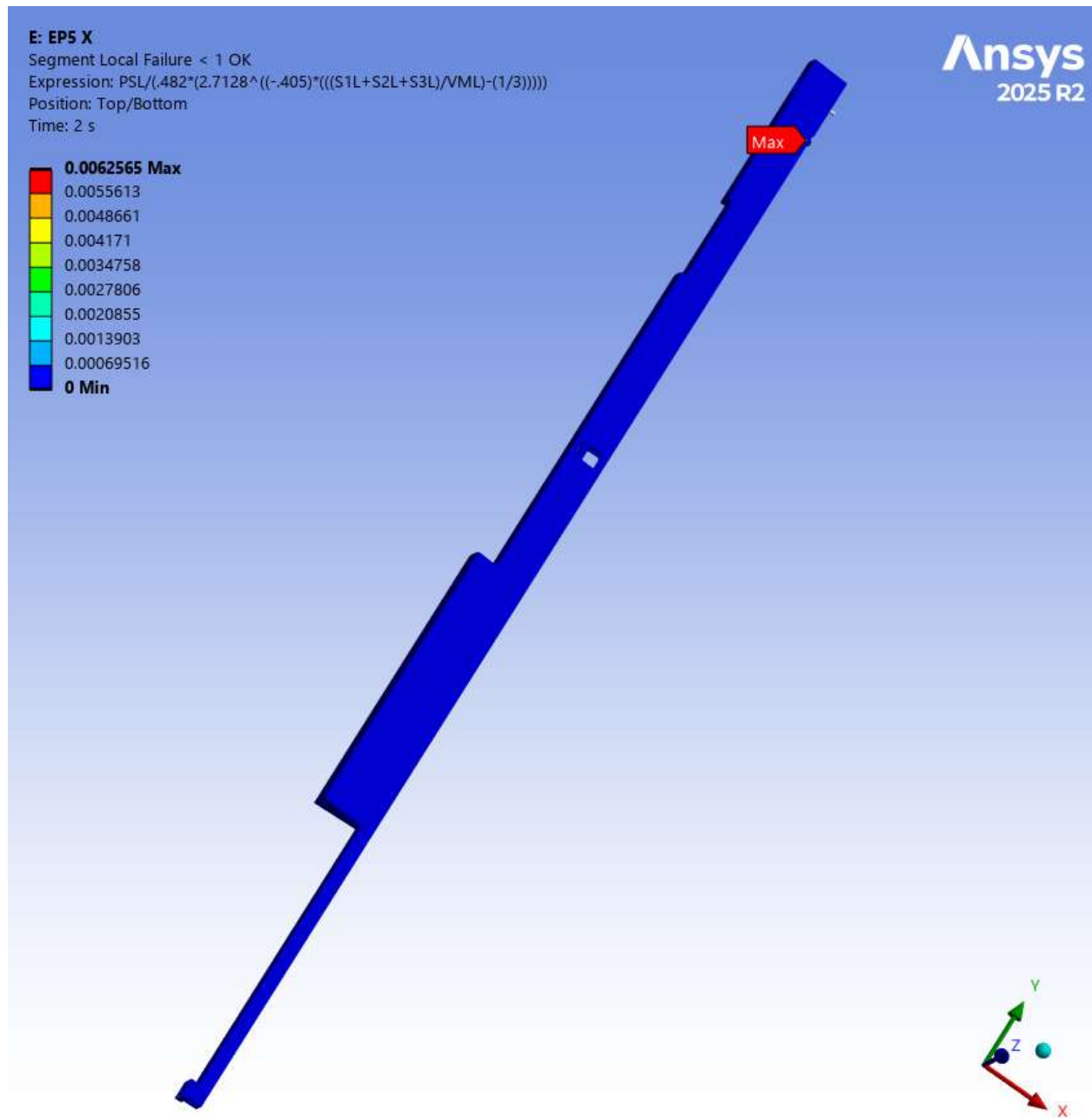


Figure 469 Segment, EP5 X Local Failure

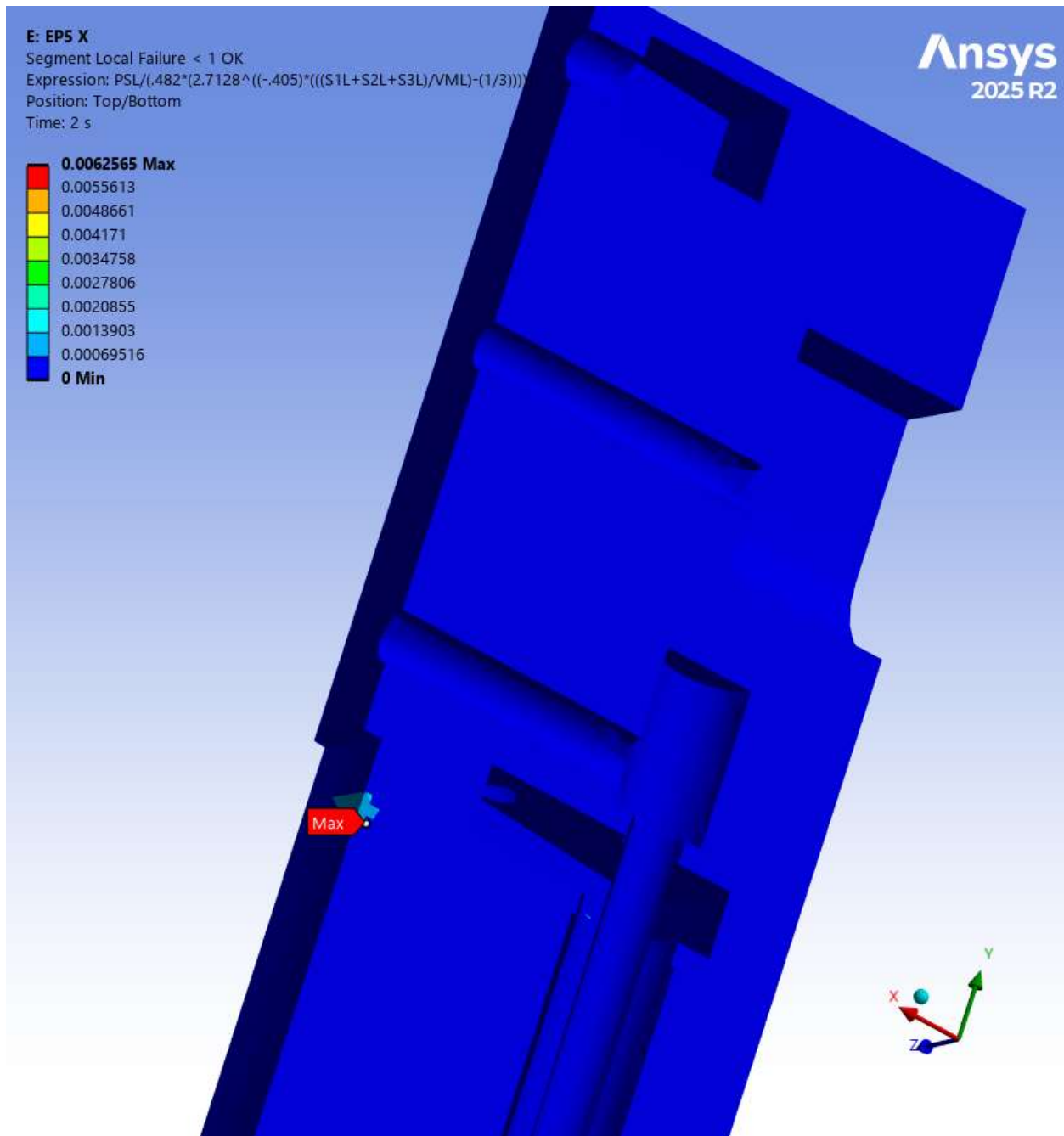


Figure 470 Segment, EP5 X Local Failure

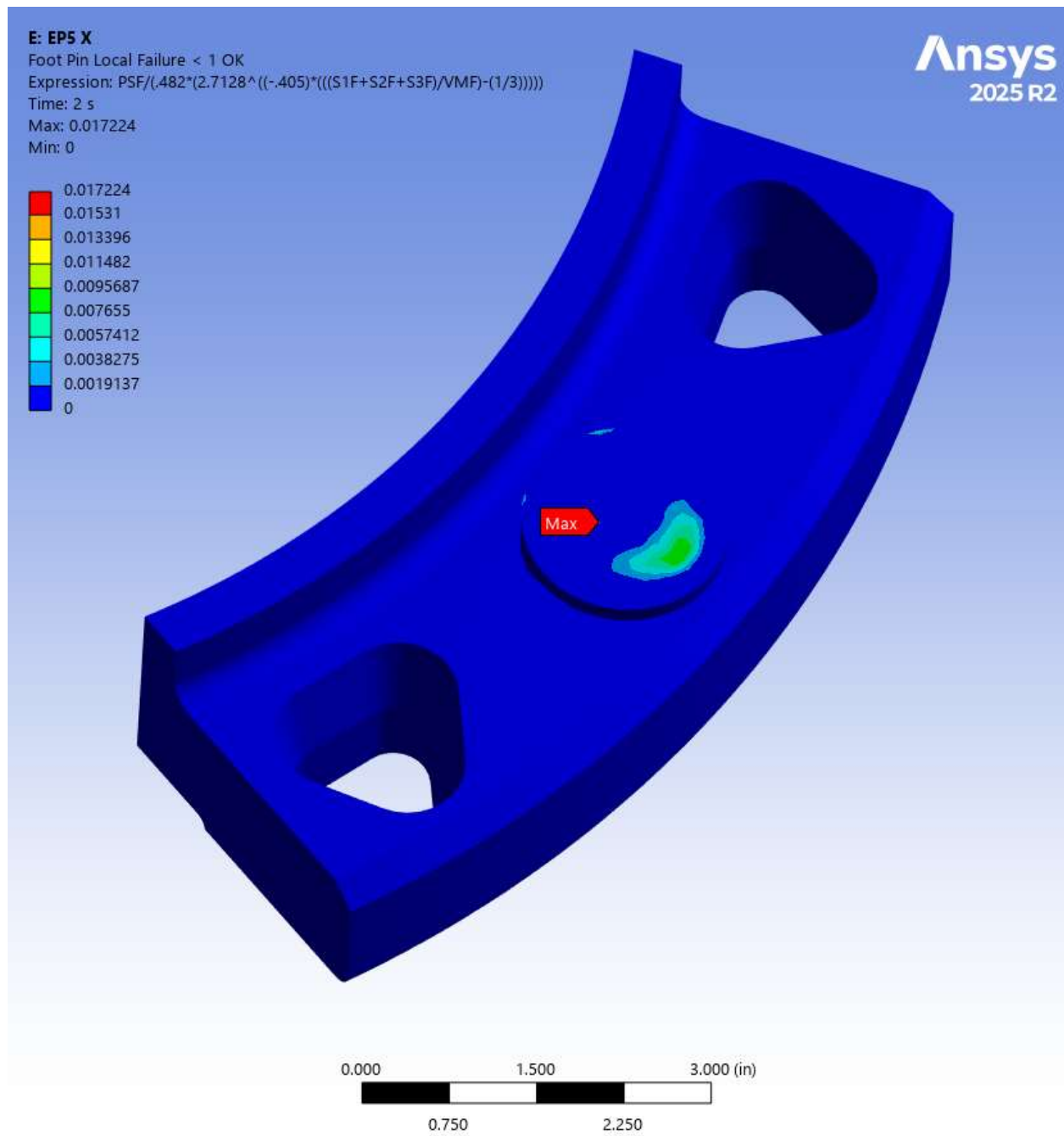


Figure 471 Segment, EP5 X Local Failure, Foot Pin

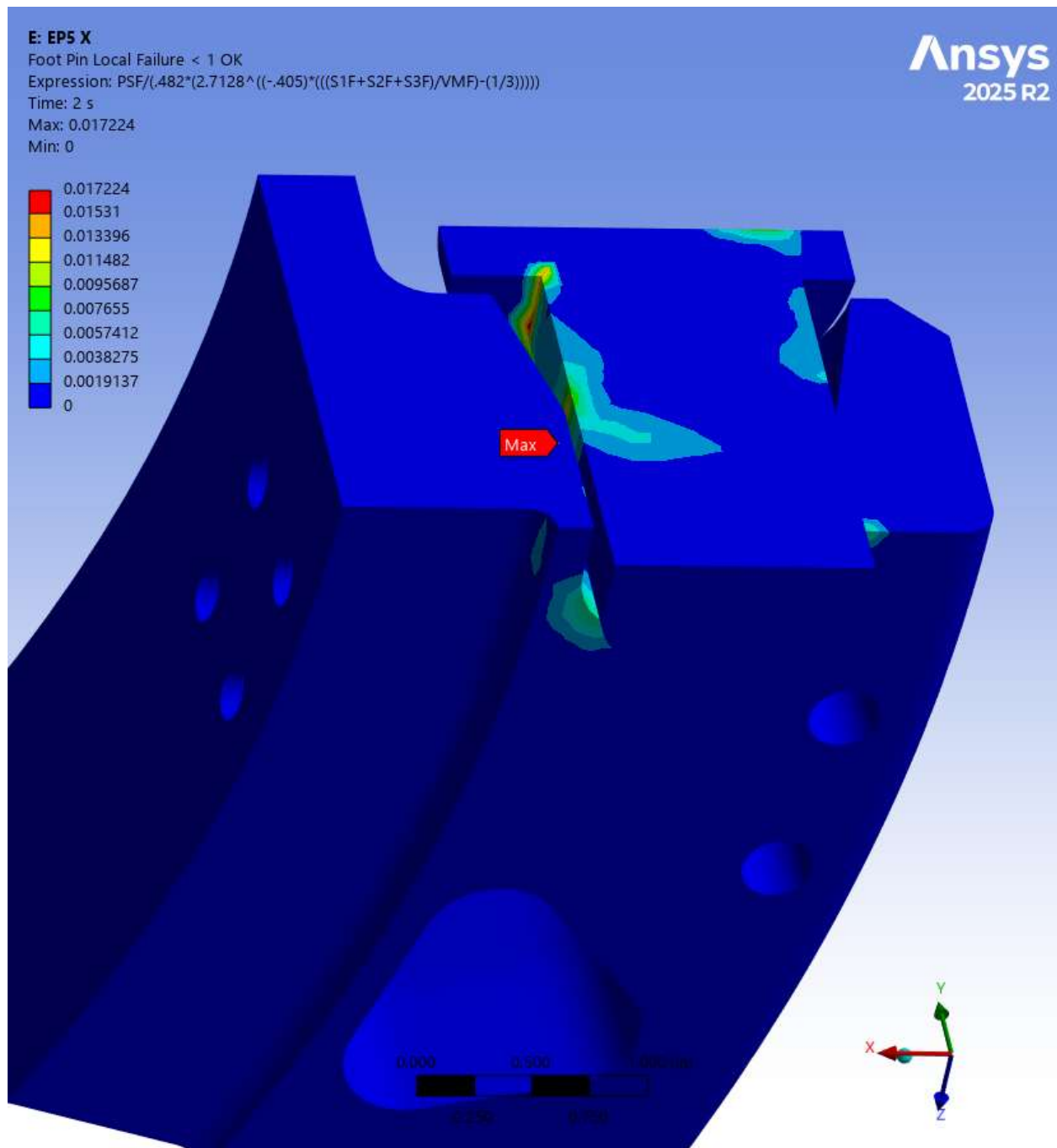


Figure 472 Segment, EP5 X Local Failure, Foot Pin

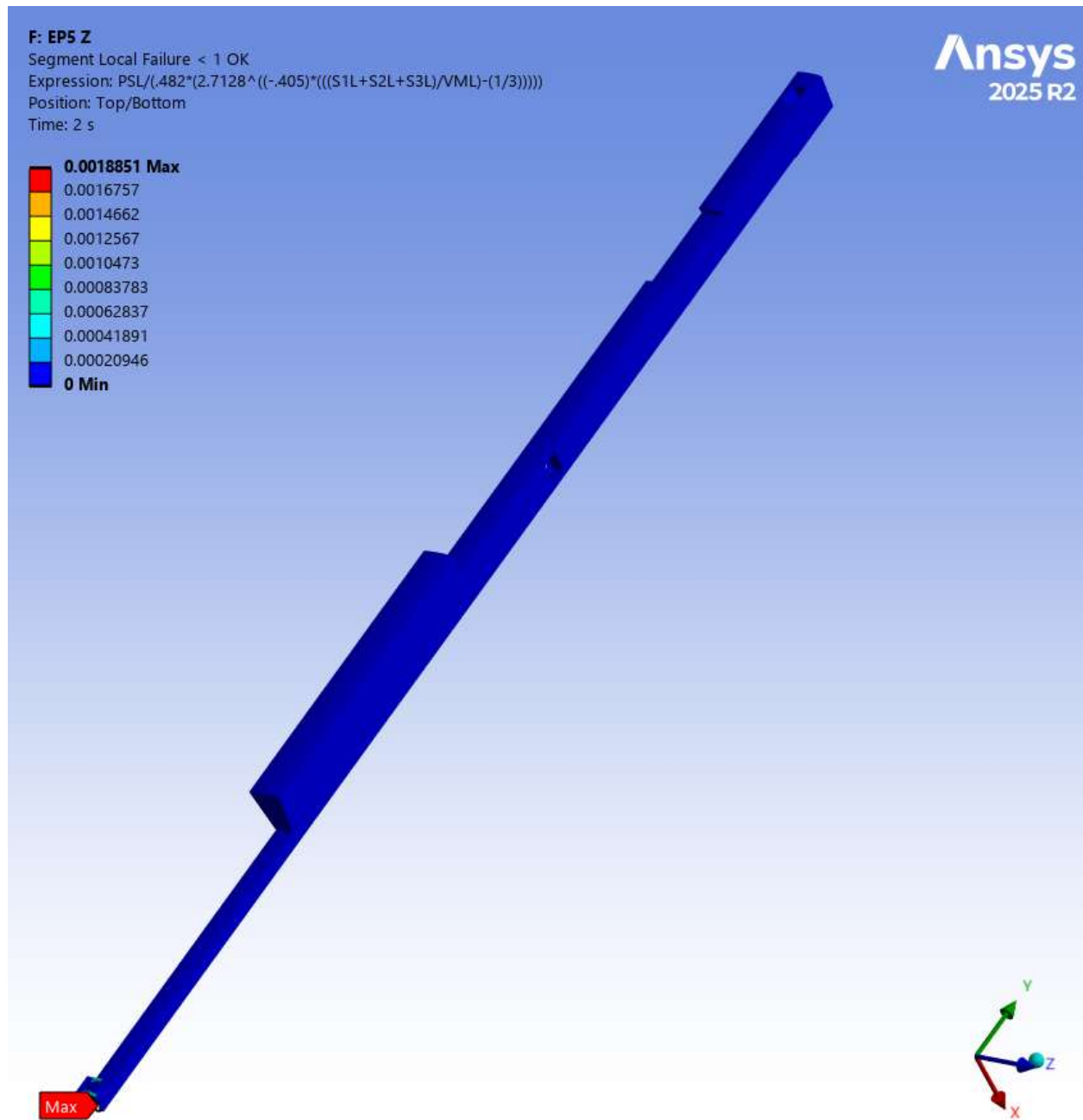


Figure 473 Segment, EP5 Z Local Failure

F: EP5 Z

Segment Local Failure < 1 OK

Expression: $\text{PSL}/(.482*(2.7128^{((-405)*(((S1L+S2L+S3L)/VML)-(1/3))))$

Position: Top/Bottom

Time: 2 s

Ansys
2025 R2

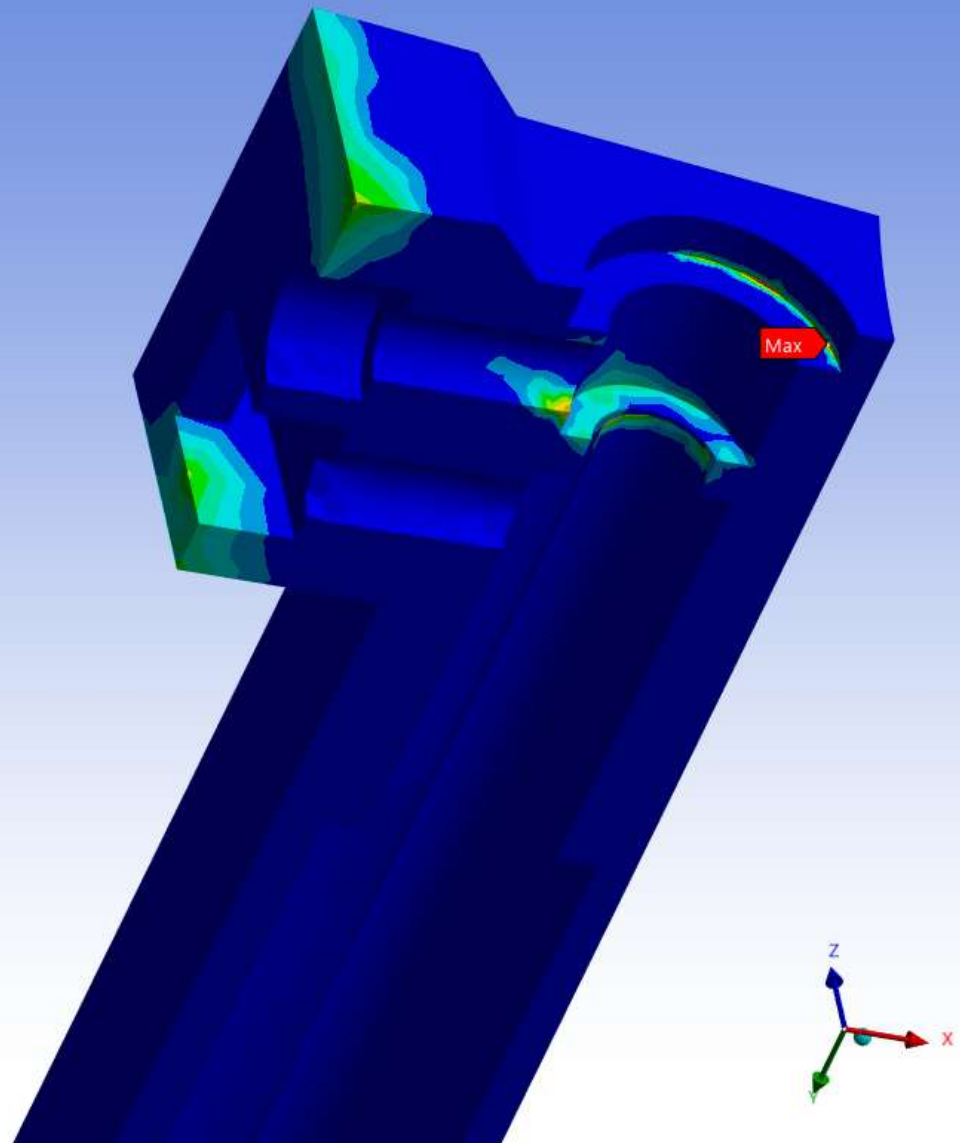
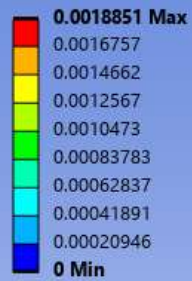


Figure 474 Segment, EP5 Z Local Failure

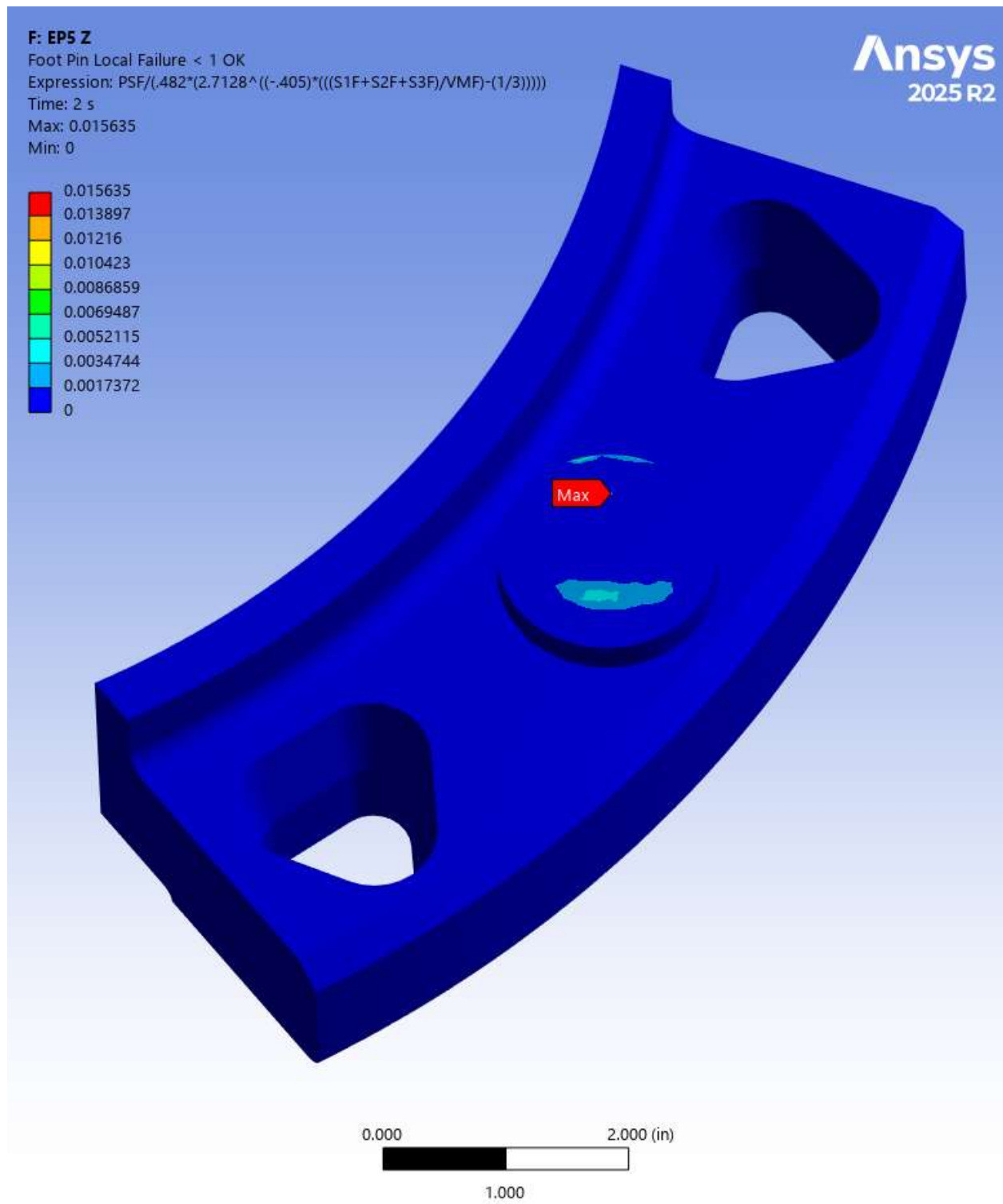


Figure 475 Segment, EP5 Z Local Failure, Foot Pin

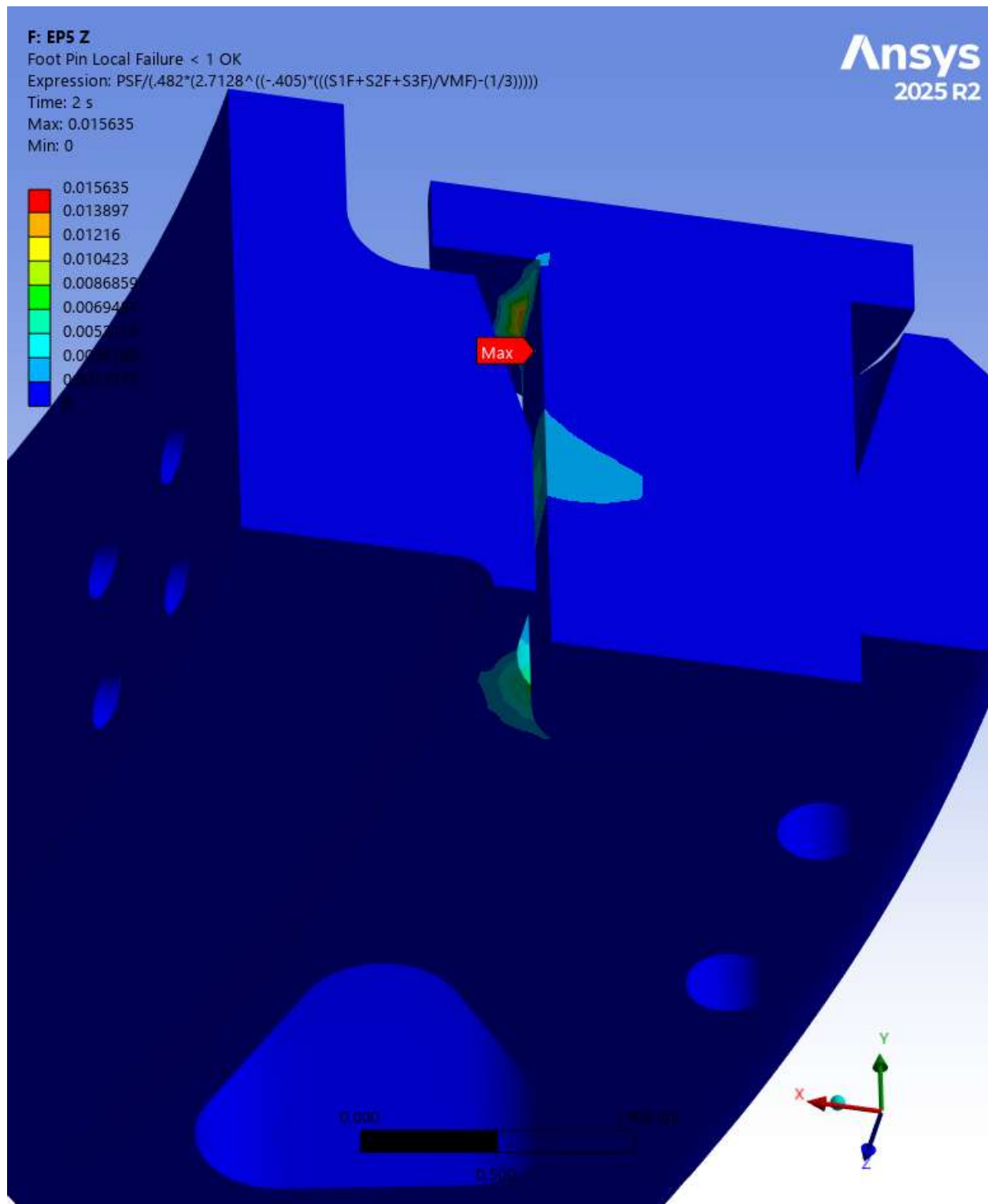


Figure 476 Segment, EP5 Z Local Failure, Foot Pin

5.1.2.3 Cyclic Loads

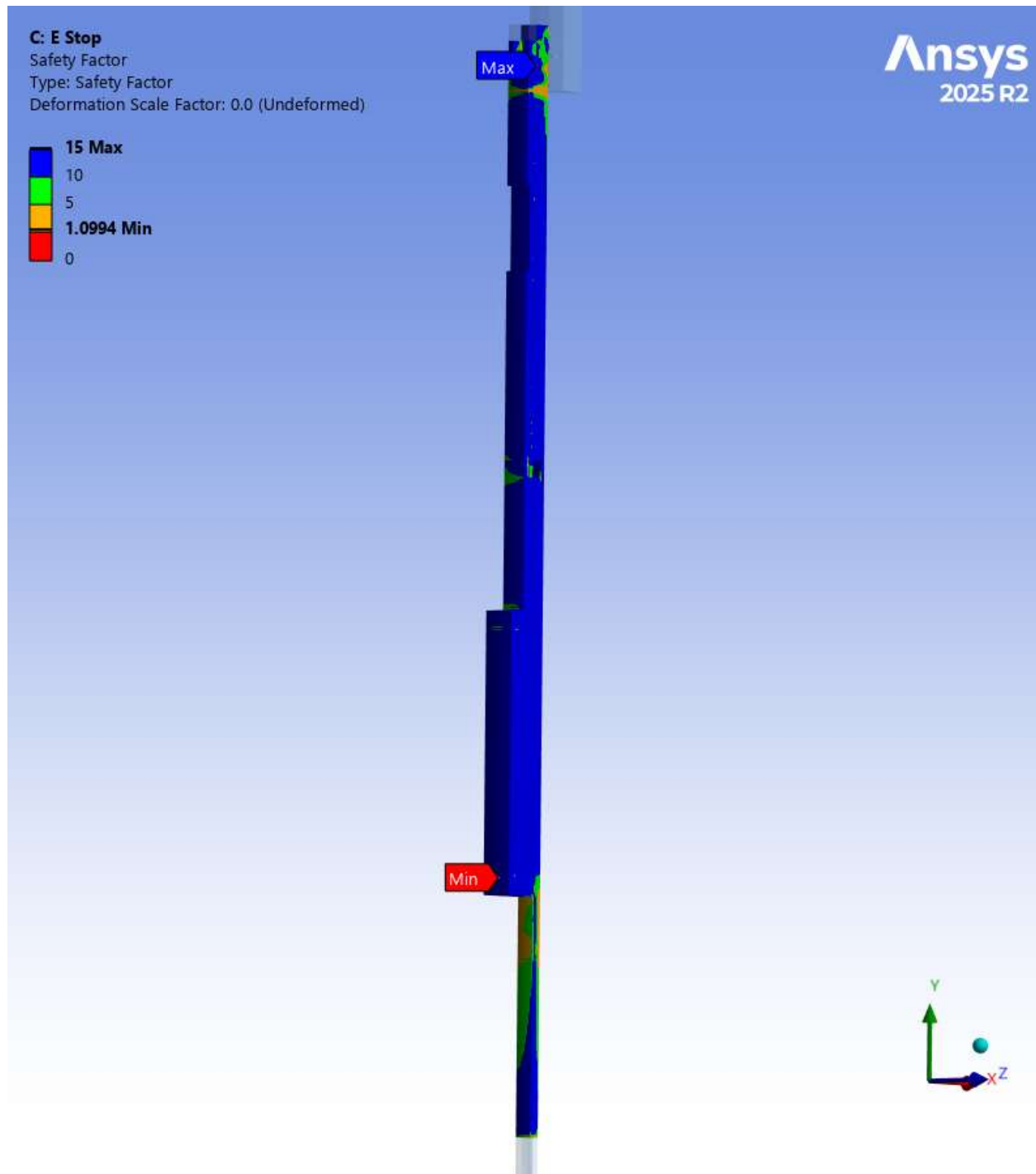


Figure 477 Segment, Cyclic Safety Factor for Segment

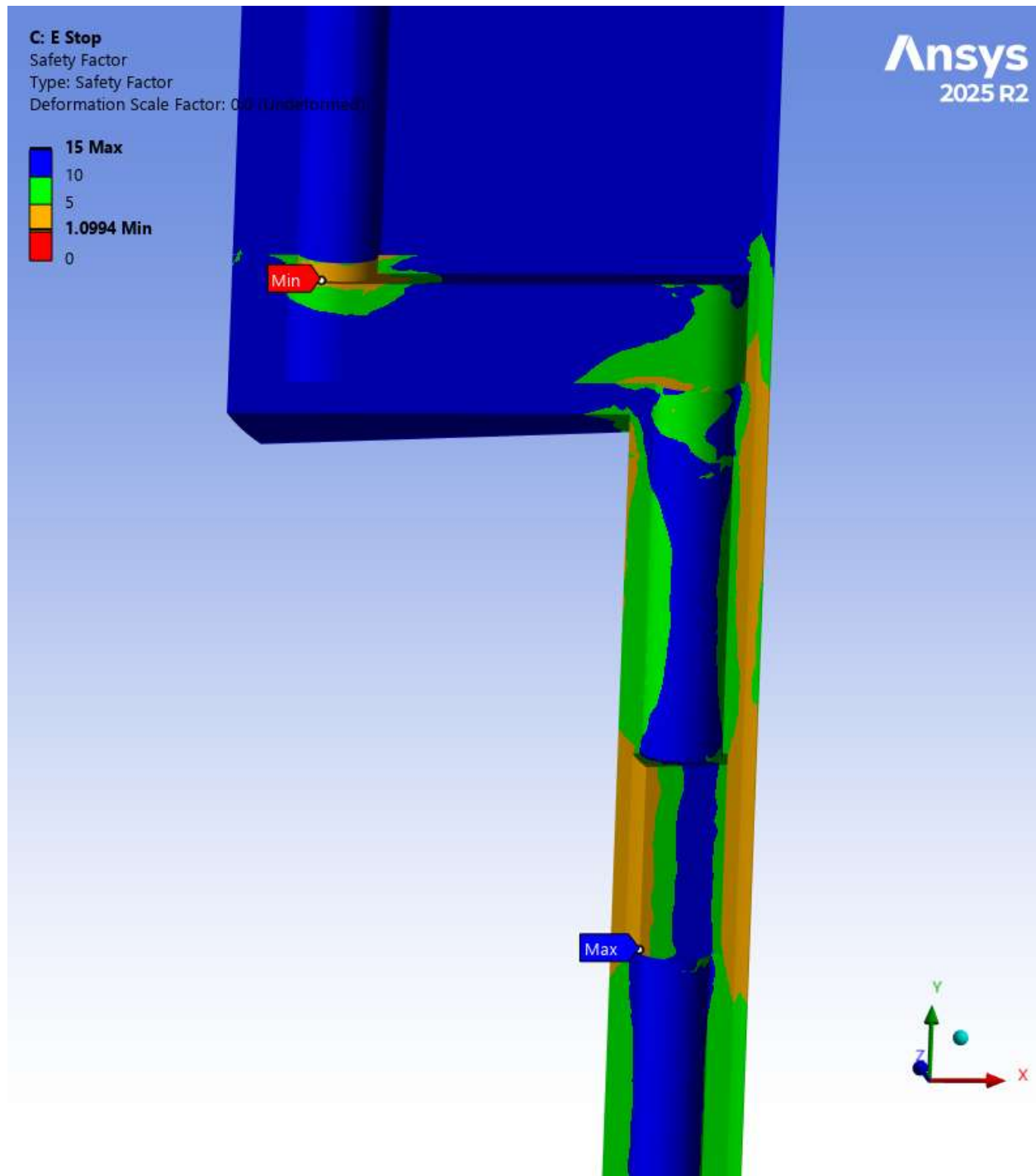


Figure 478 Segment, Cyclic Safety Factor for Segment

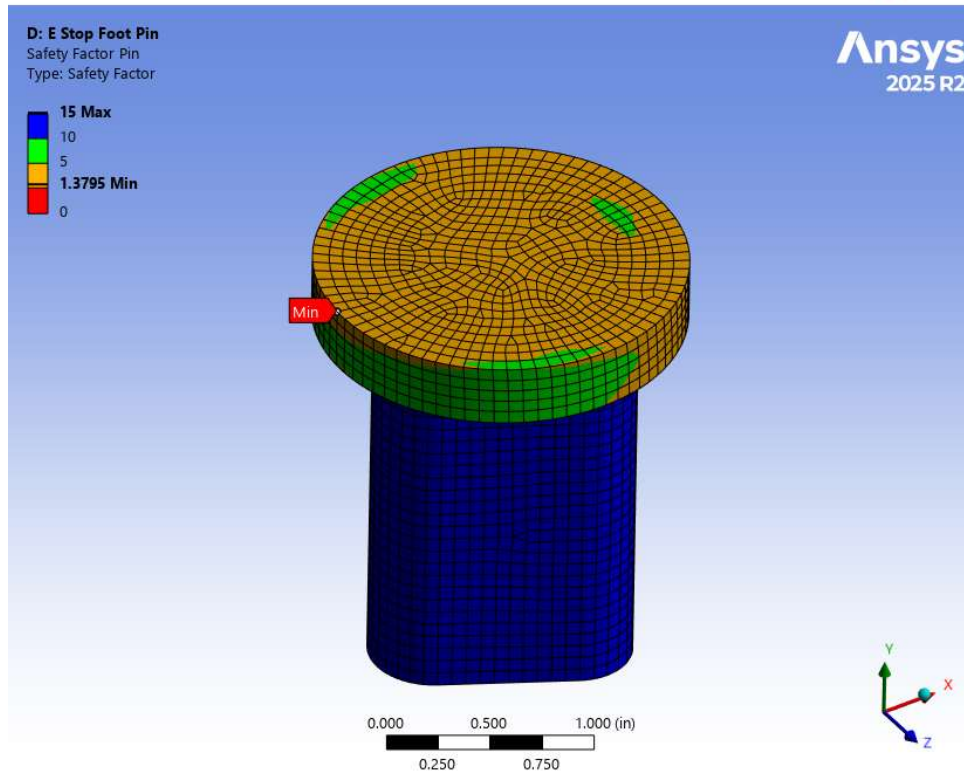
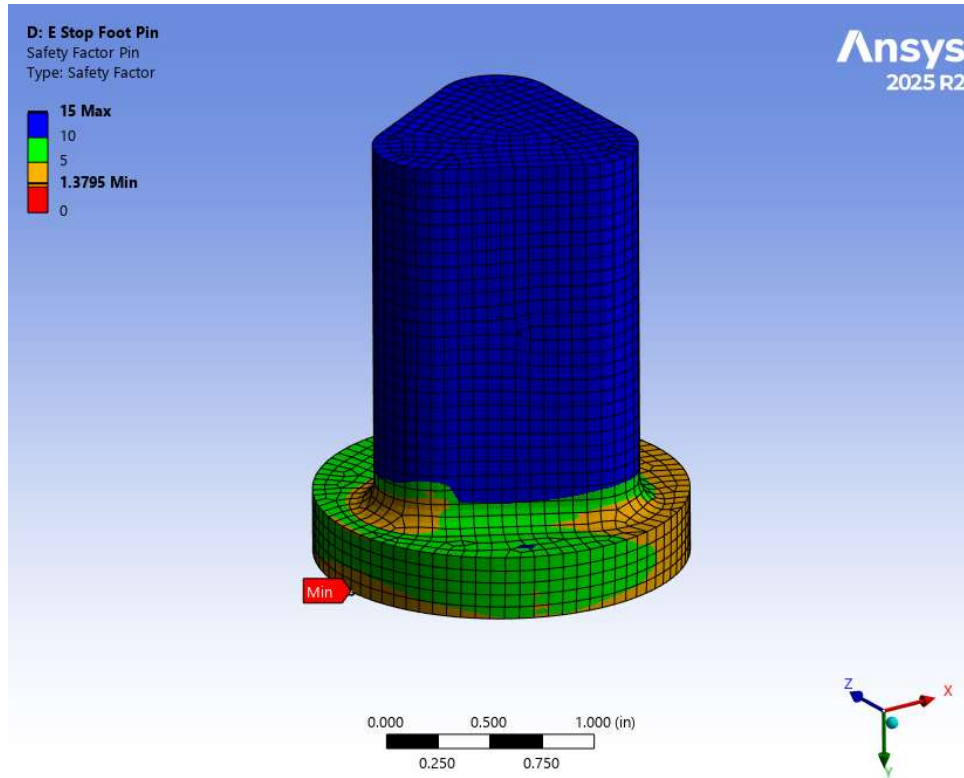


Figure 479 Segment, Cyclic Safety Factor for Segment, Foot Pin

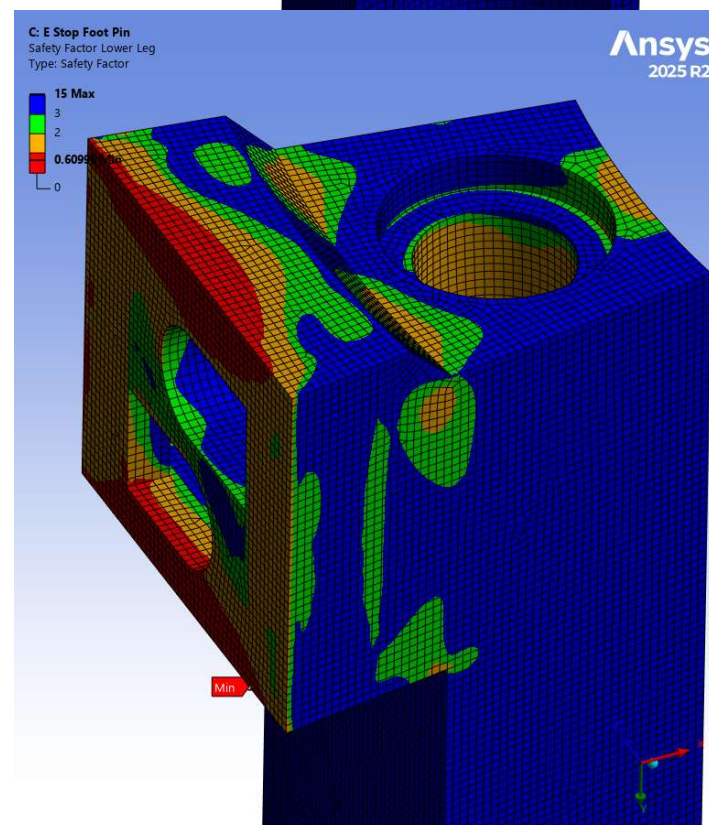
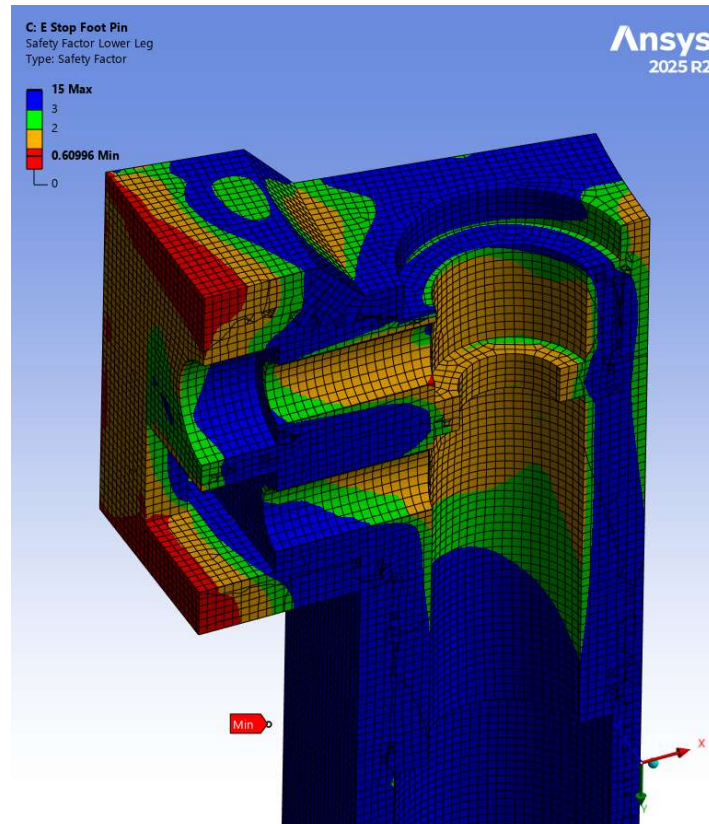


Figure 480 Segment, Cyclic Safety Factor for Segment, Lower Leg

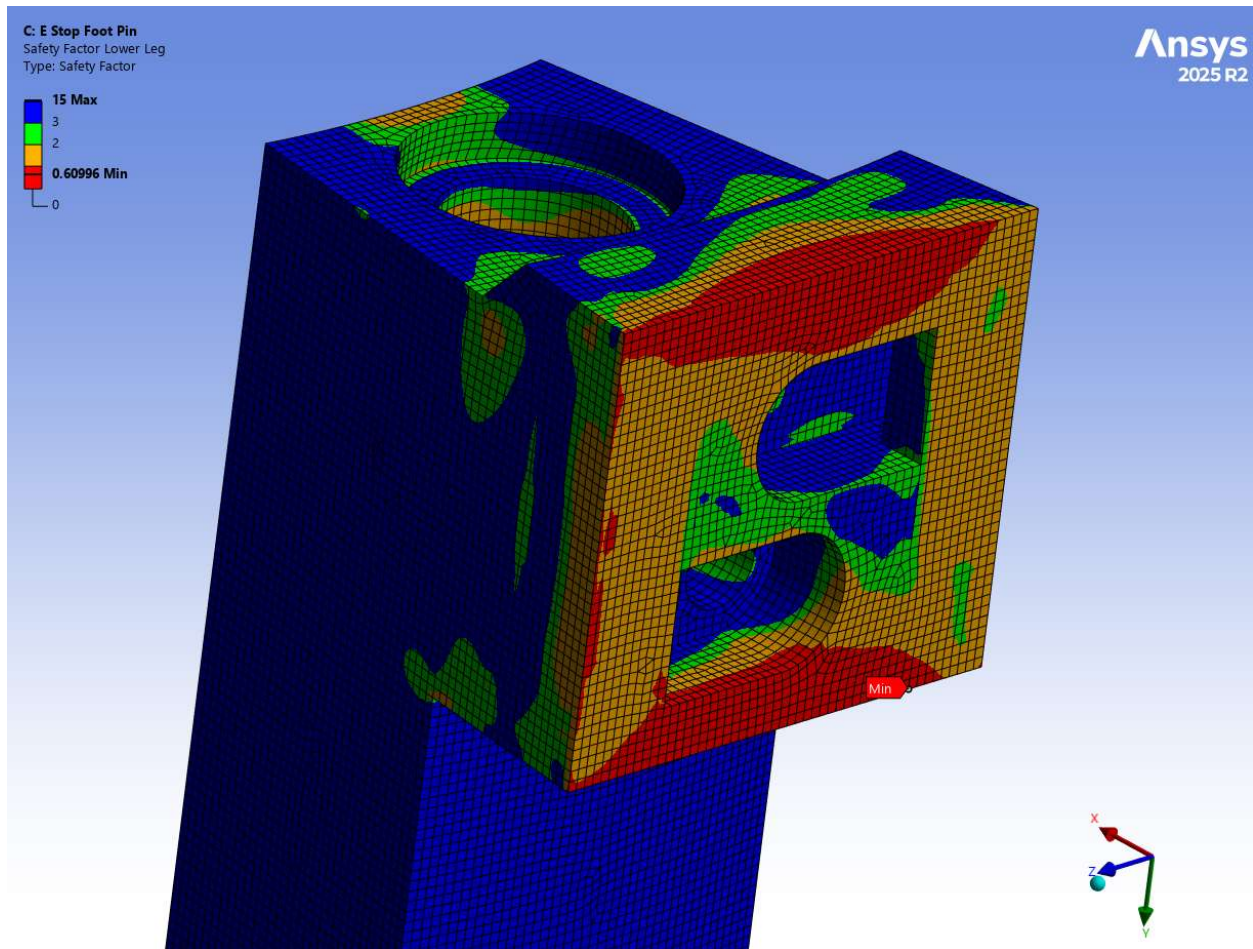


Figure 481 Segment, Cyclic Safety Factor for Segment, Lower Leg Section

Note the area of the lower leg that has a low safety factor is analyzed in a separate analysis [7].

5.1.2.4 Equivalent Stress

5.1.2.4.1 E Stop

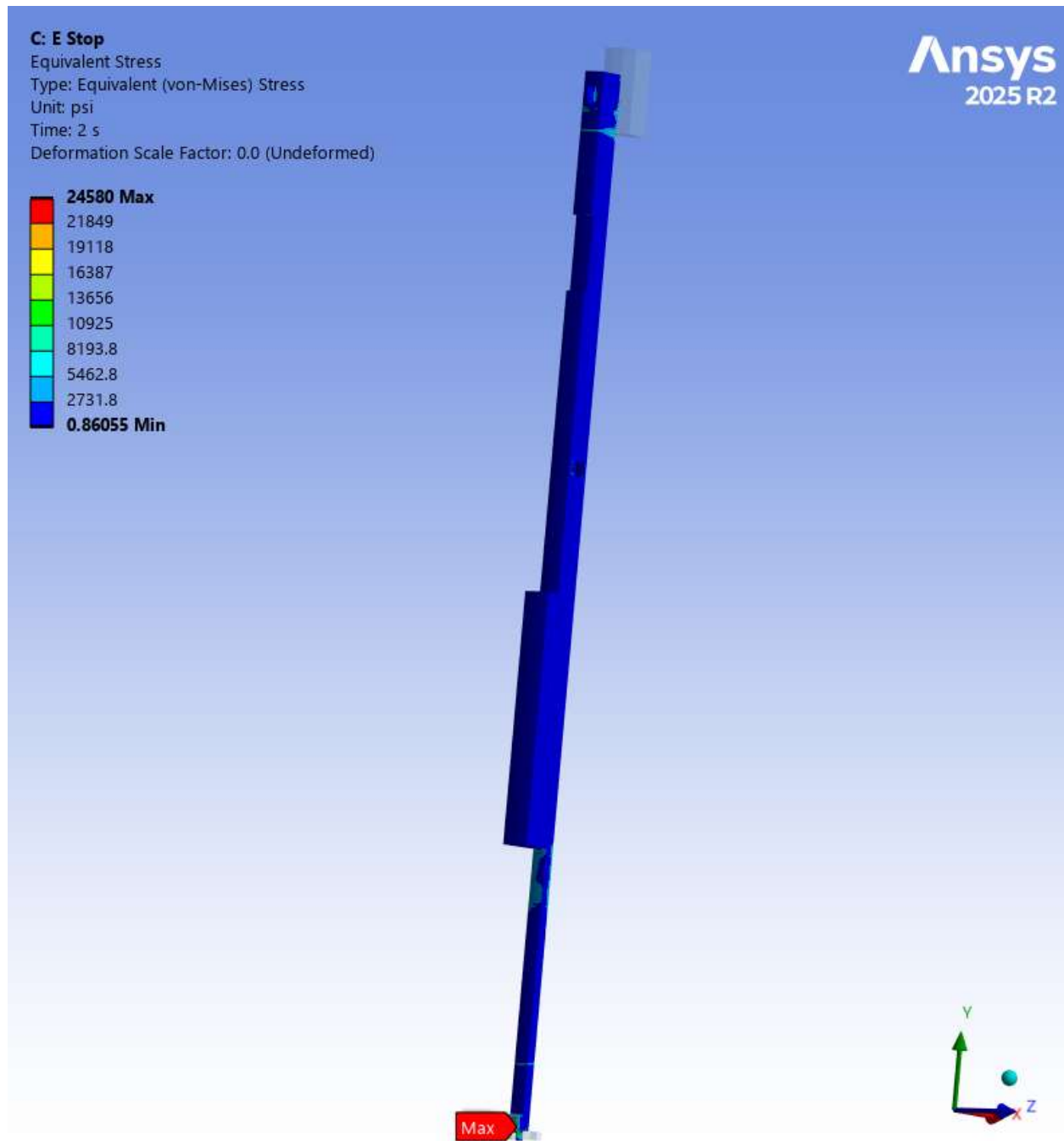


Figure 482 Segment, E Stop Equivalent Stress

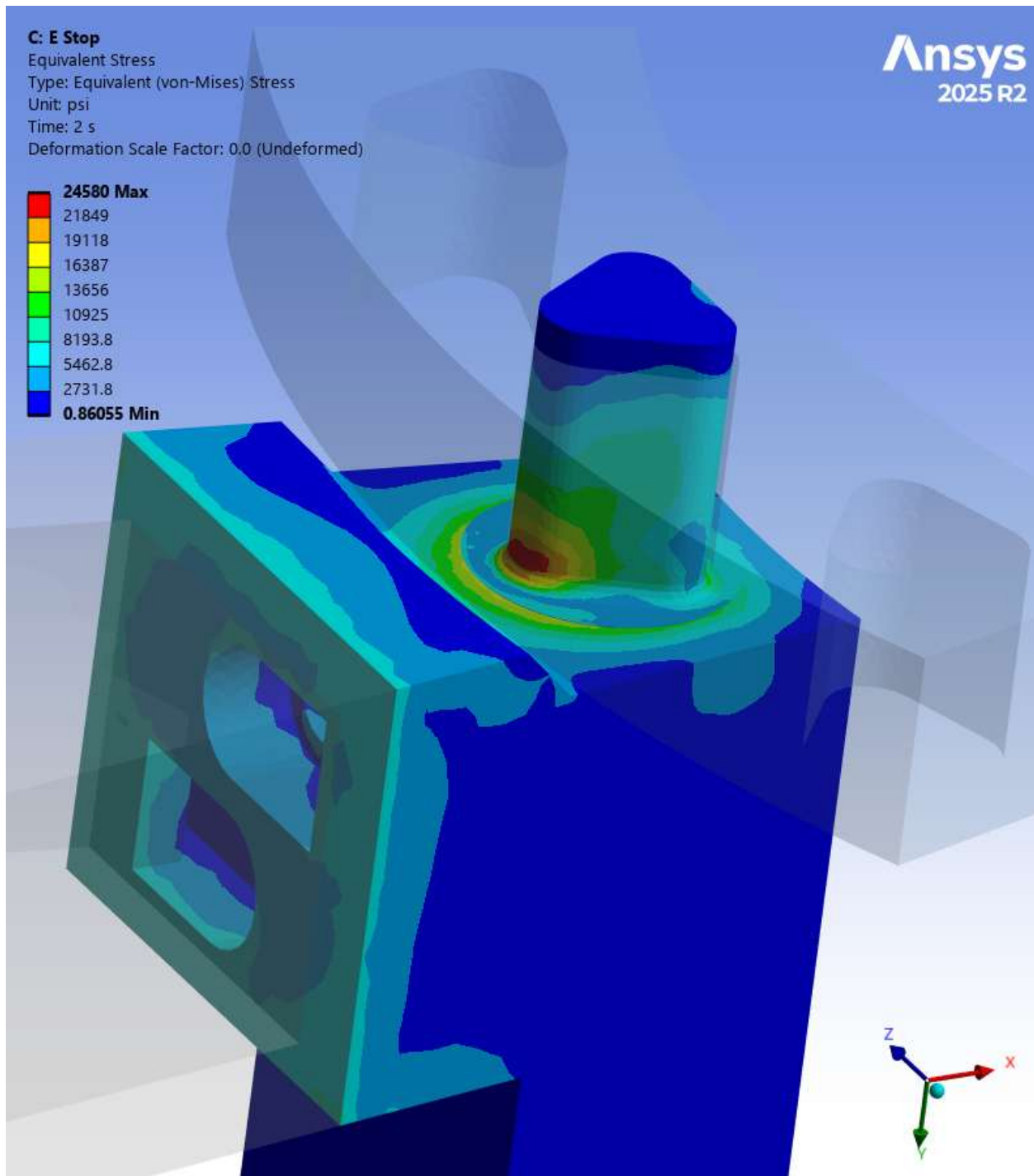


Figure 483 Segment, E Stop Equivalent Stress

5.1.2.4.2 Seismic

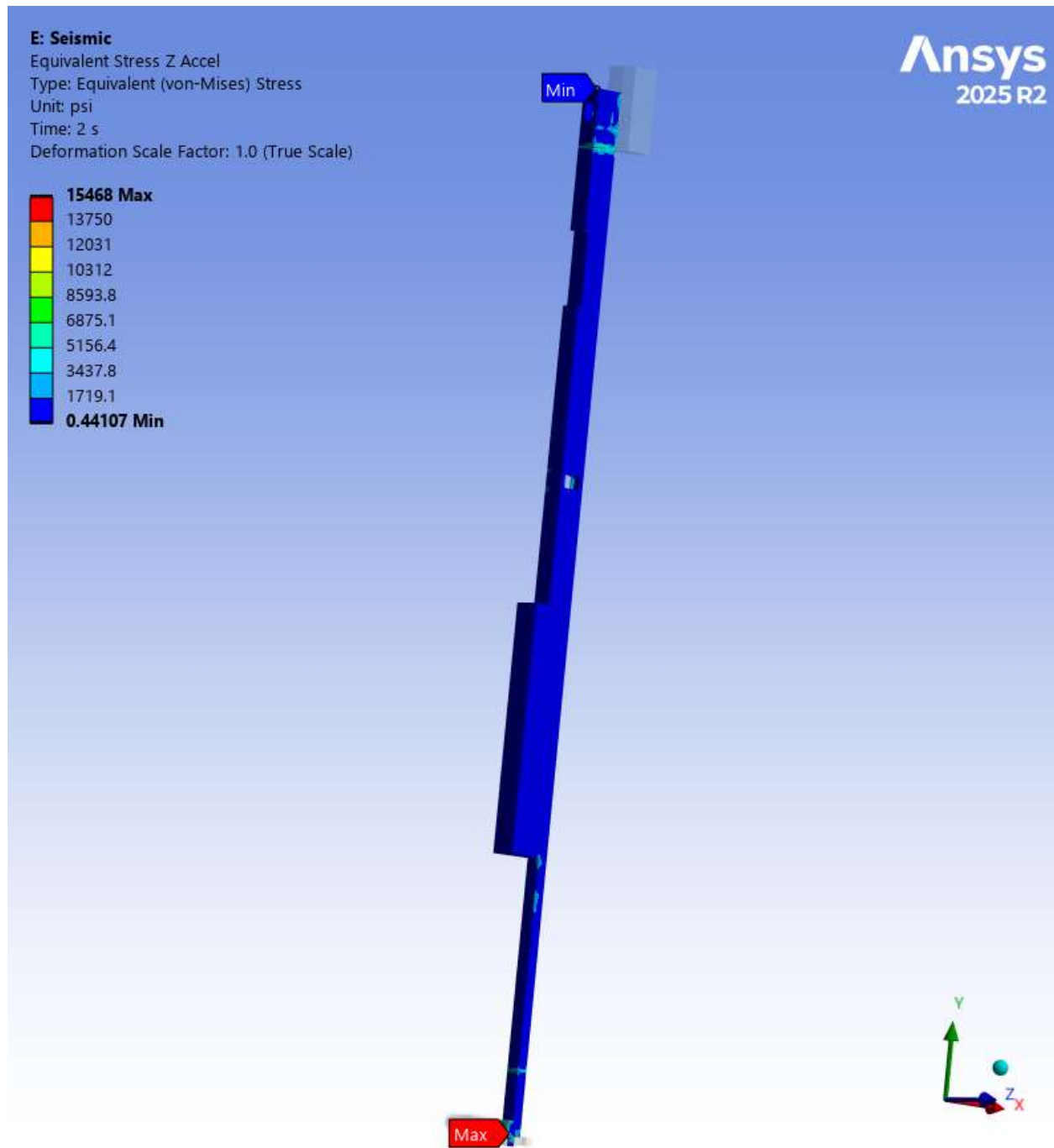


Figure 484 Segment, Seismic Equivalent Stress, Time 2

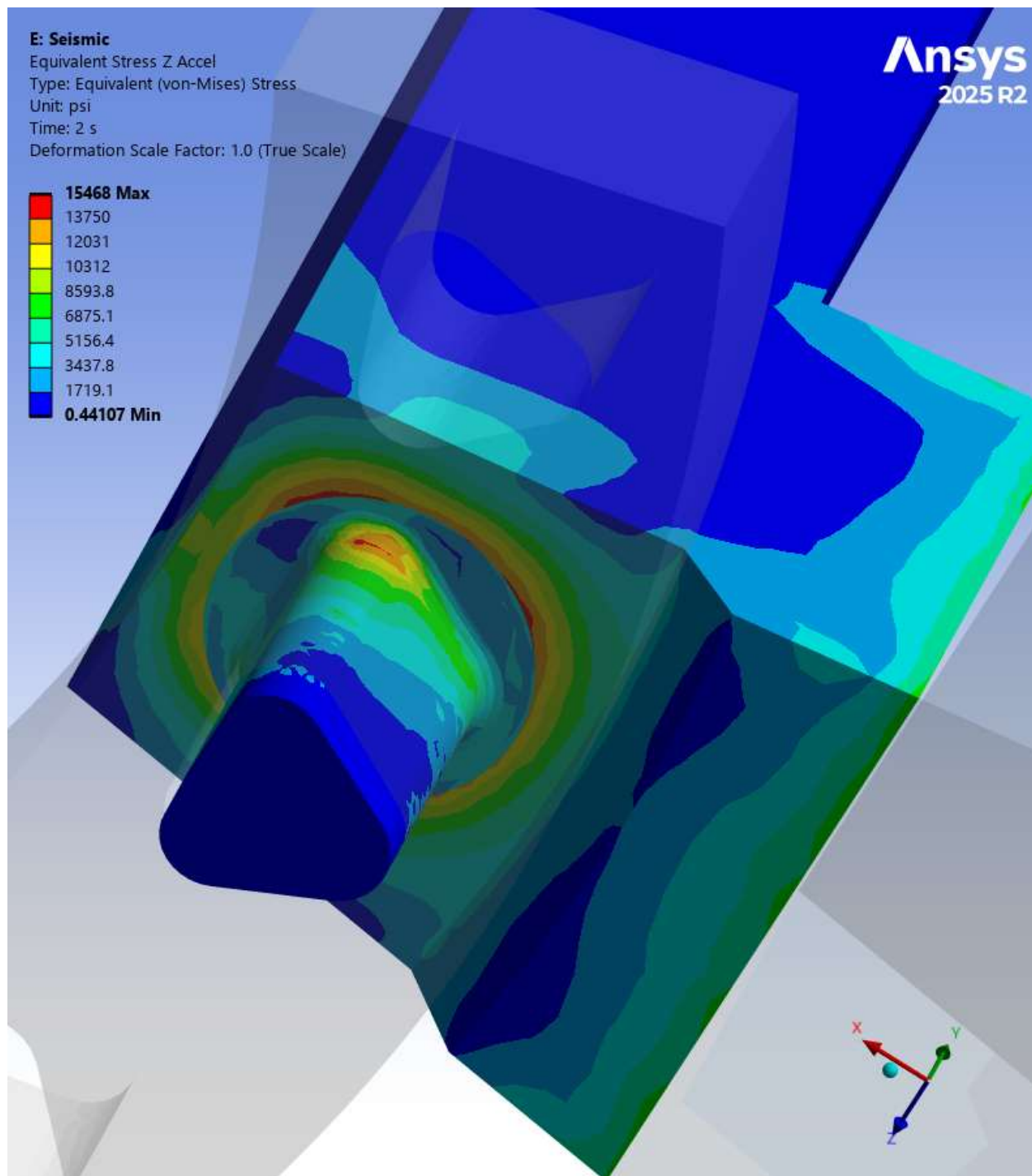


Figure 485 Segment, Seismic Equivalent Stress, Time 2

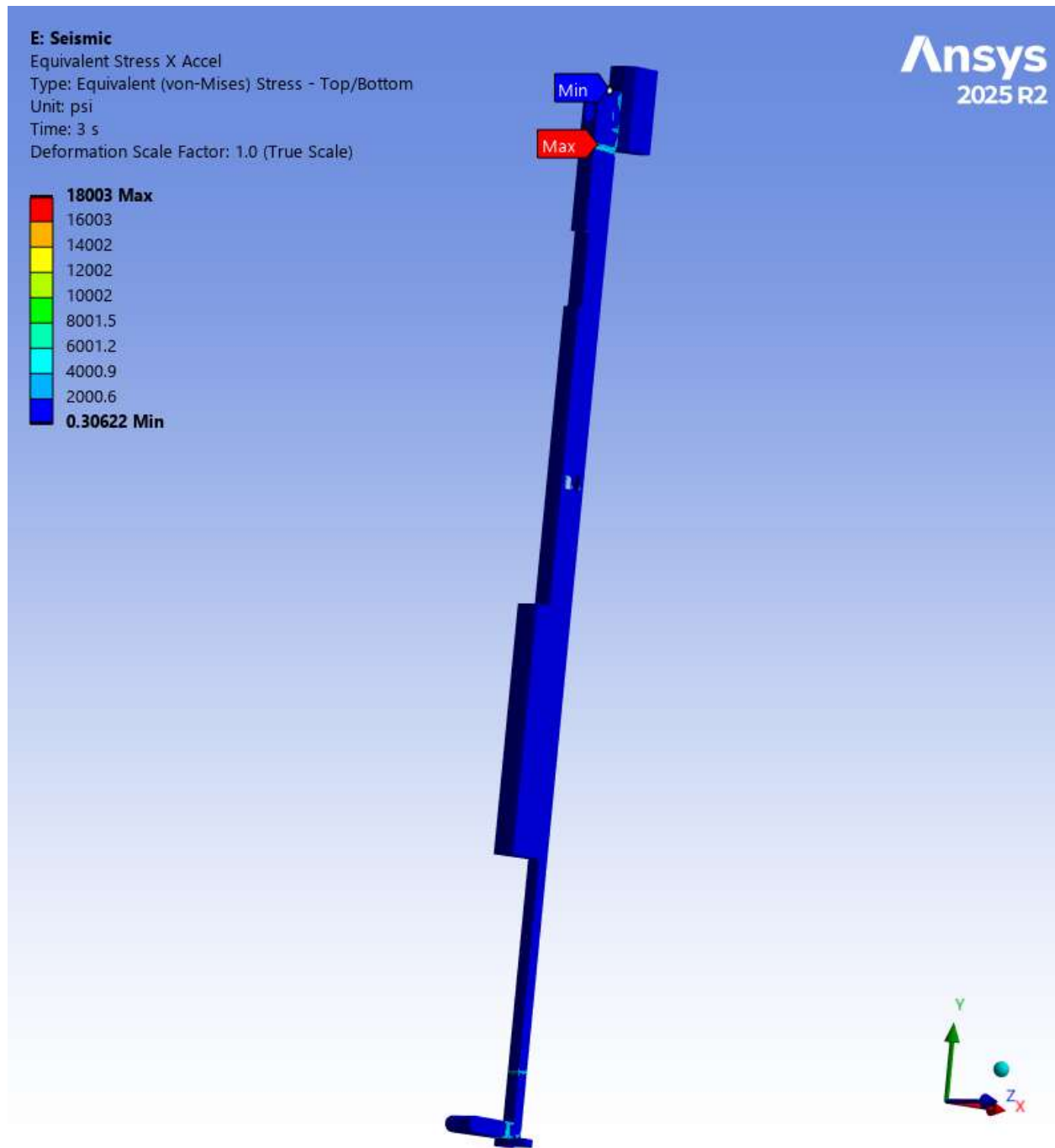


Figure 486 Segment, Seismic Equivalent Stress, Time 3

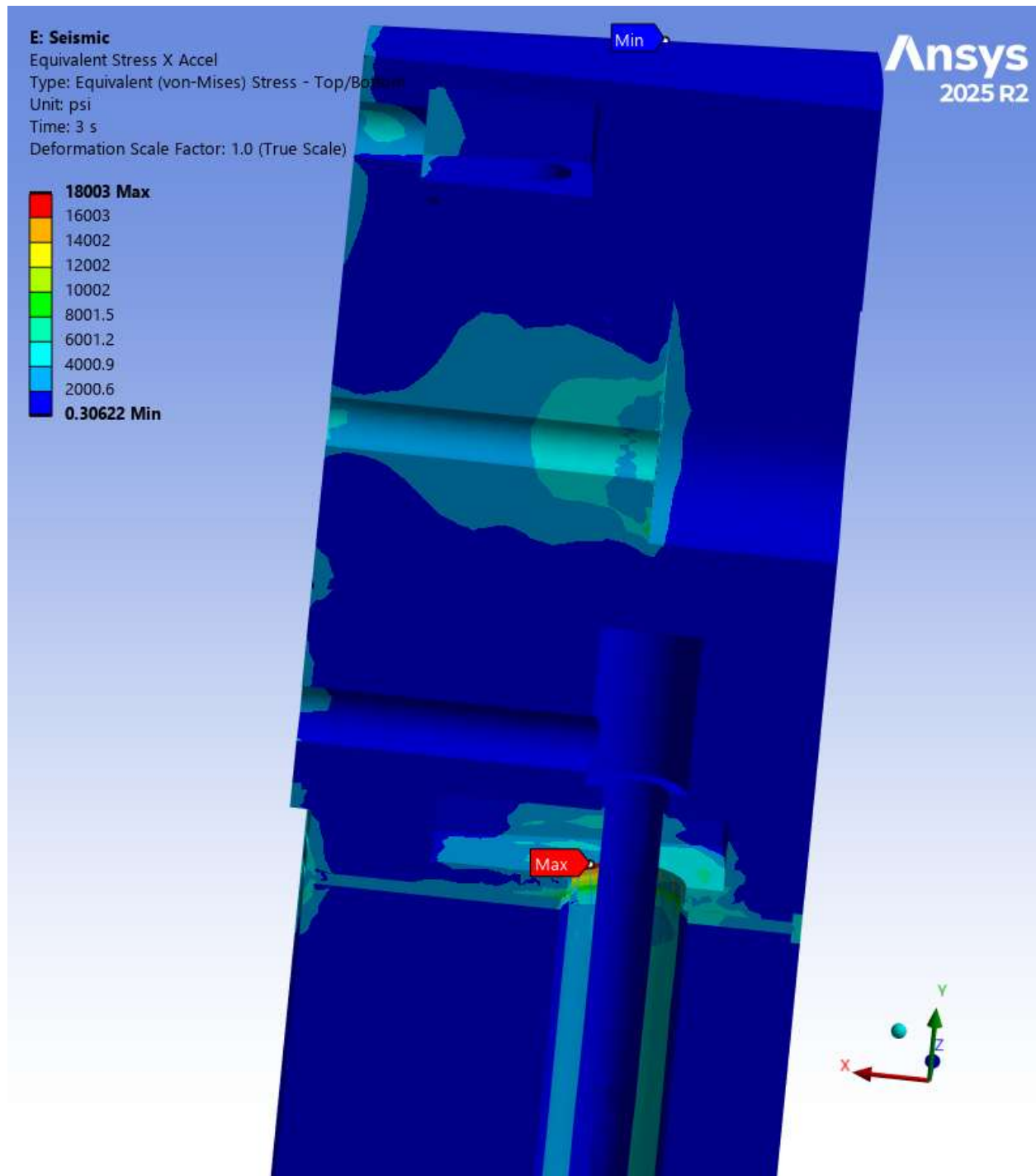


Figure 487 Segment, Seismic Equivalent Stress, Time 3

5.1.2.4.3 Seismic + Stop

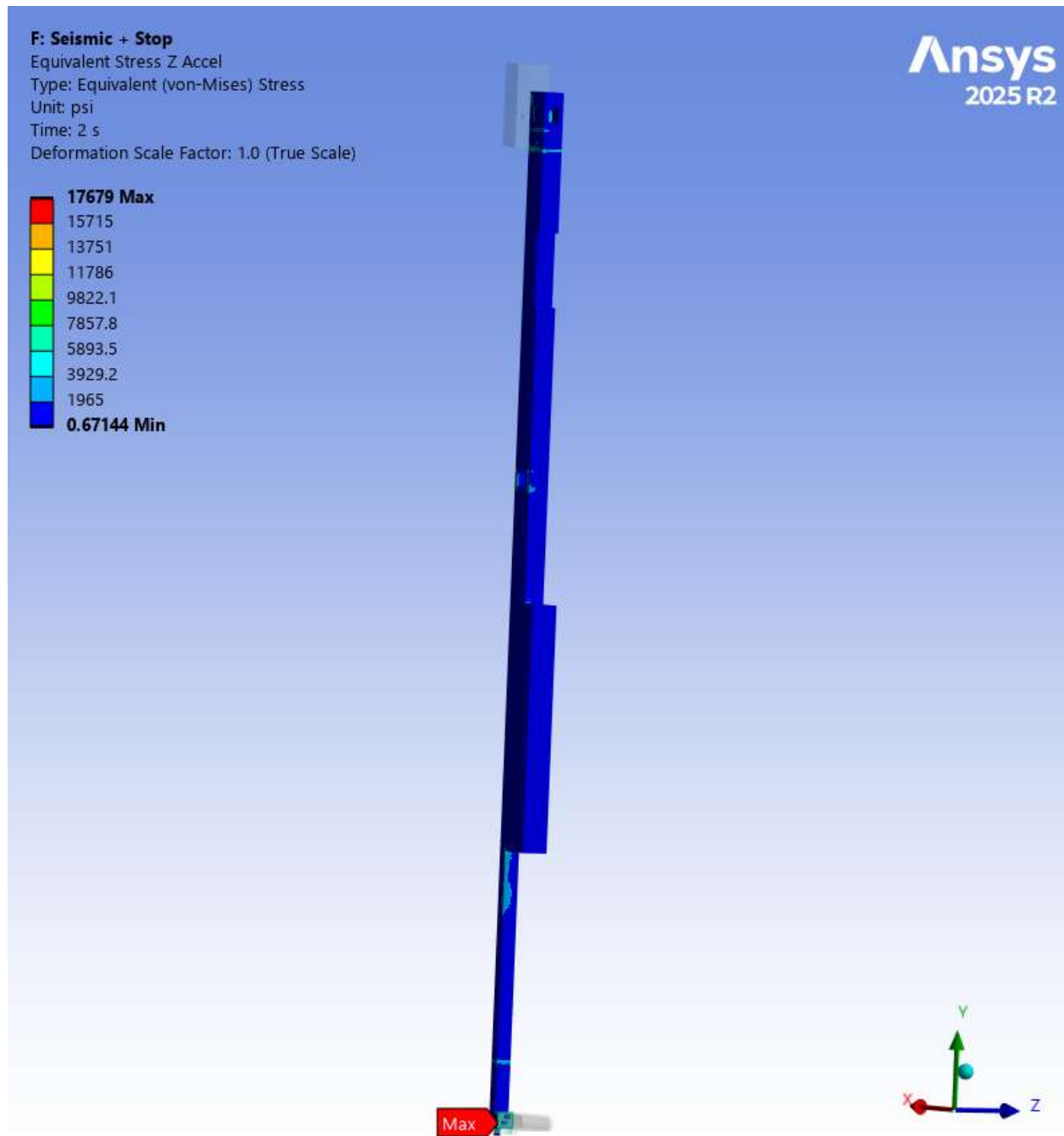


Figure 488 Segment, Seismic + Stop Equivalent Stress, Time 2

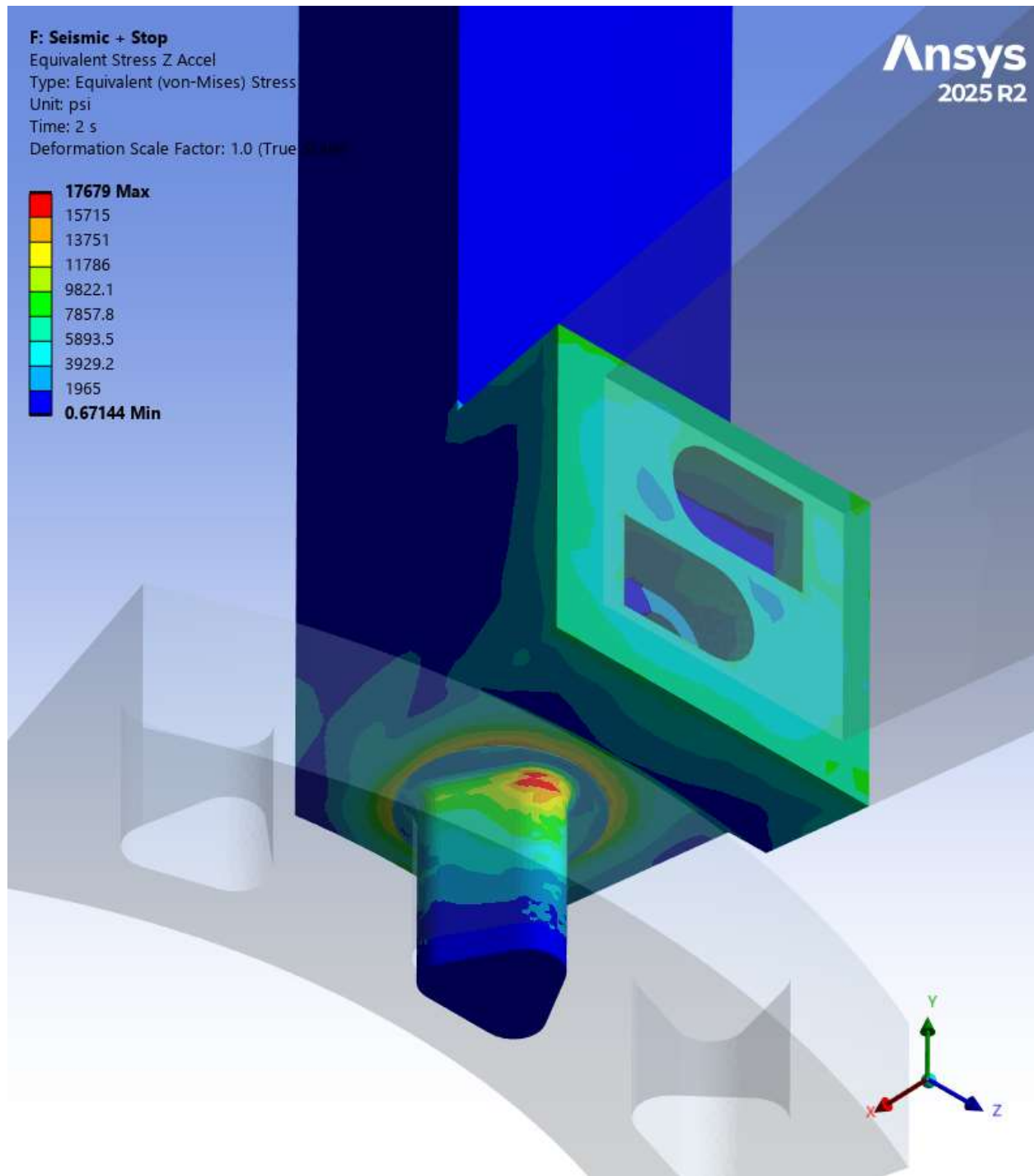


Figure 489 Segment, Seismic + Stop Equivalent Stress, Time 2

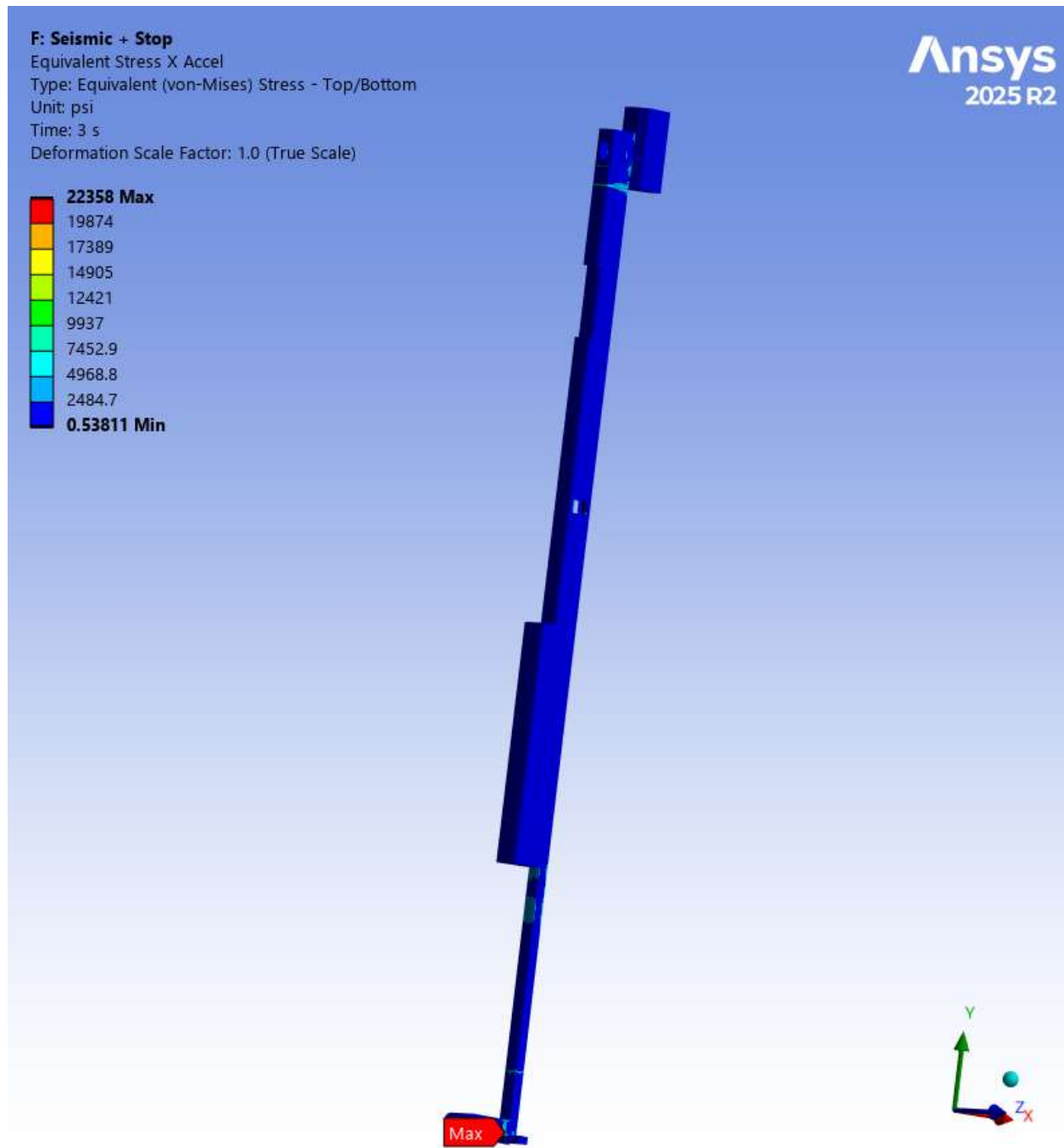


Figure 490 Segment, Seismic + Stop Equivalent Stress, Time 3

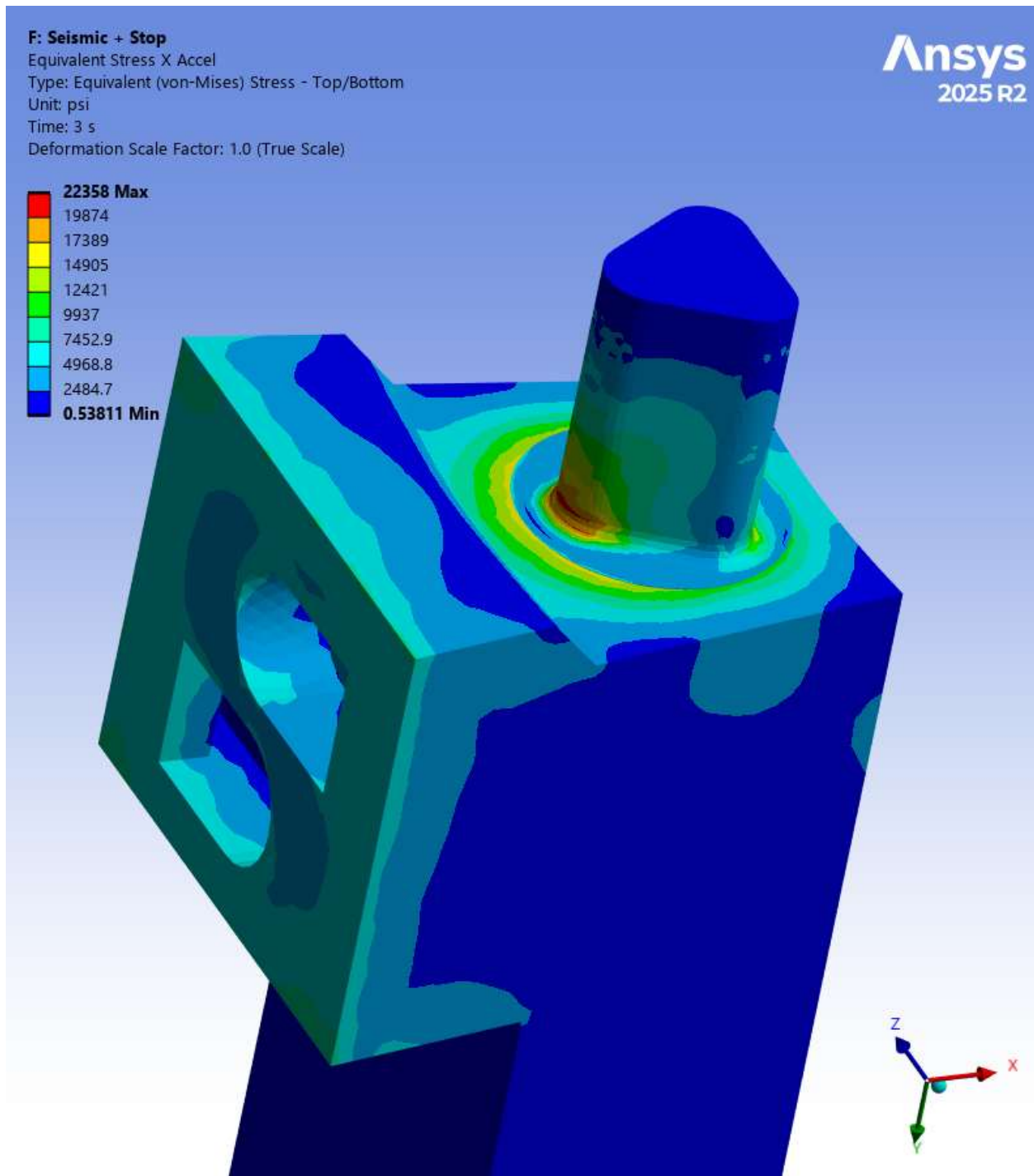


Figure 491 Segment, Seismic + Stop Equivalent Stress, Time 3

5.1.2.5 Contact Surface

5.1.2.5.1 E Stop

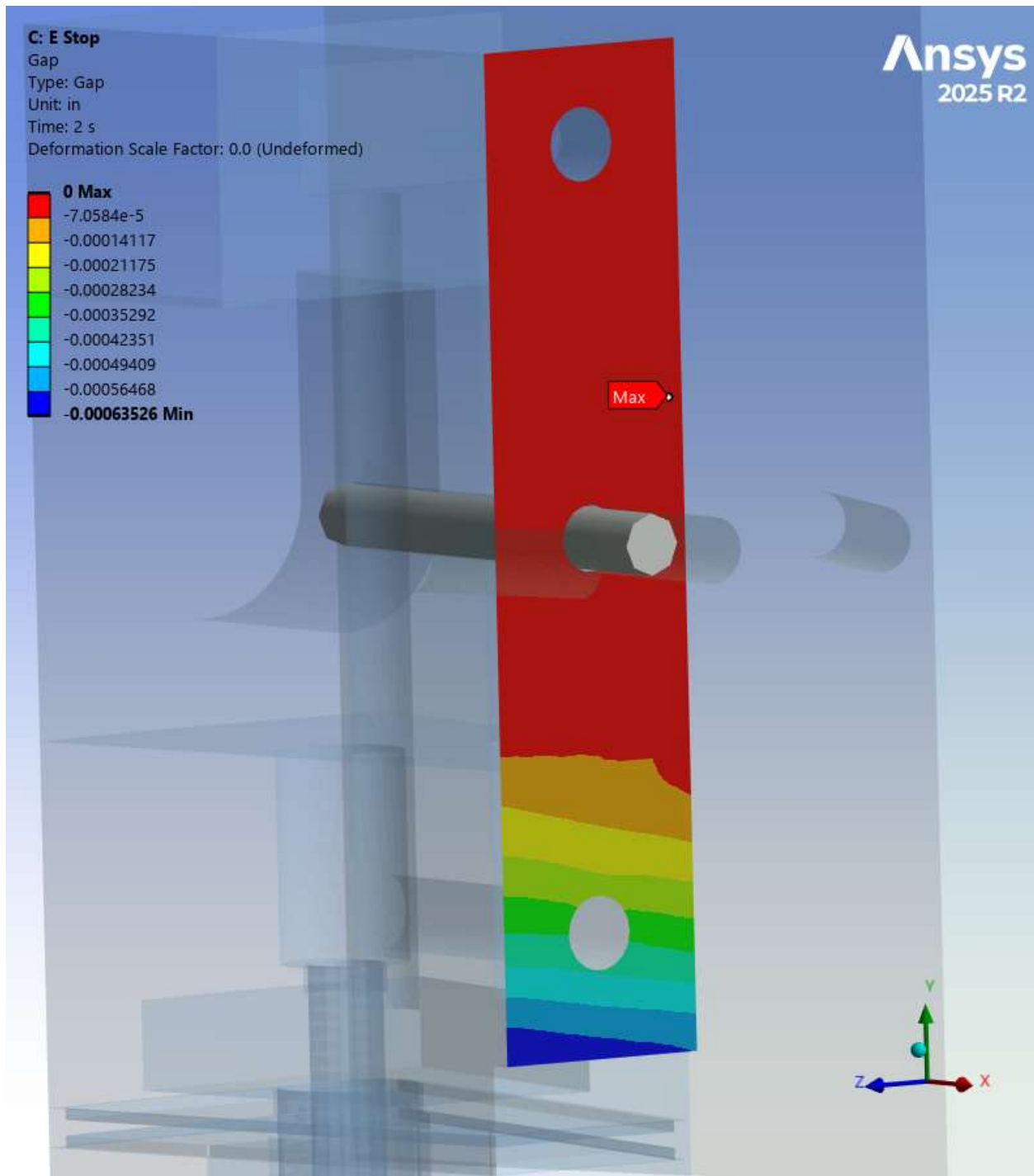


Figure 492 Segment, E Stop Contact Surface Gap

5.1.2.5.2 Seismic

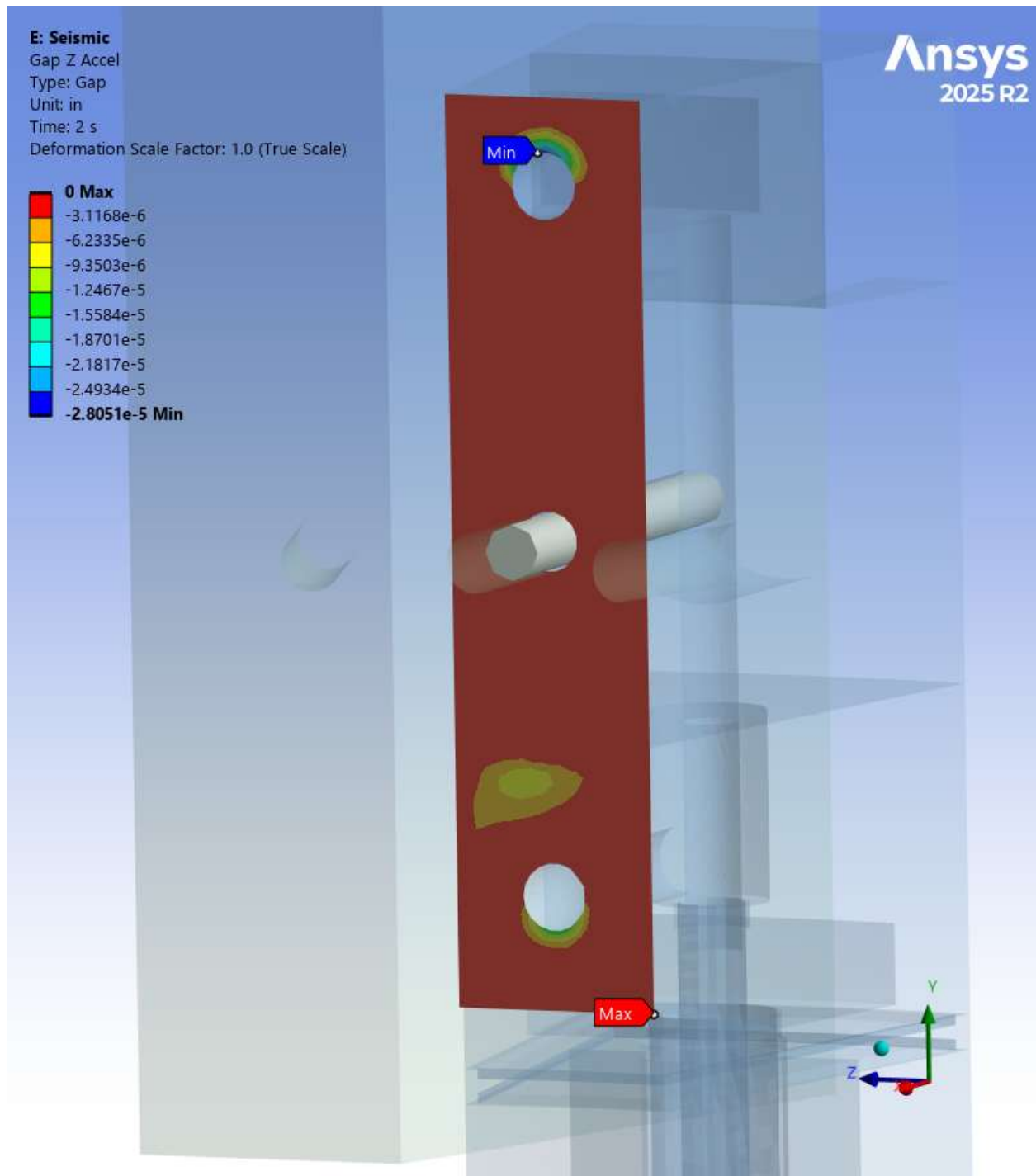


Figure 493 Segment, Seismic Contact Surface Gap, Time 2

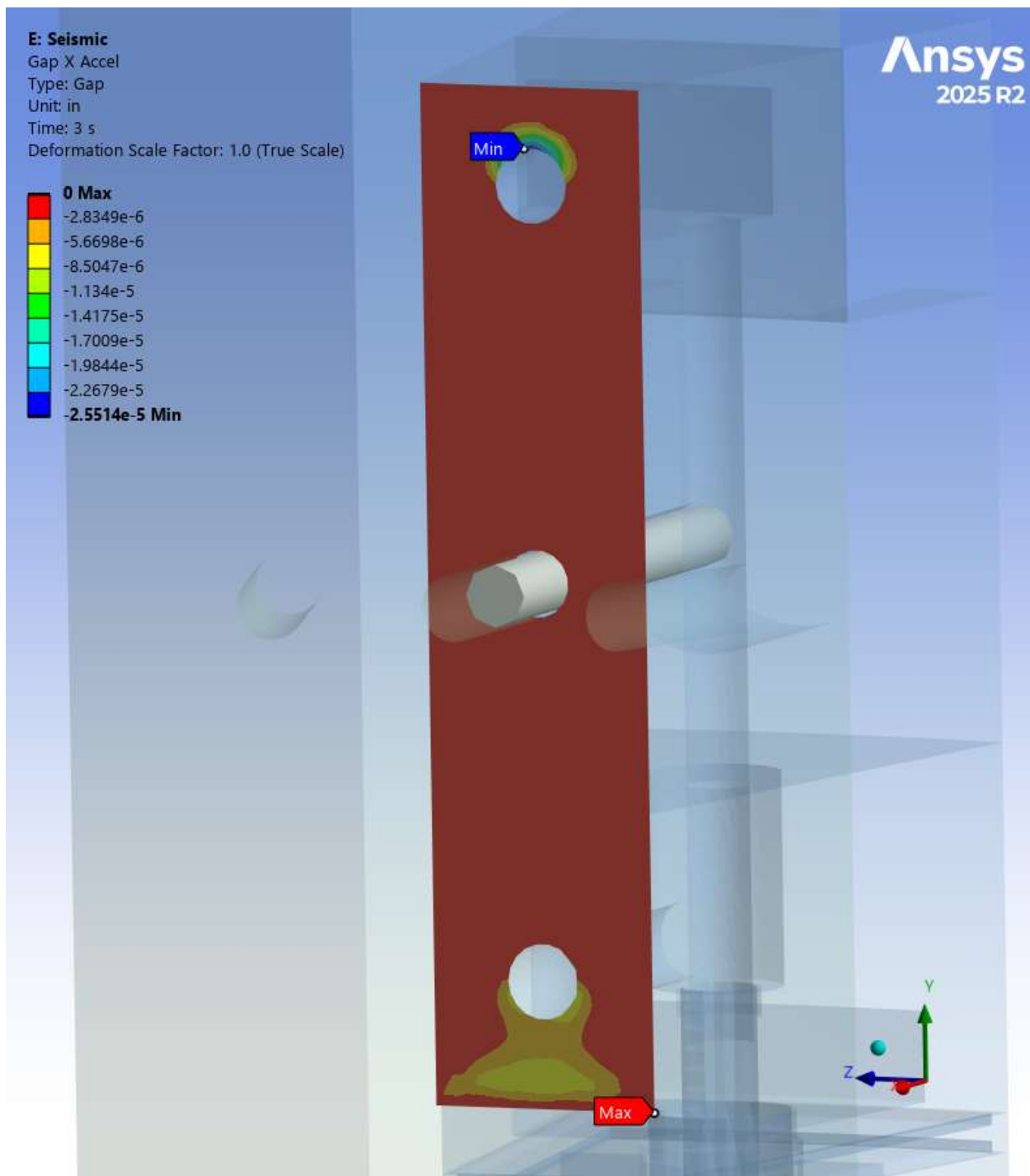


Figure 494 Segment, Seismic Contact Surface Gap, Time 3

5.1.2.5.3 Seismic + Stop

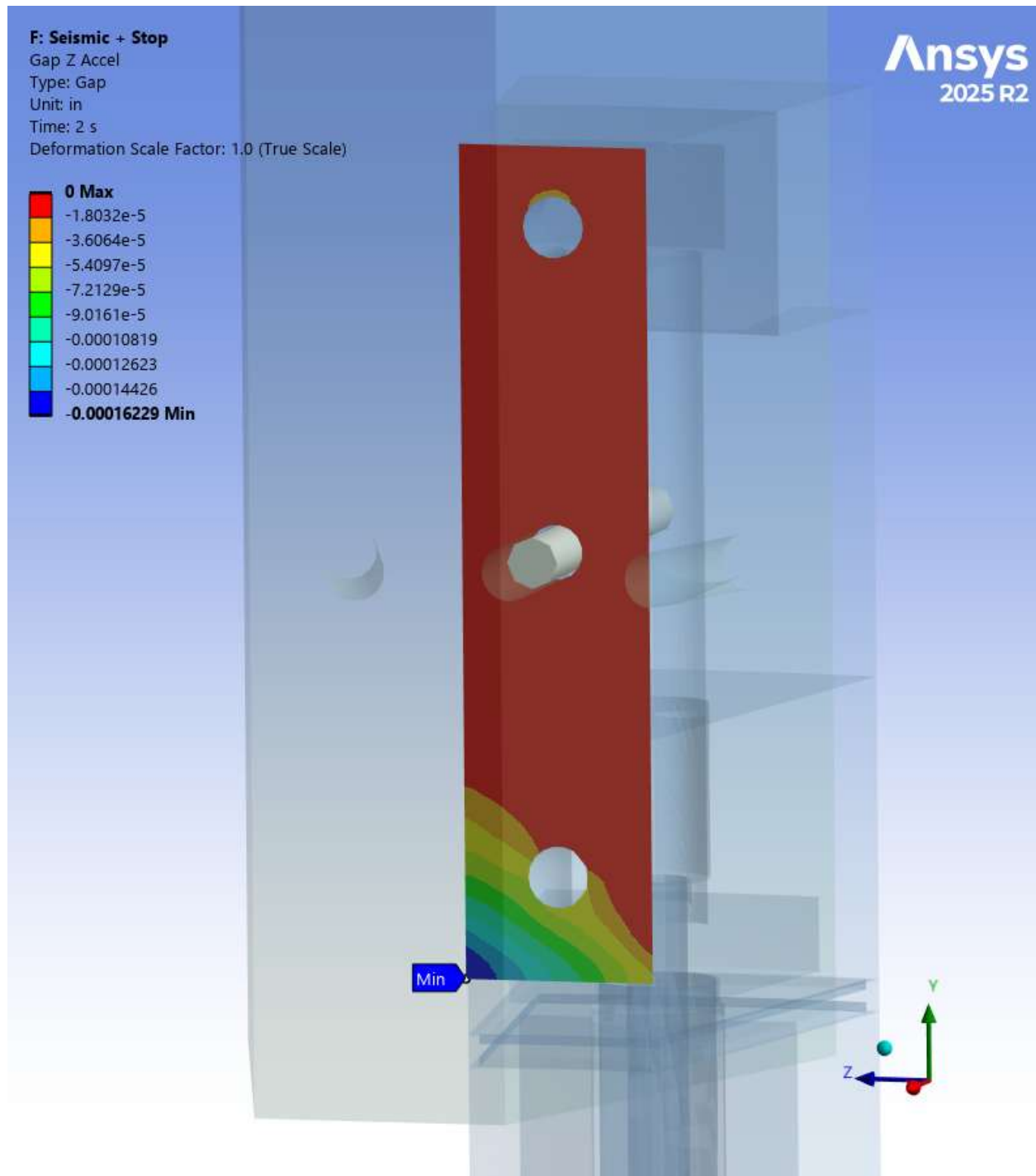


Figure 495 Segment, Seismic + Stop Contact Surface Gap, Time 2

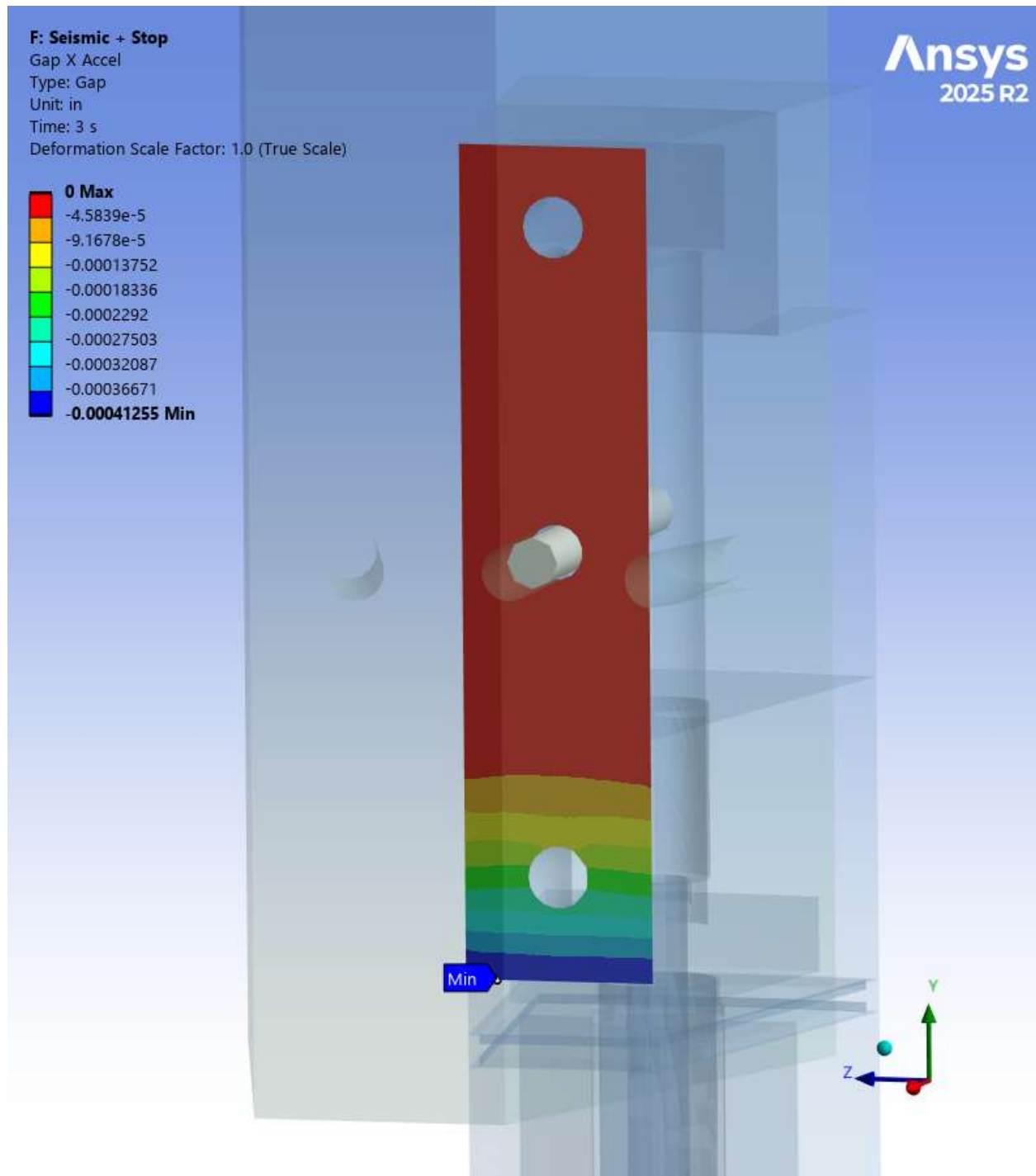


Figure 496 Segment, Seismic + Stop Contact Surface Gap, Time 3

5.1.3 Target Shaft

The Target Shaft results go in the order of Plastic Ratcheting then Local Failure. Equivalent stress and contact gap of the shaft joints are included for reference.

5.1.3.1 Plastic Ratcheting

5.1.3.1.1 E Stop Load Case

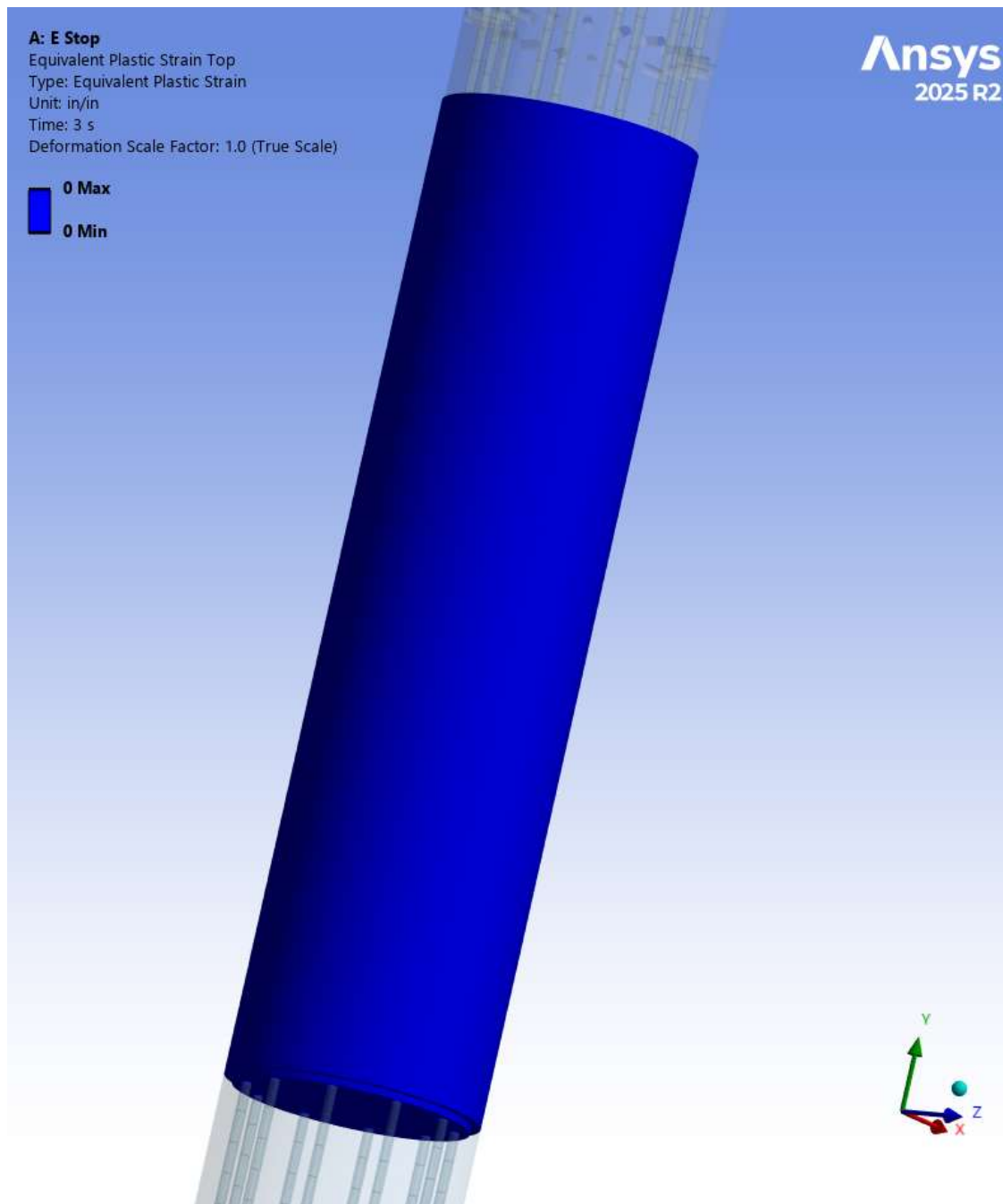


Figure 497 Shaft, E Stop Equivalent Plastic Strain, Top Section

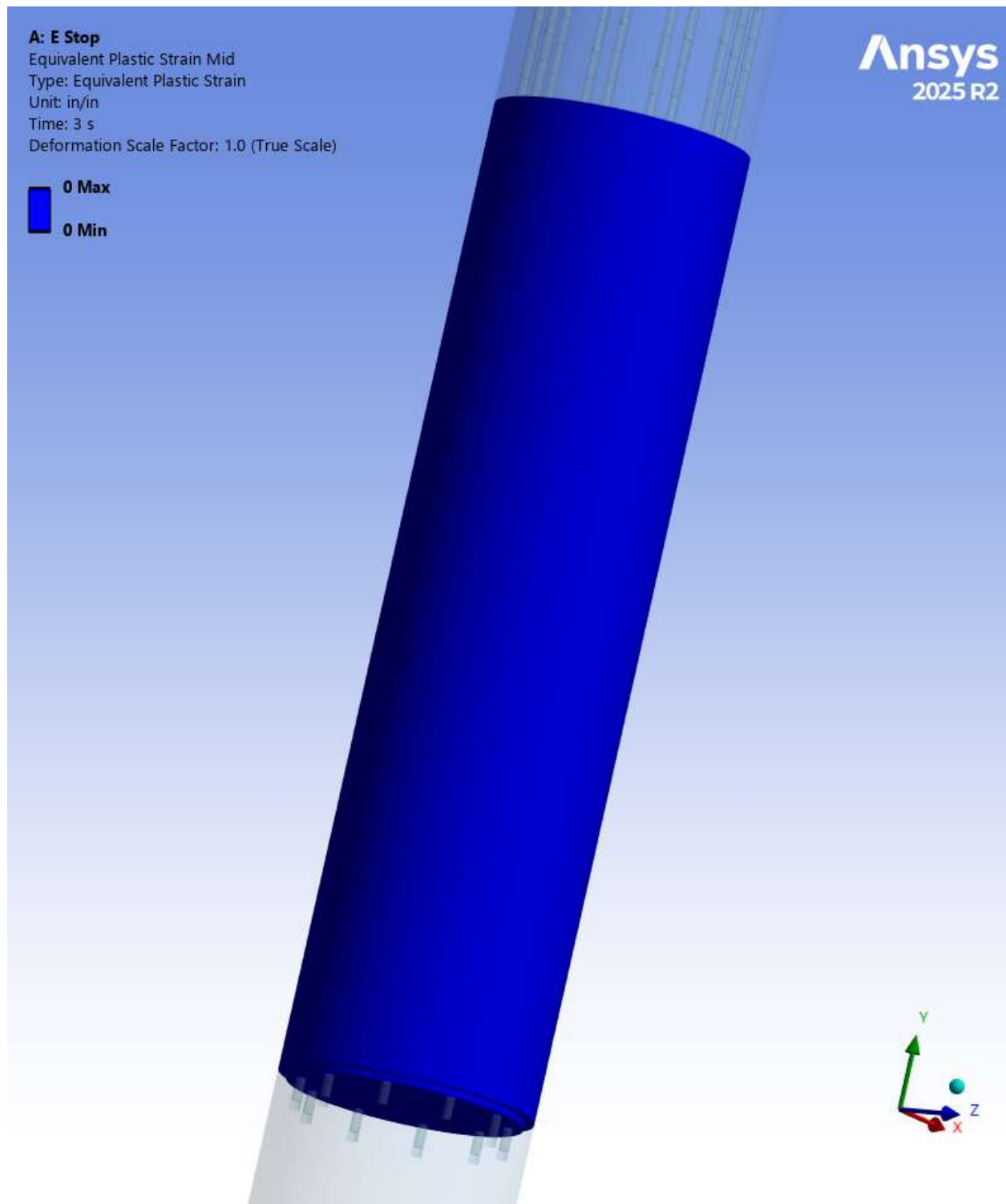


Figure 498 Shaft, E Stop Equivalent Plastic Strain, Mid Section

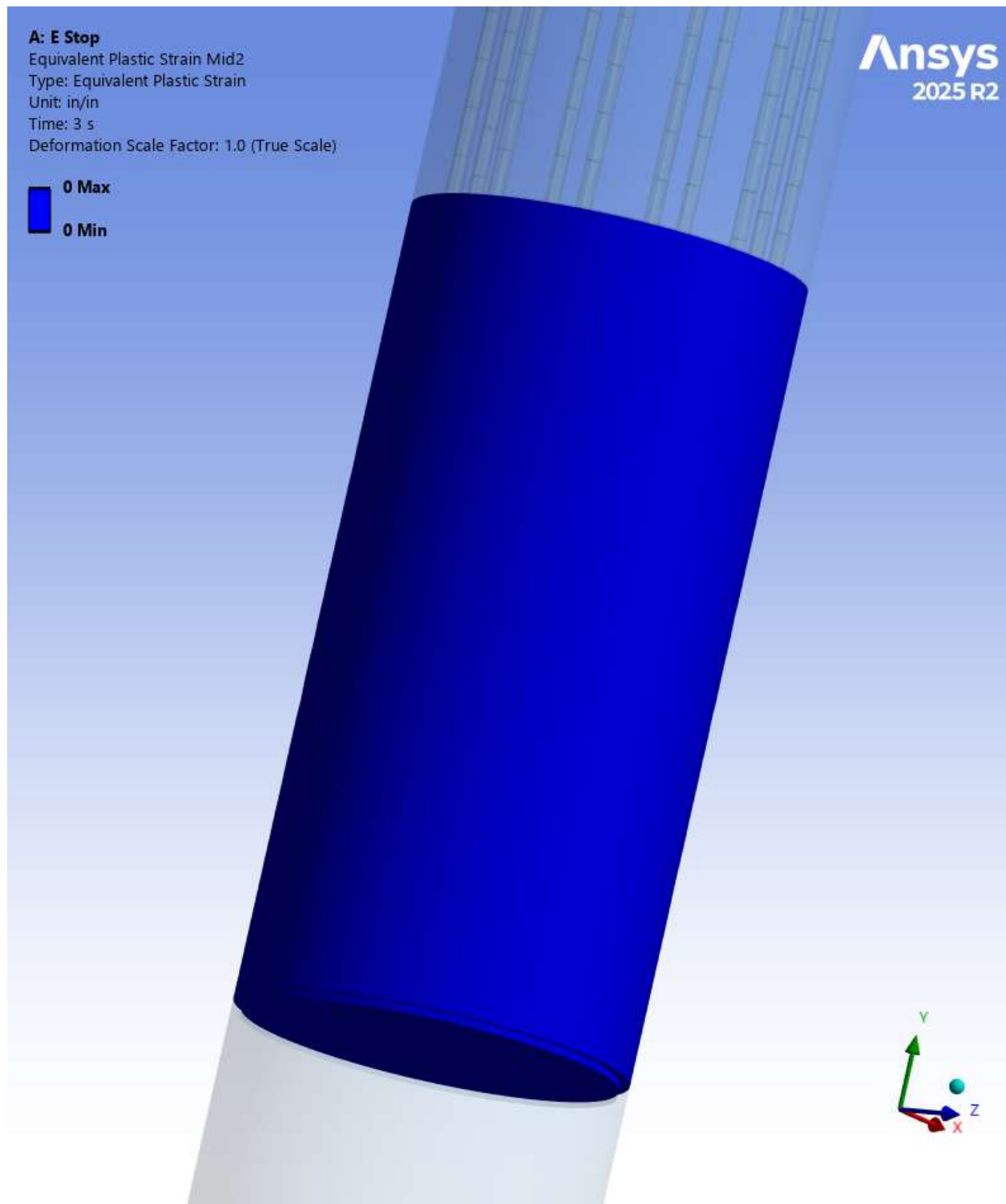


Figure 499 Shaft, E Stop Equivalent Plastic Strain, Lower Mid Section

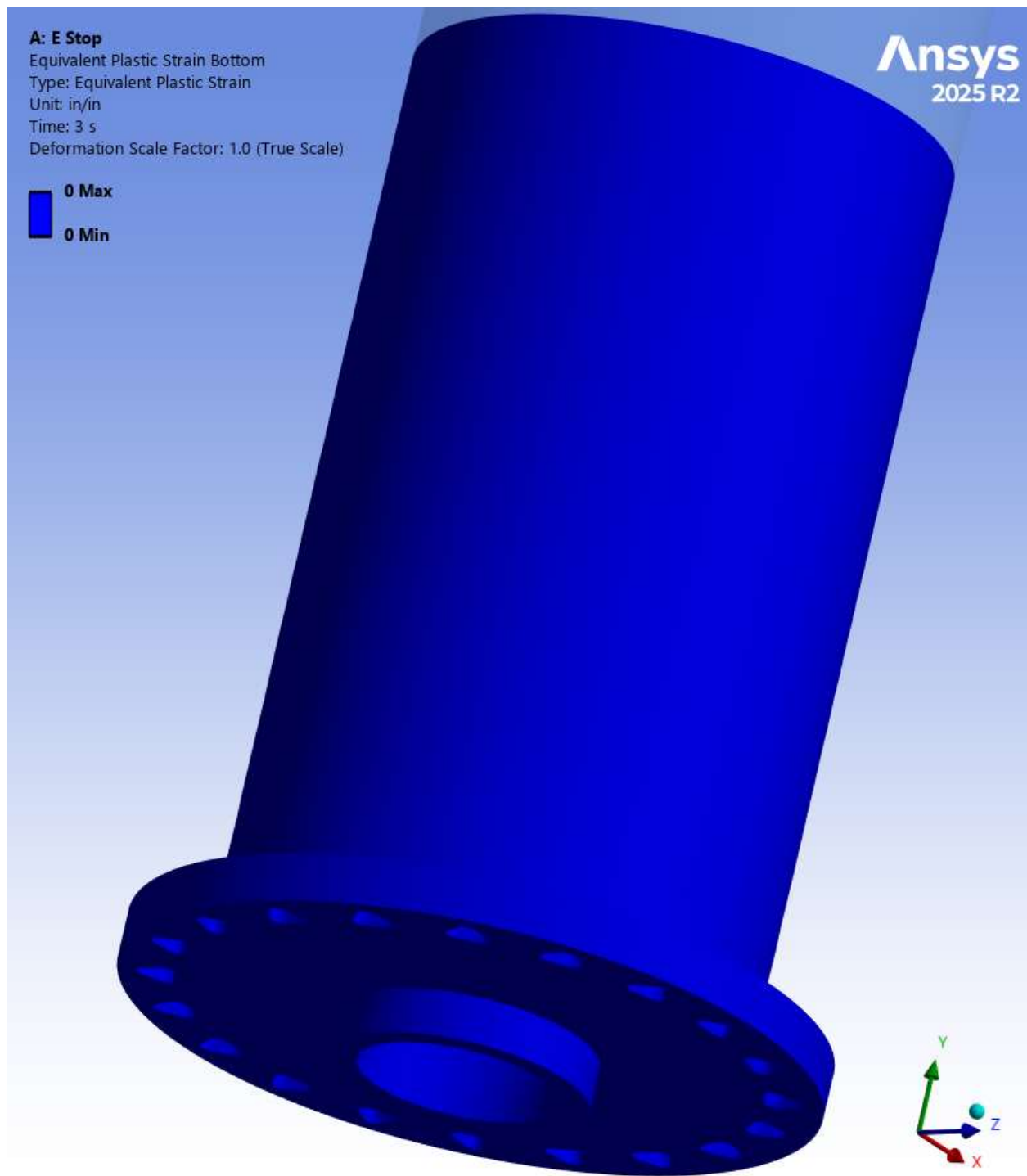


Figure 500 Shaft, E Stop Equivalent Plastic Strain, Bottom Section

5.1.3.1.2 Seismic Load Case

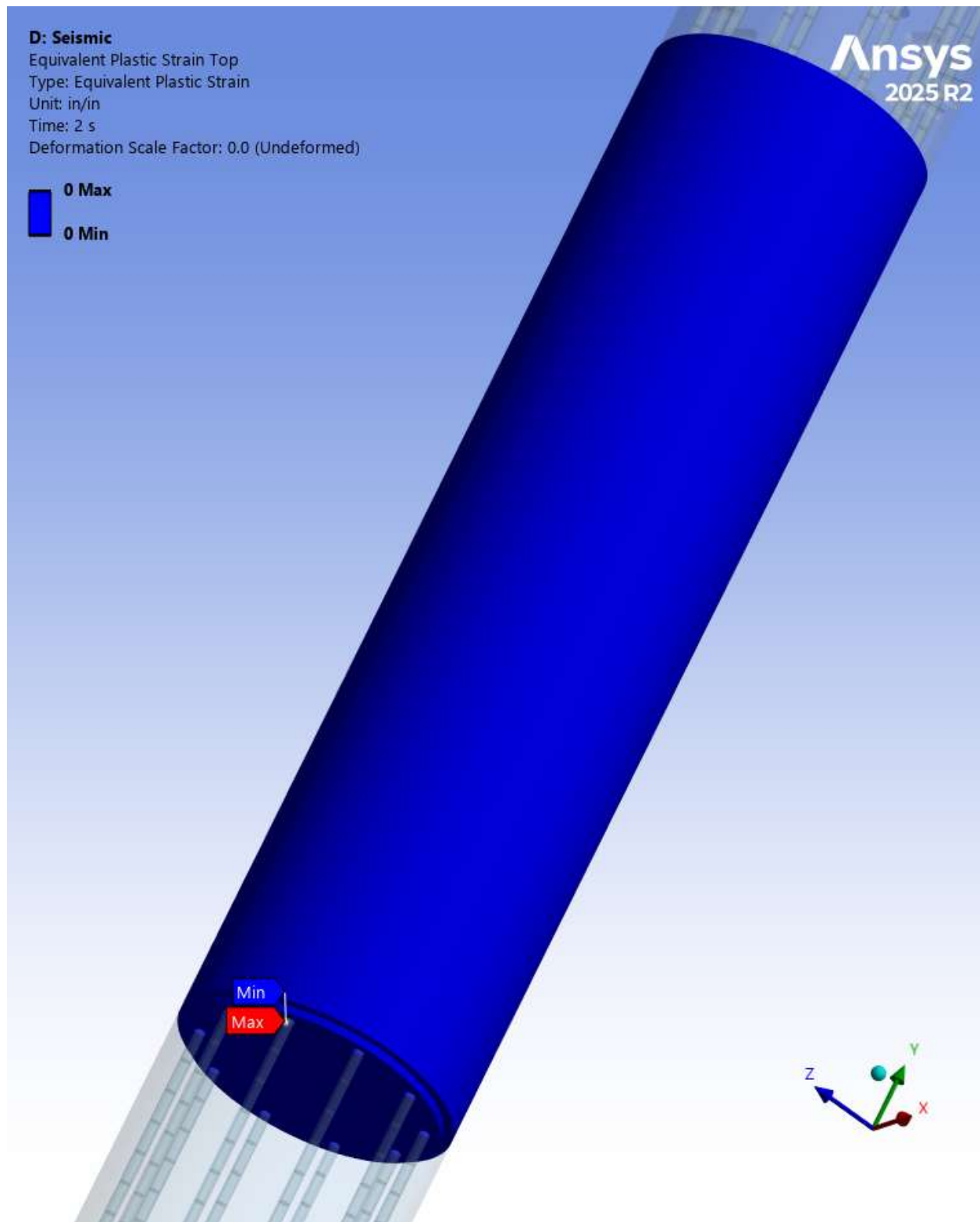


Figure 501 Shaft, Seismic Equivalent Plastic Strain, Top Section

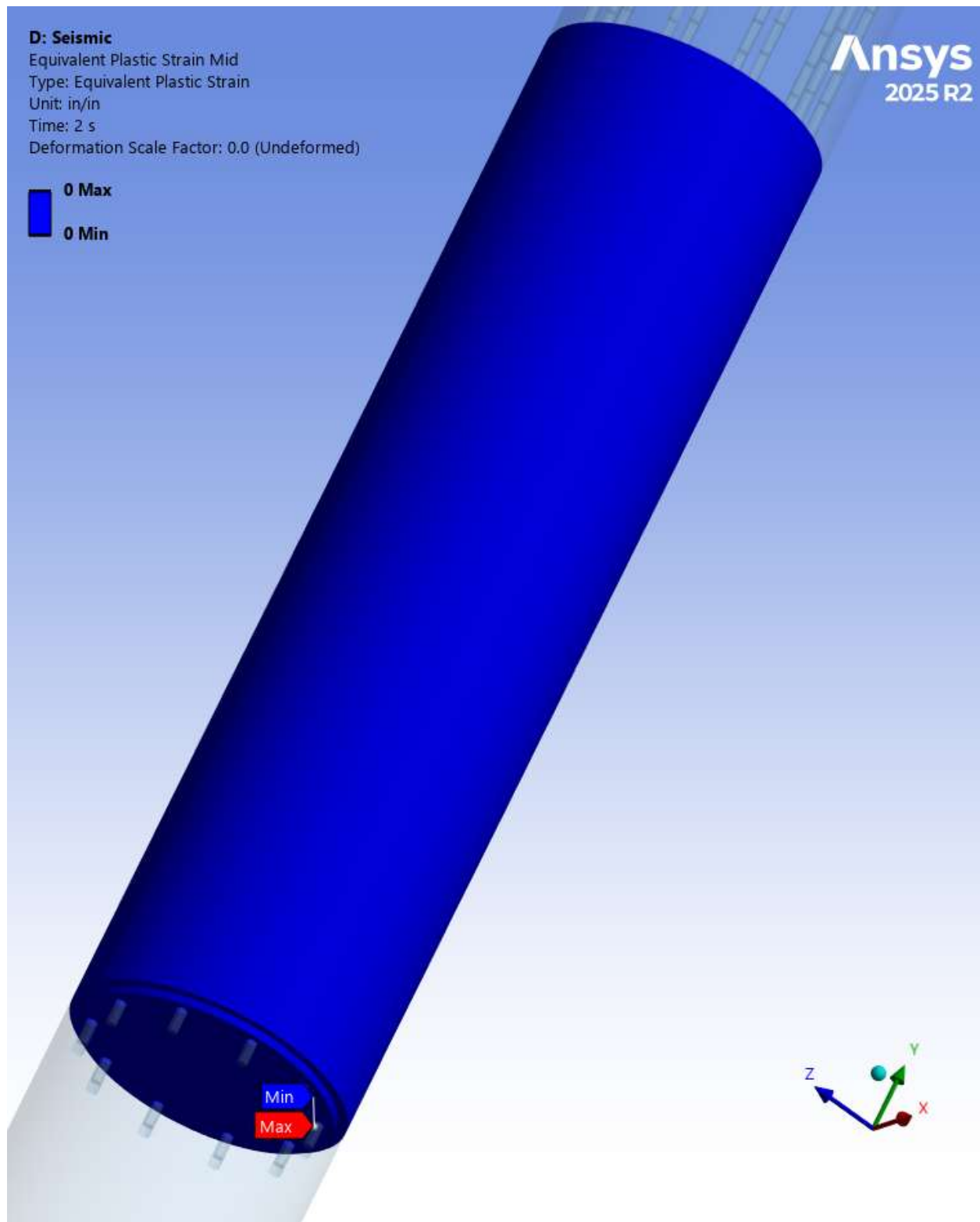


Figure 502 Shaft, Seismic Equivalent Plastic Strain, Mid Section

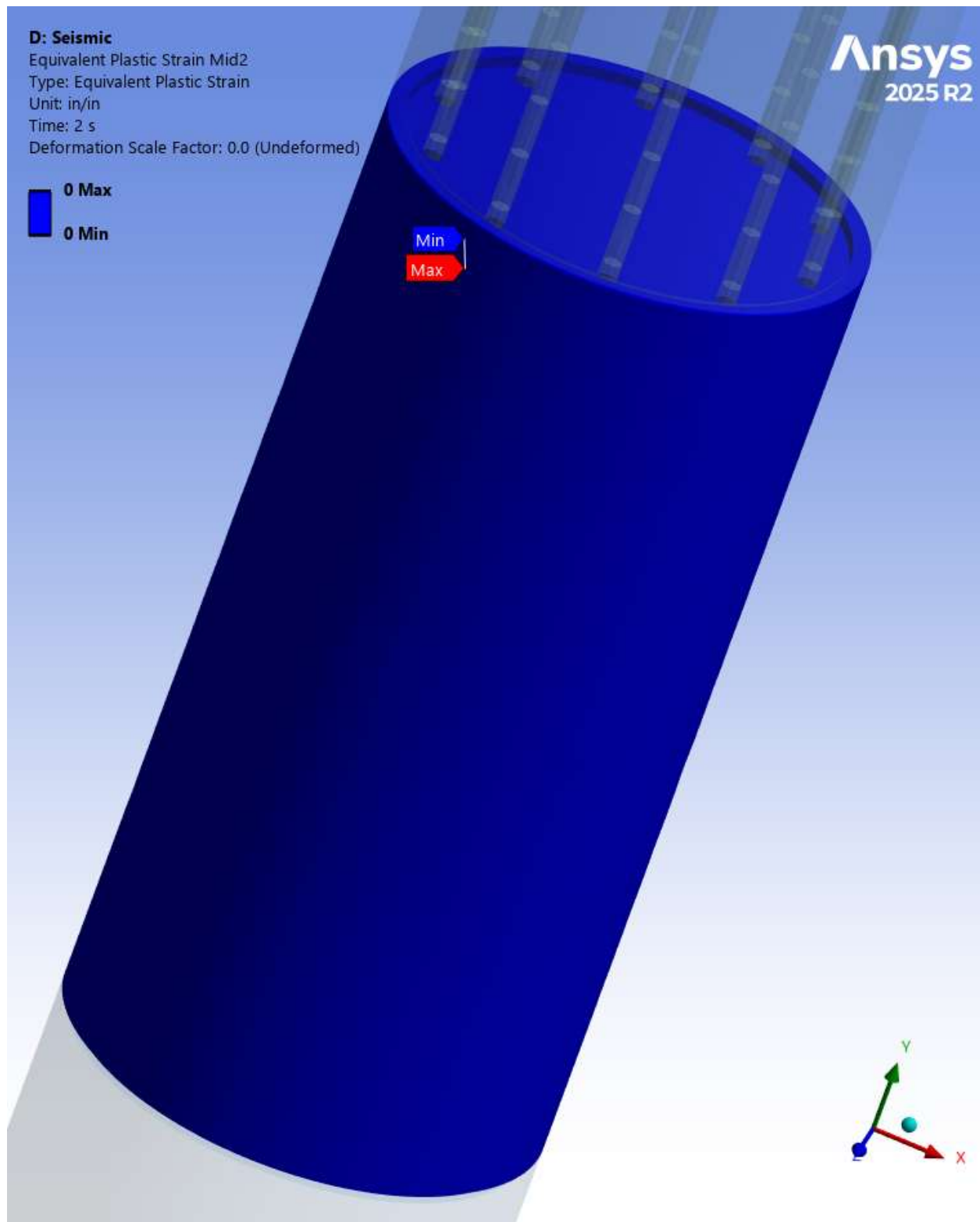


Figure 503 Shaft, Seismic Equivalent Plastic Strain, Lower Mid Section

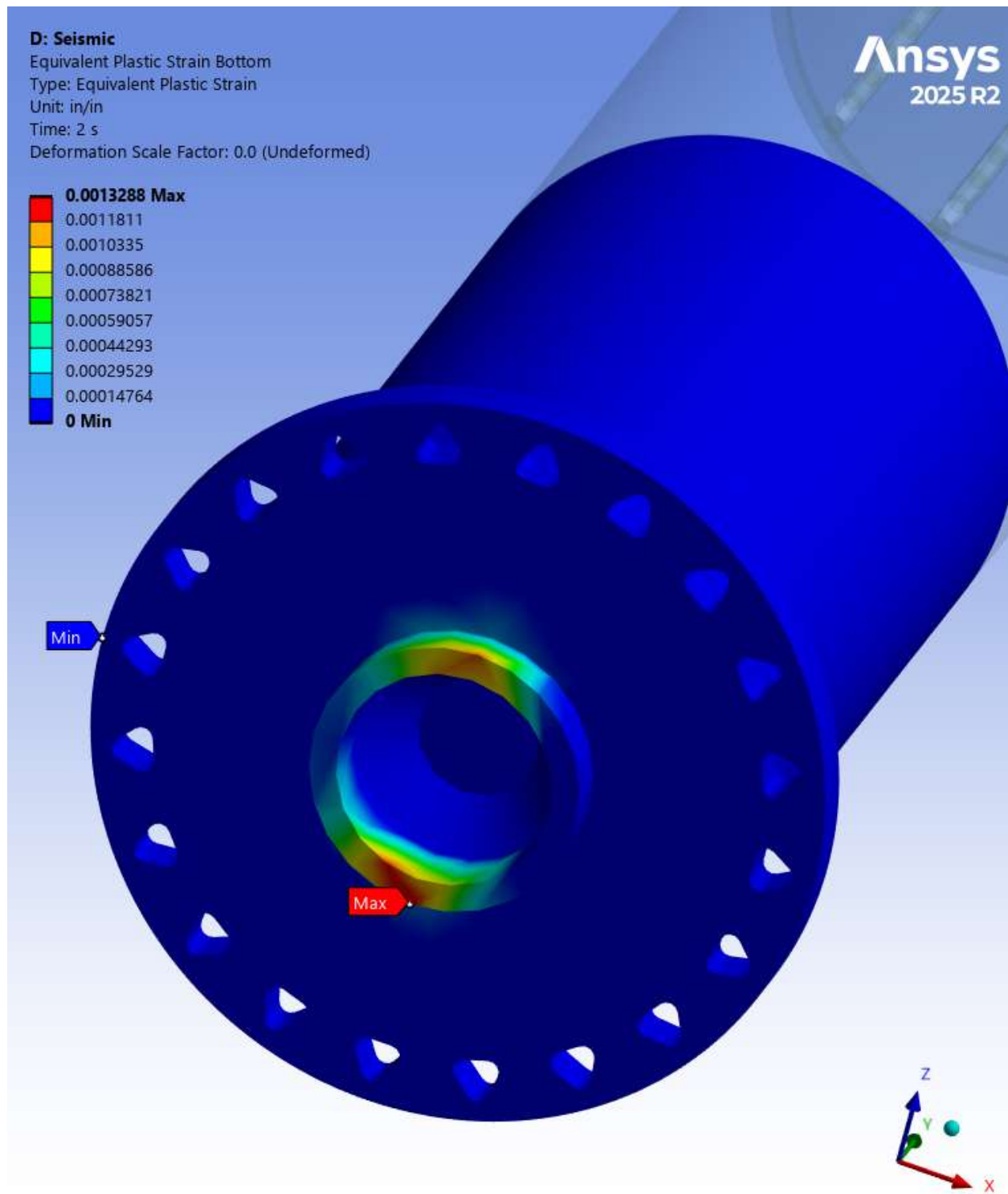


Figure 504 Shaft, Seismic Equivalent Plastic Strain, Bottom Section

Note that on the lower section of the shaft the Displacement load case is applied to the feature that is constrained by the Snubber Ring. The plastic strain shown above is not from a realistic source.

5.1.3.1.3 Seismic + Stop Load Case

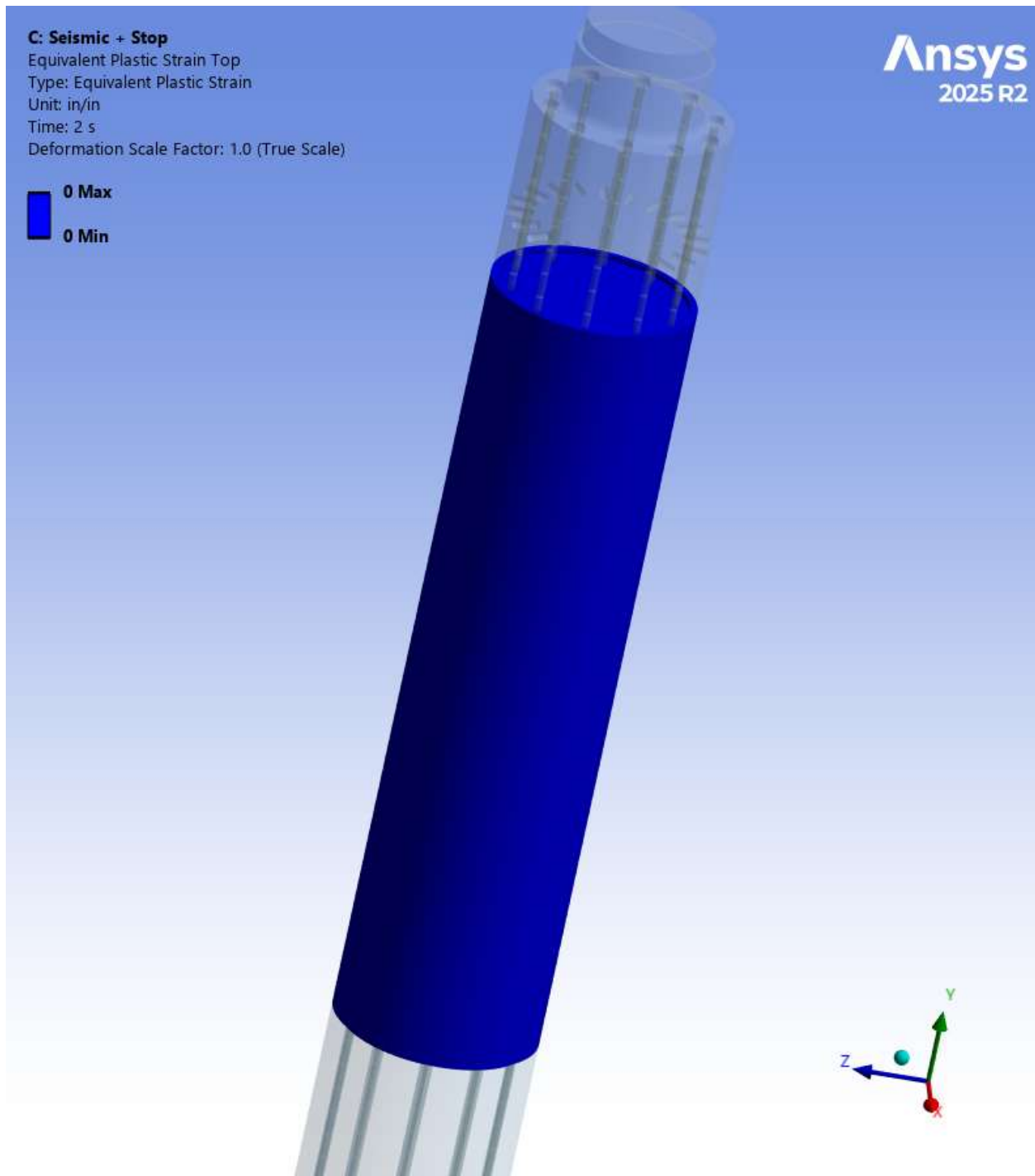


Figure 505 Shaft, Seismic + Stop Equivalent Plastic Strain, Top Section

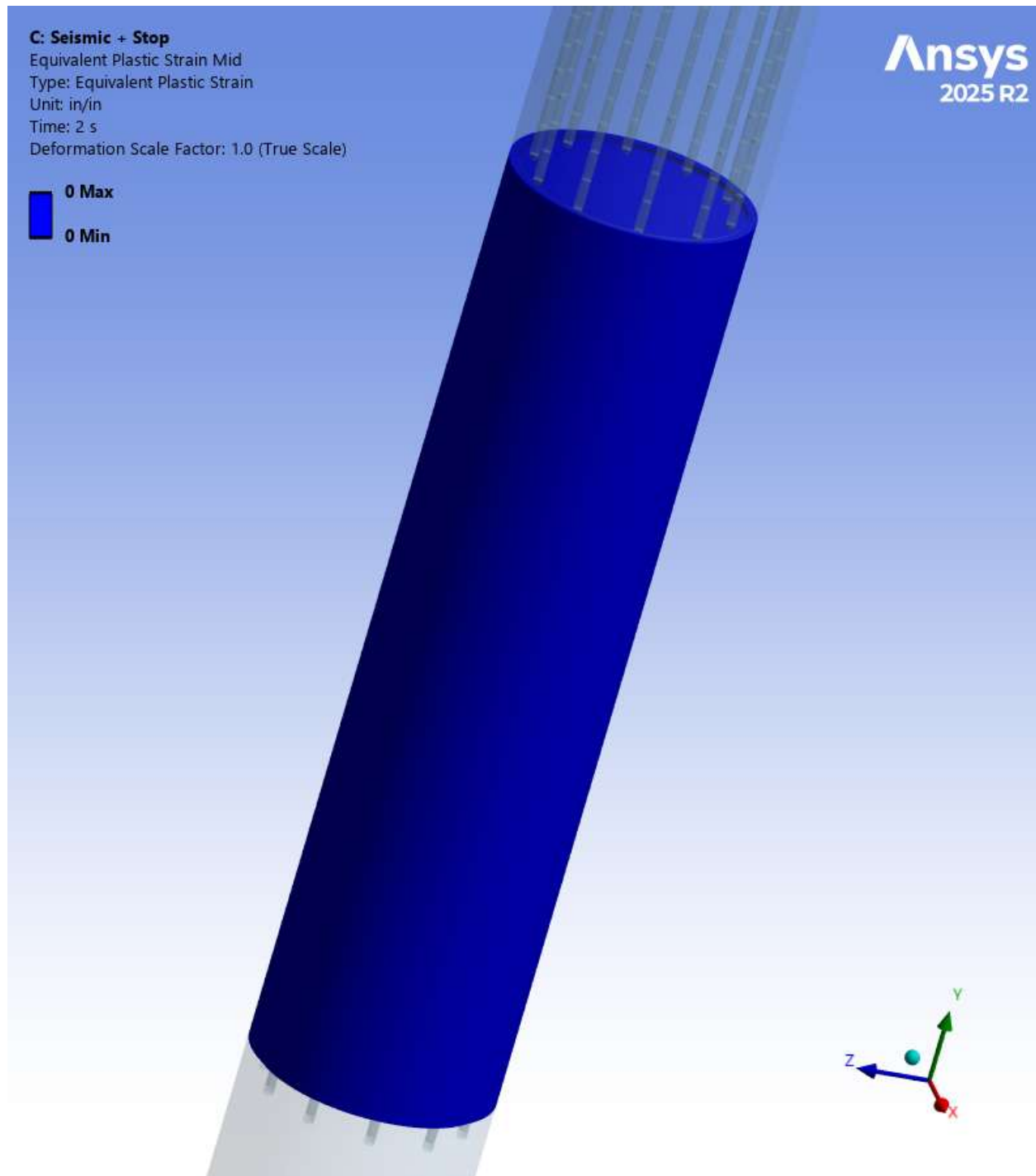


Figure 506 Shaft, Seismic + Stop Equivalent Plastic Strain, Mid Section

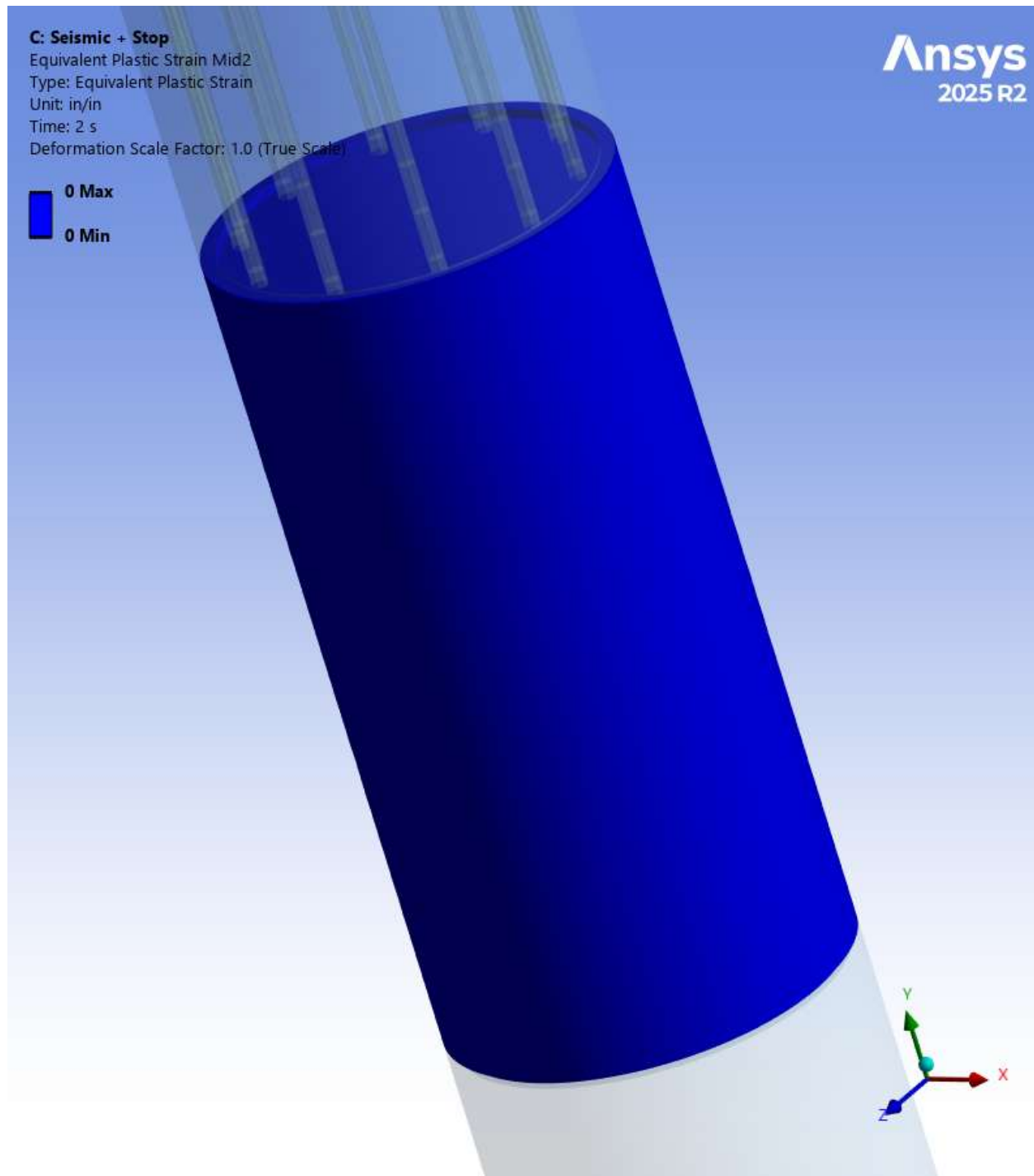


Figure 507 Shaft, Seismic + Stop Equivalent Plastic Strain, Lower Mid-Section

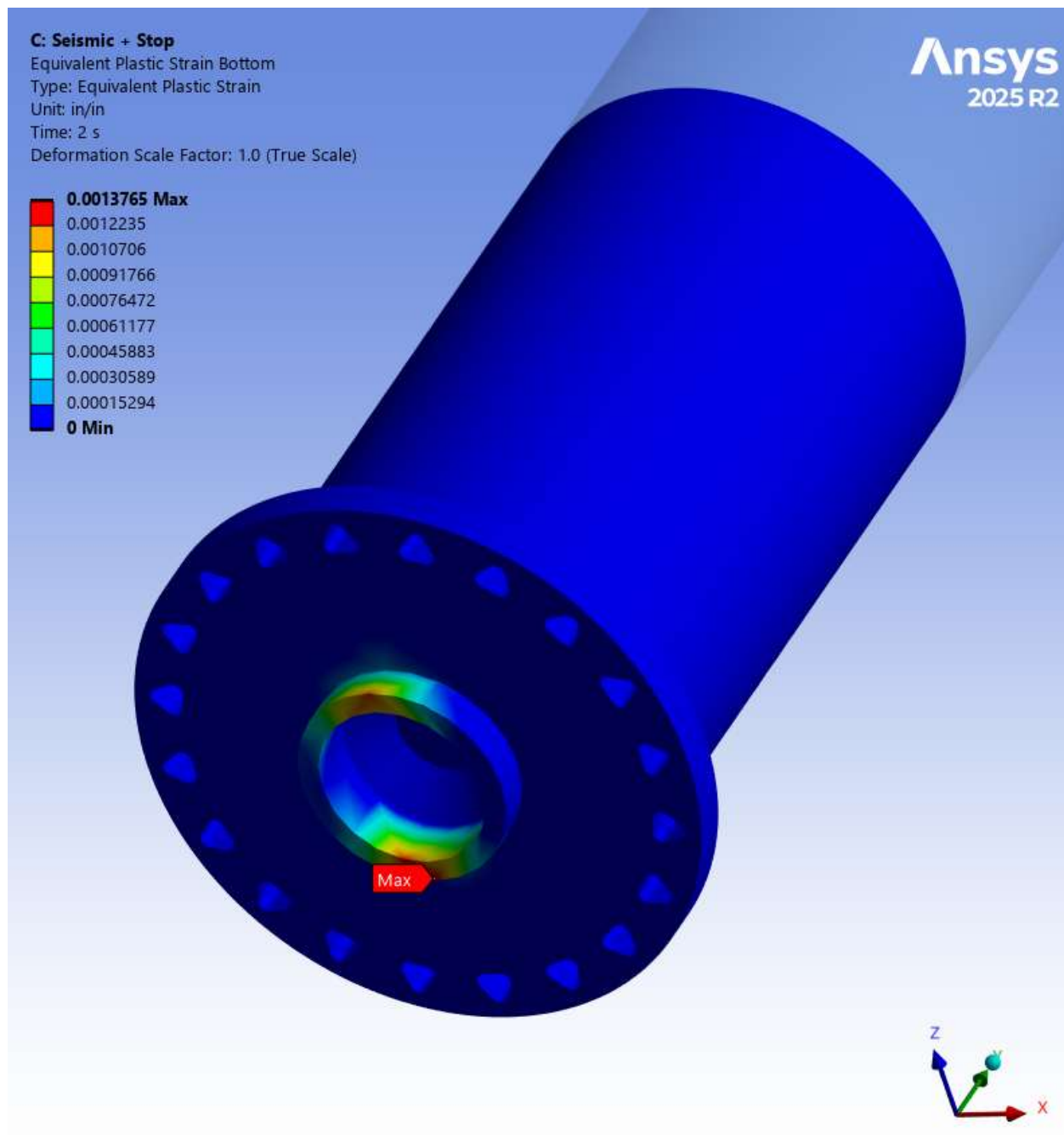


Figure 508 Shaft, Seismic + Stop Equivalent Plastic Strain, Bottom Section

Note that on the lower section of the shaft the Displacement load case is applied to the feature that is constrained by the Snubber Ring. The plastic strain shown above is not from a realistic source.

5.1.3.2 Shaft Local Failure

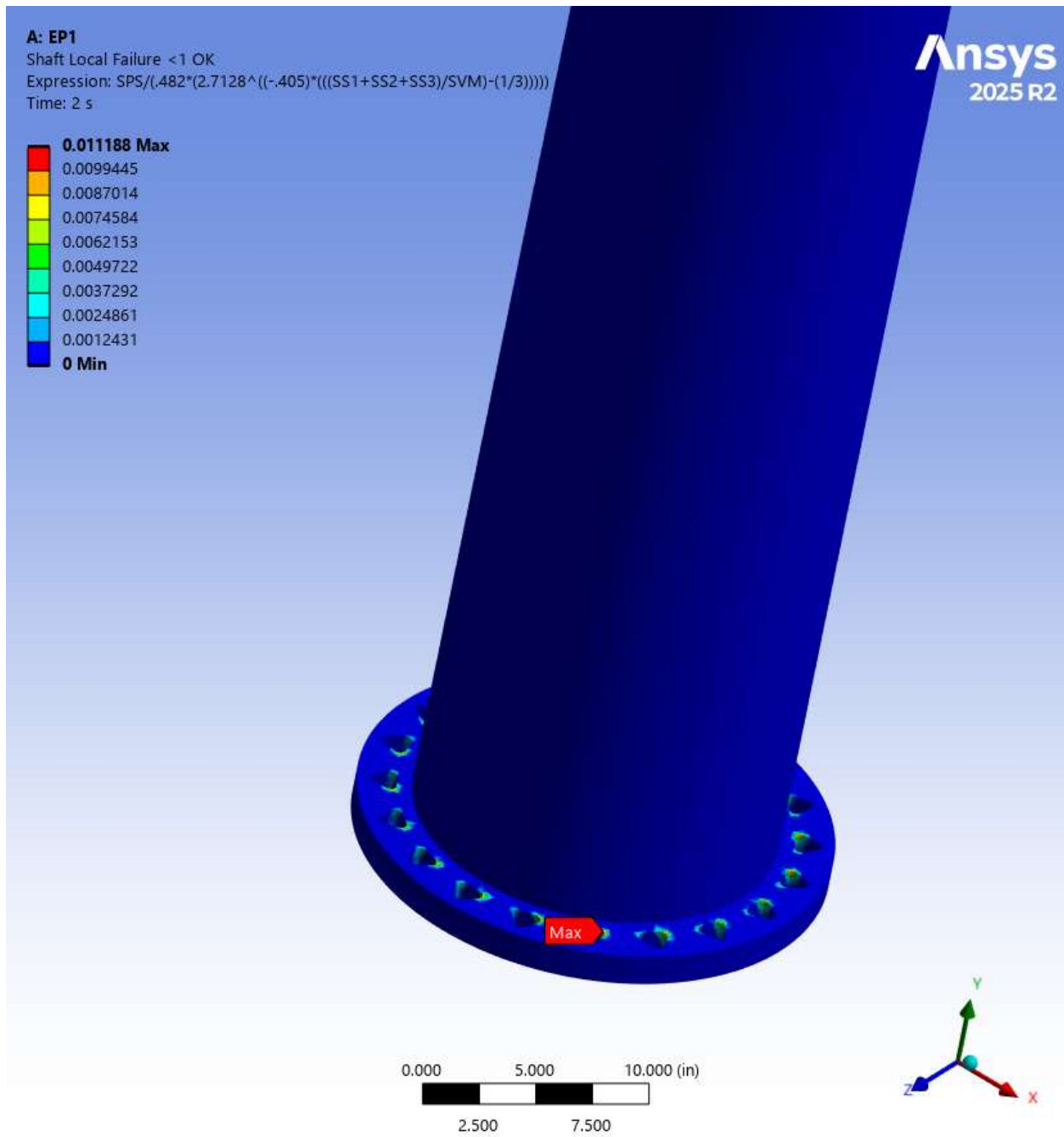


Figure 509 Shaft, Elastic Plastic Case 1 Local Failure

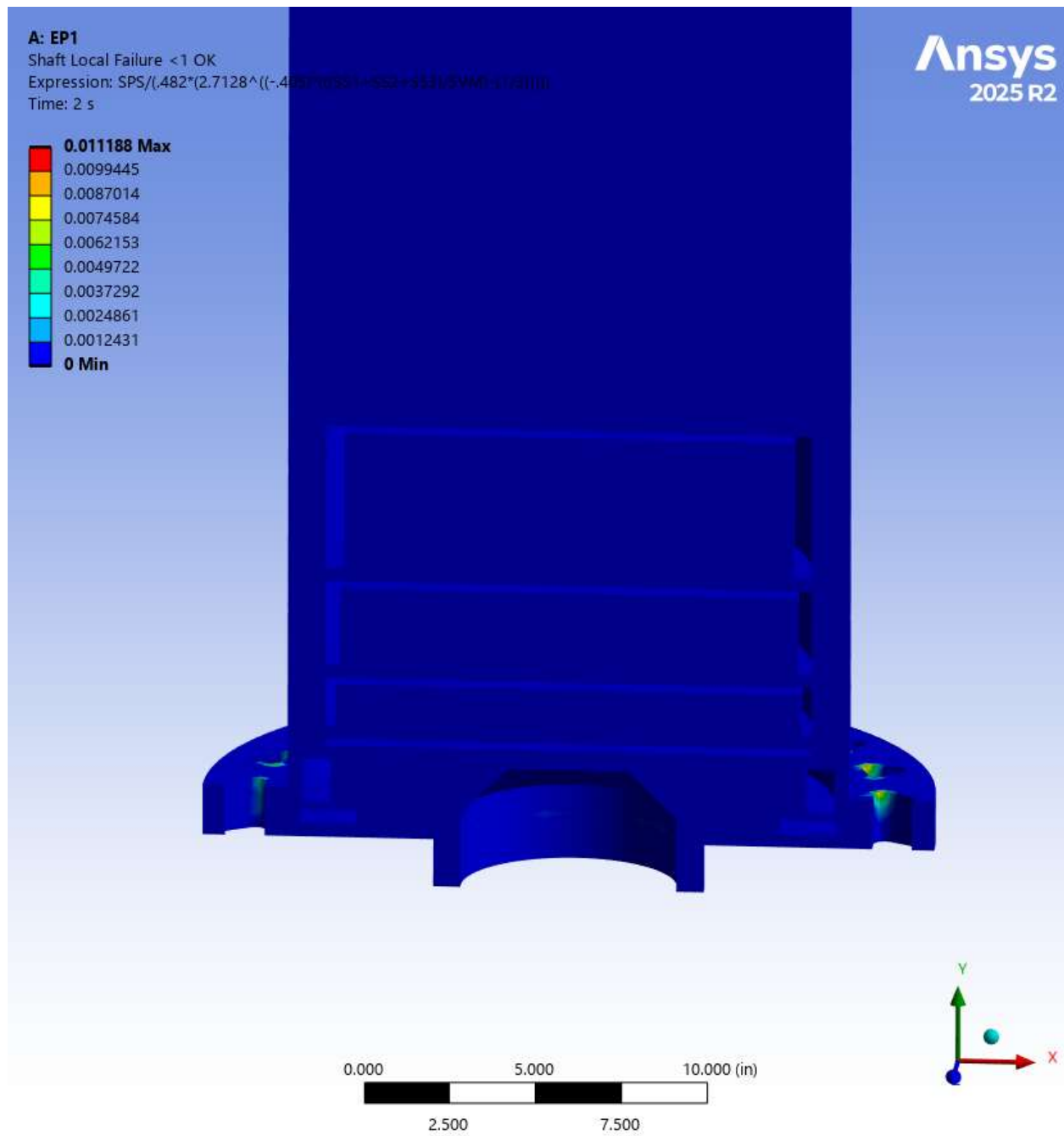


Figure 510 Shaft, Elastic Plastic Case 1 Local Failure, Closeup

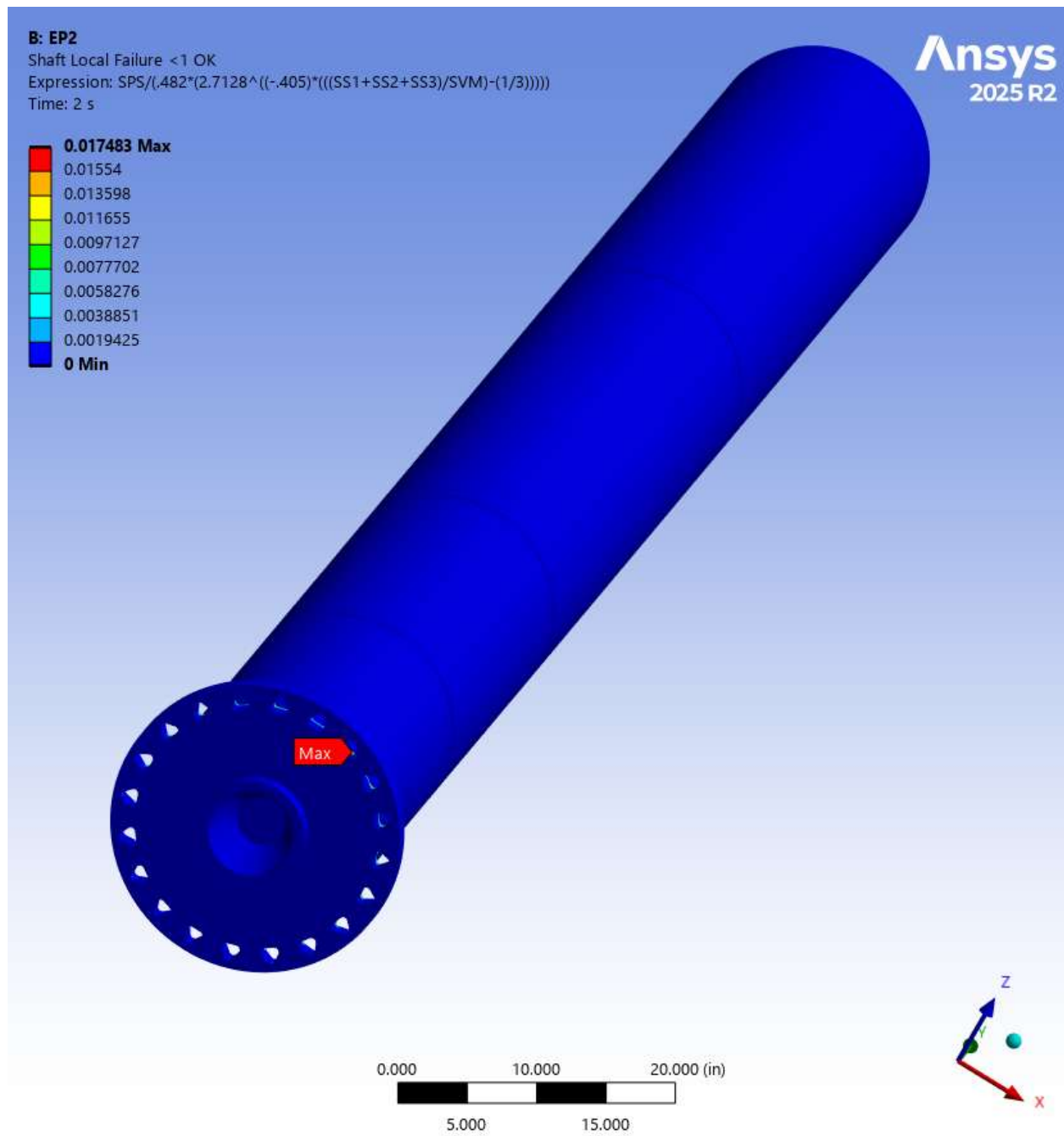


Figure 511 Shaft, Elastic Plastic 2 Local Failure

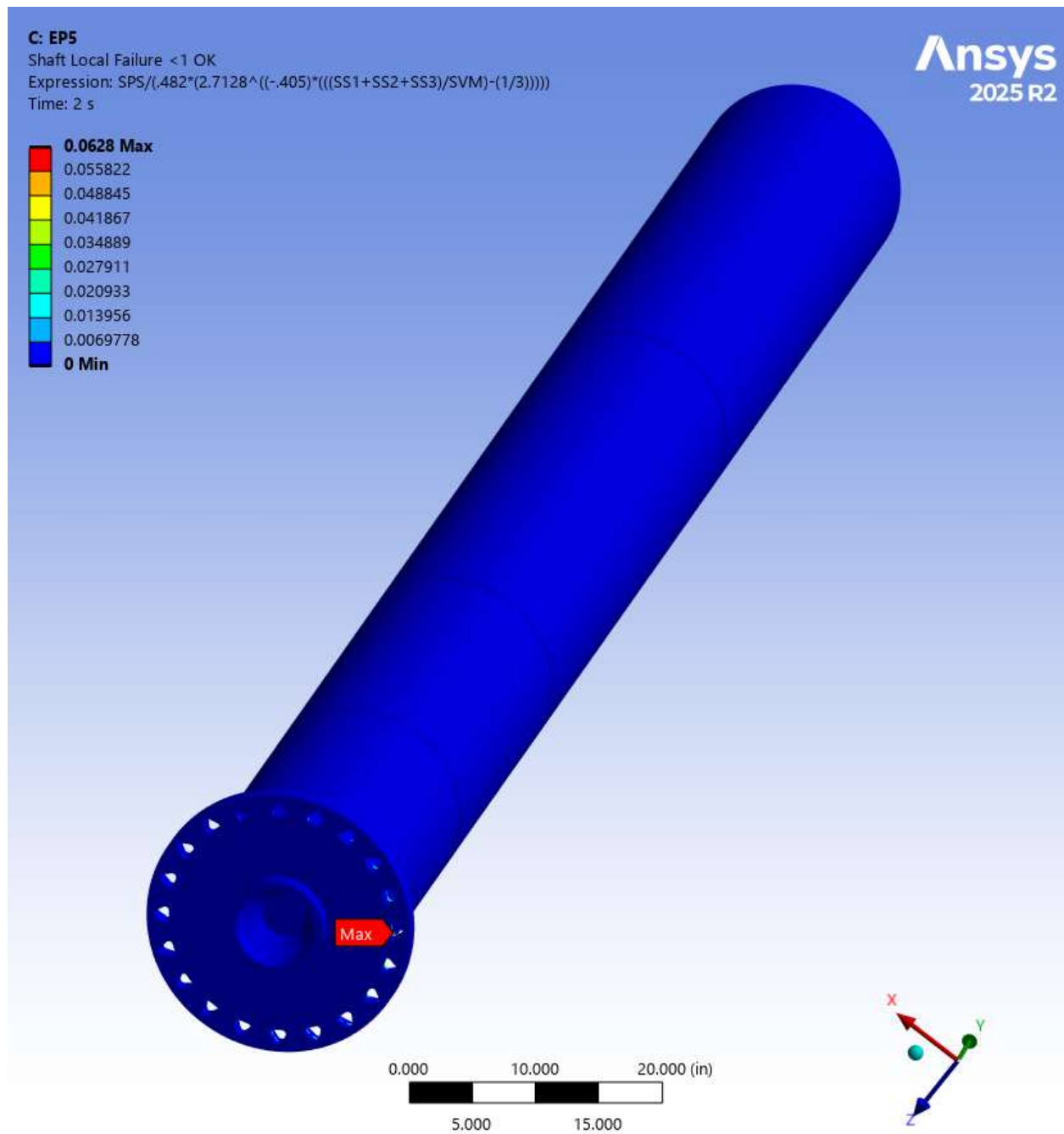


Figure 513 Shaft, Elastic Plastic Case 5 Local Failure

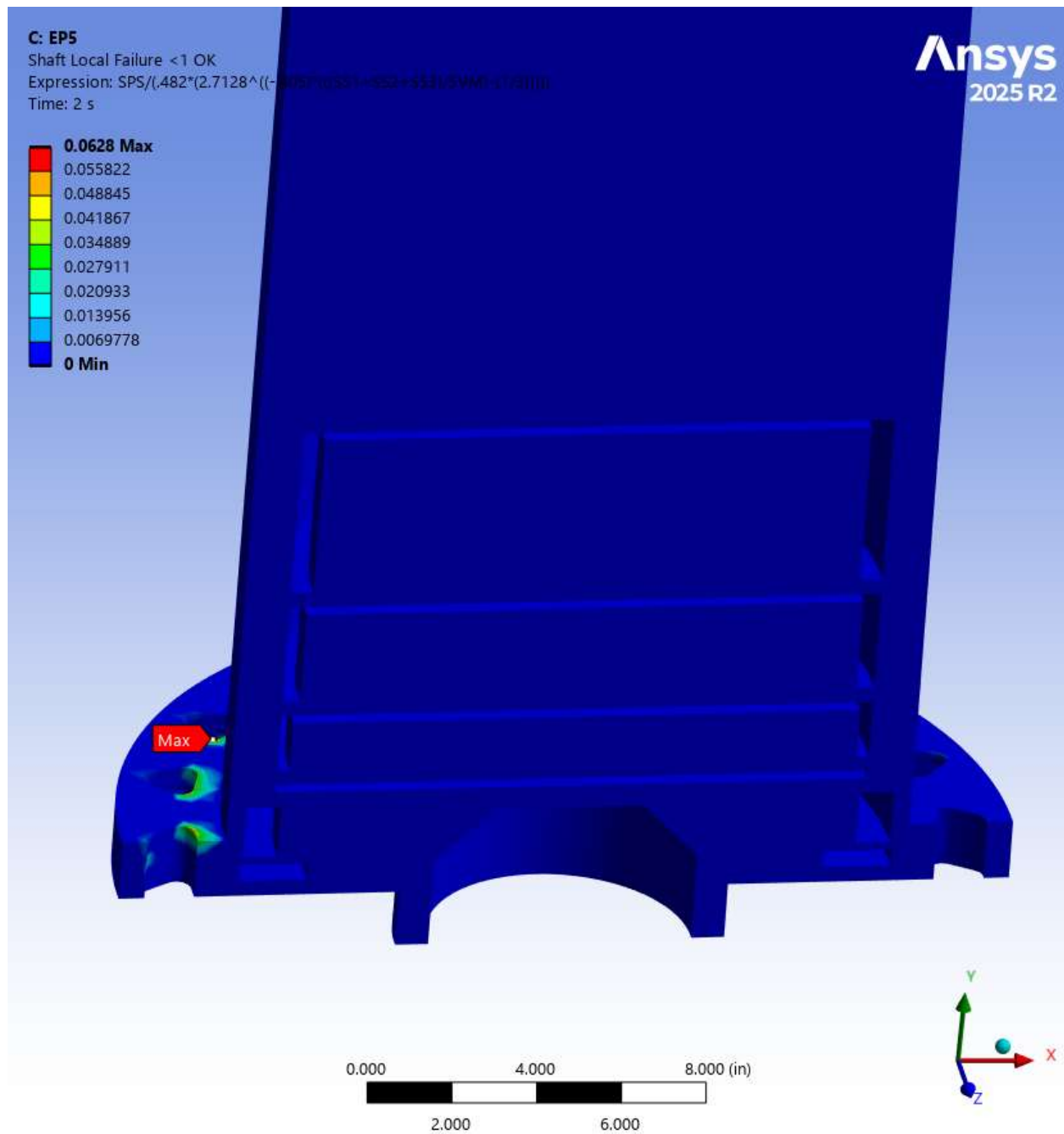


Figure 514 Shaft, Elastic Plastic Case 5 Local Failure, Closeup

5.1.3.3 Tie Rods

5.1.3.4 Cyclic Loads

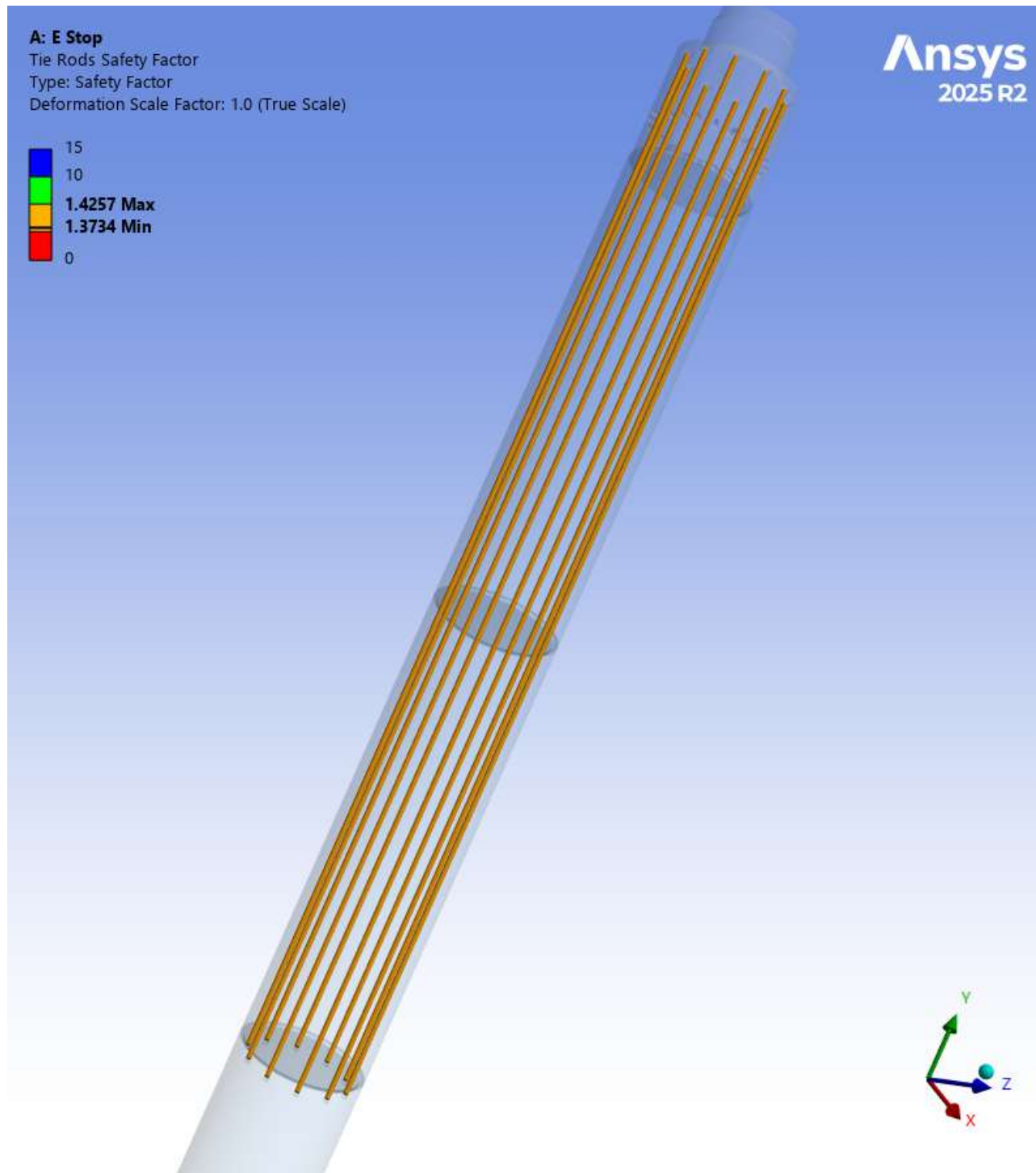


Figure 515 Tie Rod Cyclic Load Safety Factor for Life of Facility

Note that since the Tie Rods are actual components from CAD they can have fatigue life measured. They are also evaluated for fatigue with the rest of the fasteners in Section 5.1.4.

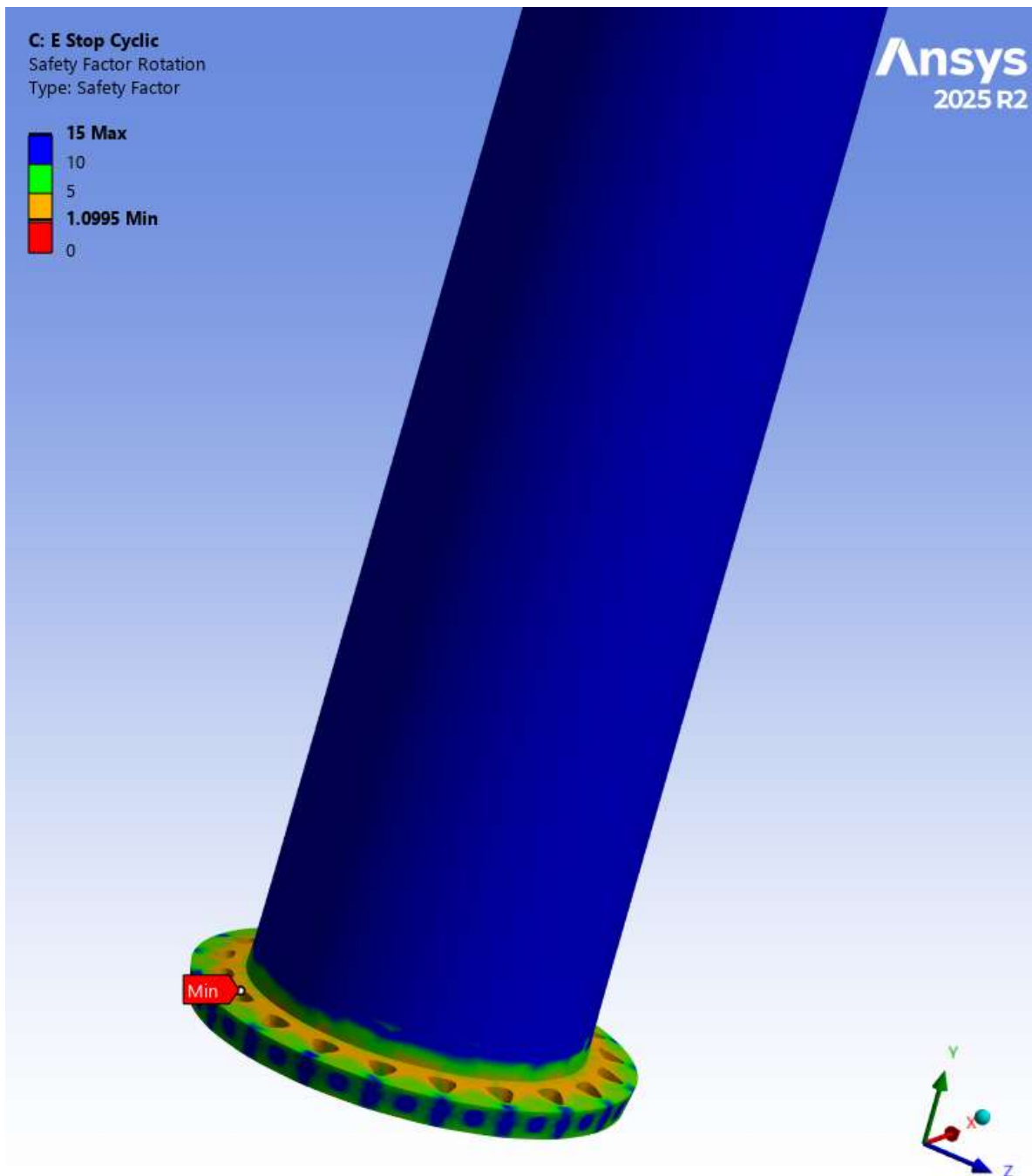


Figure 516 Shaft Cyclic Load Rotational Safety Factor

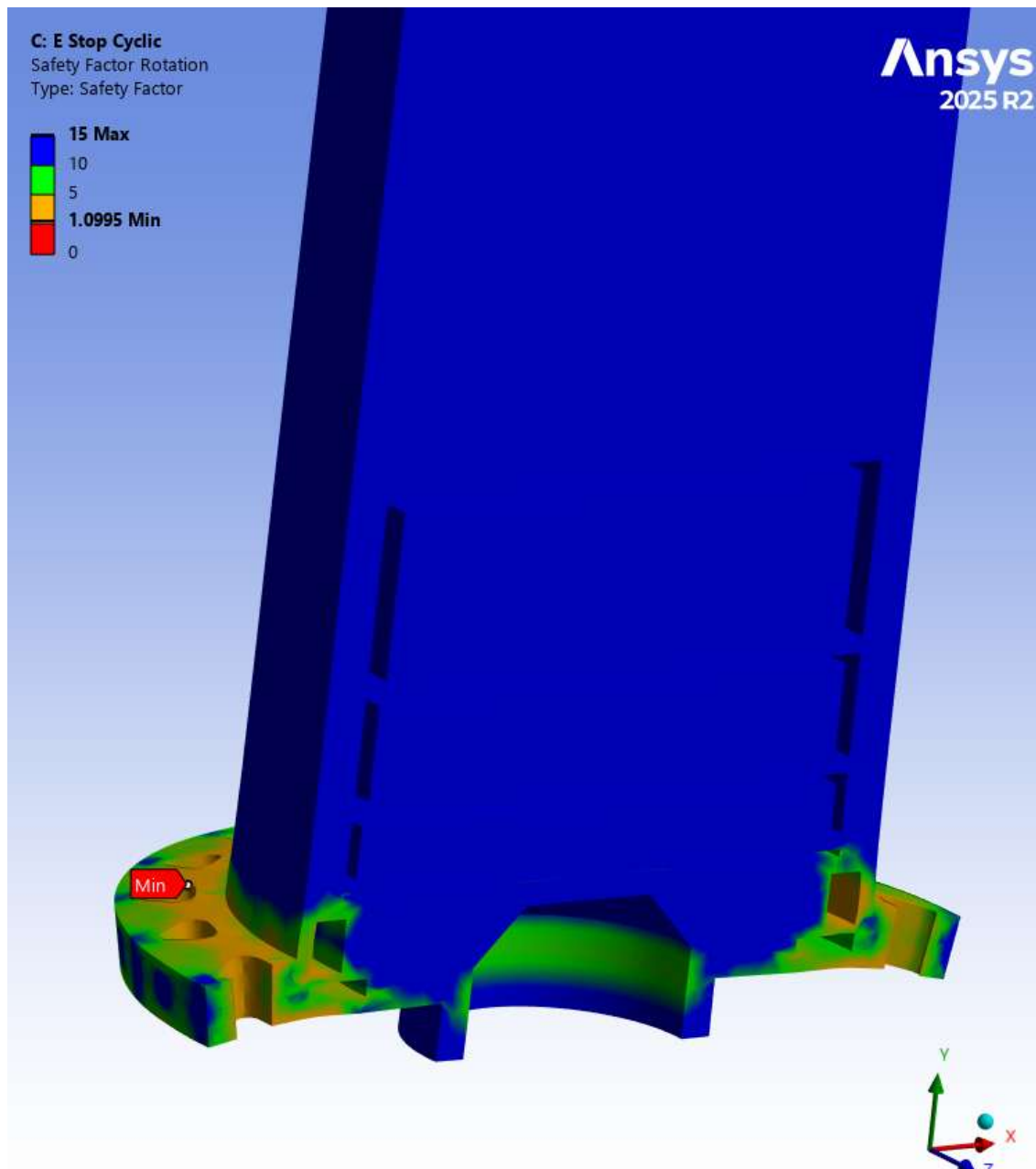


Figure 517 Shaft Cyclic Load Rotational Safety Factor

Note in the following Figures, the fatigue cycle count is for Beam trips, this is a cyclic thermal load with a cycle count of 10^5 . The equivalent stress at this location for the mechanical loads is near 0 therefore no additional damage is calculated here.

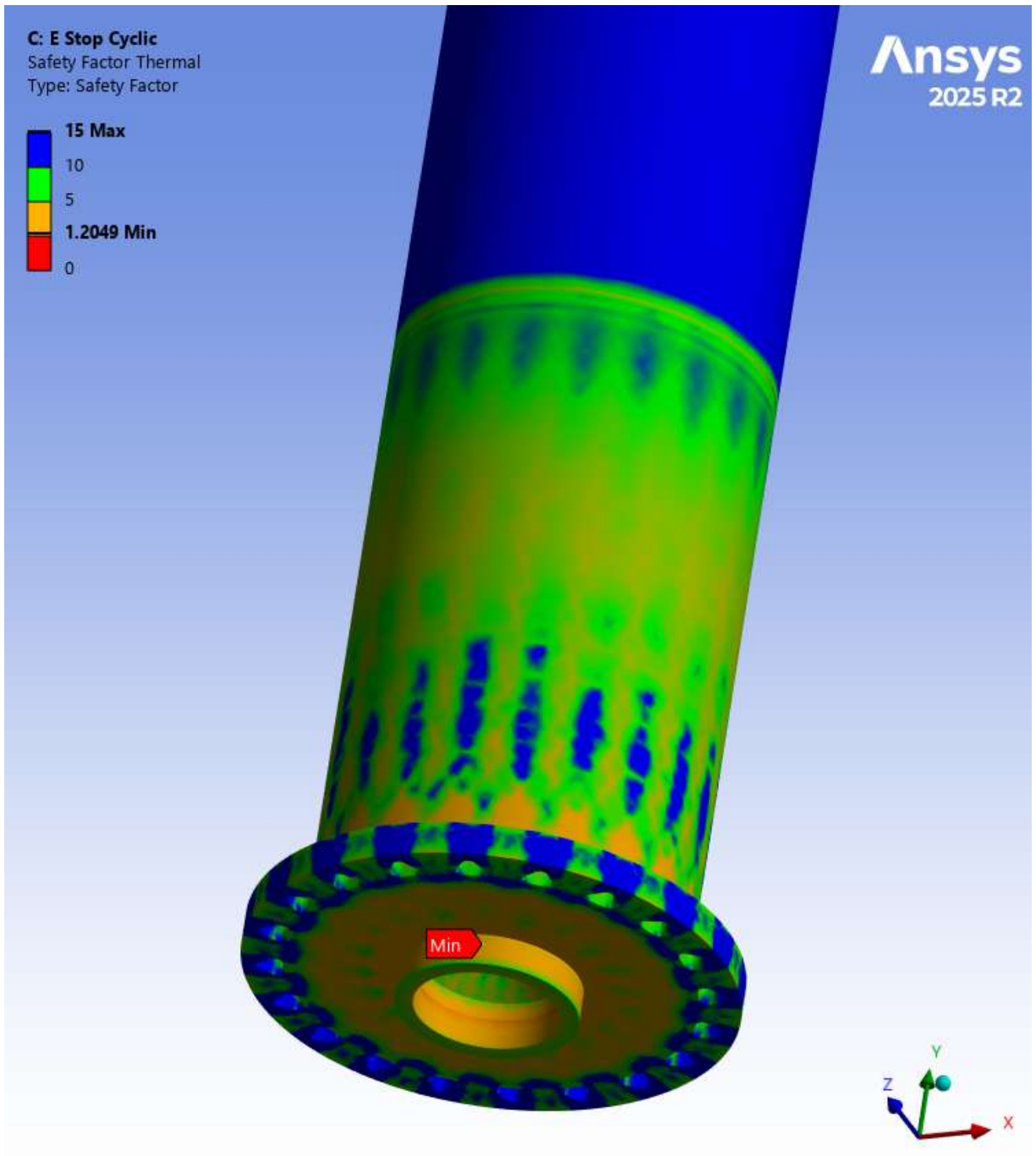


Figure 518 Shaft Cyclic Load Thermal Safety Factor

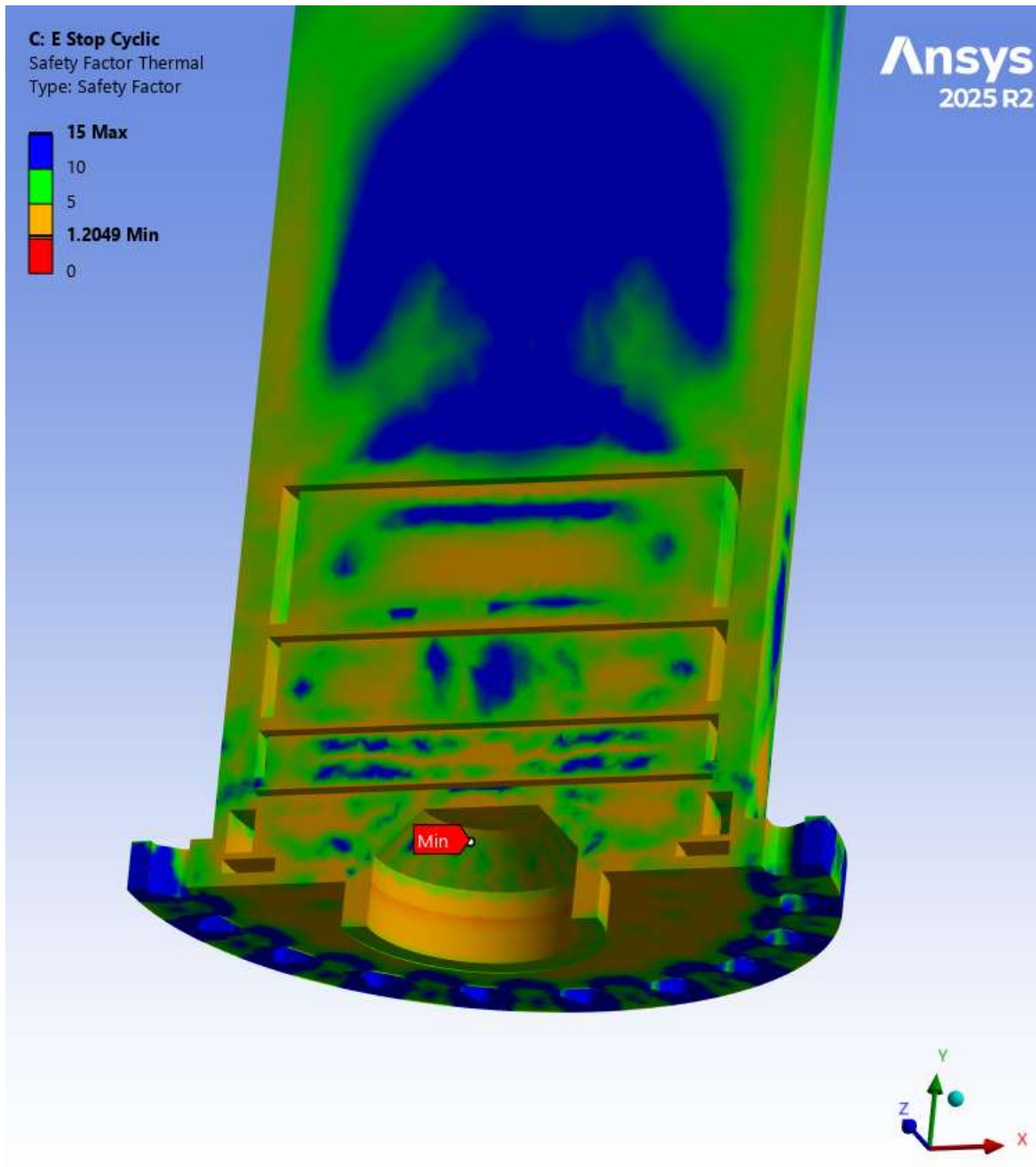


Figure 519 Shaft Cyclic Load Thermal Safety Factor

5.1.3.5 Equivalent Stress

Stress plots of the equivalent stress from the elastic load cases are included for reference.

5.1.3.5.1 E Stop Load Case

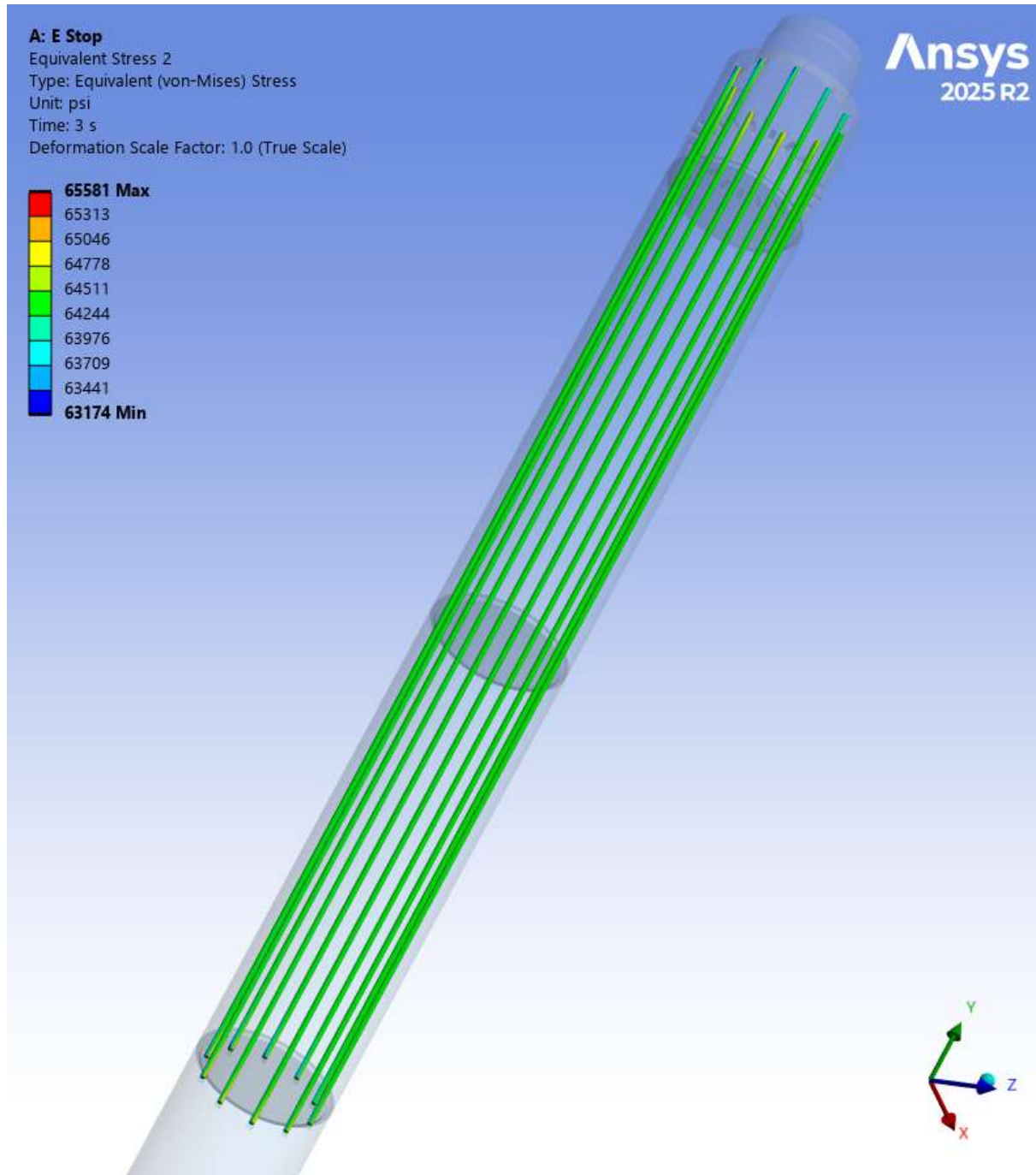


Figure 520 Tie Rods, E Stop Equivalent Stress

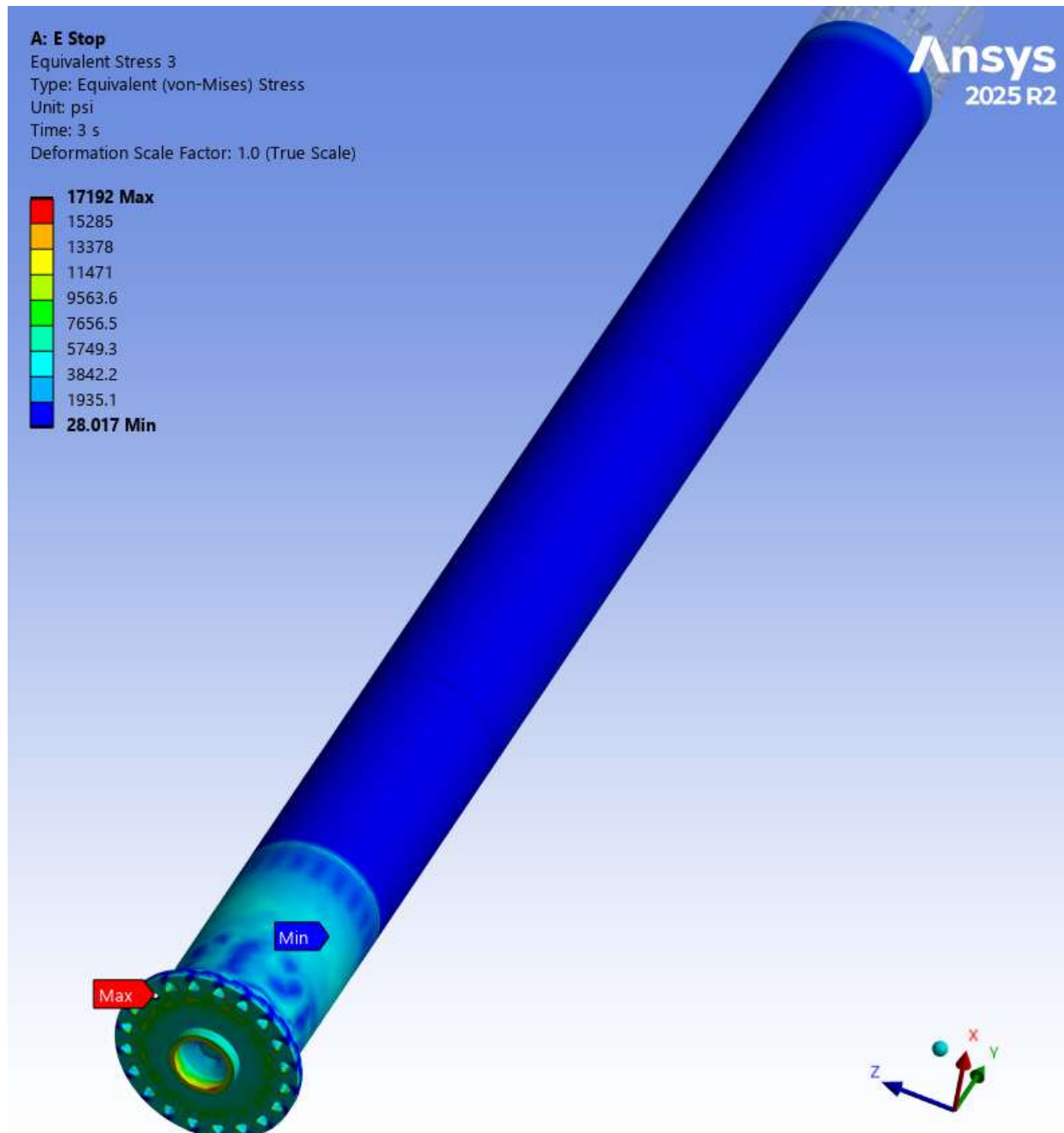


Figure 521 Shaft, E Stop Equivalent Stress

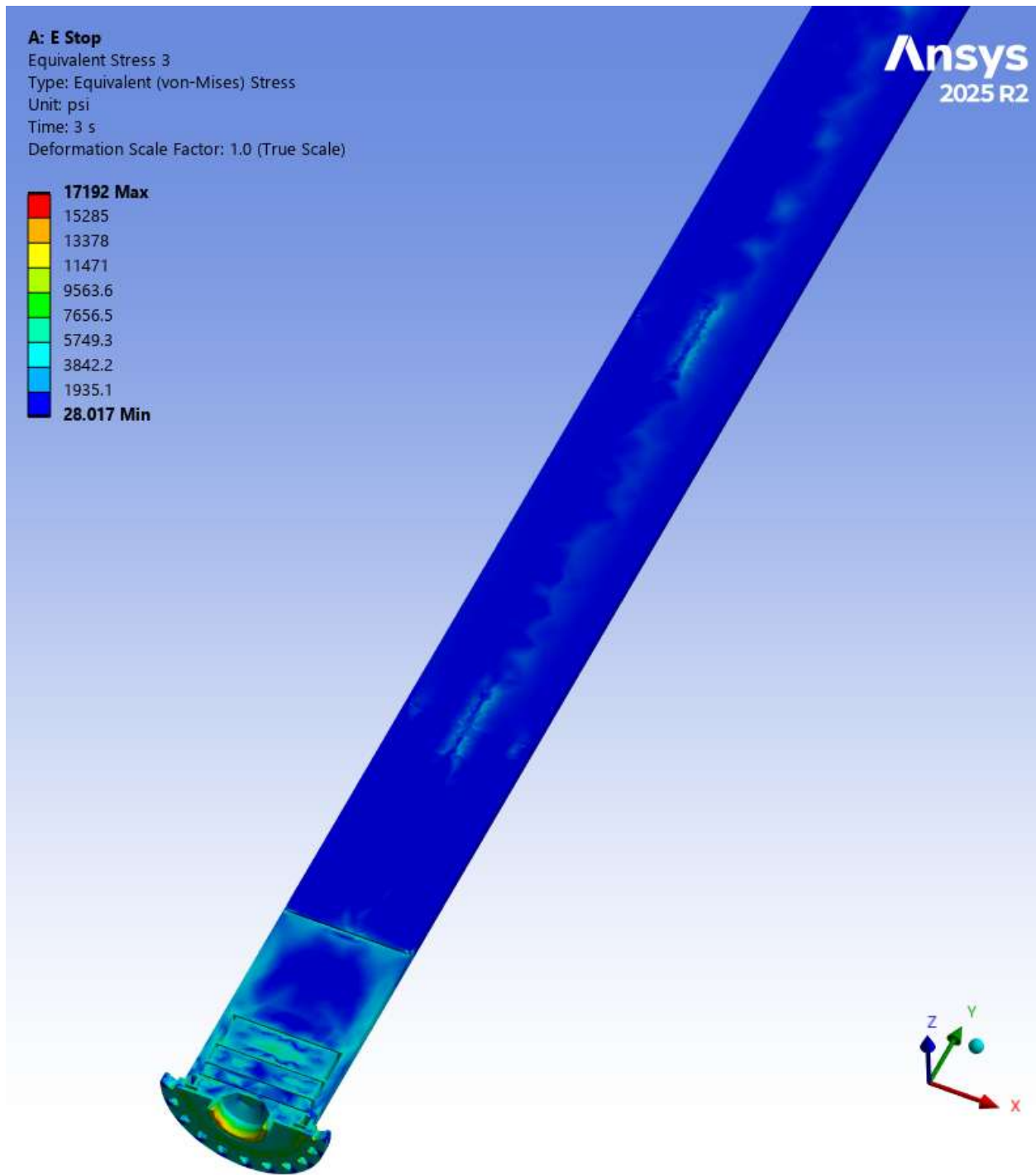


Figure 522 Shaft, E Stop Equivalent Stress

5.1.3.5.2 Seismic Load Case

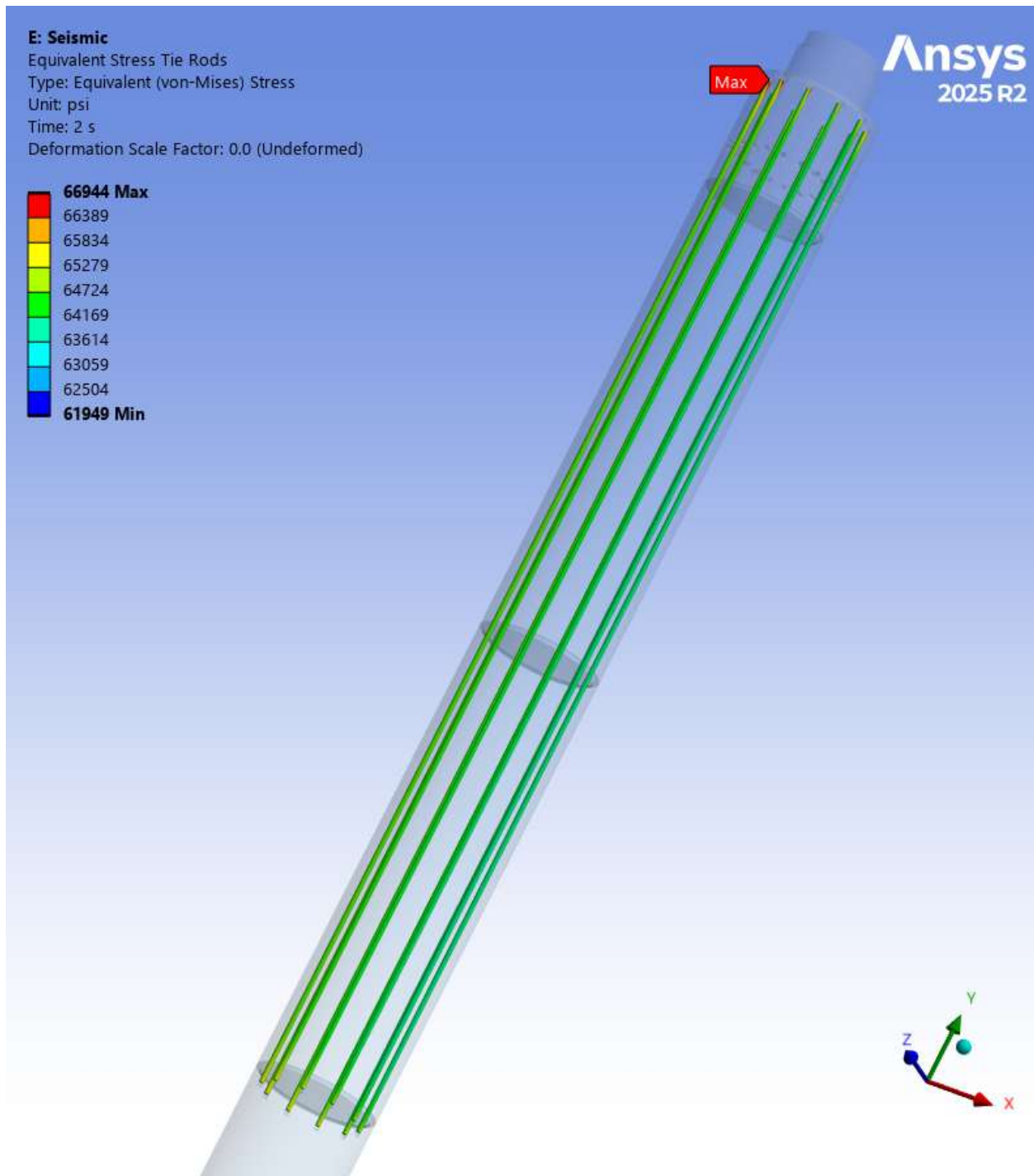


Figure 523 Tie Rods, Seismic Equivalent Stress

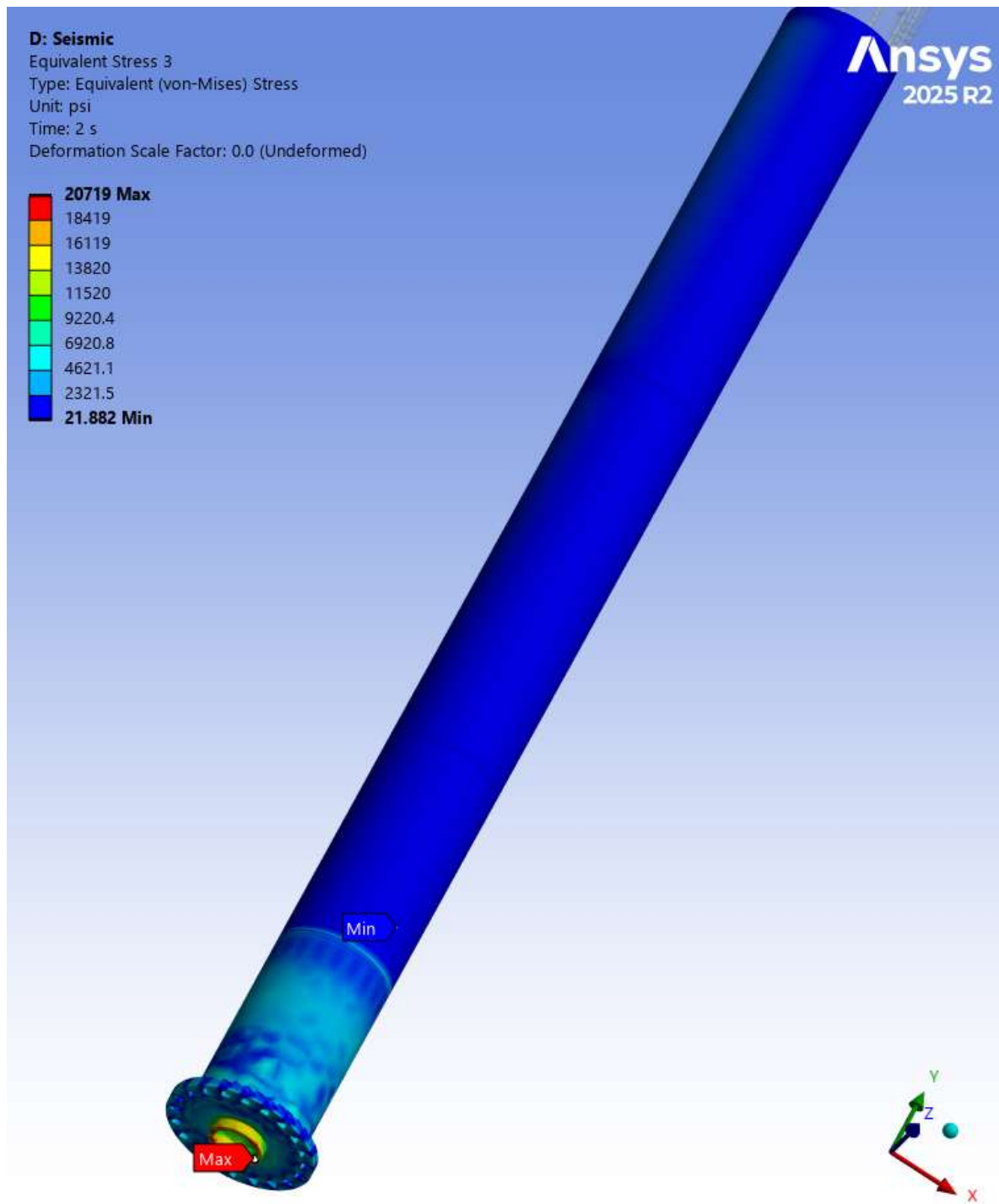


Figure 524 Shaft, Seismic Equivalent Stress

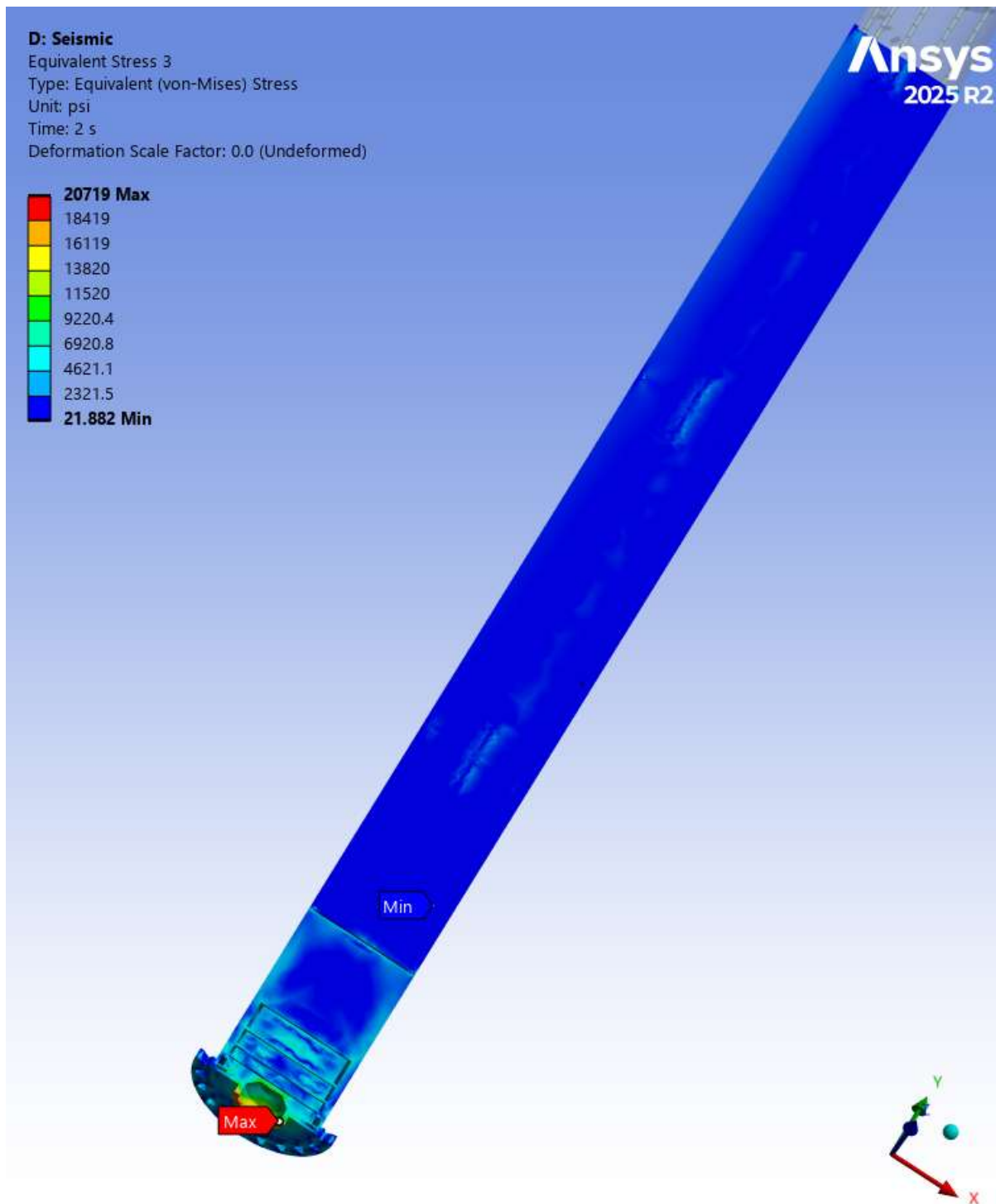


Figure 525 Shaft, Seismic Equivalent Stress

5.1.3.5.3 Seismic + Stop Load Case

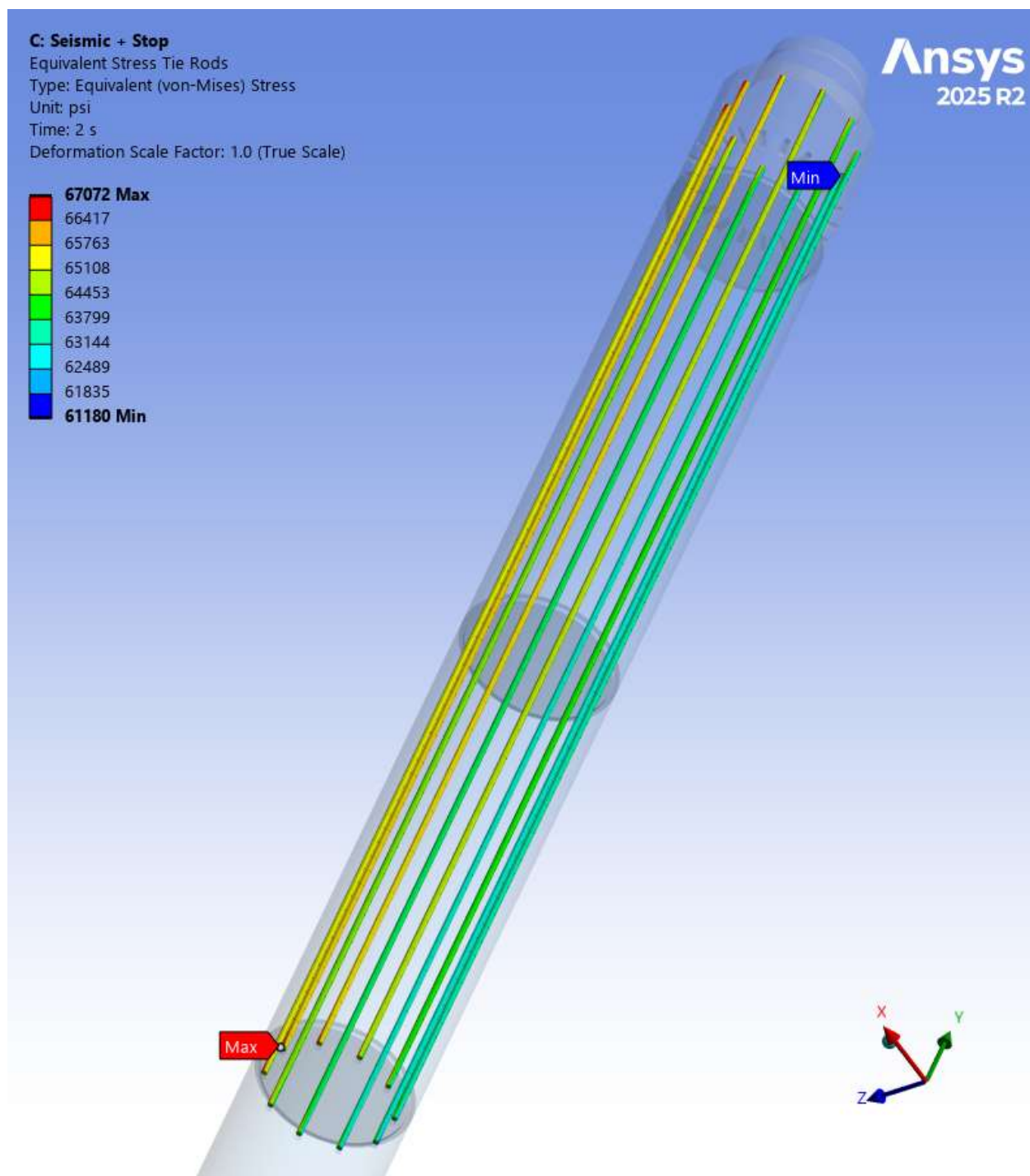


Figure 526 Tie Rods, Seismic + Stop Equivalent Stress

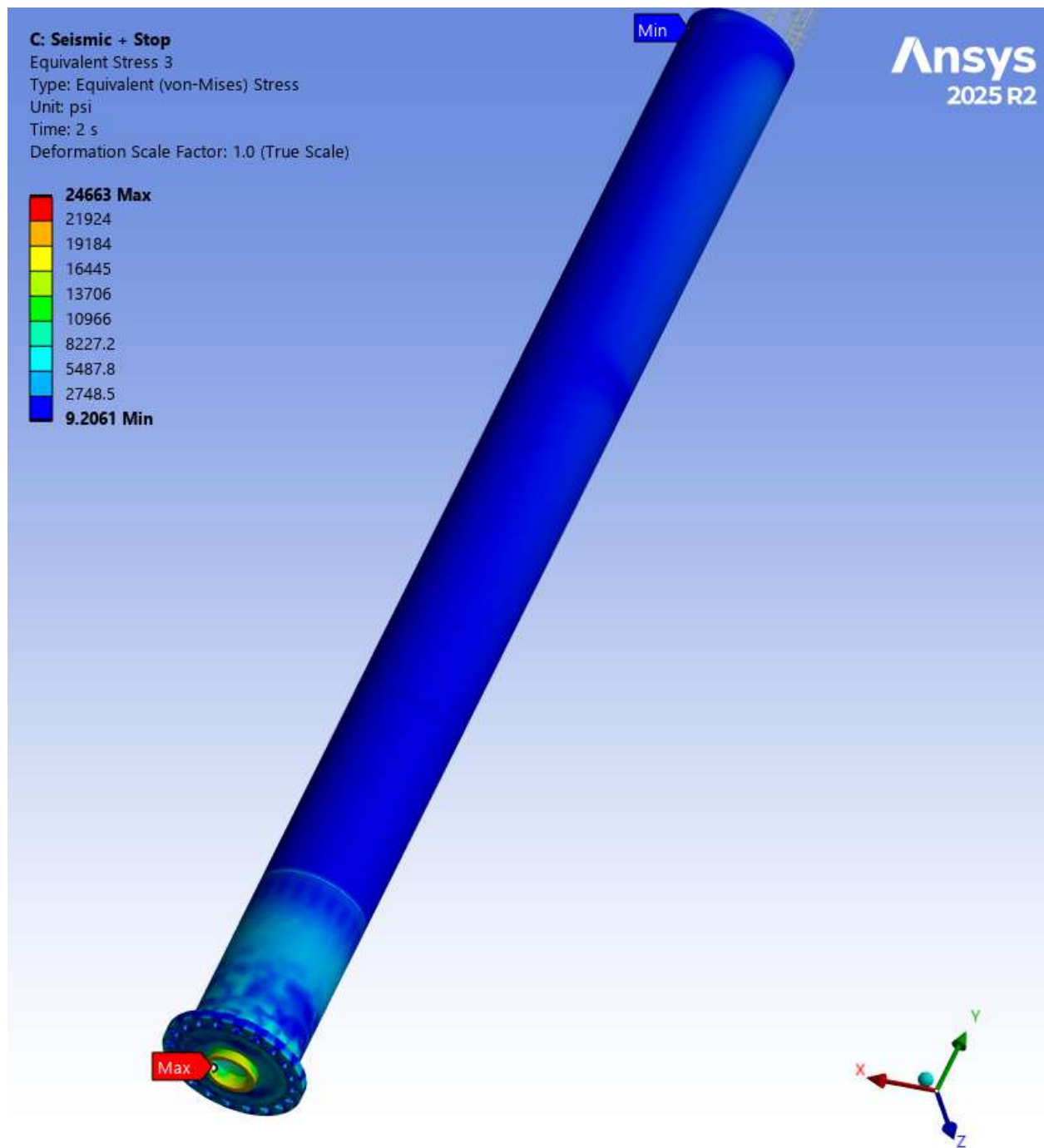


Figure 527 Shaft, Seismic + Stop Equivalent Stress

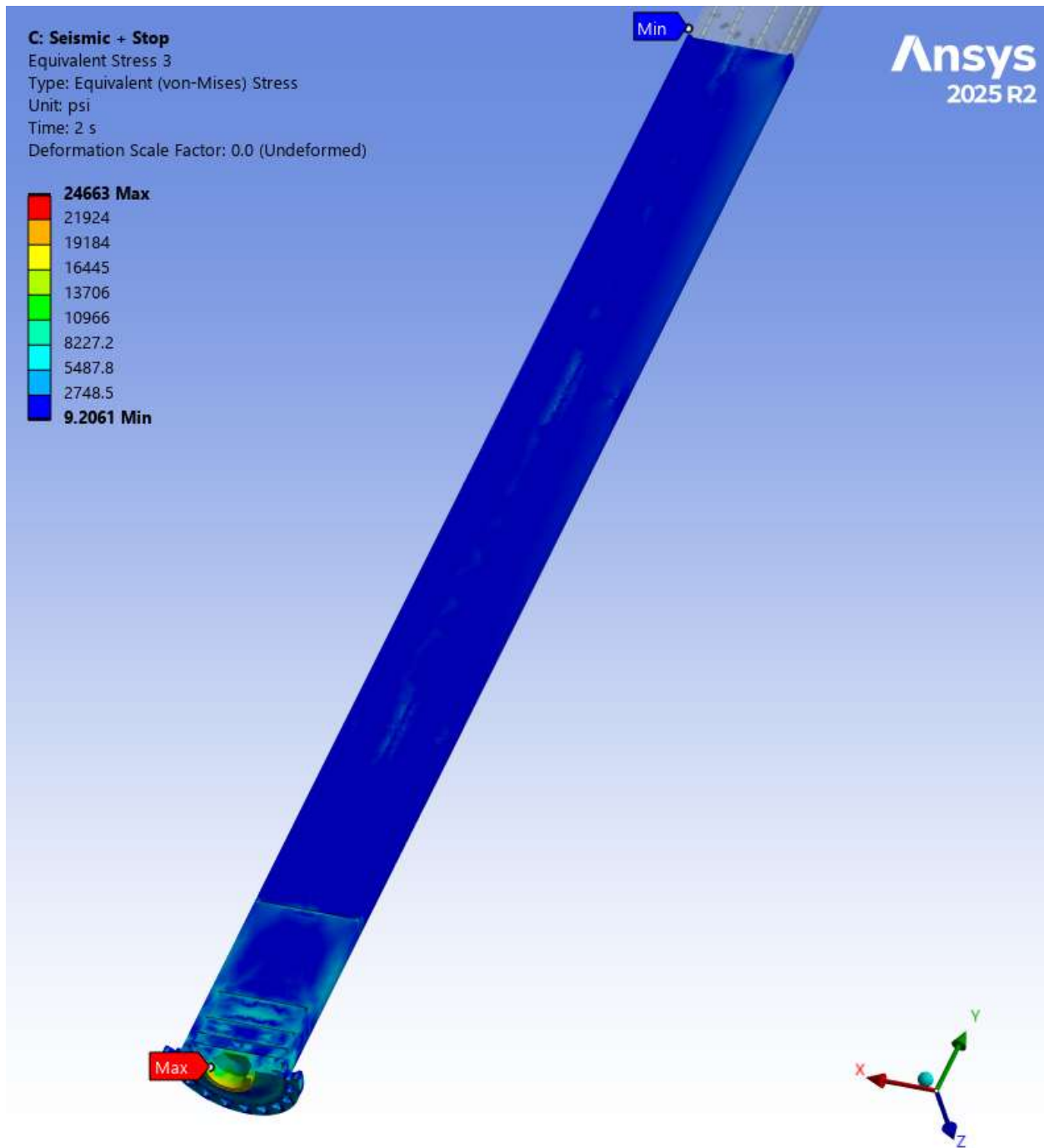


Figure 528 Shaft, Seismic + Stop Equivalent Stress

5.1.3.6 Contact Surfaces

Contact pressure from the surface interfaces are included for reference.

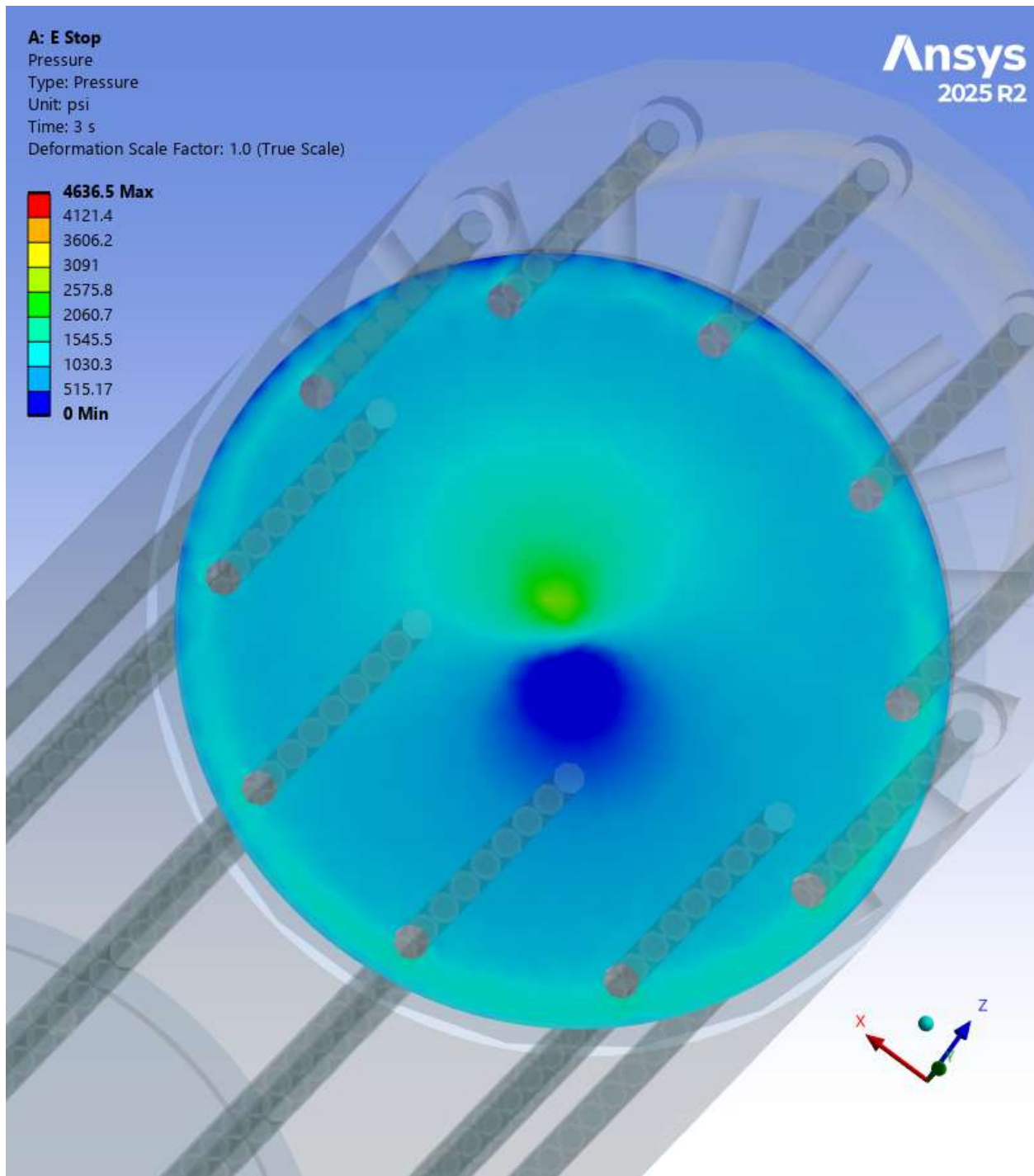


Figure 529 Shaft, E Stop Crown to Shaft Surface Pressure

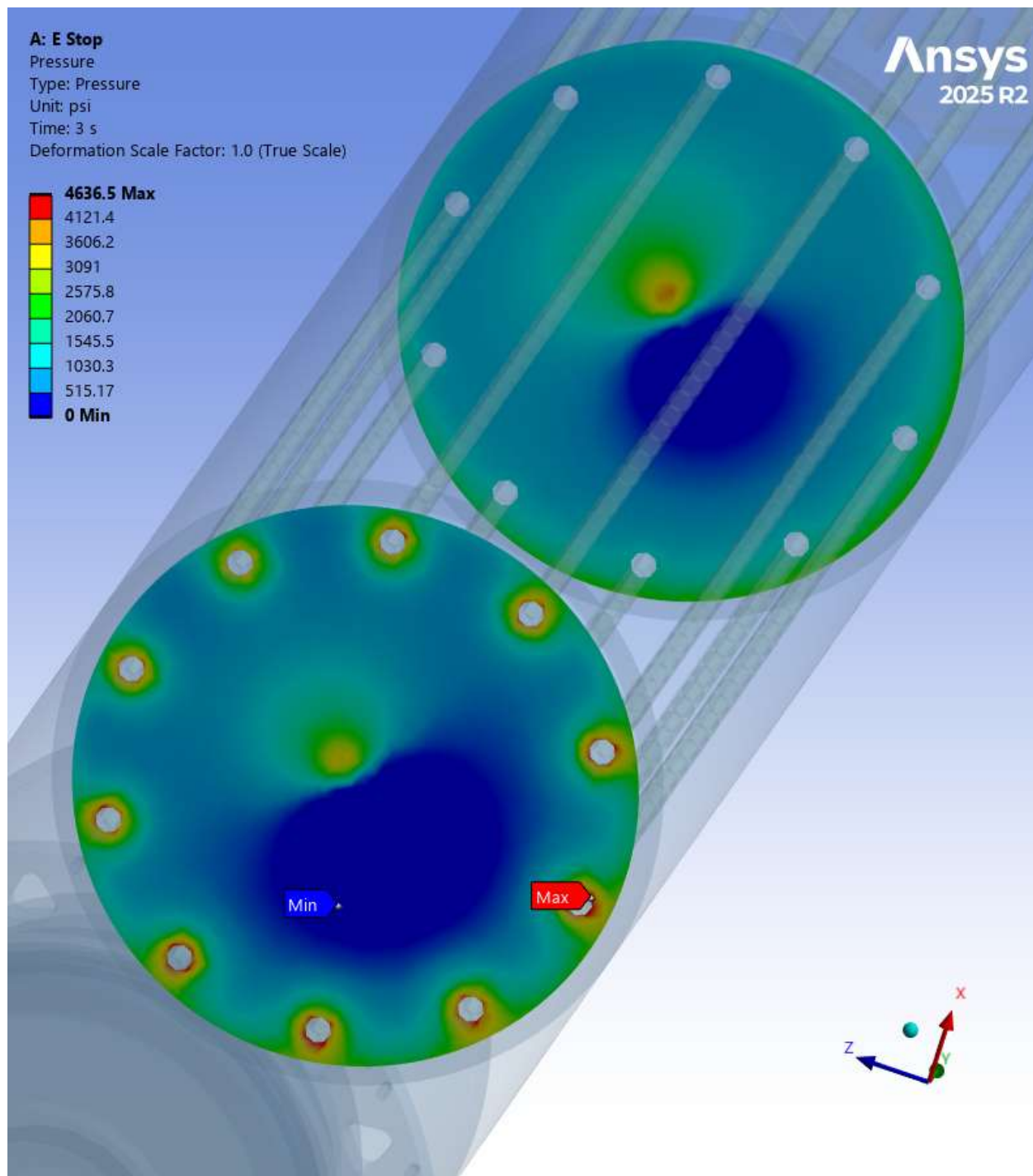


Figure 530 Shaft, E Stop Shaft Interfaces Surface Pressure

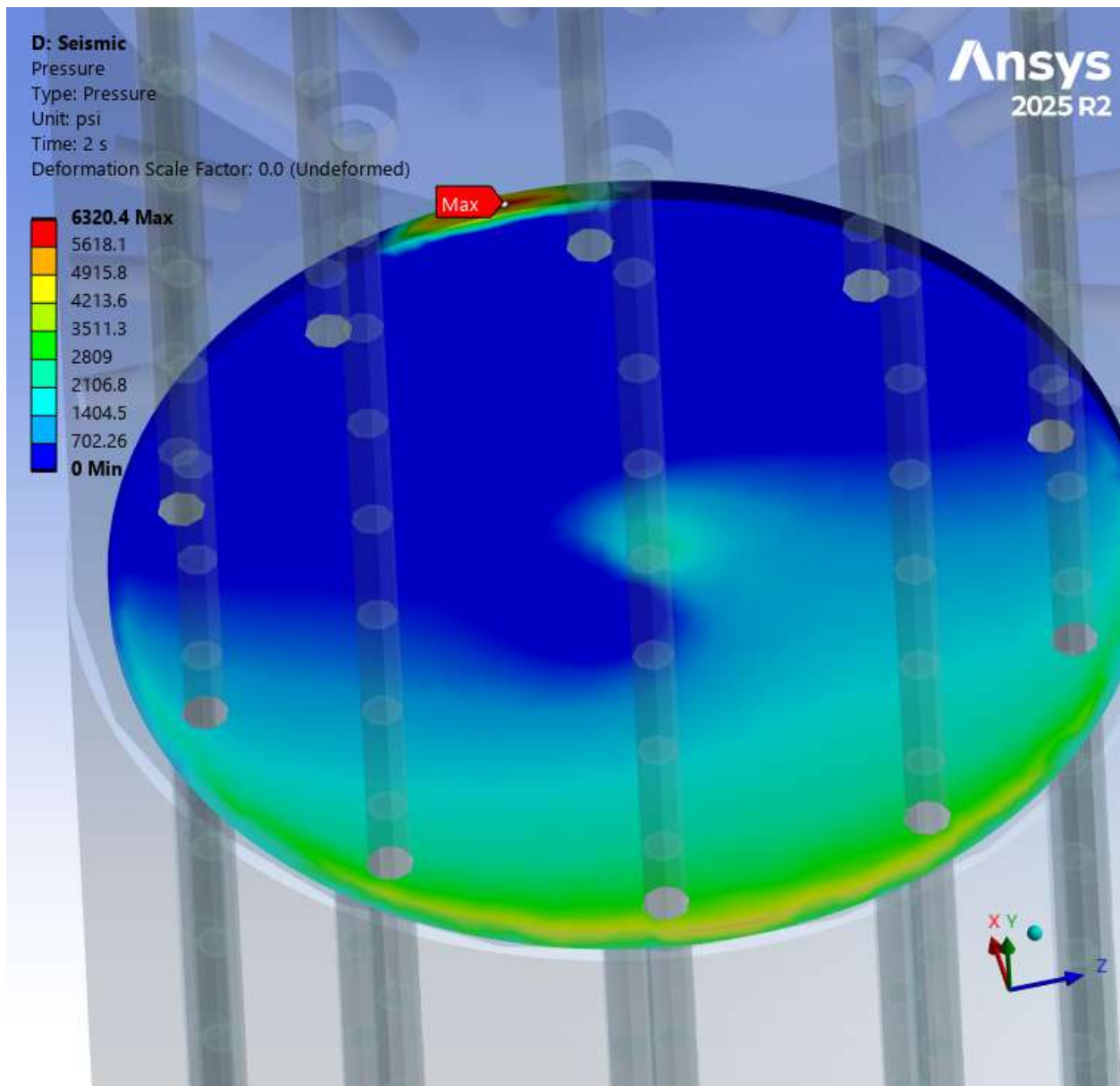


Figure 531 Shaft, Seismic Crown to Shaft Surface Pressure

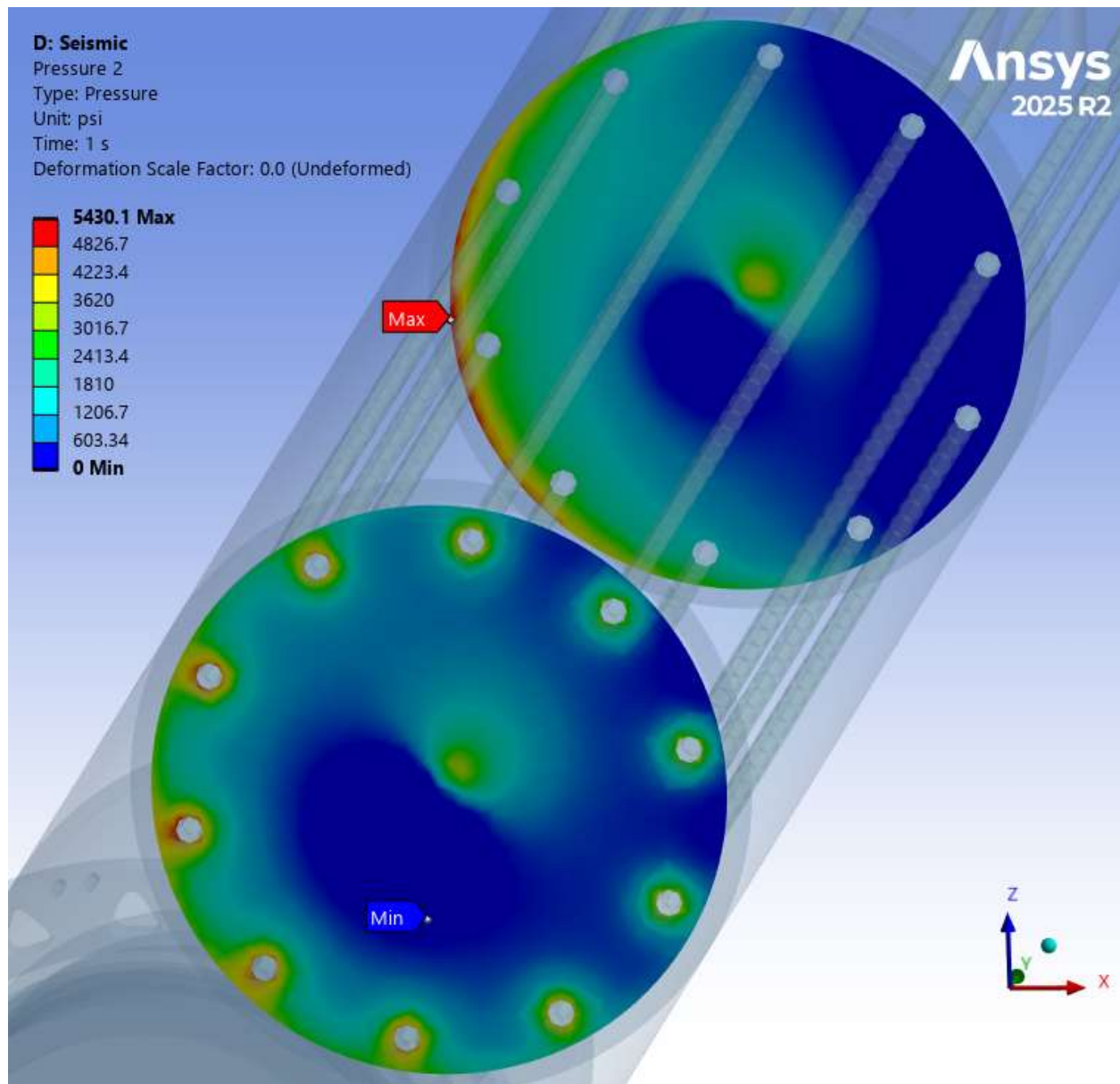


Figure 532 Shaft, Seismic Shaft Interfaces Surface Pressure

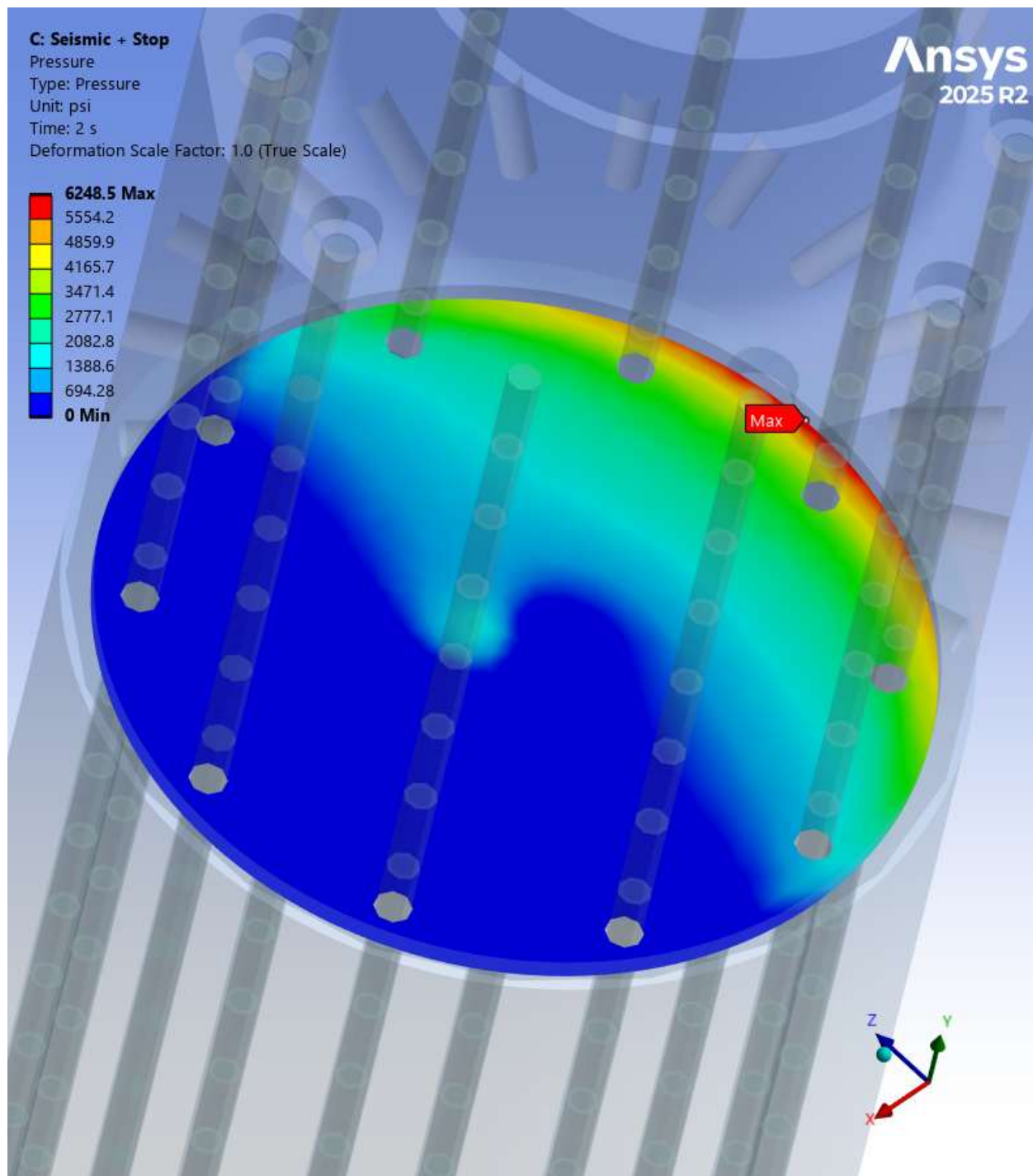


Figure 533 Shaft, Seismic + Stop Crown to Shaft Surface Pressure

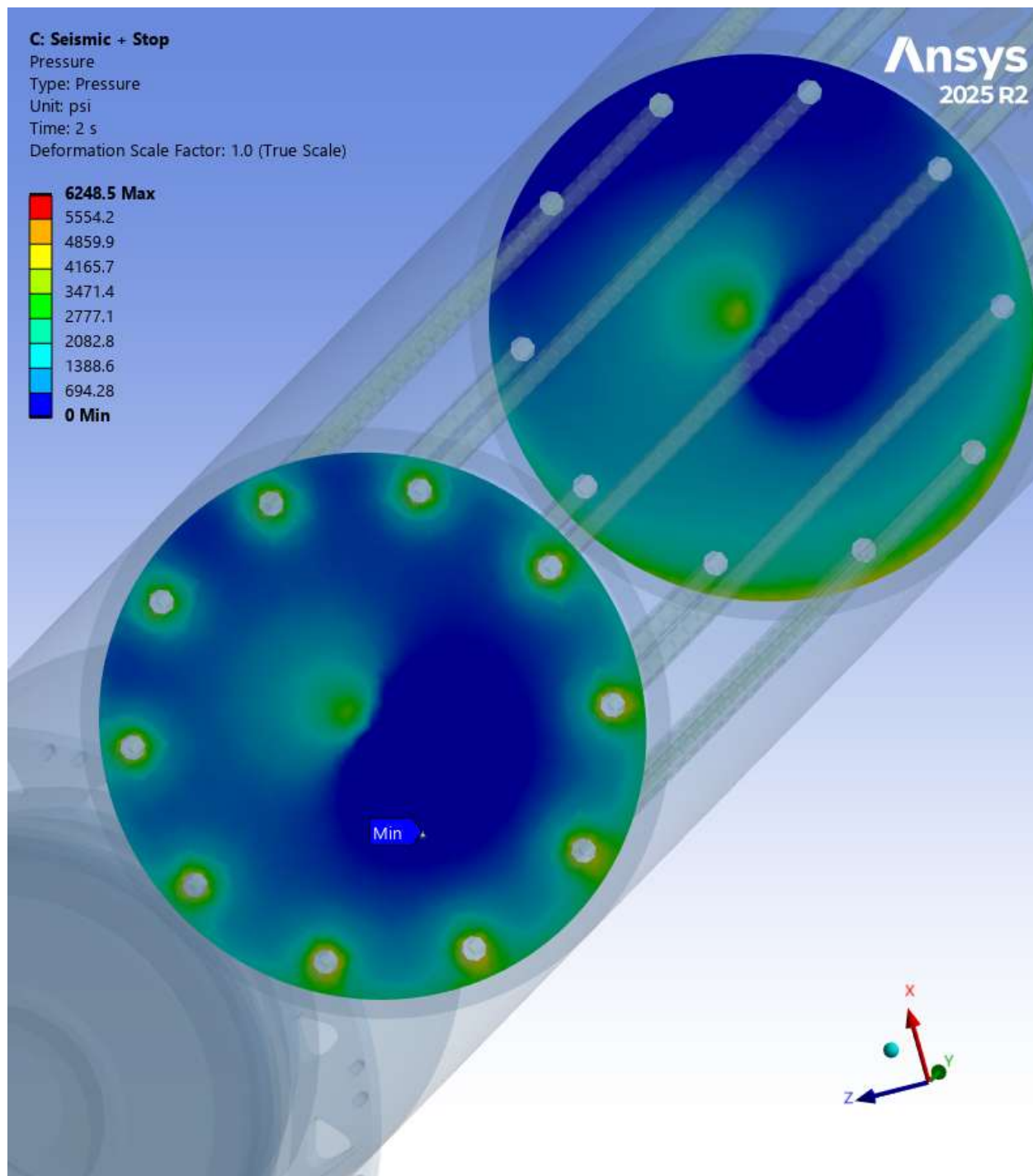


Figure 534 Shaft, Seismic + Stop Shaft Interfaces Surface Pressure

5.1.4 Crown and Drive

5.1.4.1 Plastic Ratcheting

5.1.4.1.1 E Stop Load Case

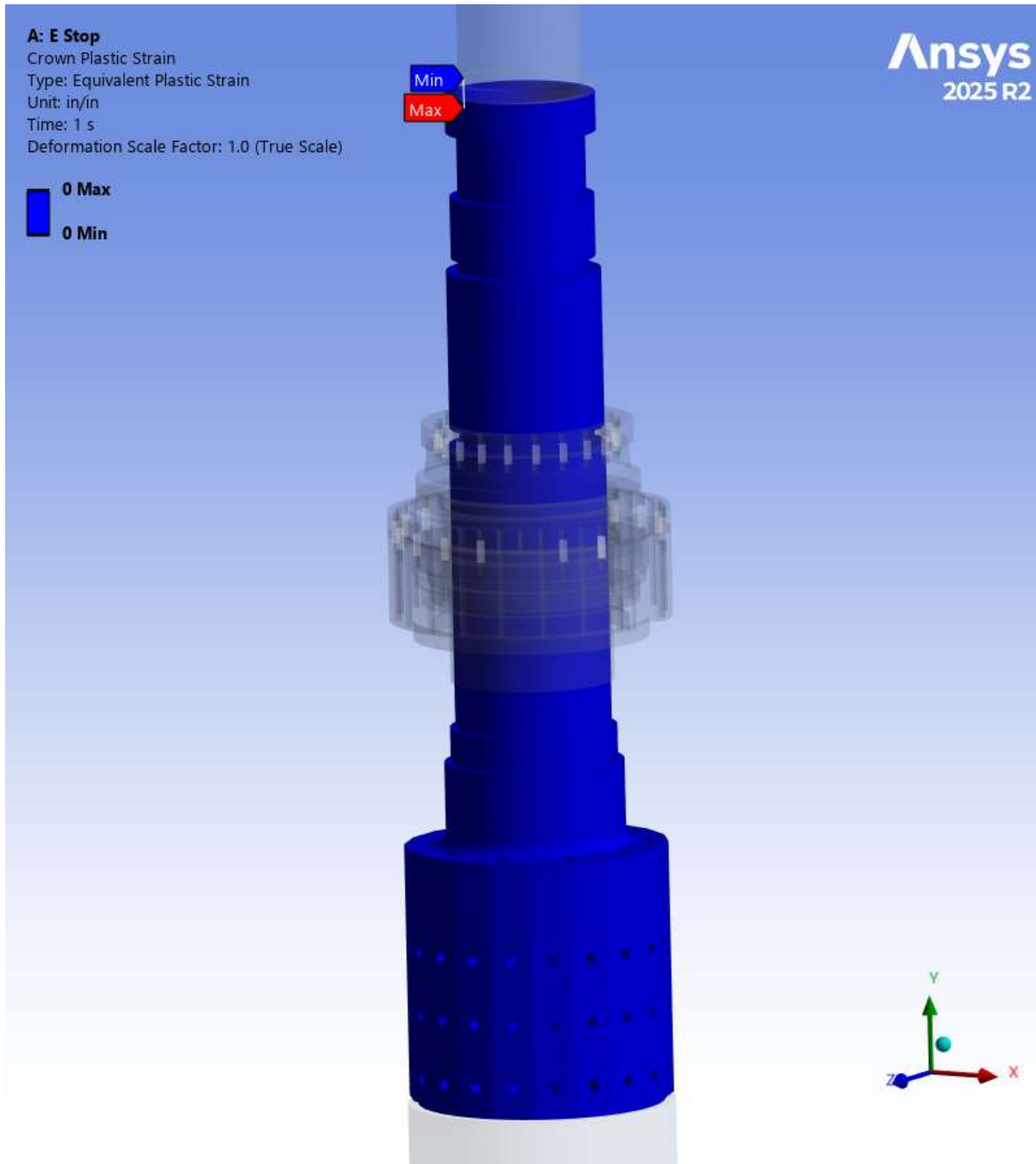


Figure 535 Crown and Drive, E Stop Equivalent Plastic Strain, Crown

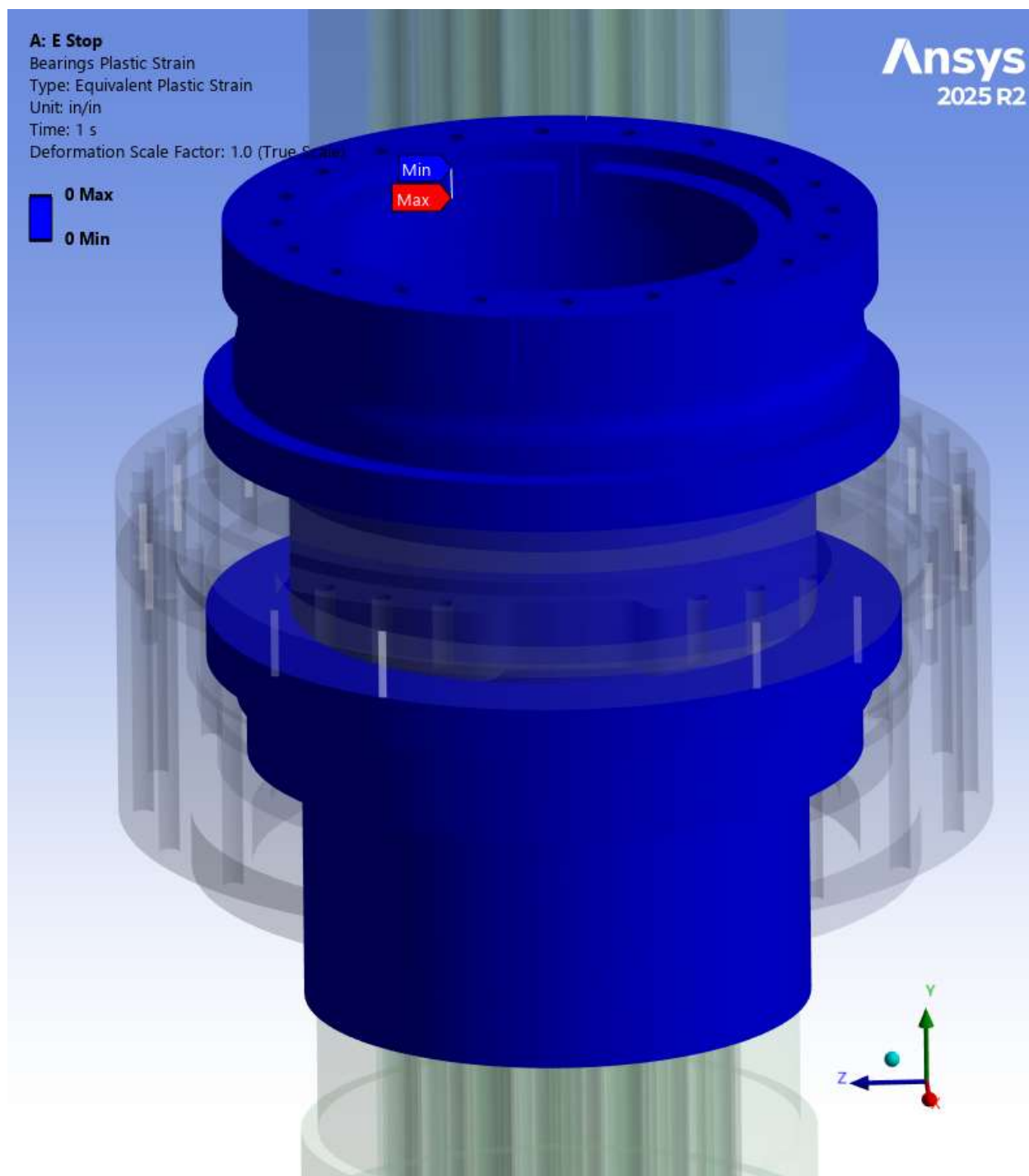


Figure 536 Crown and Drive, E Stop Equivalent Plastic Strain, Inner Components

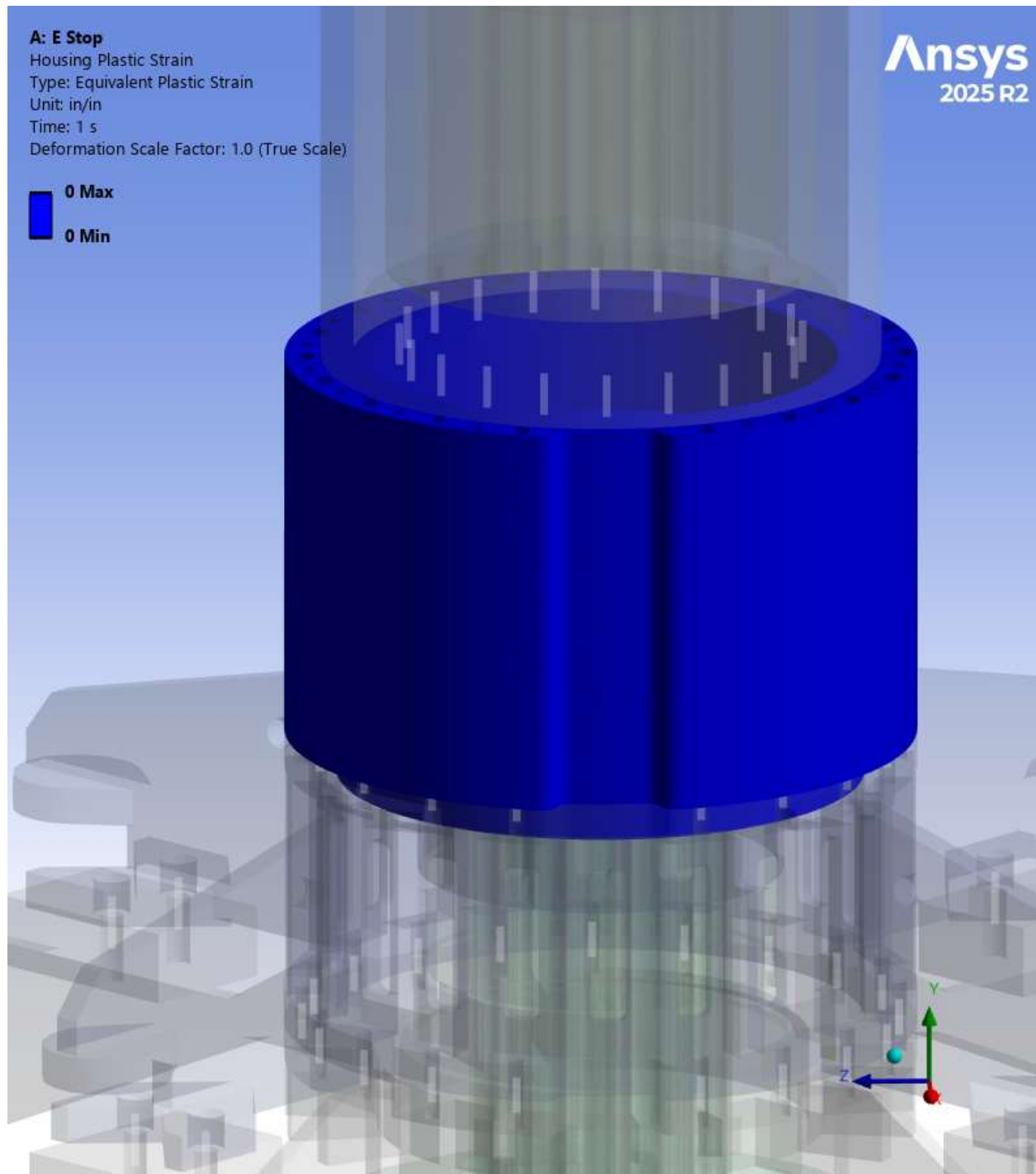


Figure 537 Crown and Drive, E Stop Equivalent Plastic Strain, Outer Housing

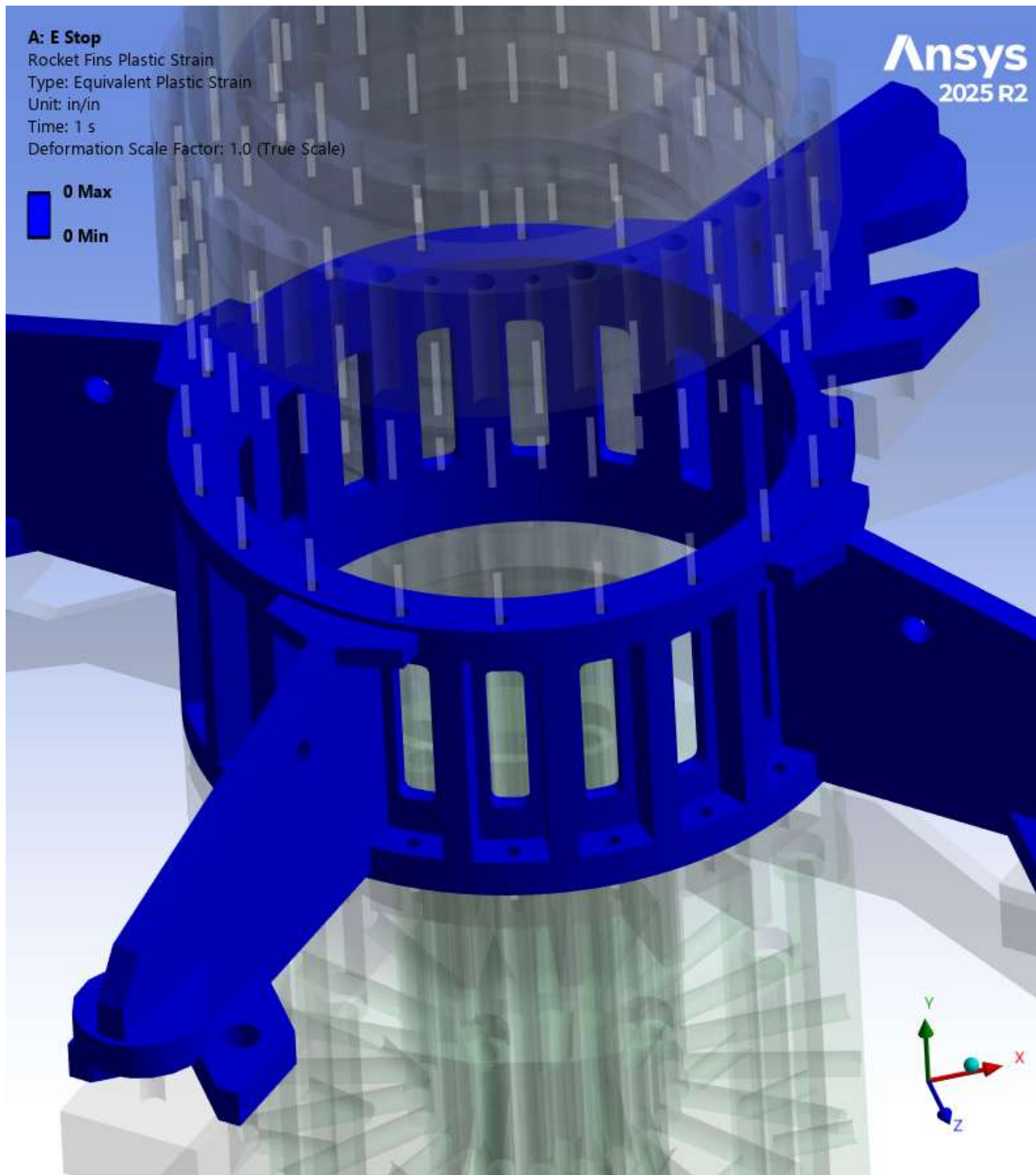


Figure 538 Crown and Drive, E Stop Equivalent Plastic Strain, Rocket Fins

5.1.4.1.2 Seismic Load Case

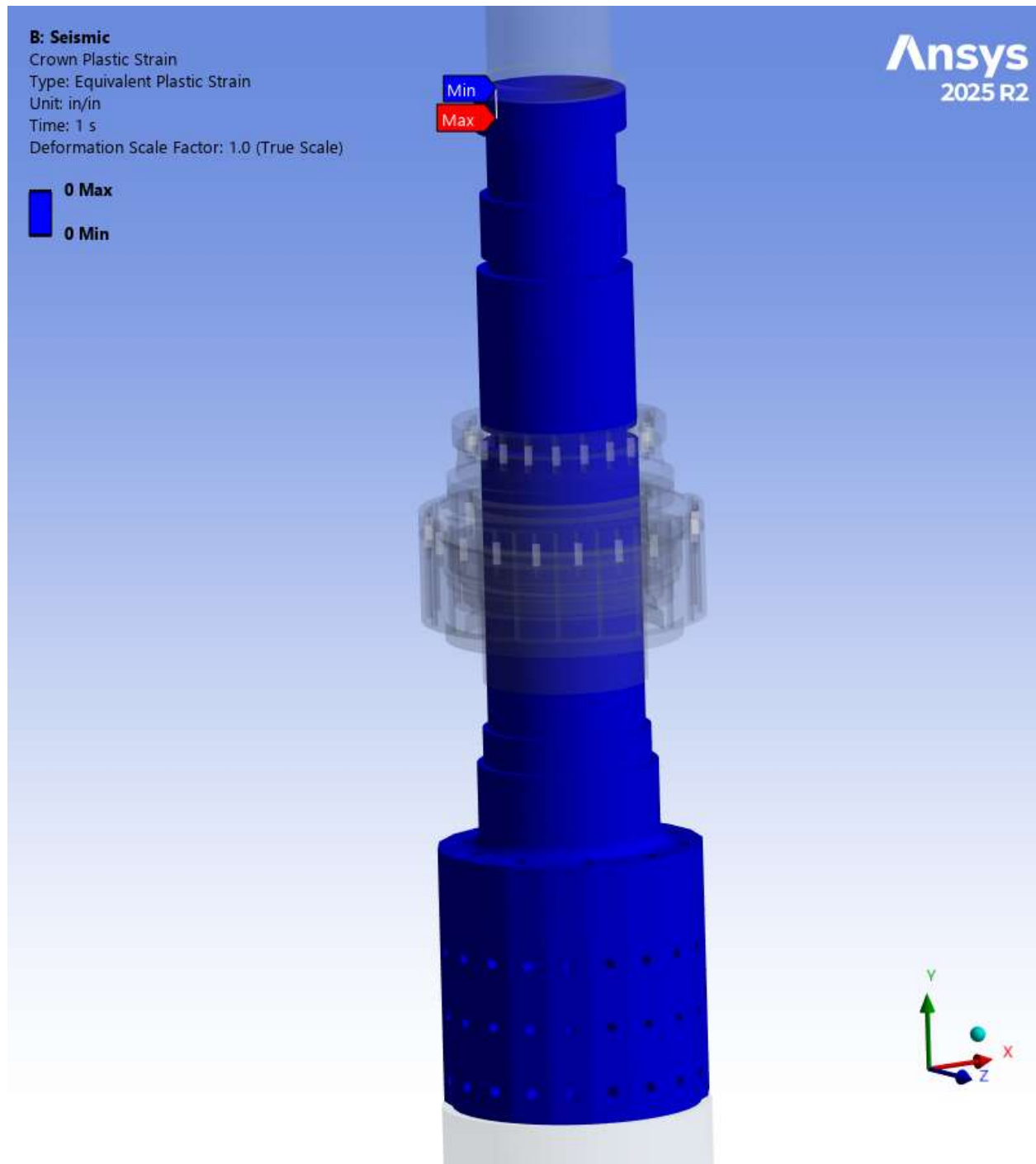


Figure 539 Crown and Drive, Seismic Equivalent Plastic Strain, Crown

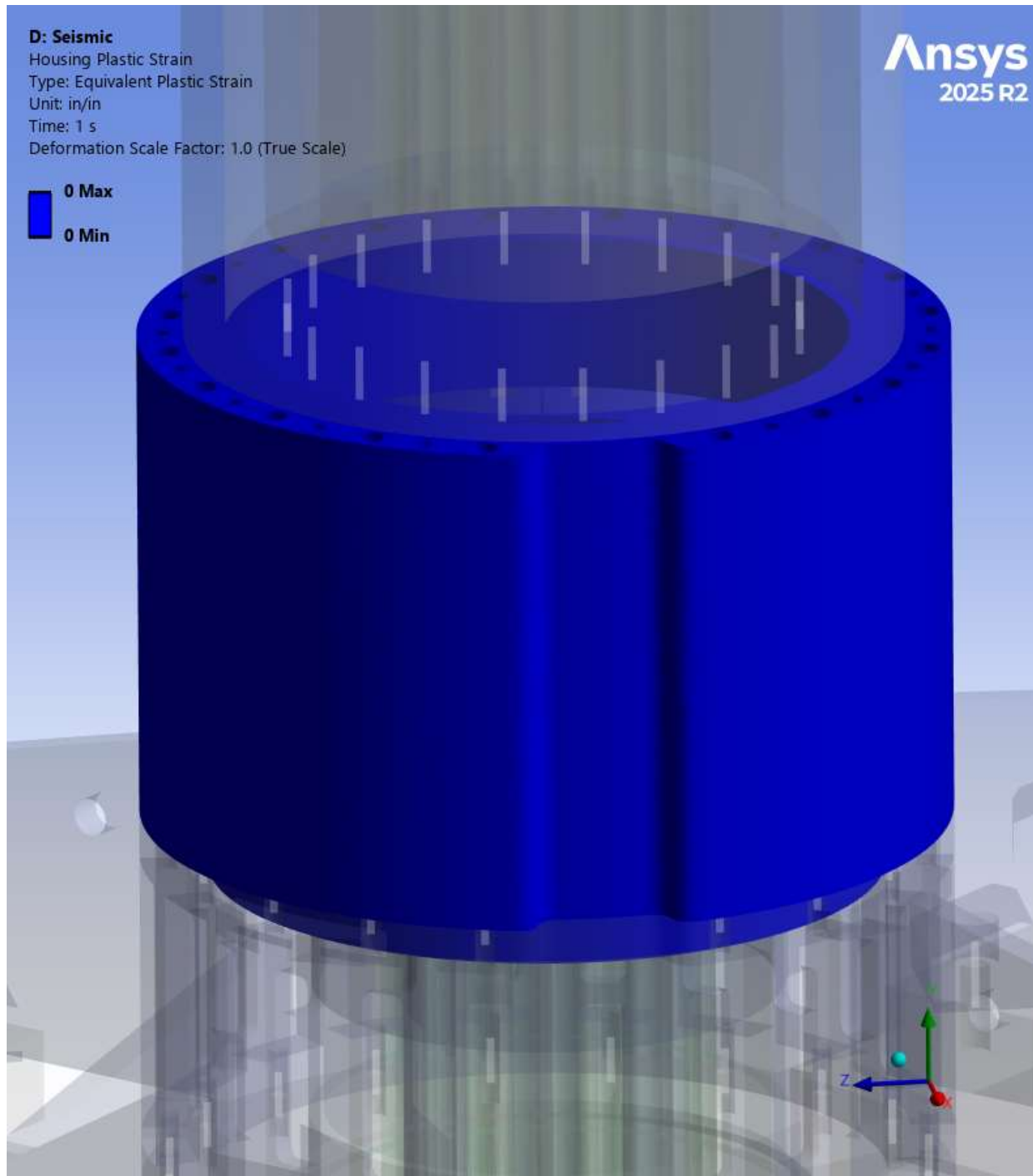


Figure 541 Crown and Drive, Seismic Equivalent Plastic Strain, Outer Housing

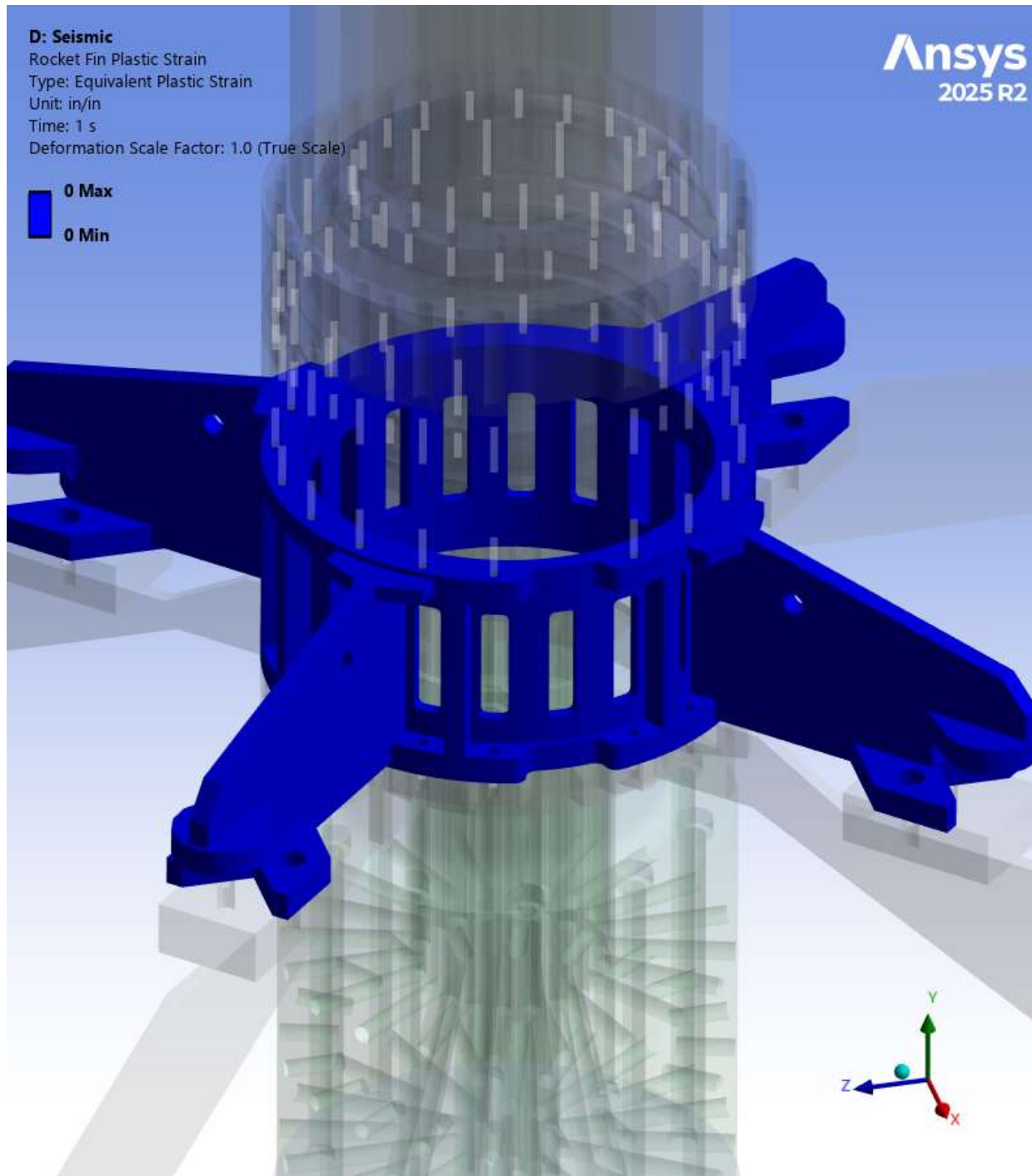


Figure 542 Crown and Drive, Seismic Equivalent Plastic Strain, Rocket Fins

5.1.4.1.3 Seismic + Stop Load Case

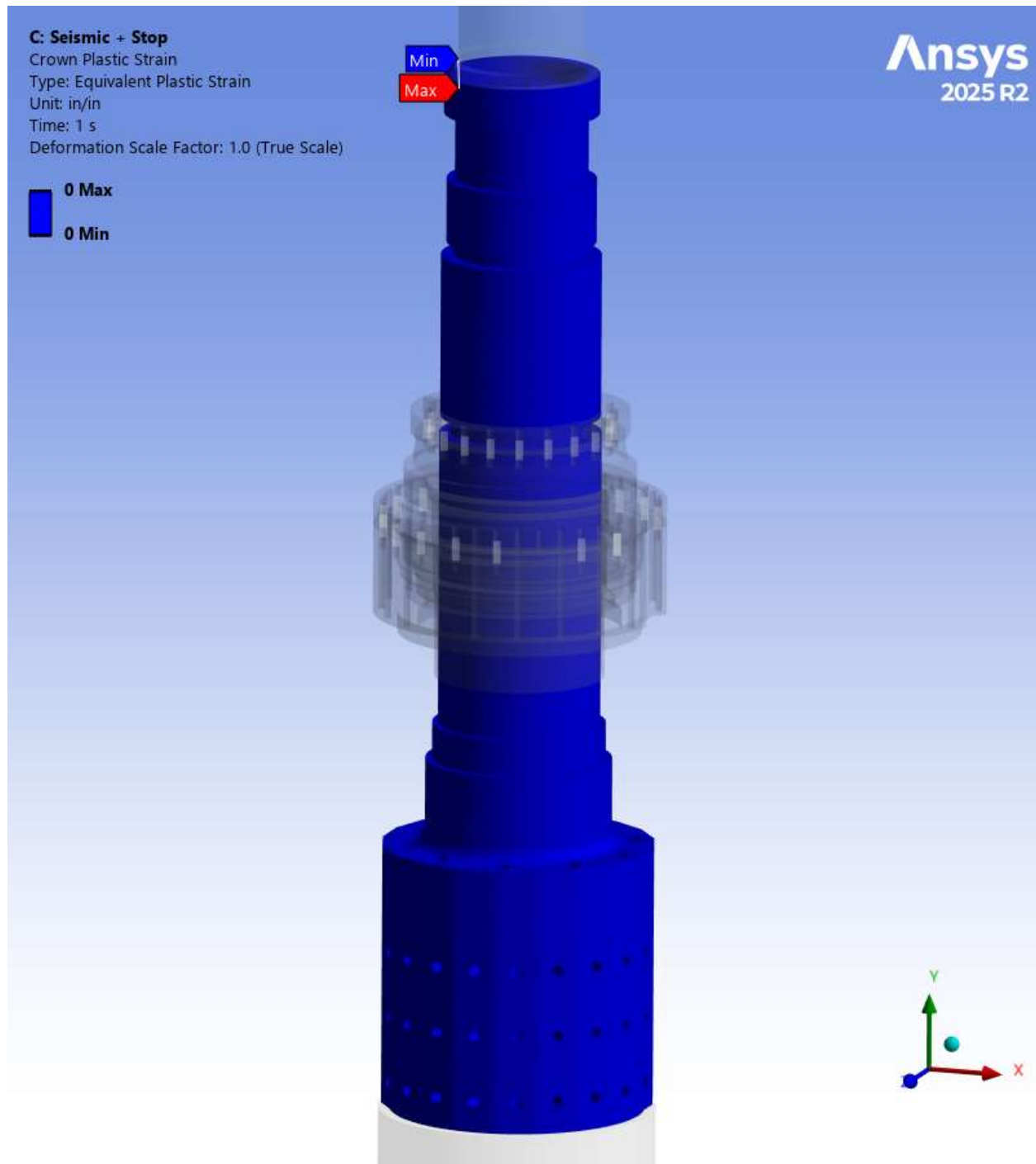


Figure 543 Crown and Drive, Seismic + Stop Equivalent Plastic Strain, Crown

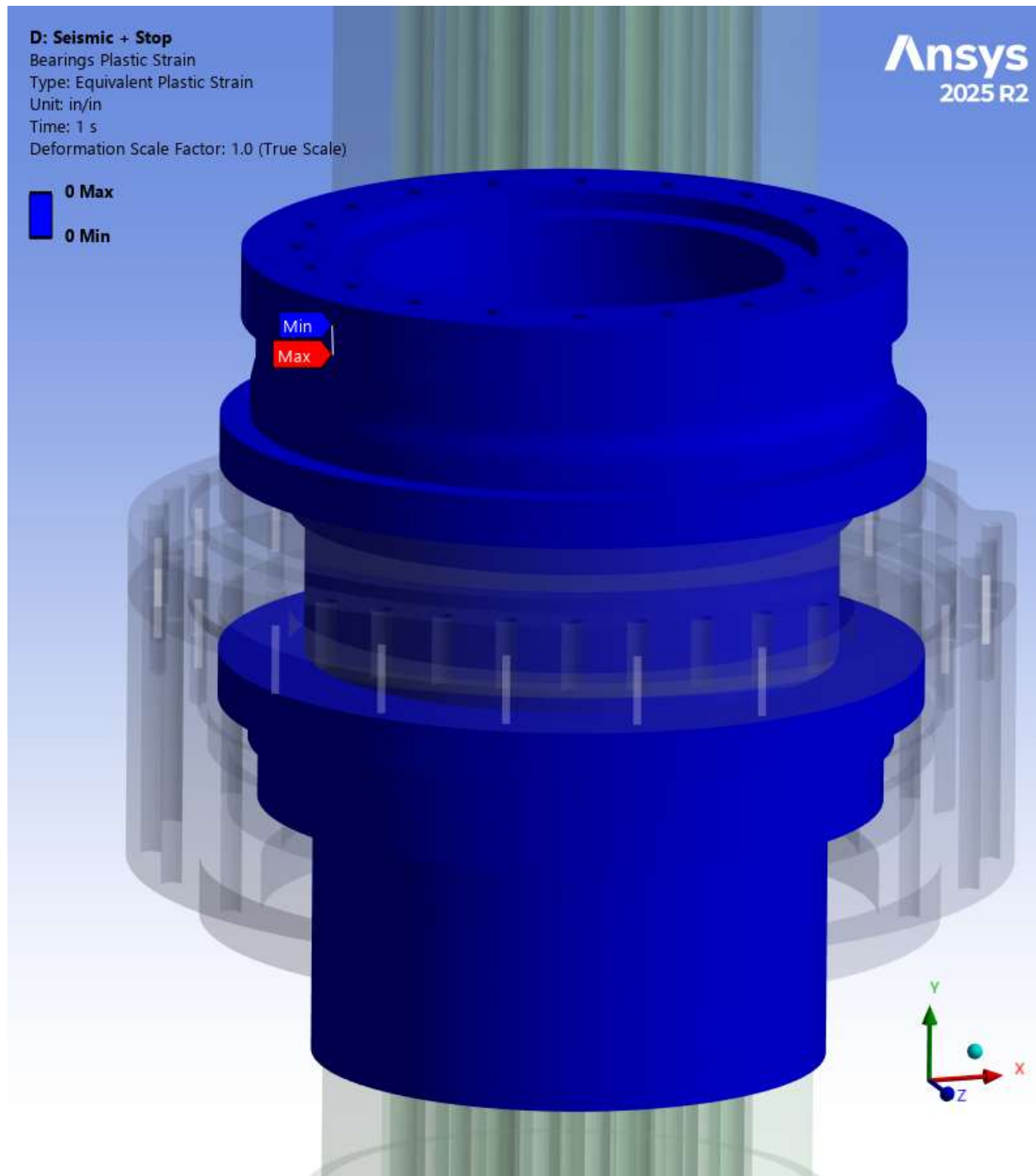


Figure 544 Crown and Drive, Seismic + Stop Equivalent Plastic Strain, Inner Components

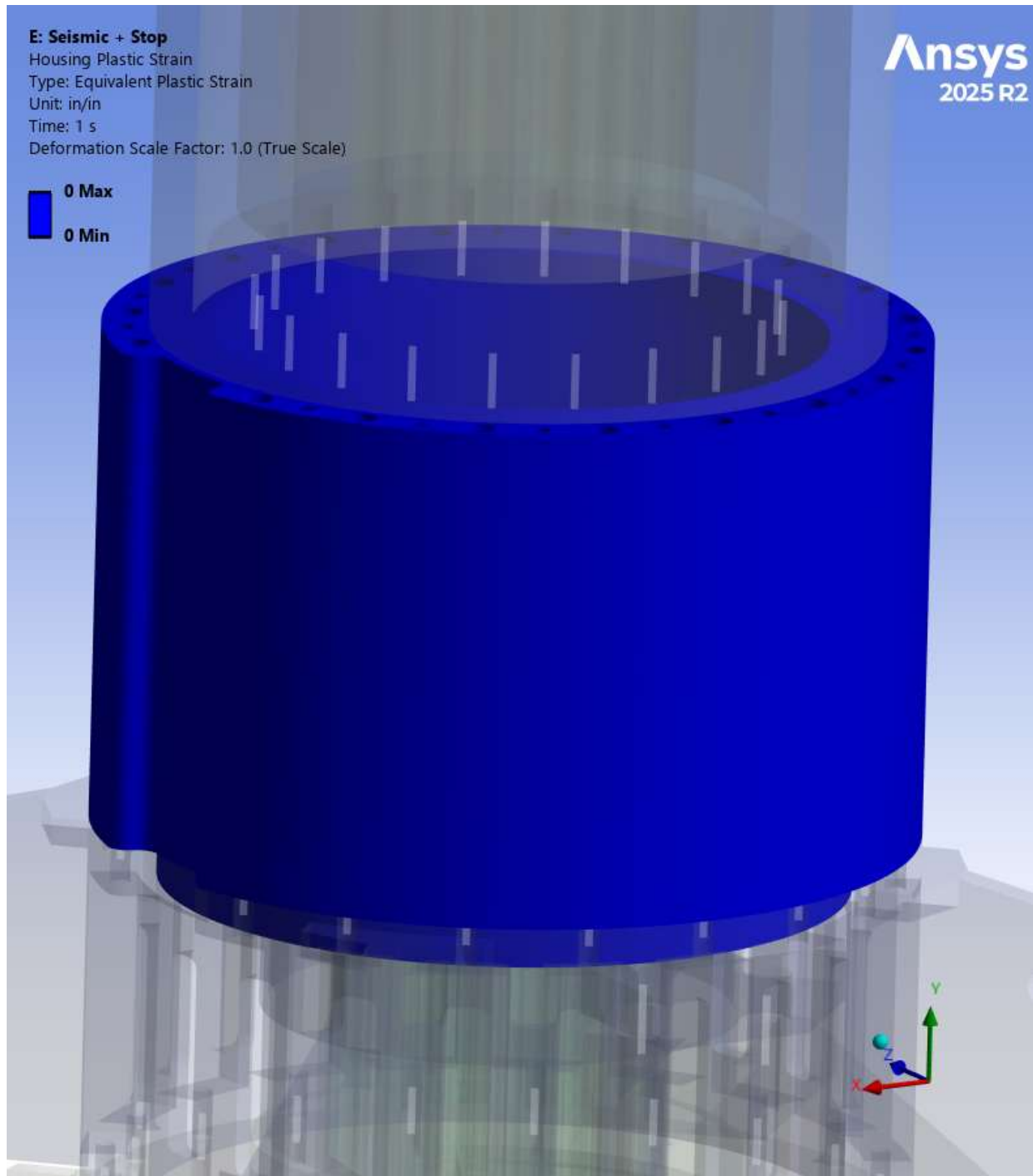


Figure 545 Crown and Drive, Seismic + Stop Equivalent Plastic Strain, Outer Housing

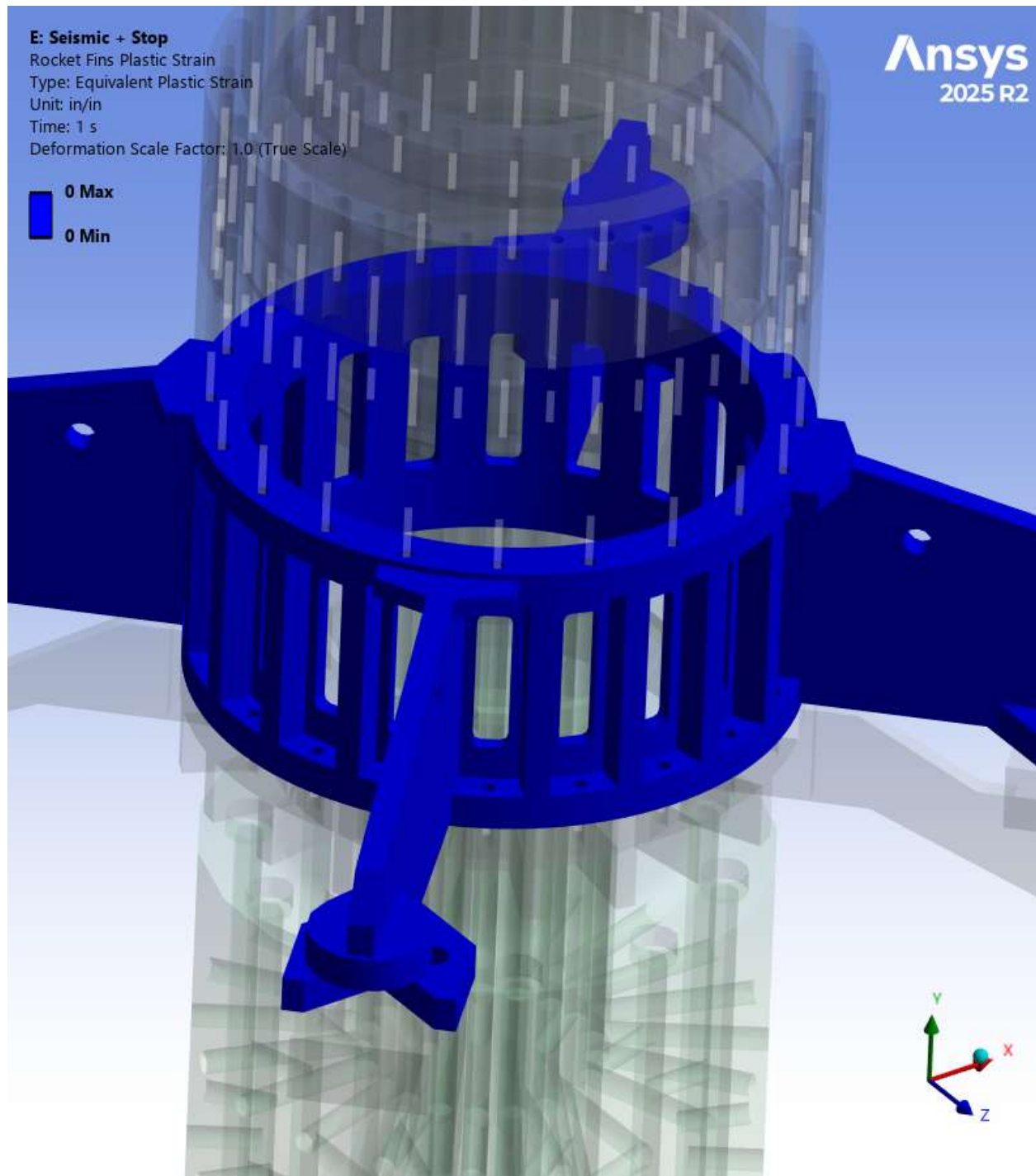


Figure 546 Crown and Drive, Seismic + Stop Equivalent Plastic Strain, Rocket Fins

5.1.4.2 Local Failure

5.1.4.2.1 Elastic Plastic Case 1

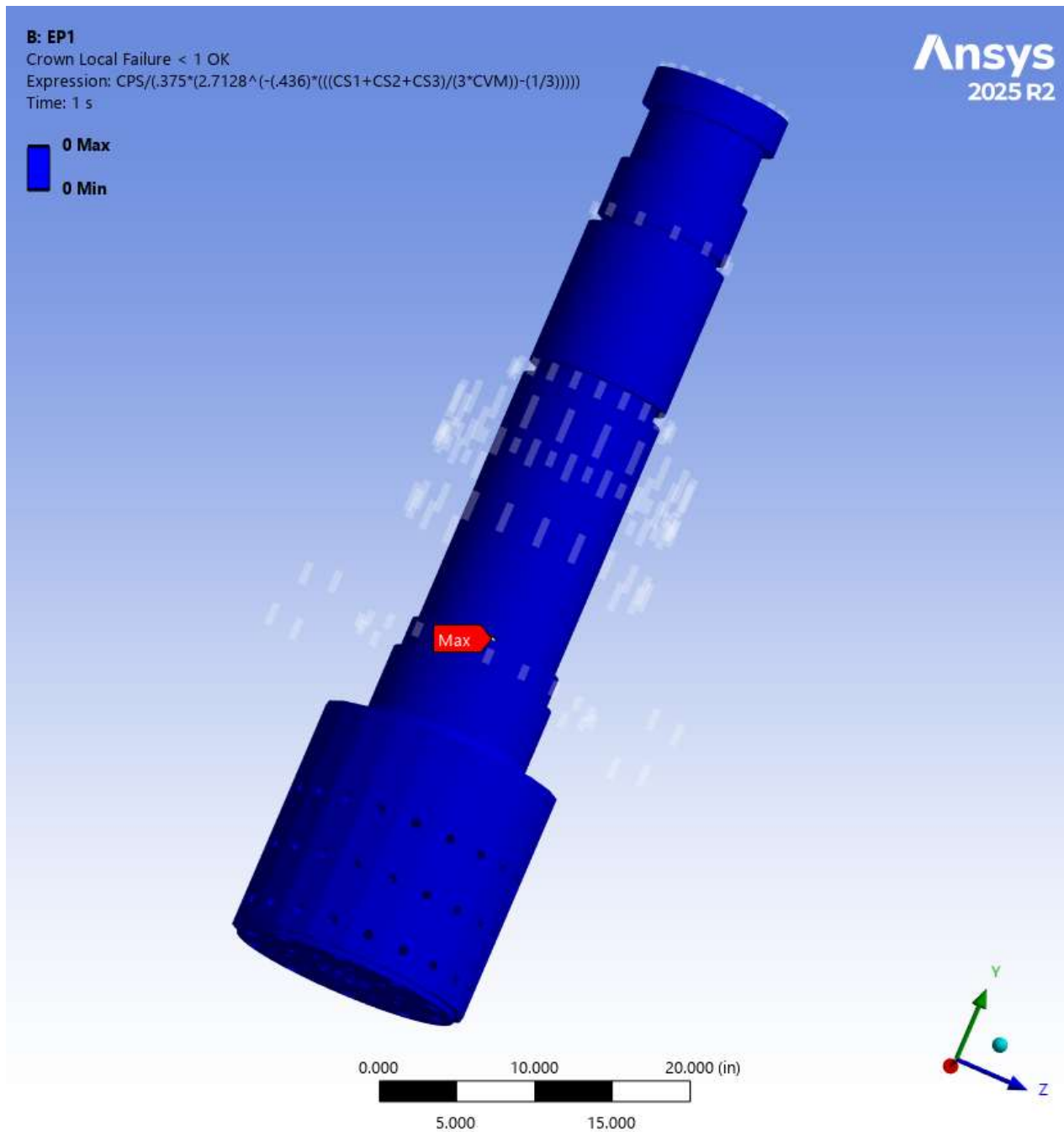


Figure 547 Crown and Drive, Elastic Plastic Case 1 Local Failure, Crown

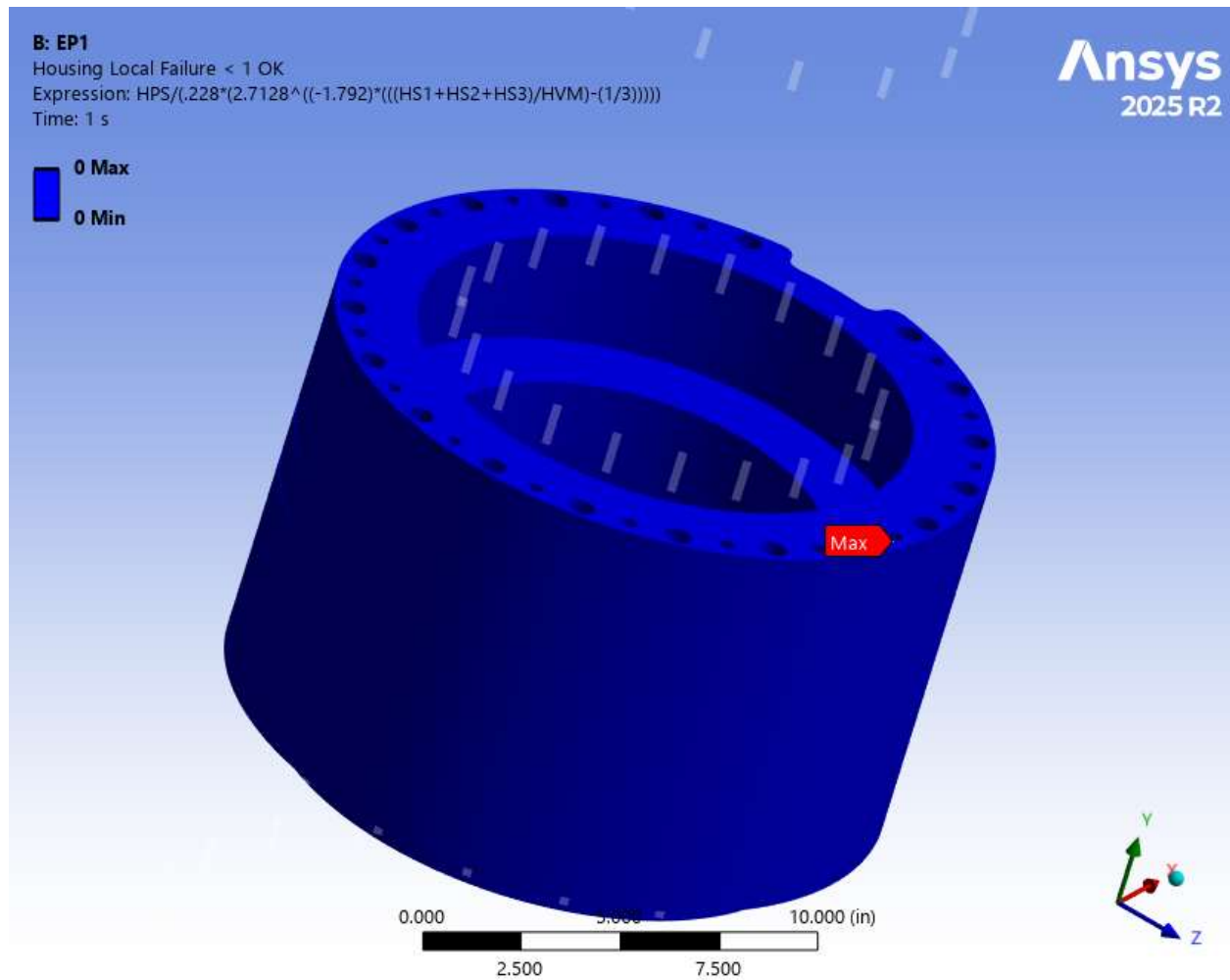


Figure 548 Crown and Drive, Elastic Plastic Case 1 Local Failure, Housing

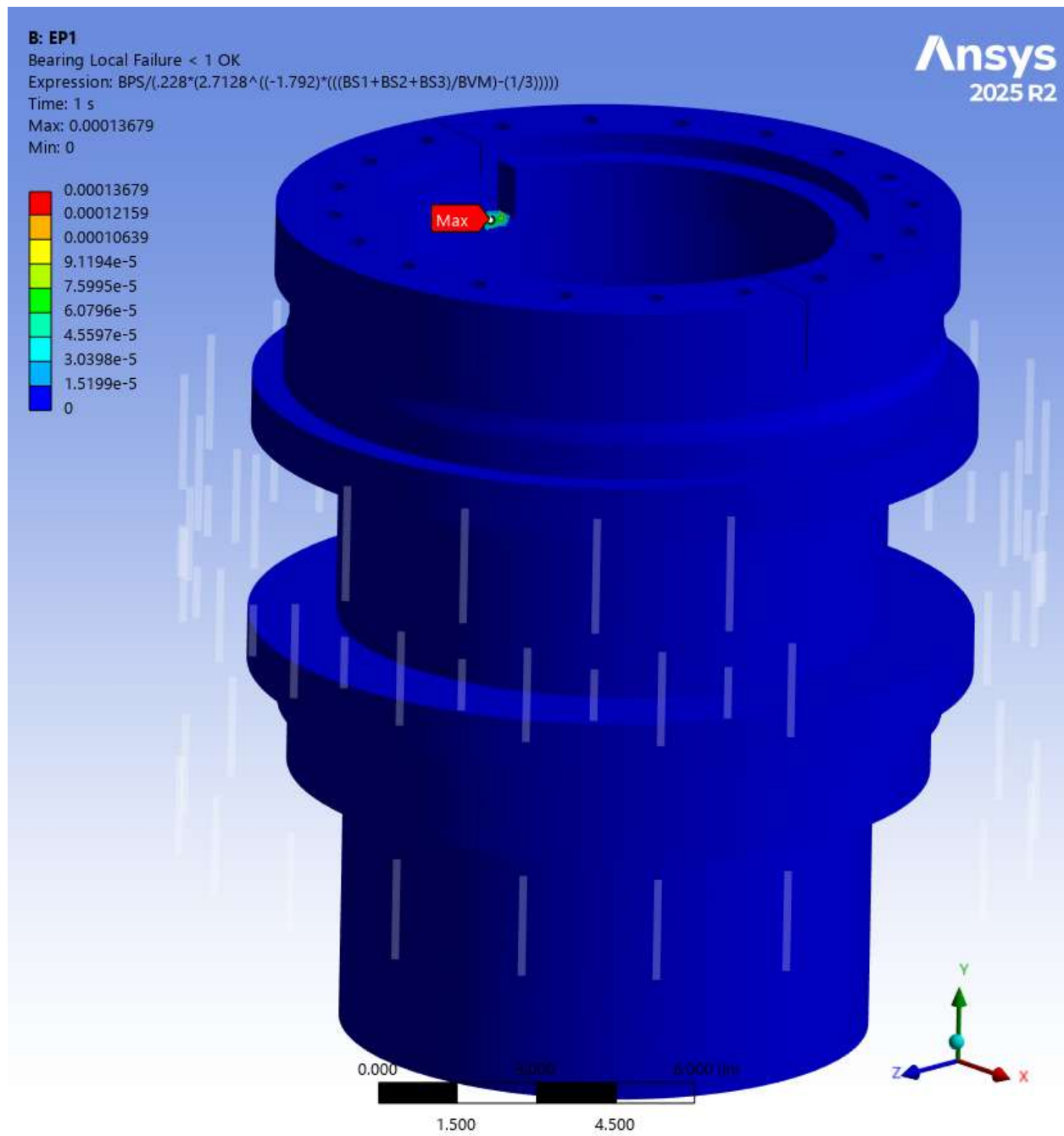


Figure 549 Crown and Drive, Elastic Plastic Case 1 Local Failure, Bearing Components

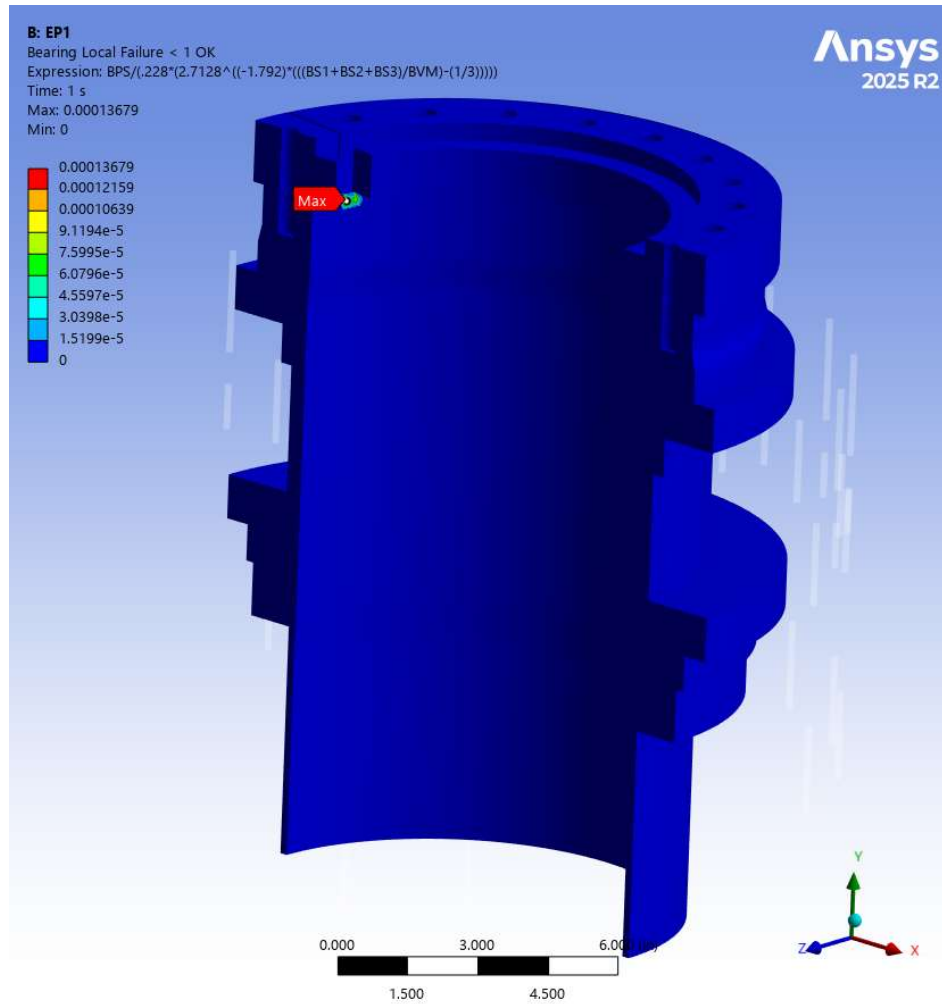


Figure 550 Crown and Drive, Elastic Plastic Case 1 Local Failure, Bearing Components

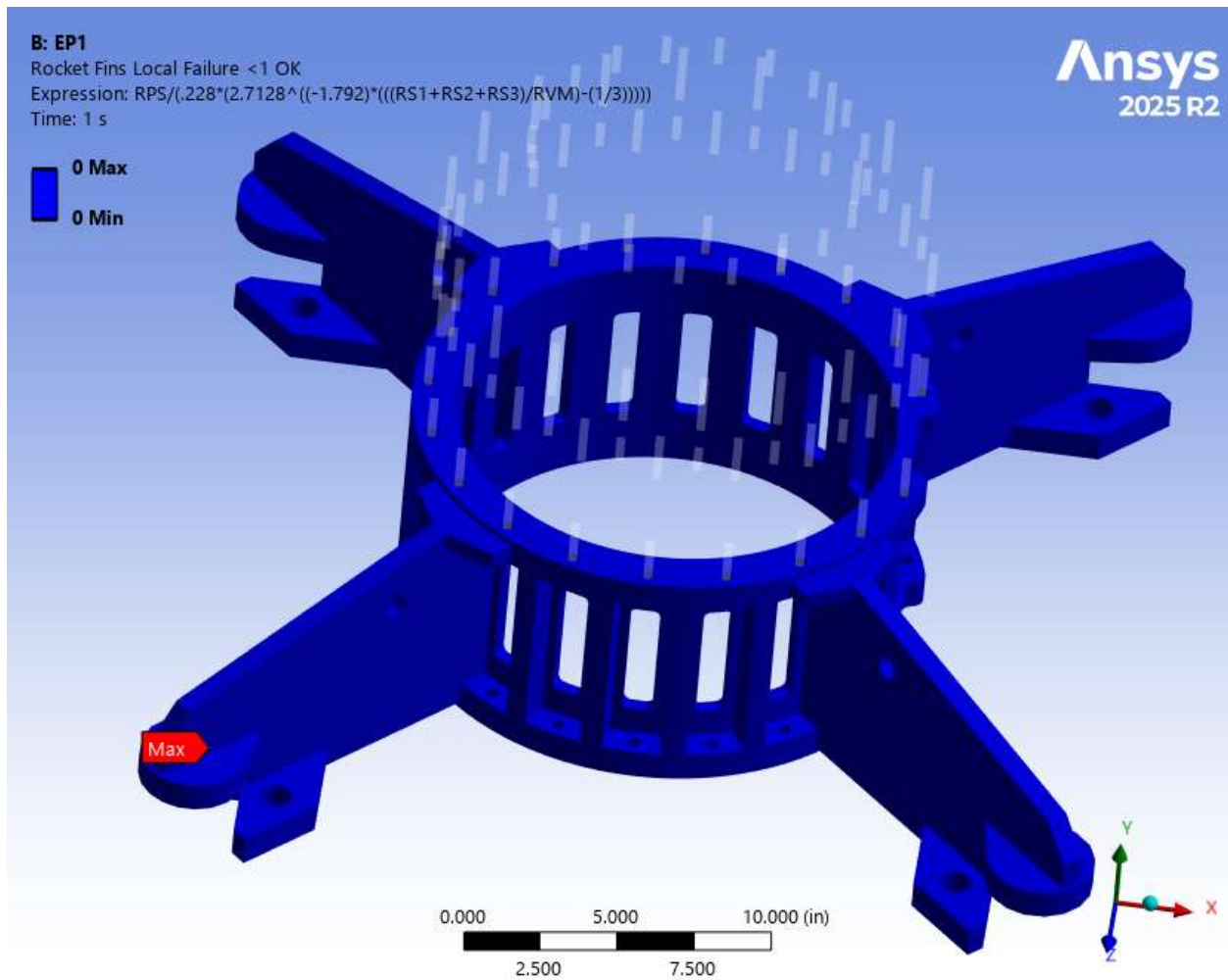


Figure 551 Crown and Drive, E Stop Local Failure, Rocket Fins

5.1.4.2.2 Elastic Plastic Case 2

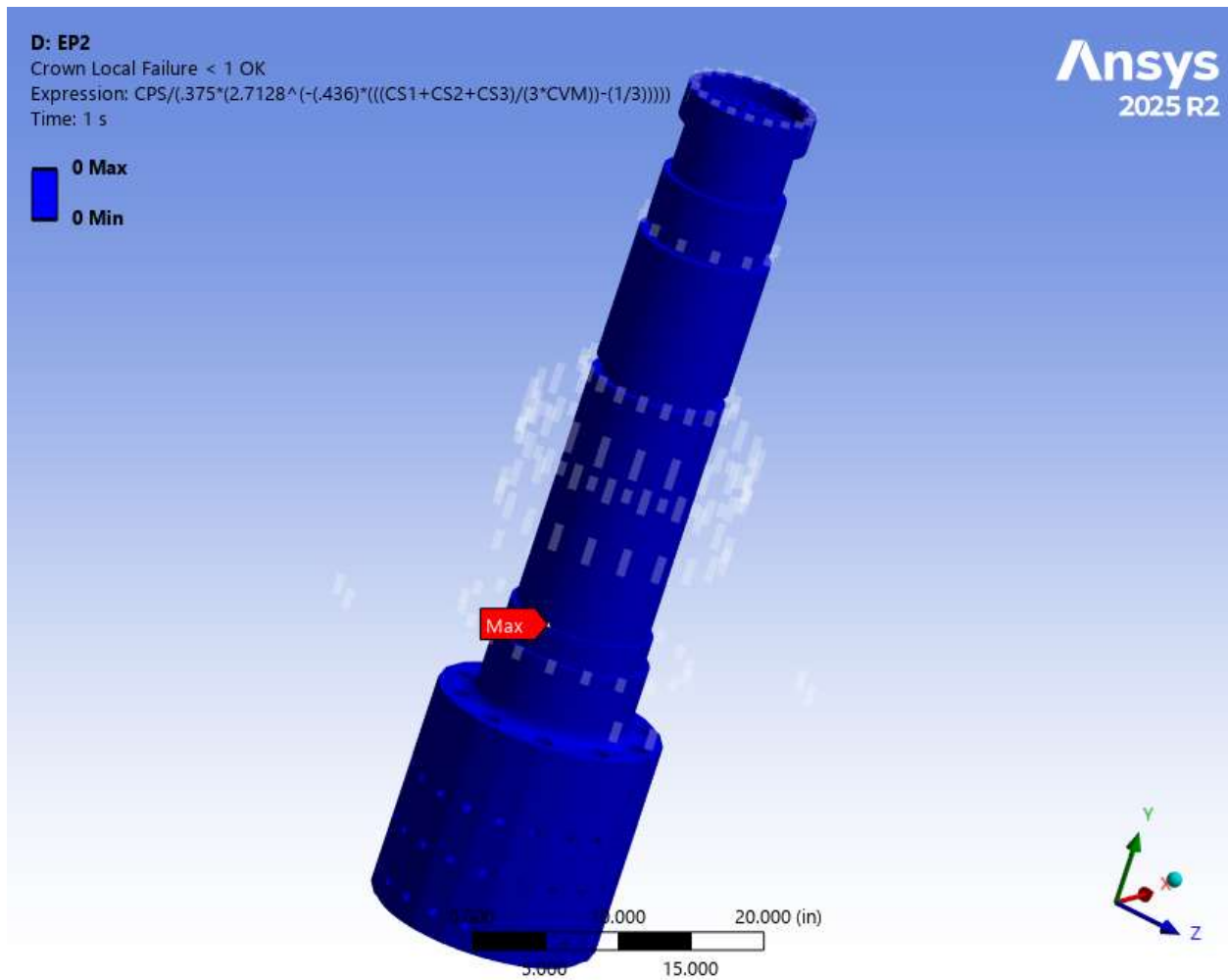


Figure 552 Crown and Drive, Elastic Plastic Case 2 Local Failure, Crown

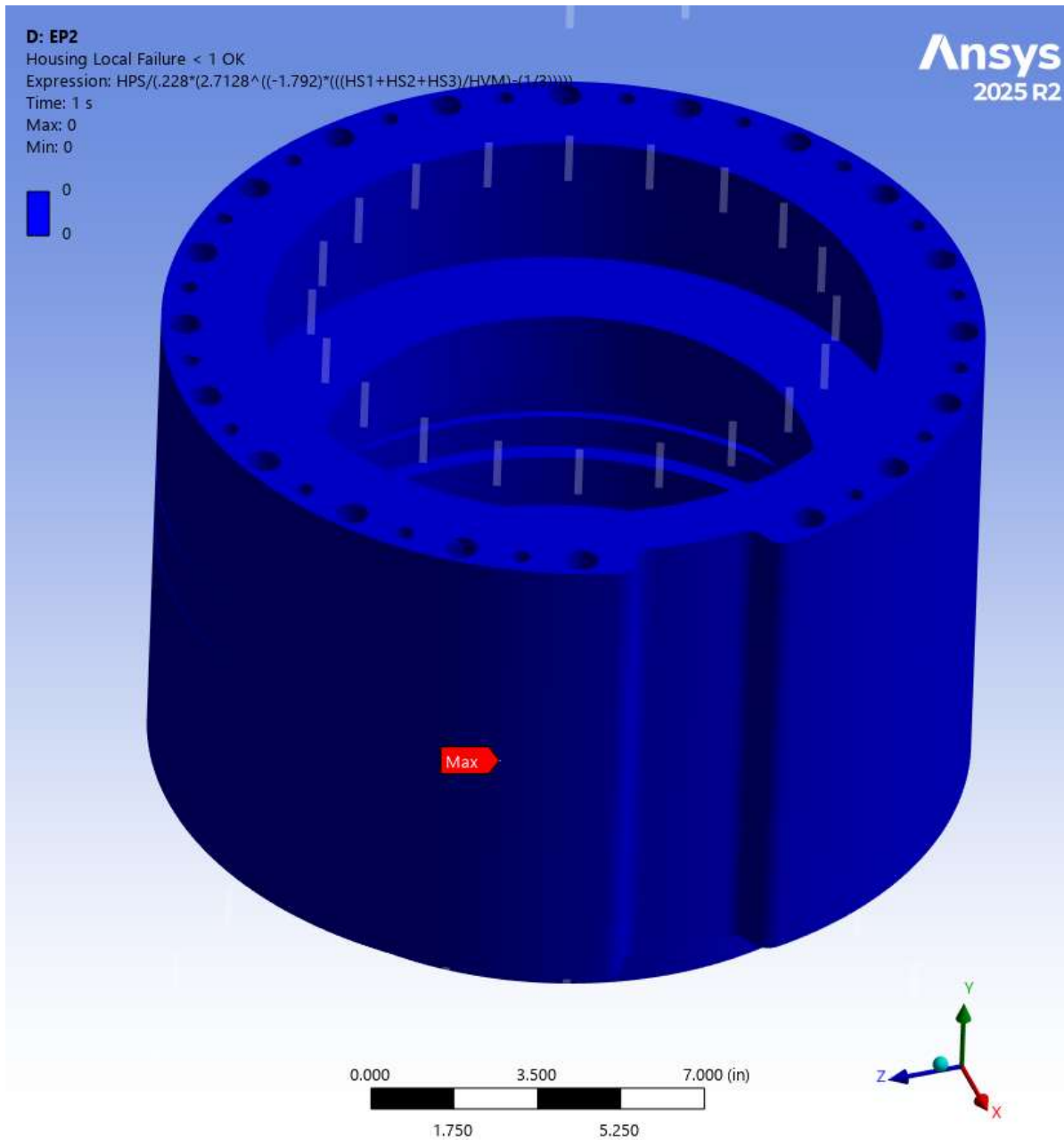


Figure 553 Crown and Drive, Elastic Plastic Case 2 Local Failure, Housing

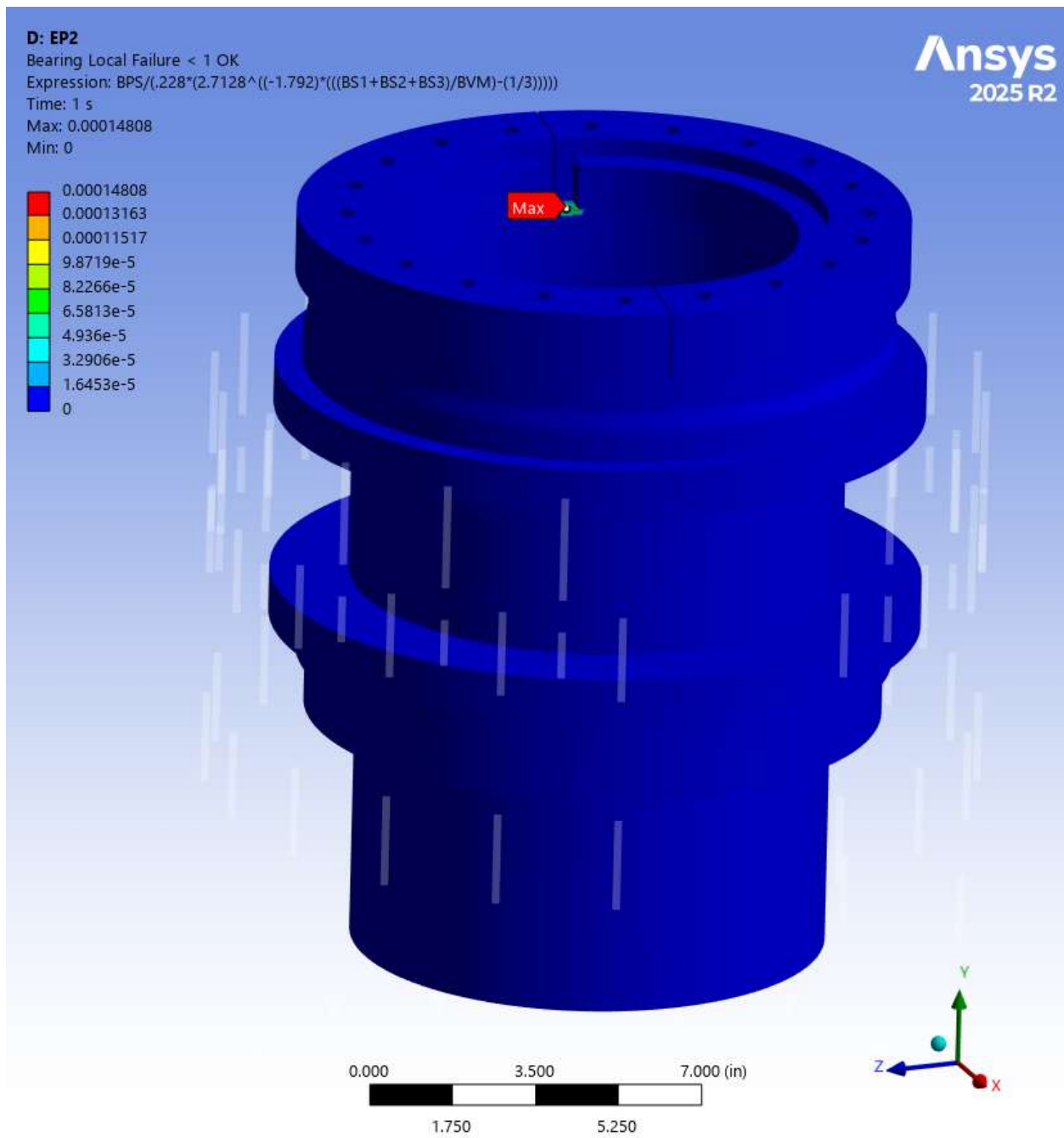


Figure 554 Crown and Drive, Elastic Plastic Case 2 Local Failure, Bearing Components

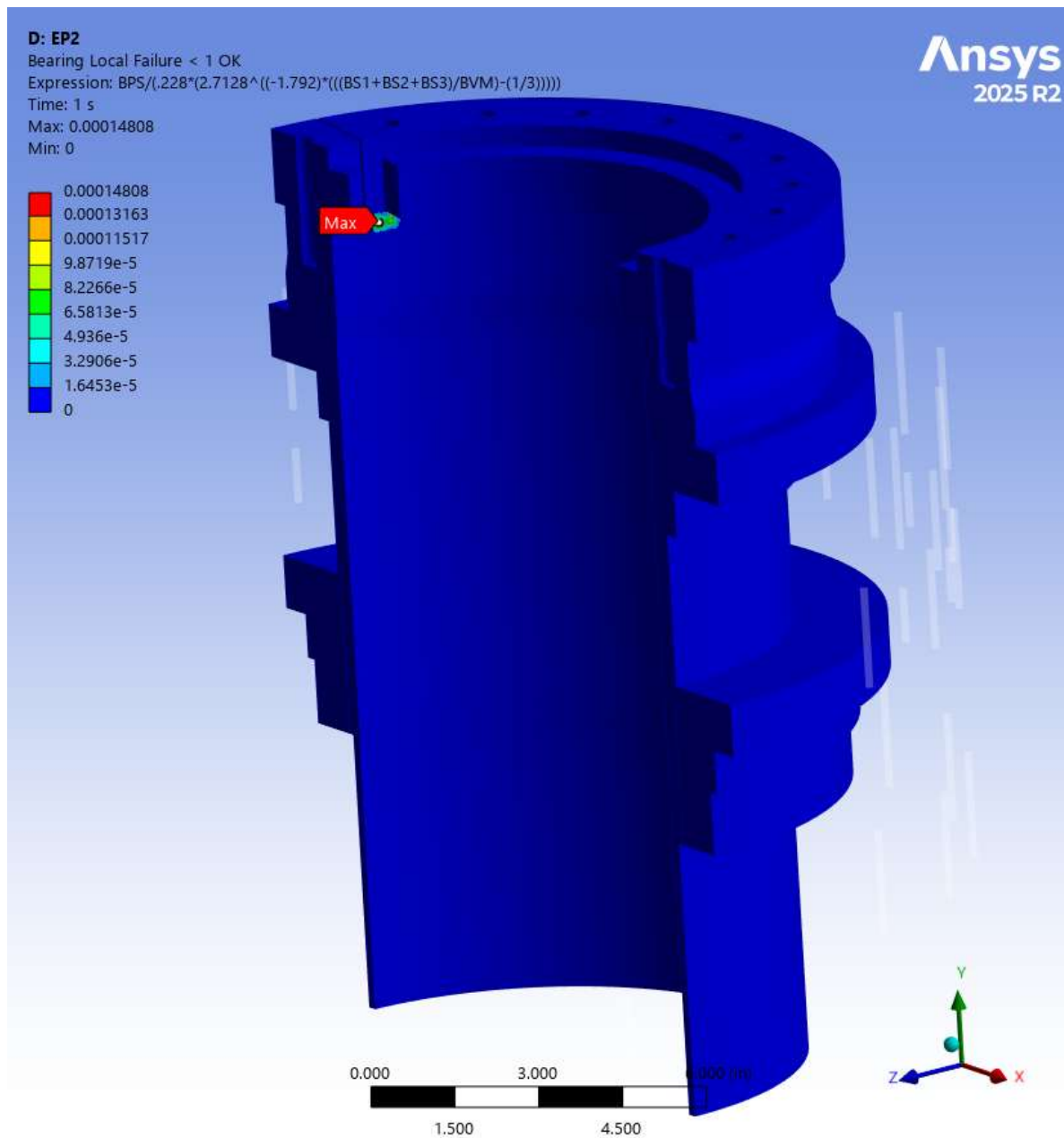


Figure 555 Crown and Drive, Elastic Plastic Case 2 Local Failure, Bearing Components

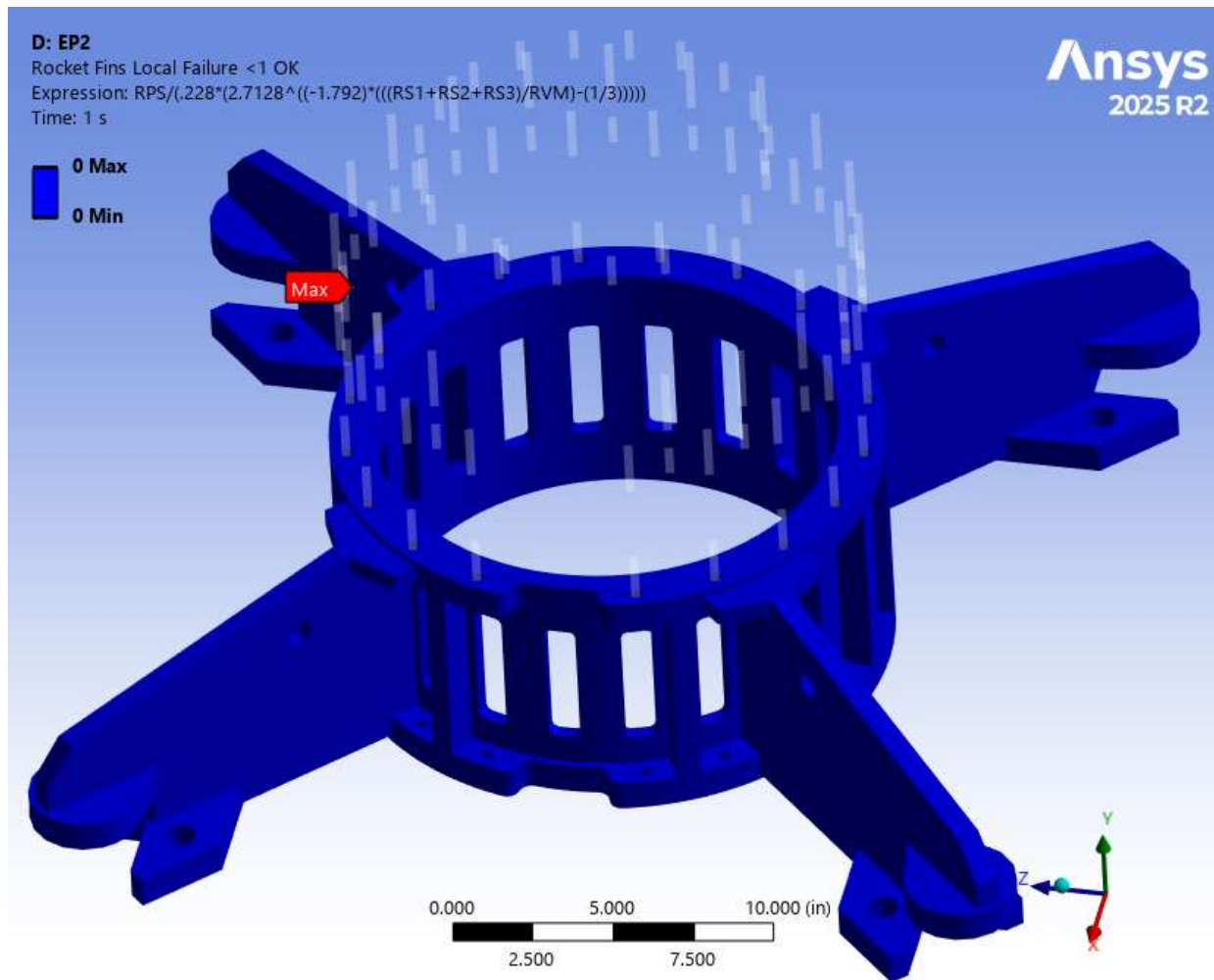


Figure 556 Crown and Drive, Elastic Plastic Case 2 Local Failure, Rocket Fins

5.1.4.2.3 Elastic Plastic Case 5

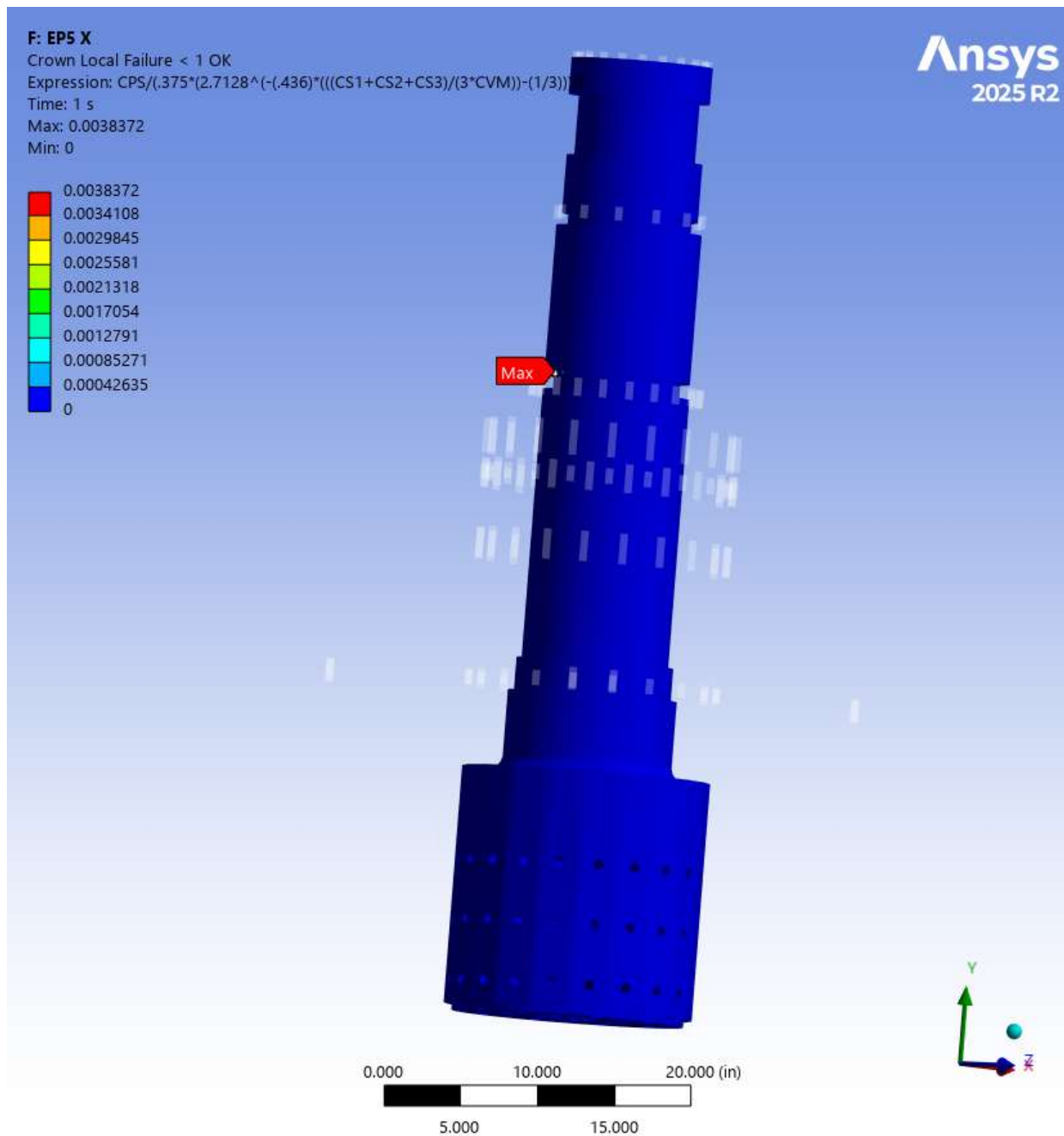


Figure 557 Crown and Drive, Elastic Plastic Case 5 Local Failure, Crown

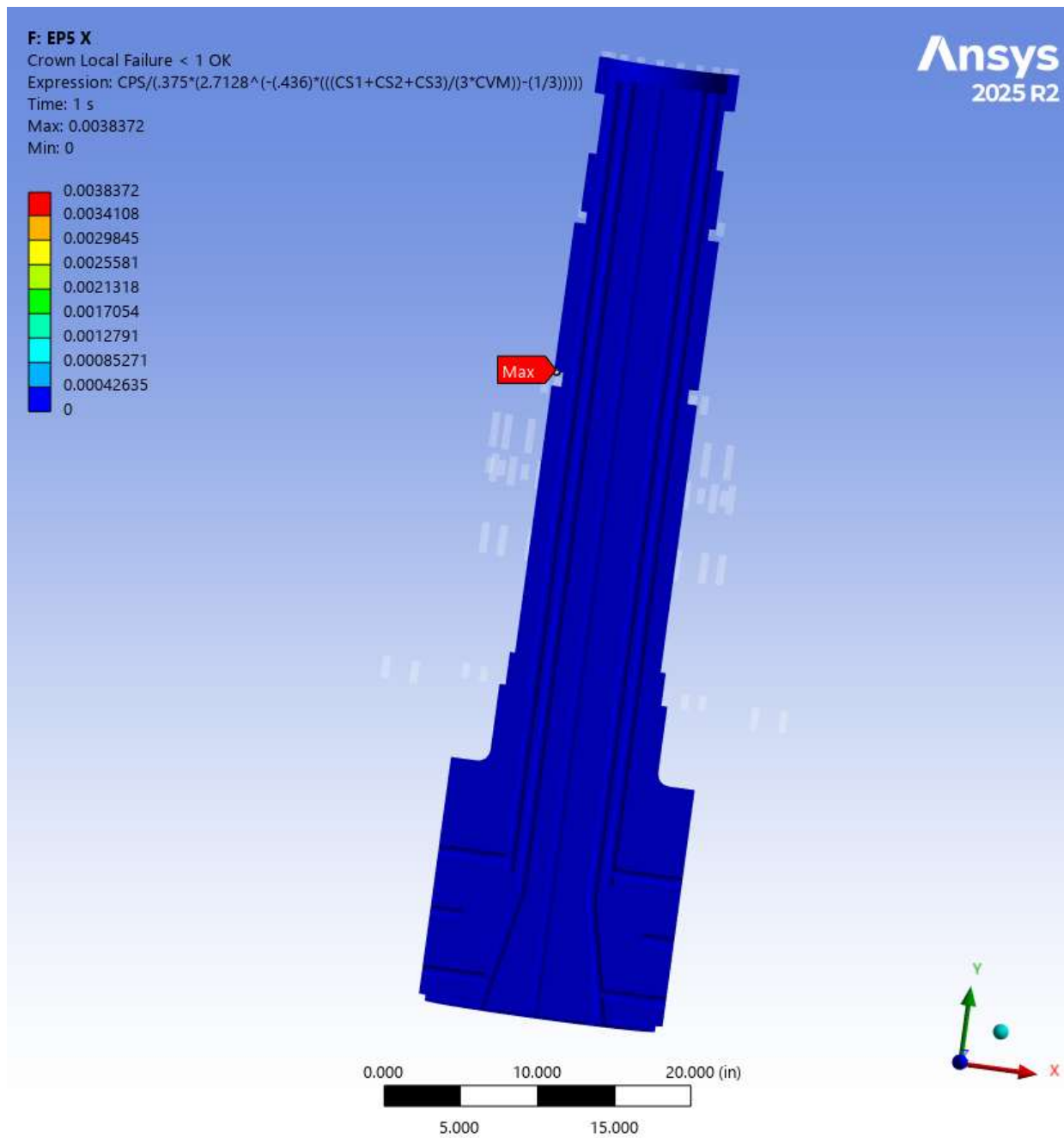


Figure 558 Crown and Drive, Elastic Plastic Case 5 Local Failure, Crown

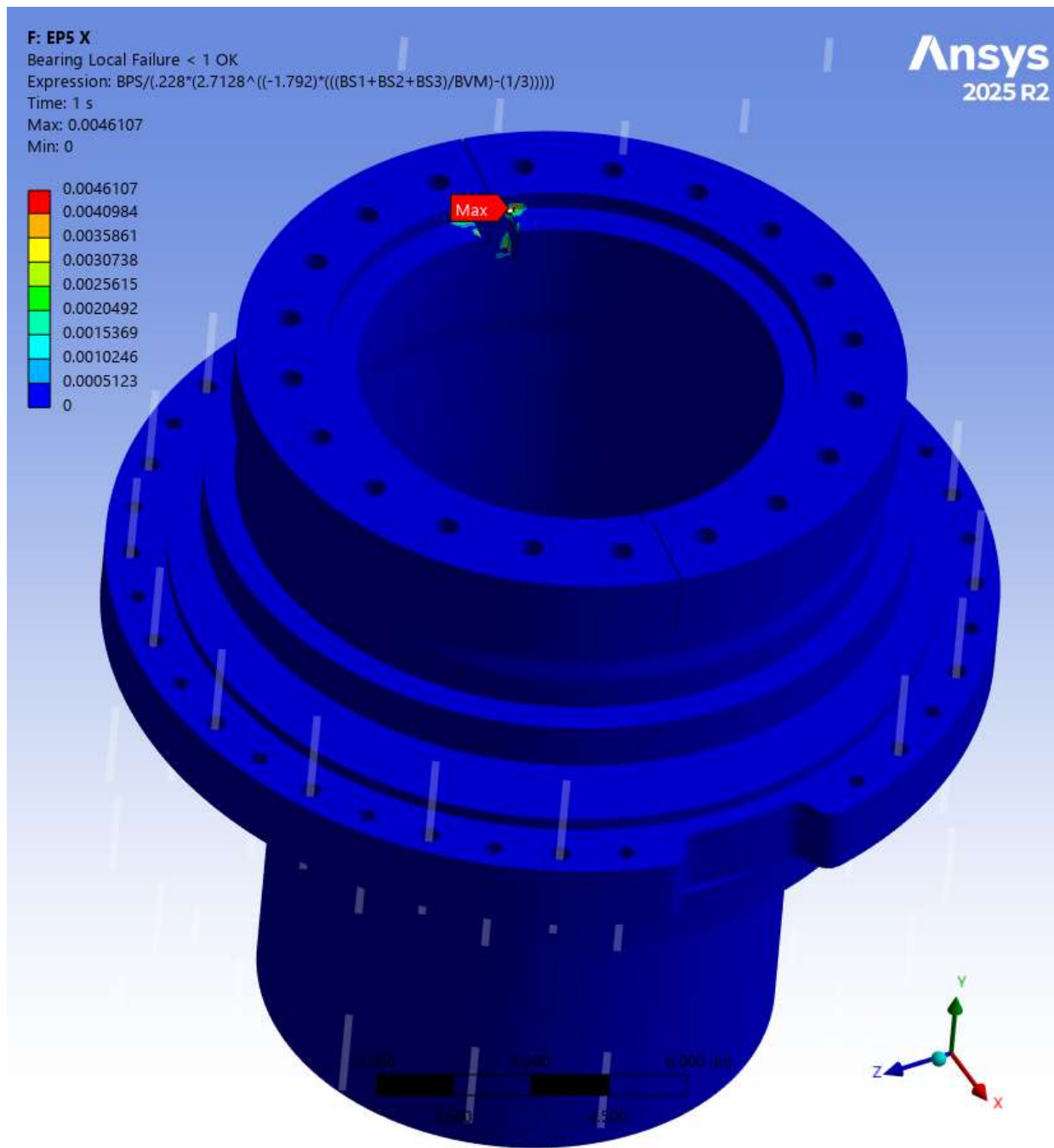


Figure 559 Crown and Drive, Elastic Plastic Case 5 Local Failure, Inner Components

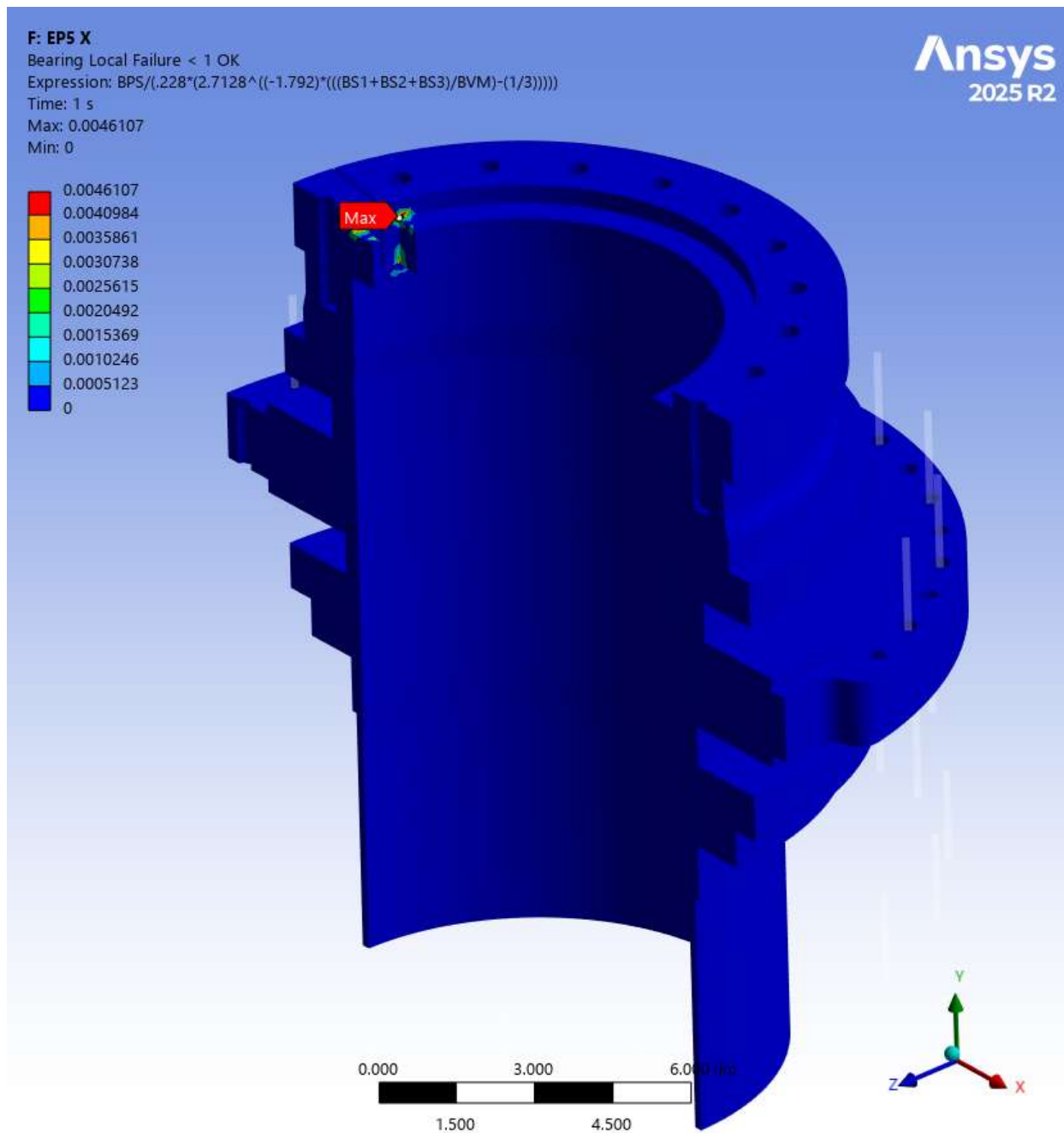


Figure 560 Crown and Drive, Elastic Plastic Case 5 Local Failure, Inner Components

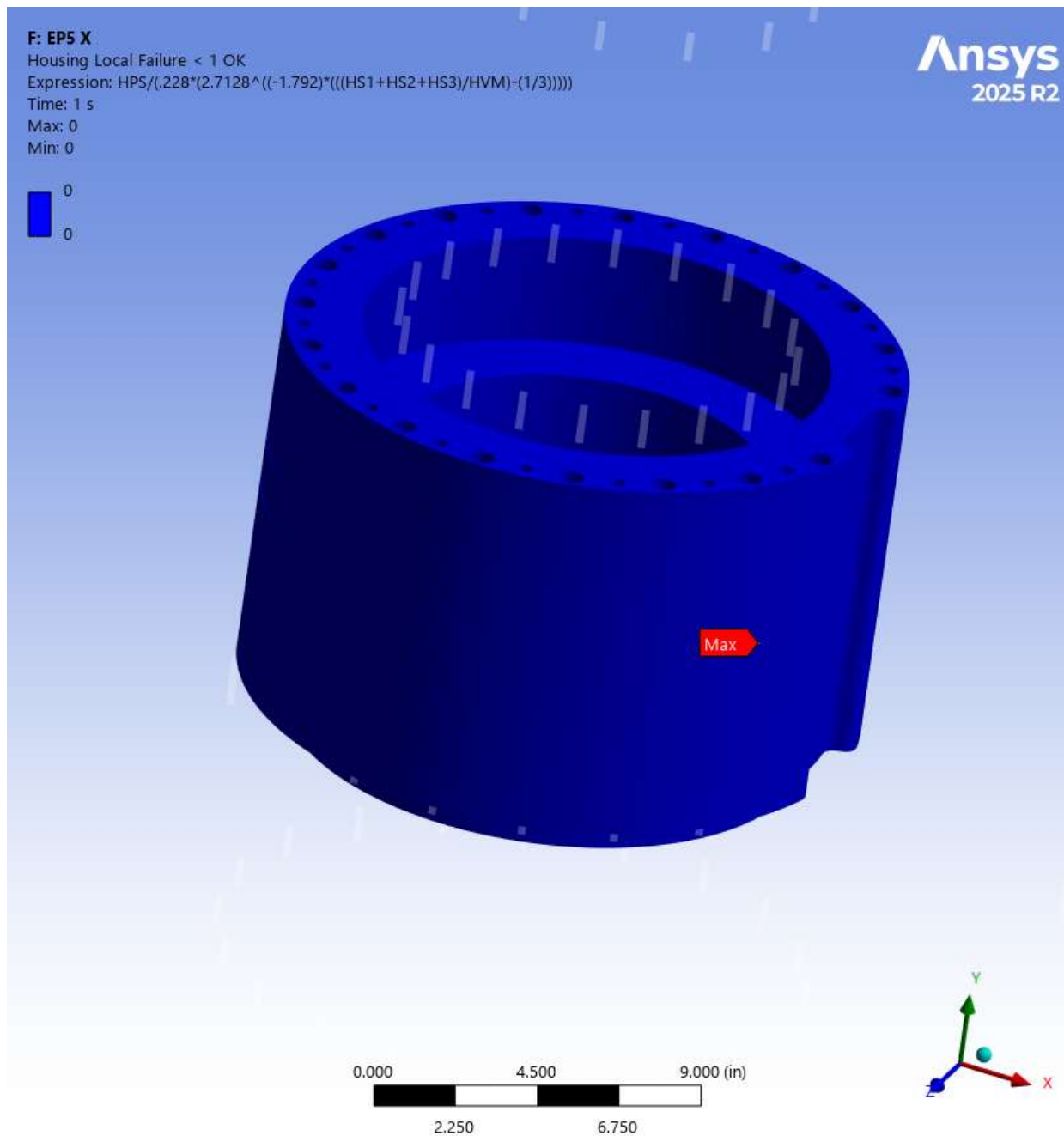


Figure 561 Crown and Drive, Elastic Plastic Case 5 Local Failure, Outer Housing

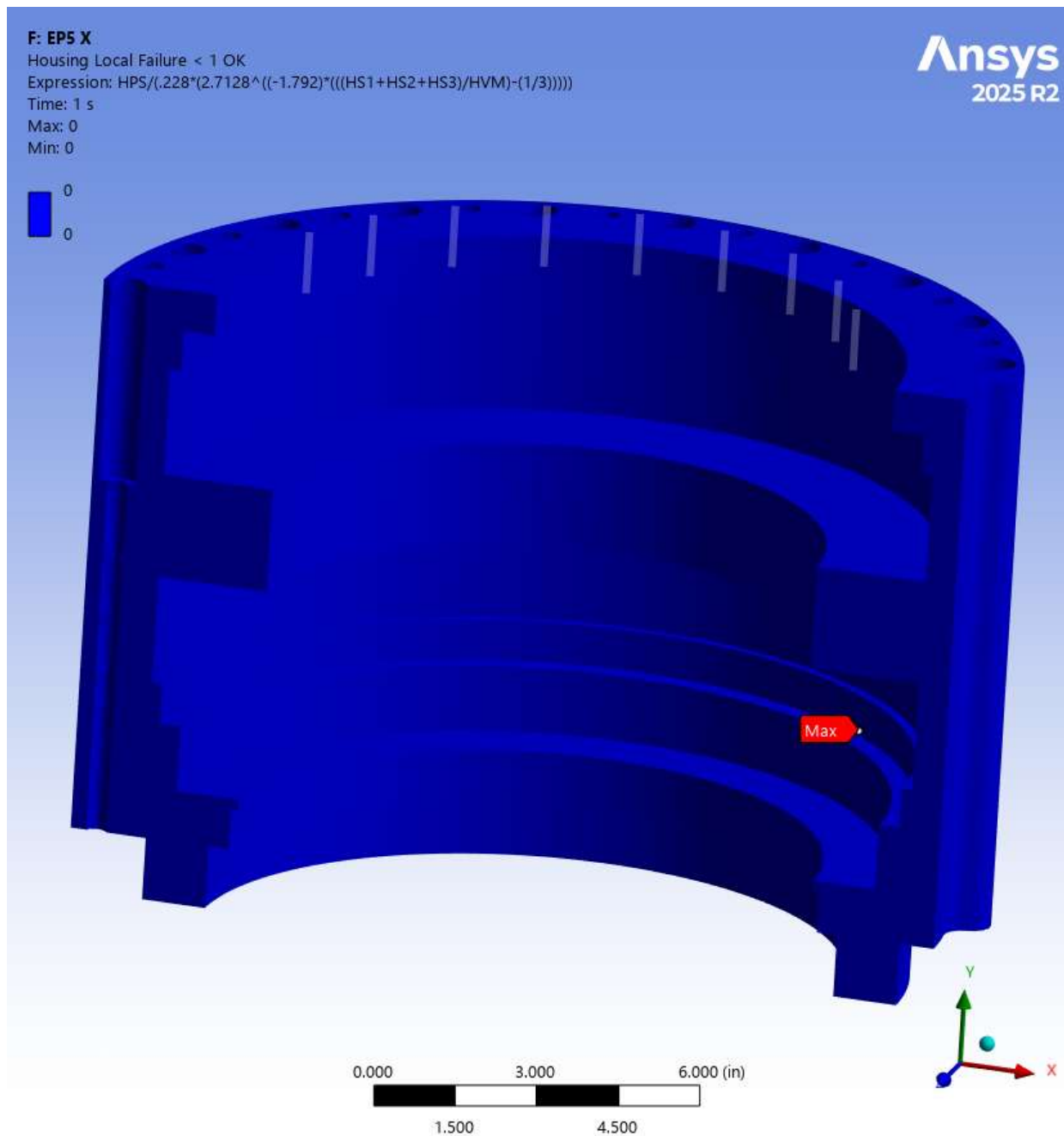


Figure 562 Crown and Drive, Elastic Plastic Case 5 Local Failure, Outer Housing

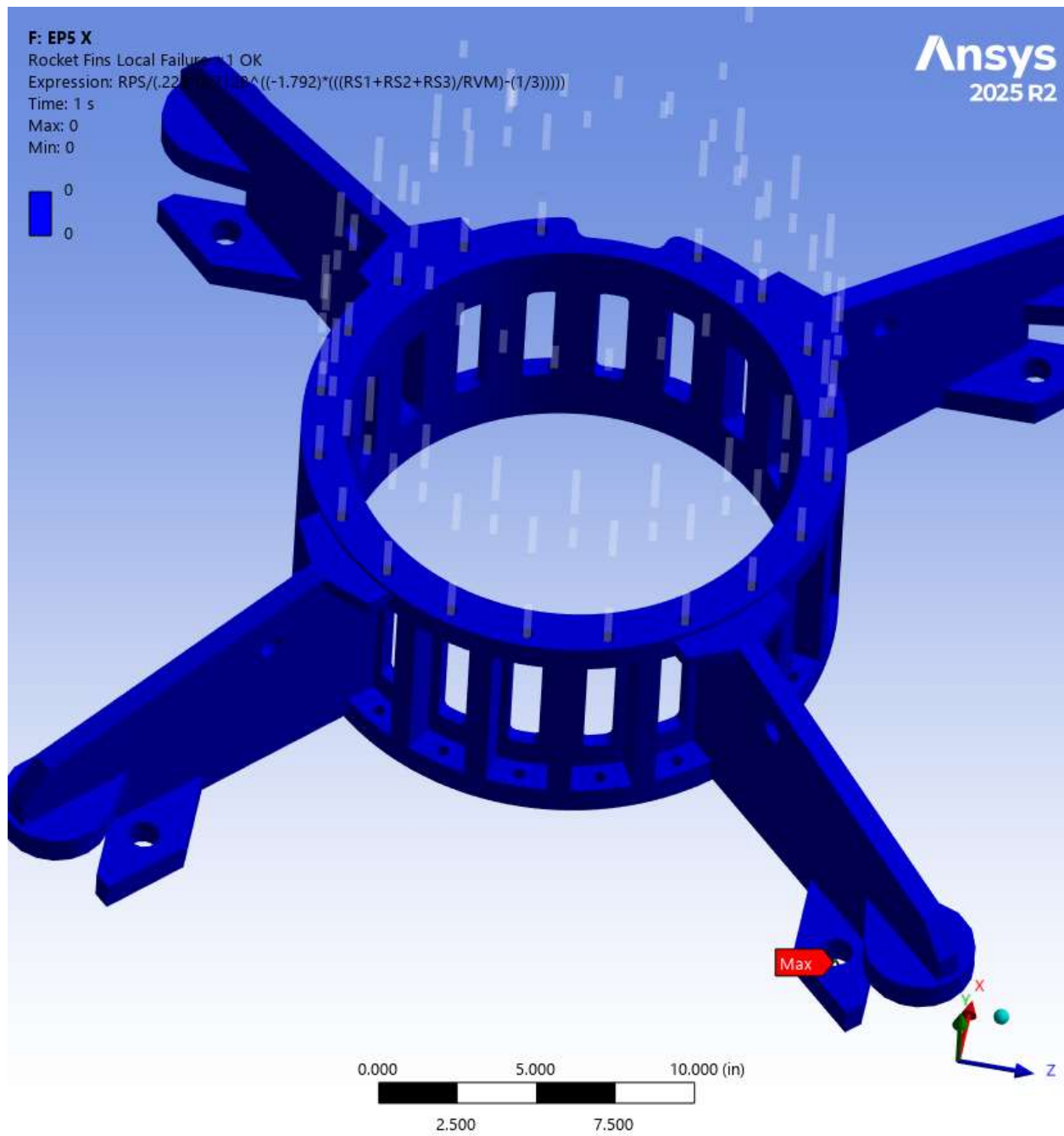


Figure 563 Crown and Drive, Elastic Plastic Case 5 Local Failure, Rocket Fins

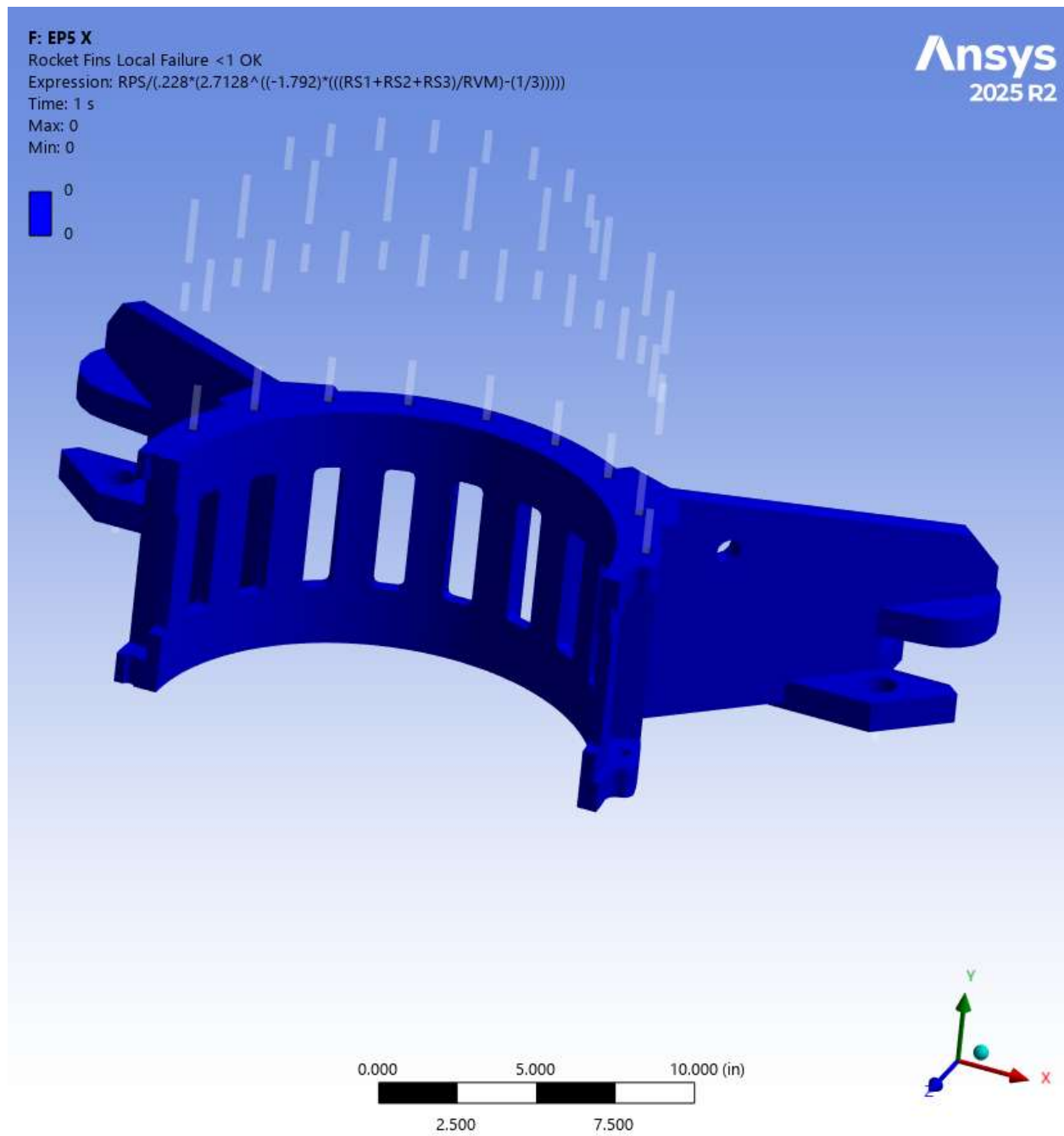


Figure 564 Crown and Drive, Elastic Plastic Case 5 Local Failure, Rocket Fins

5.1.4.3 Cyclic Loads

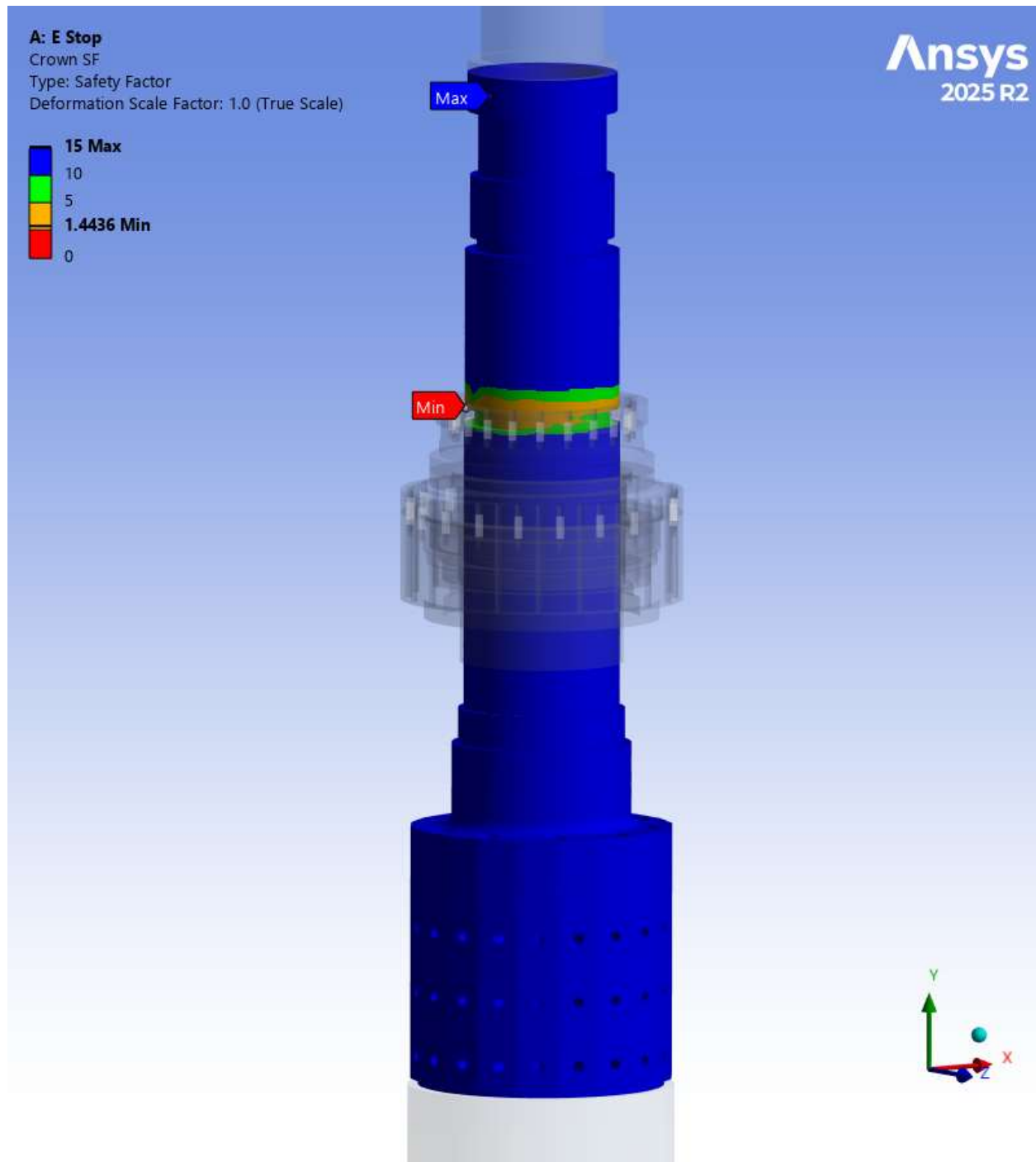


Figure 565 Crown and Drive, Cyclic Load Safety Factor for LoF, Crown

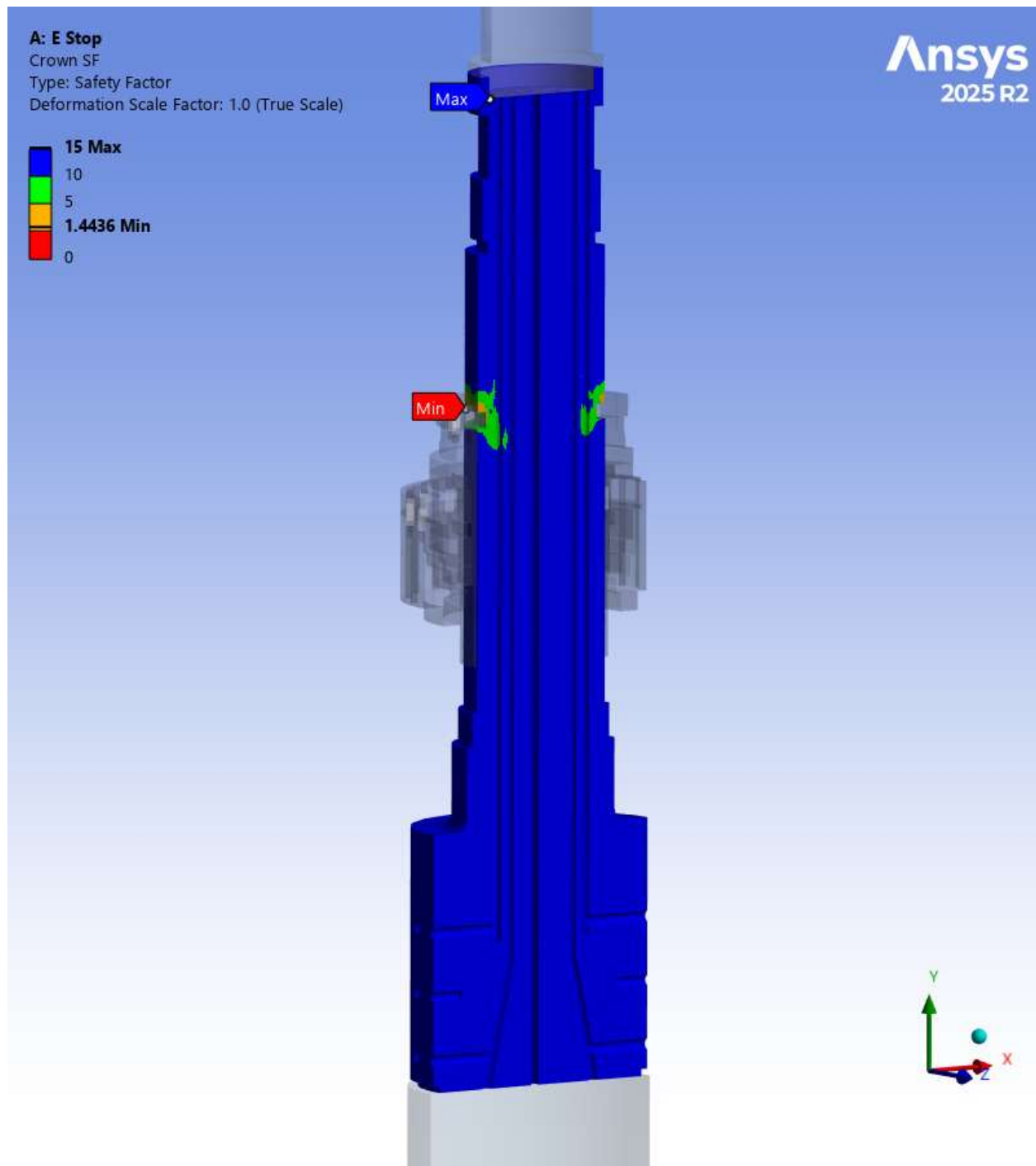


Figure 566 Crown and Drive, Cyclic Load Safety Factor for LoF, Crown Section

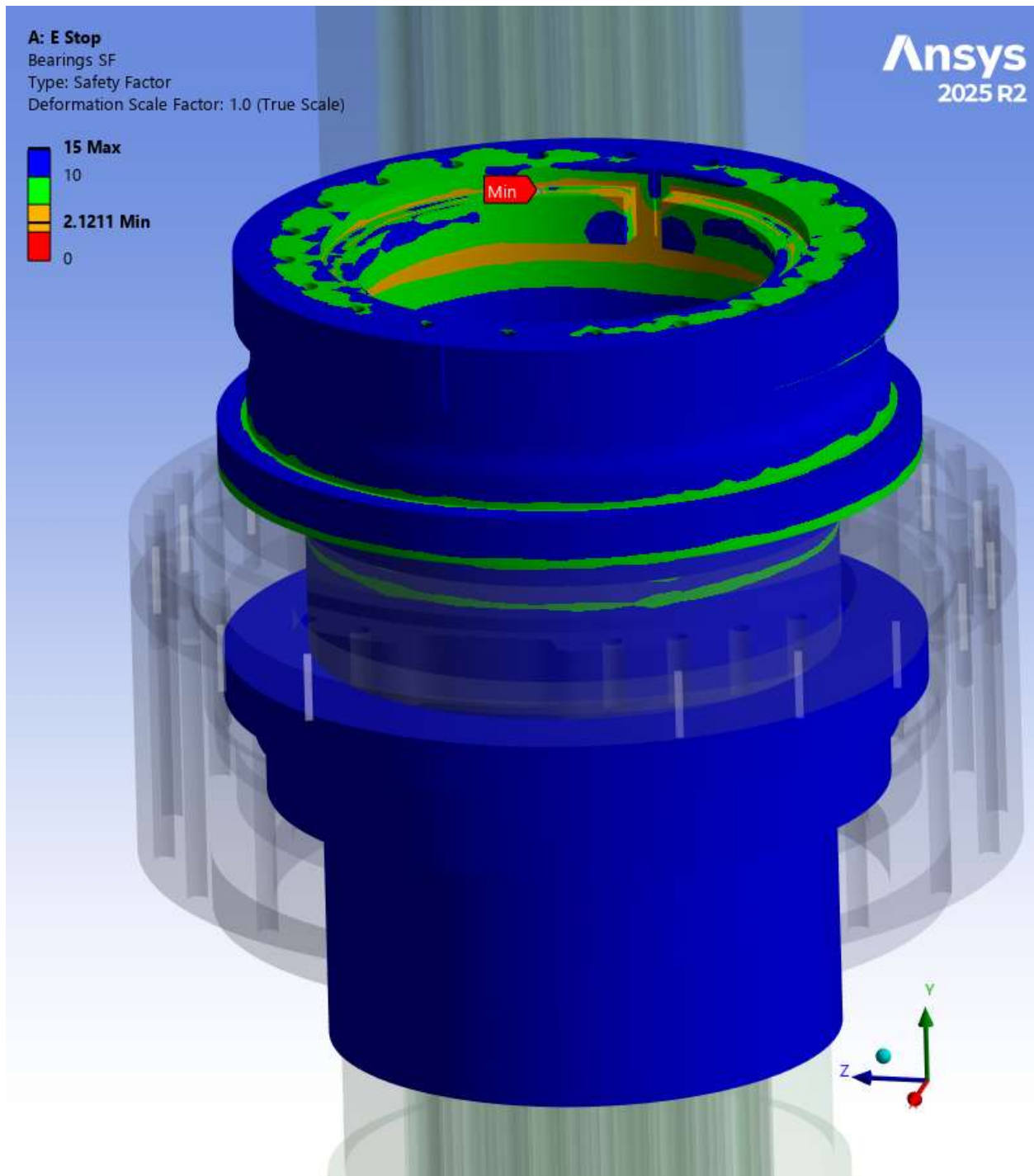


Figure 567 Crown and Drive, Cyclic Load Safety Factor for LoF, Inner Components

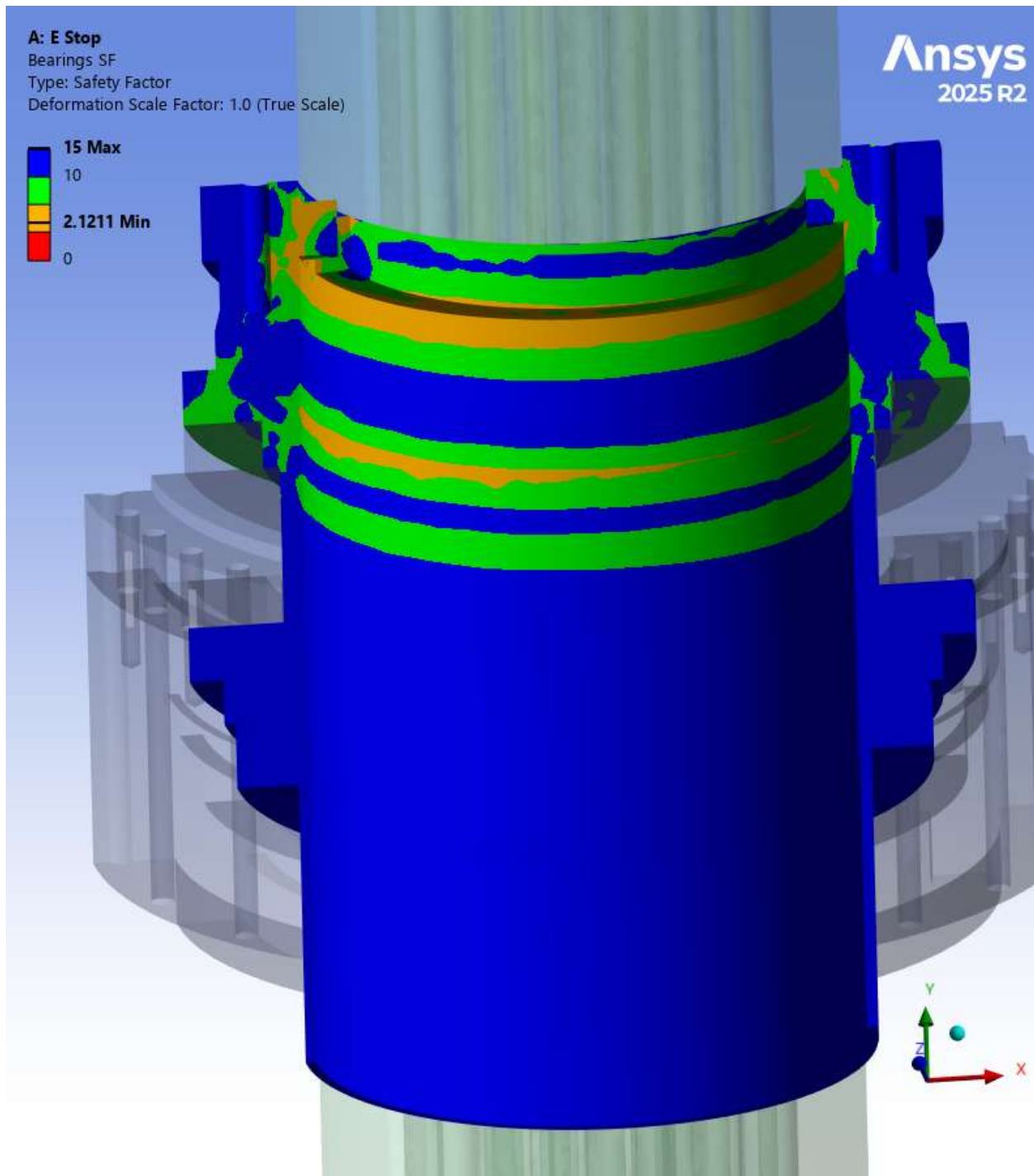


Figure 568 Crown and Drive, Cyclic Load Safety Factor for LoF, Inner Components Section

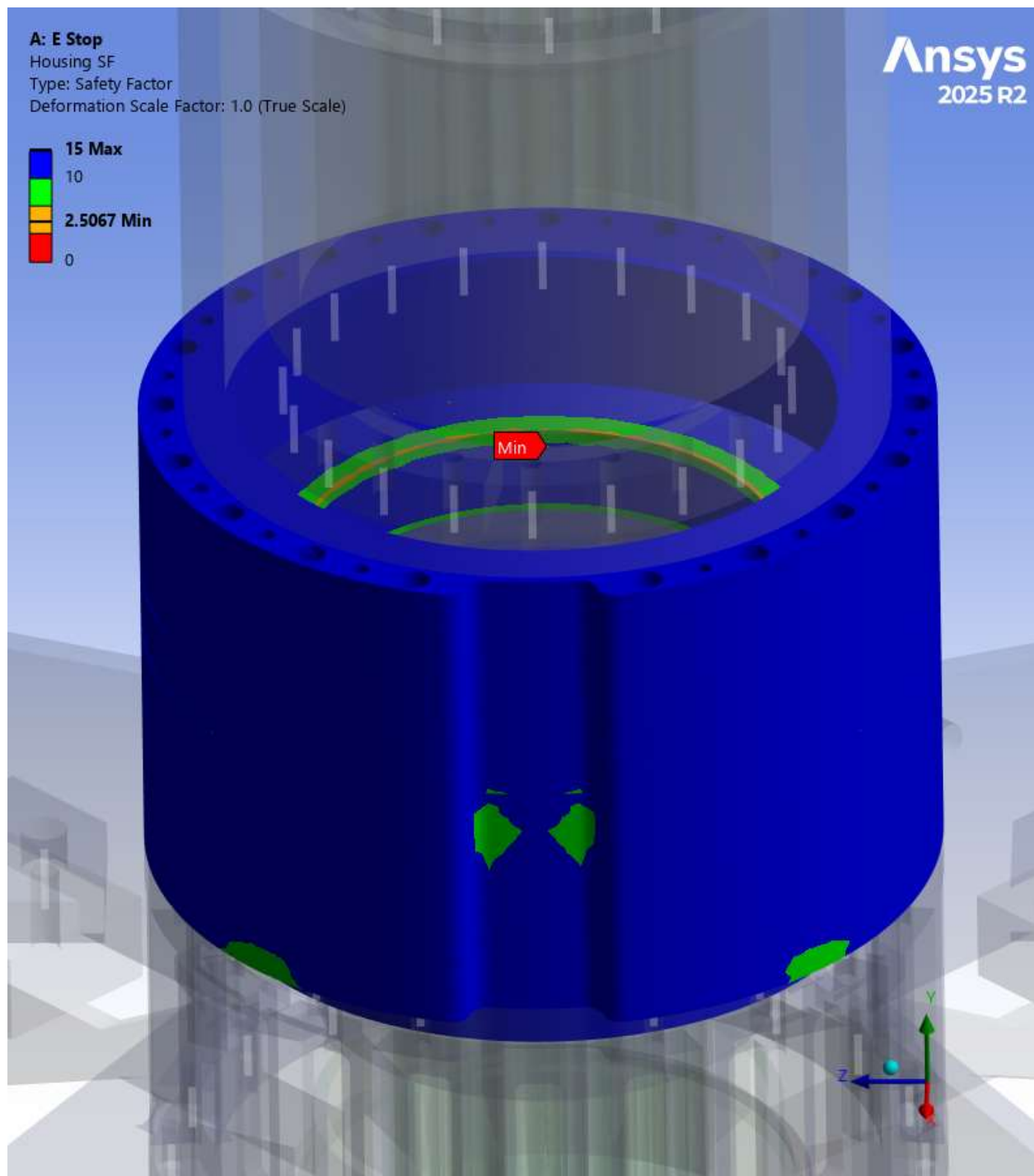


Figure 569 Crown and Drive, Cyclic Load Safety Factor for LoF, Outer Housing

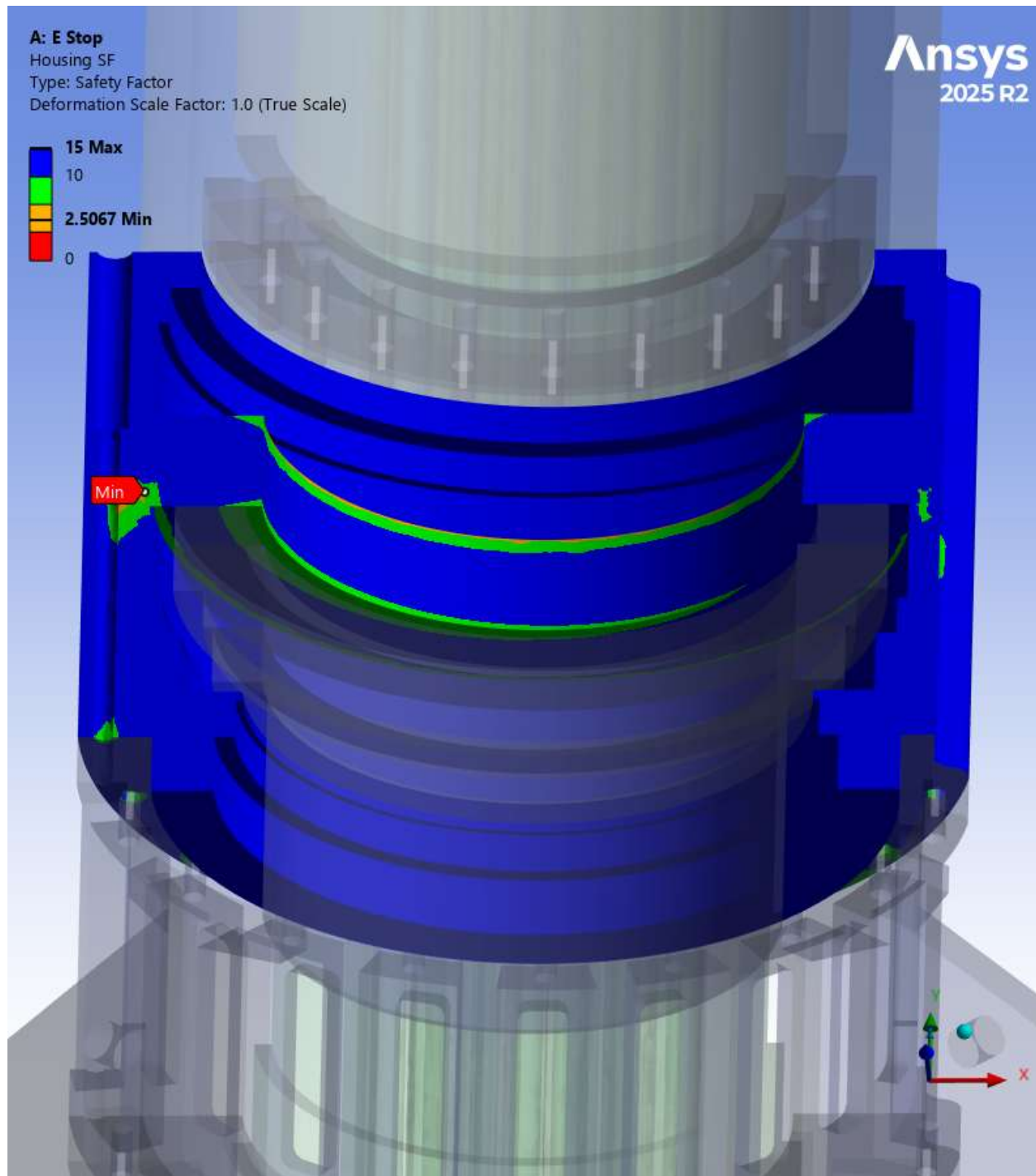


Figure 570 Crown and Drive, Cyclic Load Safety Factor for LoF, Outer Housing Section

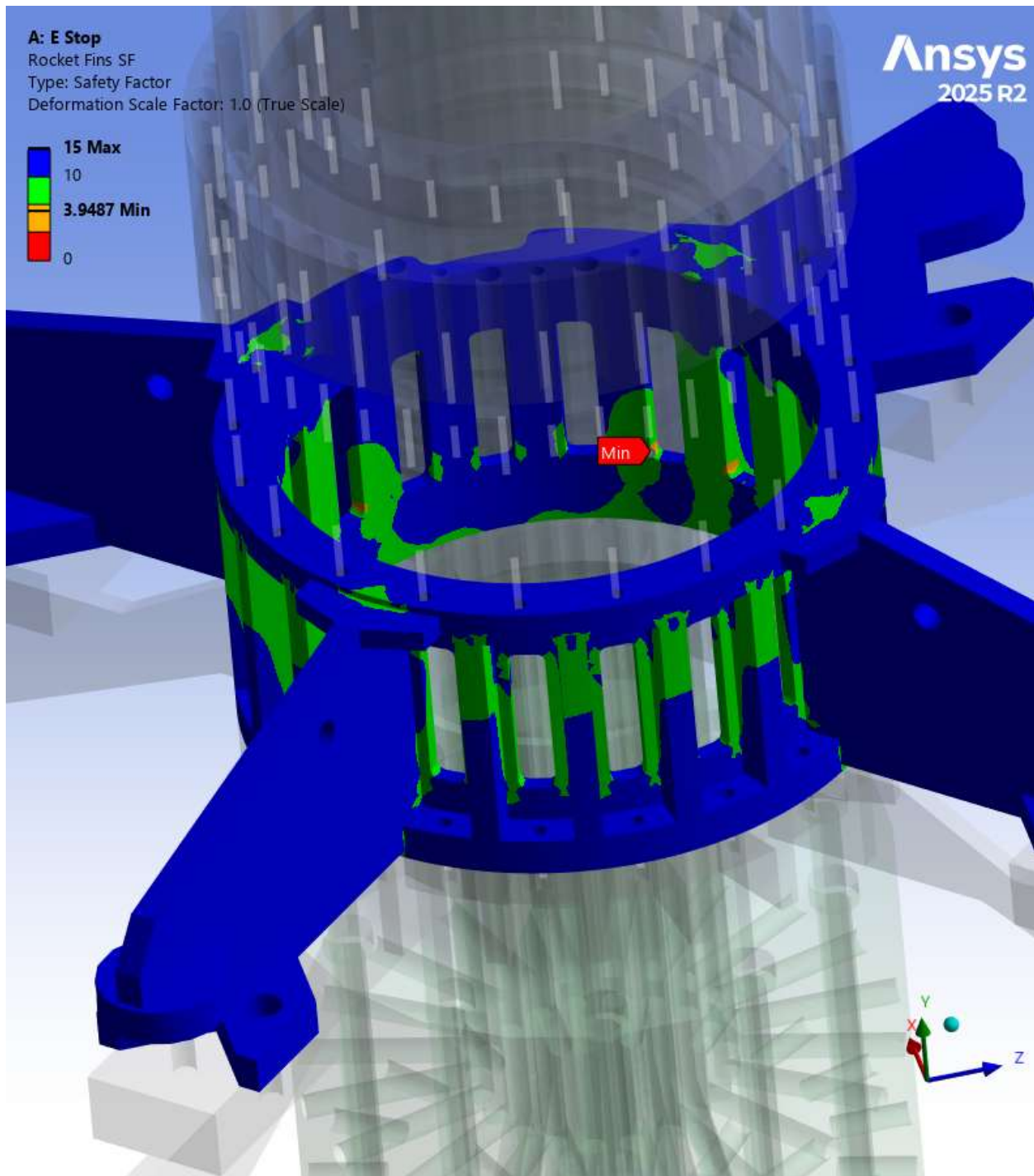


Figure 571 Crown and Drive, Cyclic Load Safety Factor for LoF, Rocket Fins

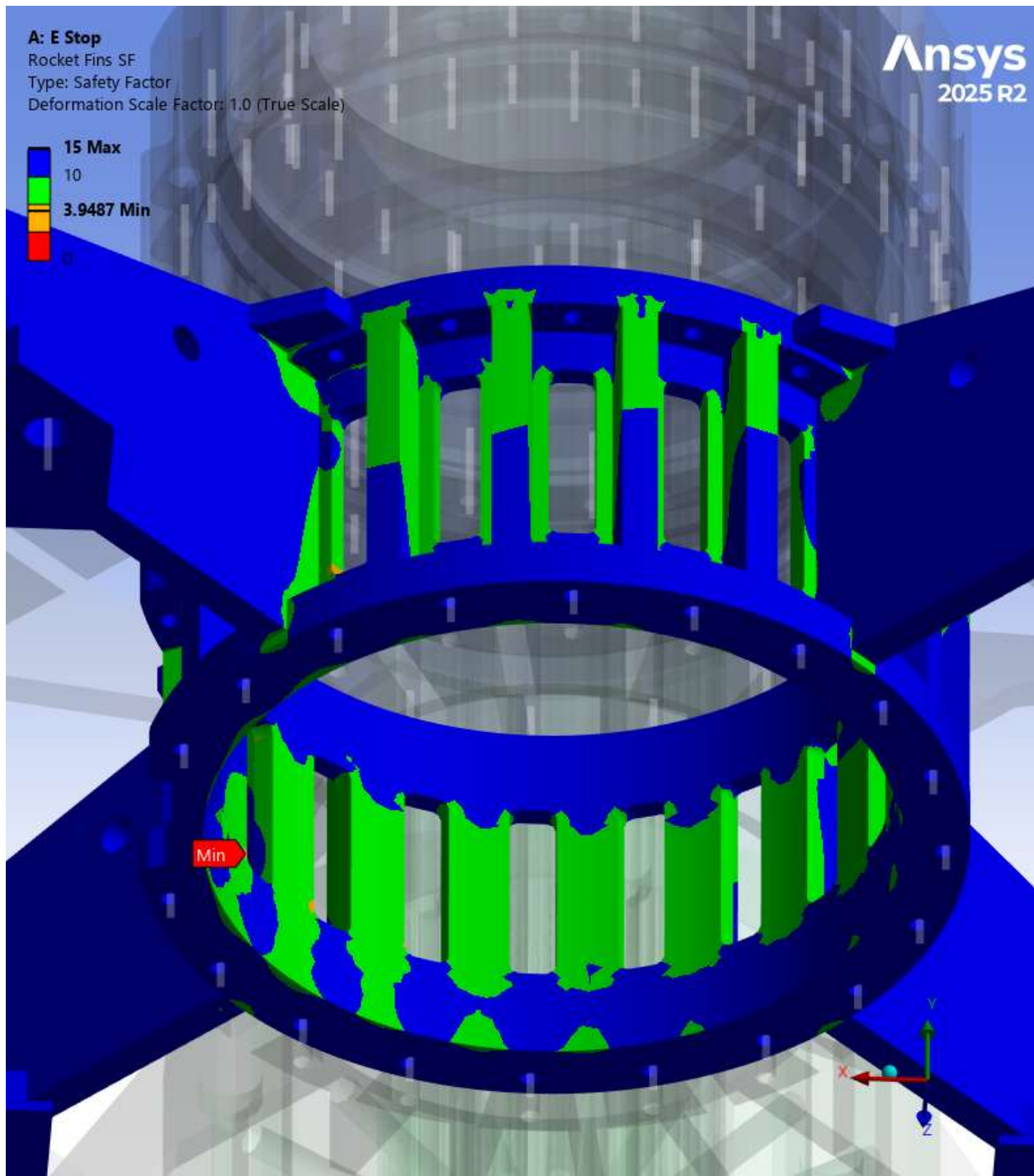


Figure 572 Crown and Drive, Cyclic Load Safety Factor for LoF, Rocket Fins

5.1.4.4 Equivalent Stress

The equivalent stress plots are included for reference.

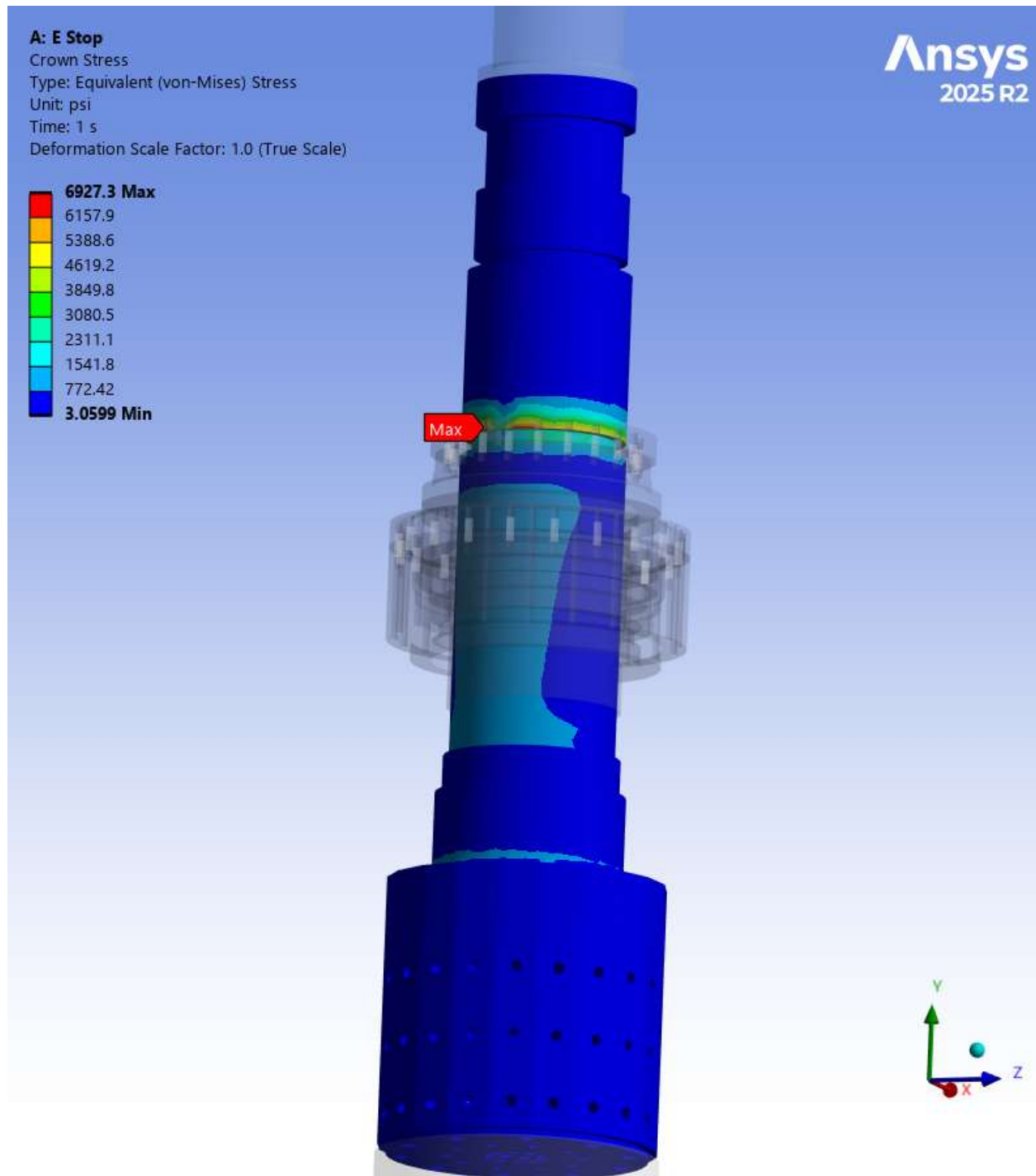


Figure 573 Crown and Drive, E Stop Equivalent Stress, Crown

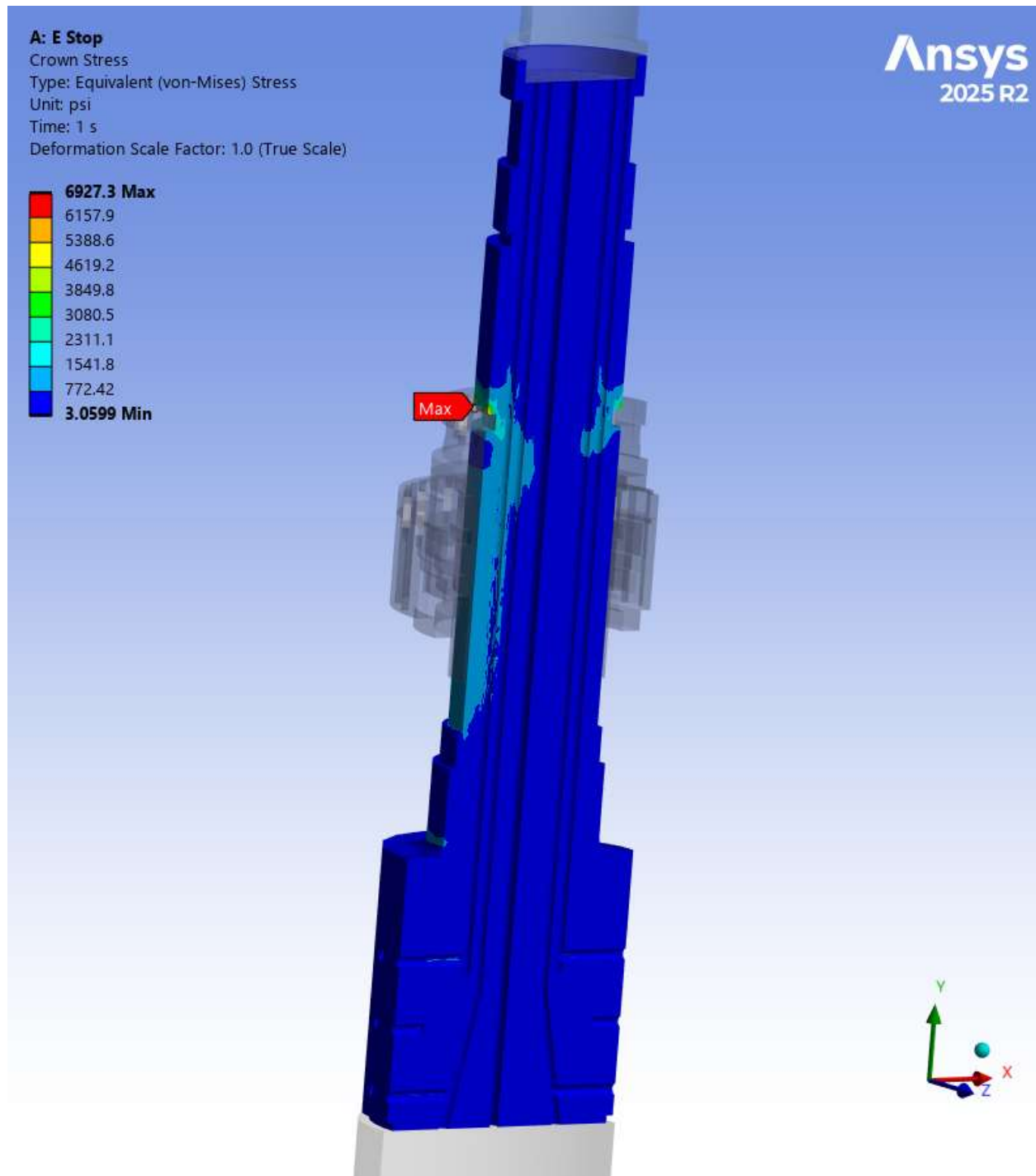


Figure 574 Crown and Drive, E Stop Equivalent Stress, Crown

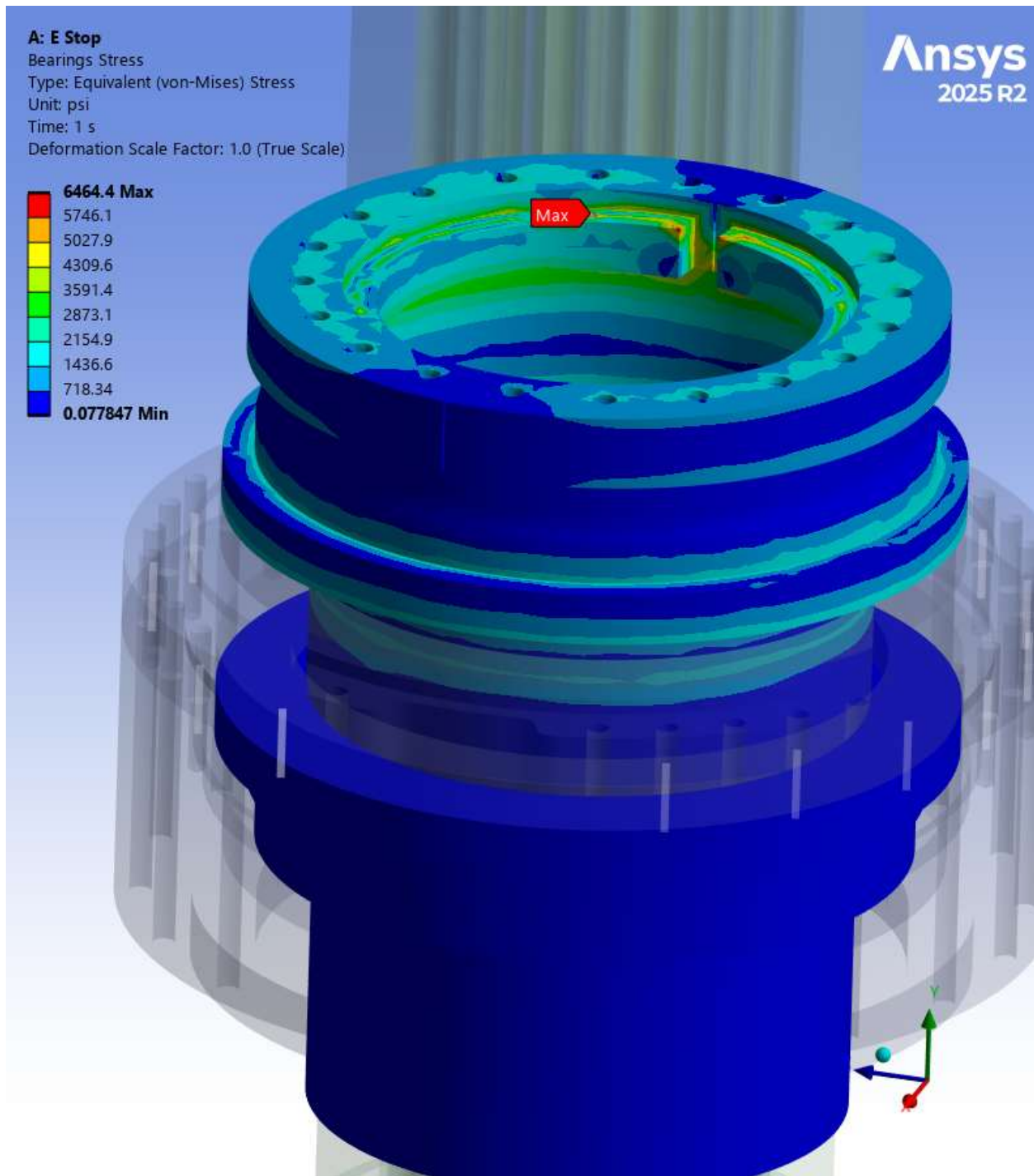


Figure 575 Crown and Drive, E Stop Equivalent Stress, Inner Components

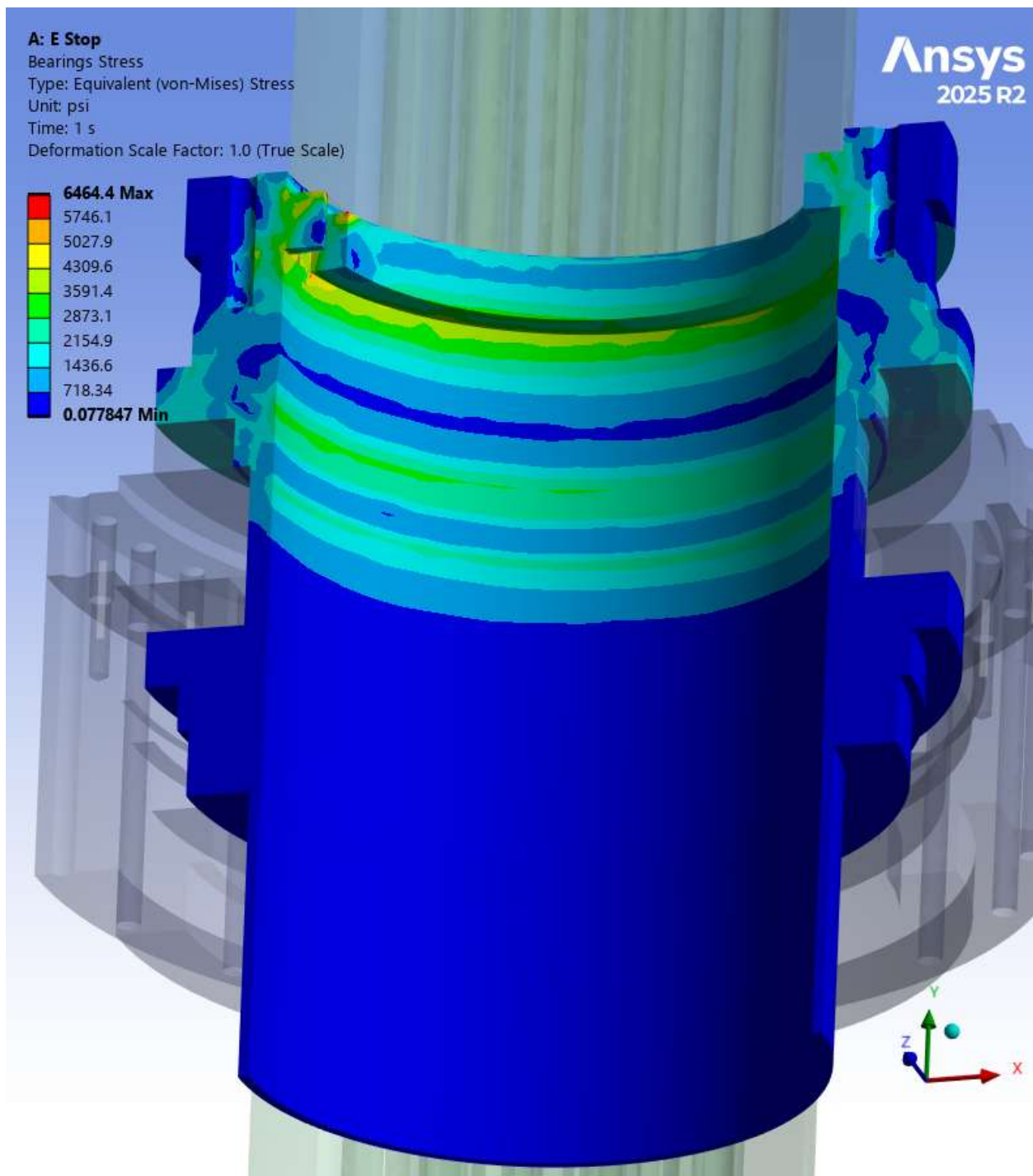


Figure 576 Crown and Drive, E Stop Equivalent Stress, Inner Components

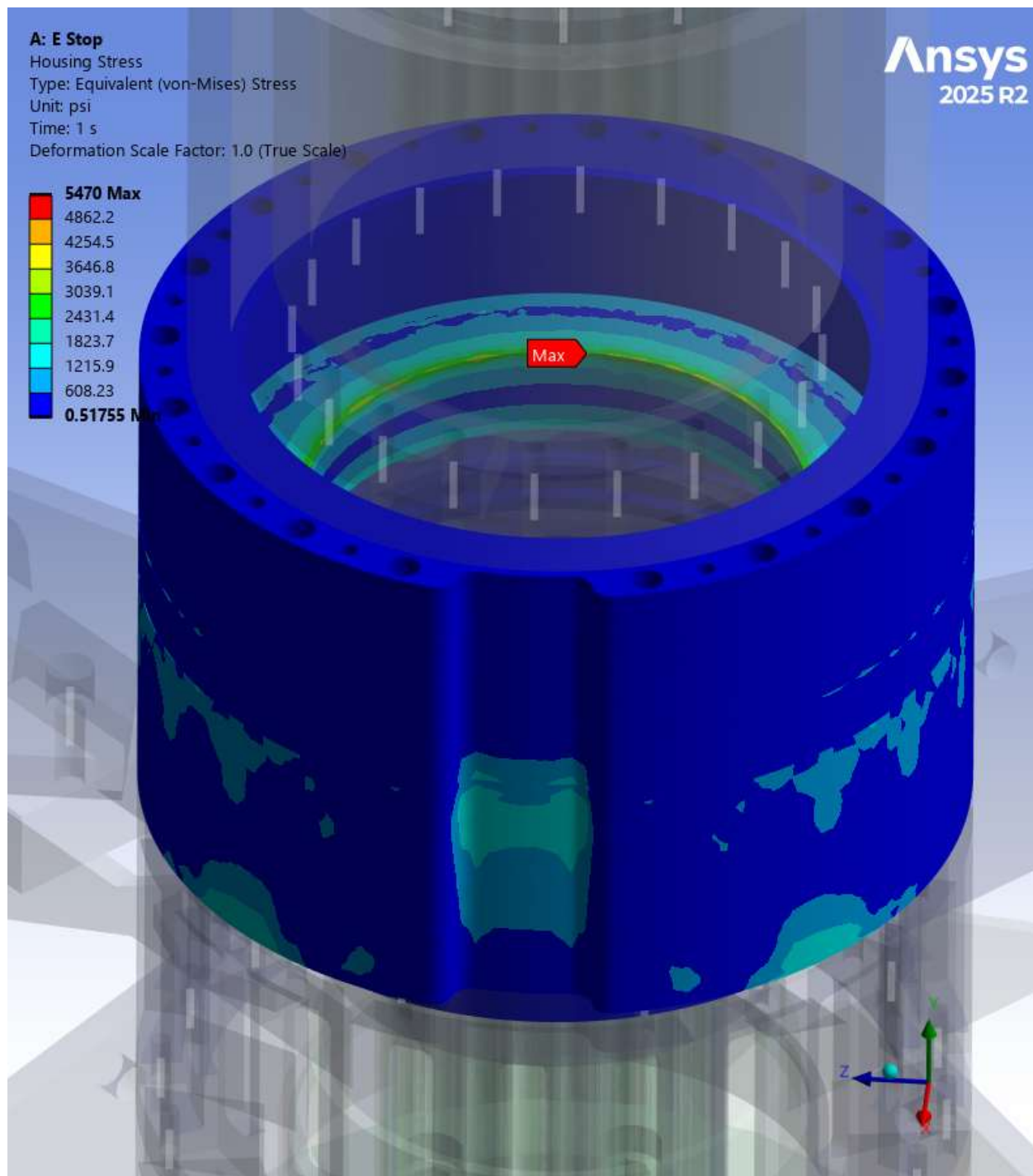


Figure 577 Crown and Drive, E Stop Equivalent Stress, Outer Housing

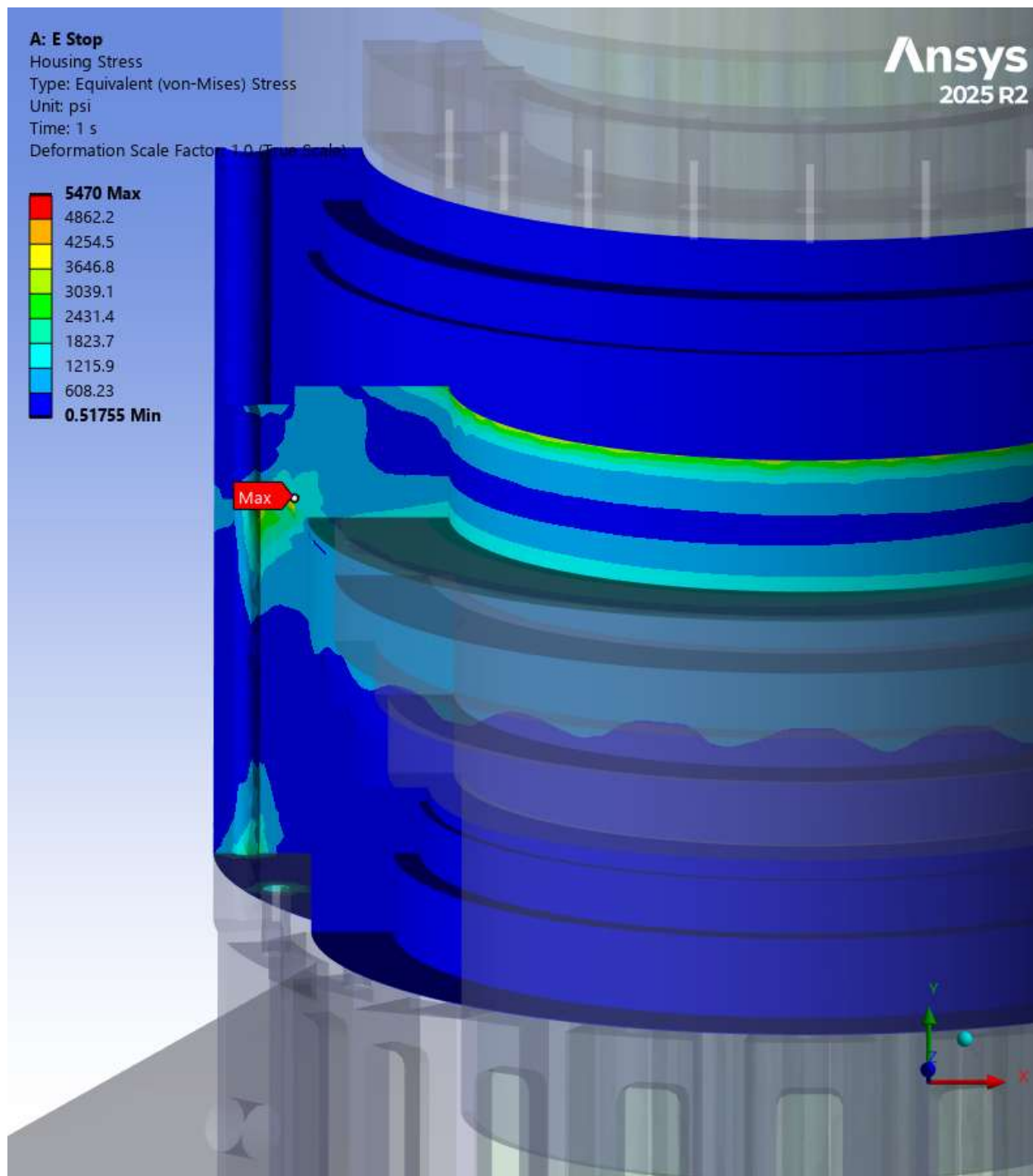


Figure 578 Crown and Drive, E Stop Equivalent Stress, Outer Housing

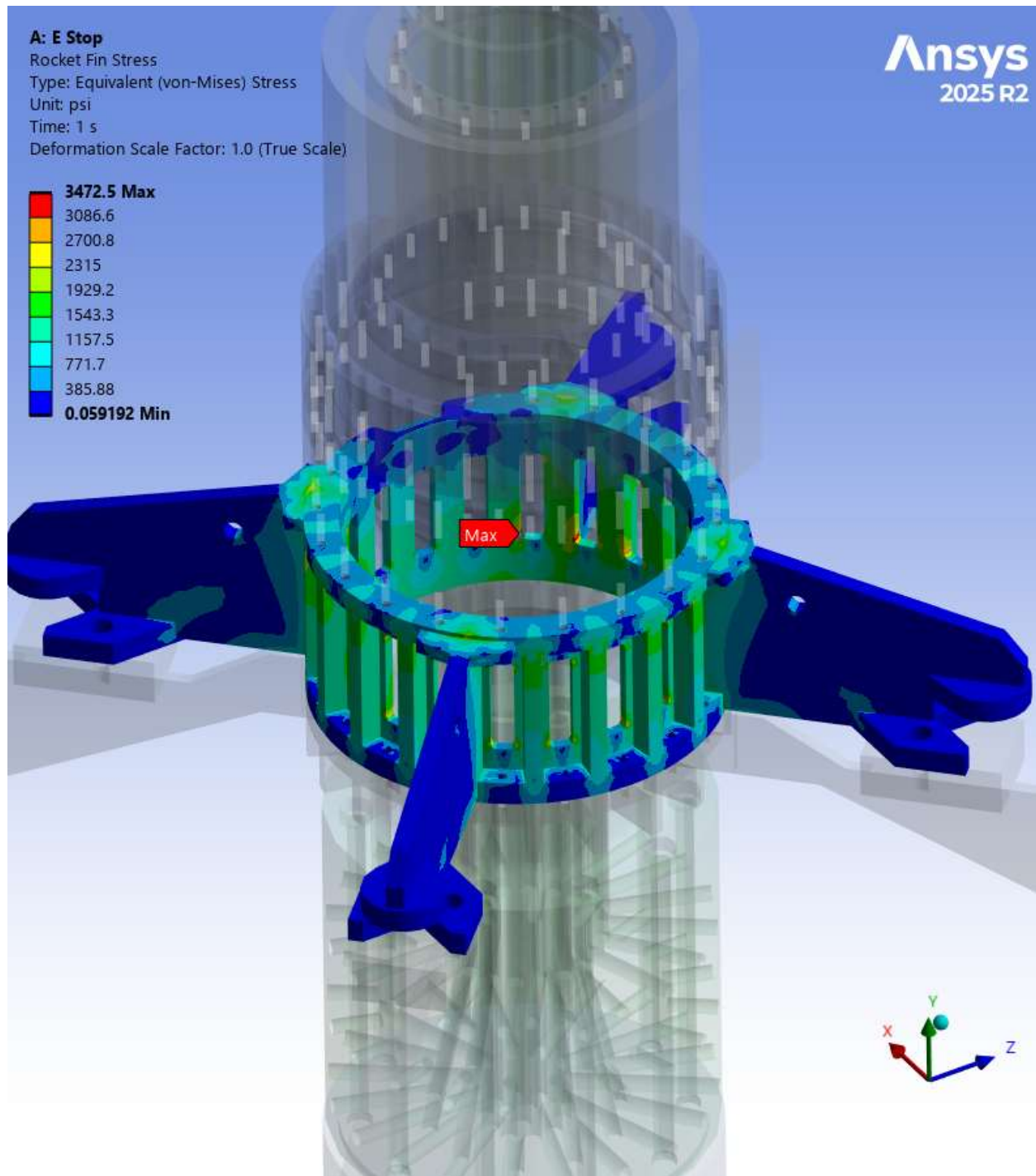


Figure 579 Crown and Drive, E Stop Equivalent Stress, Rocket Fins

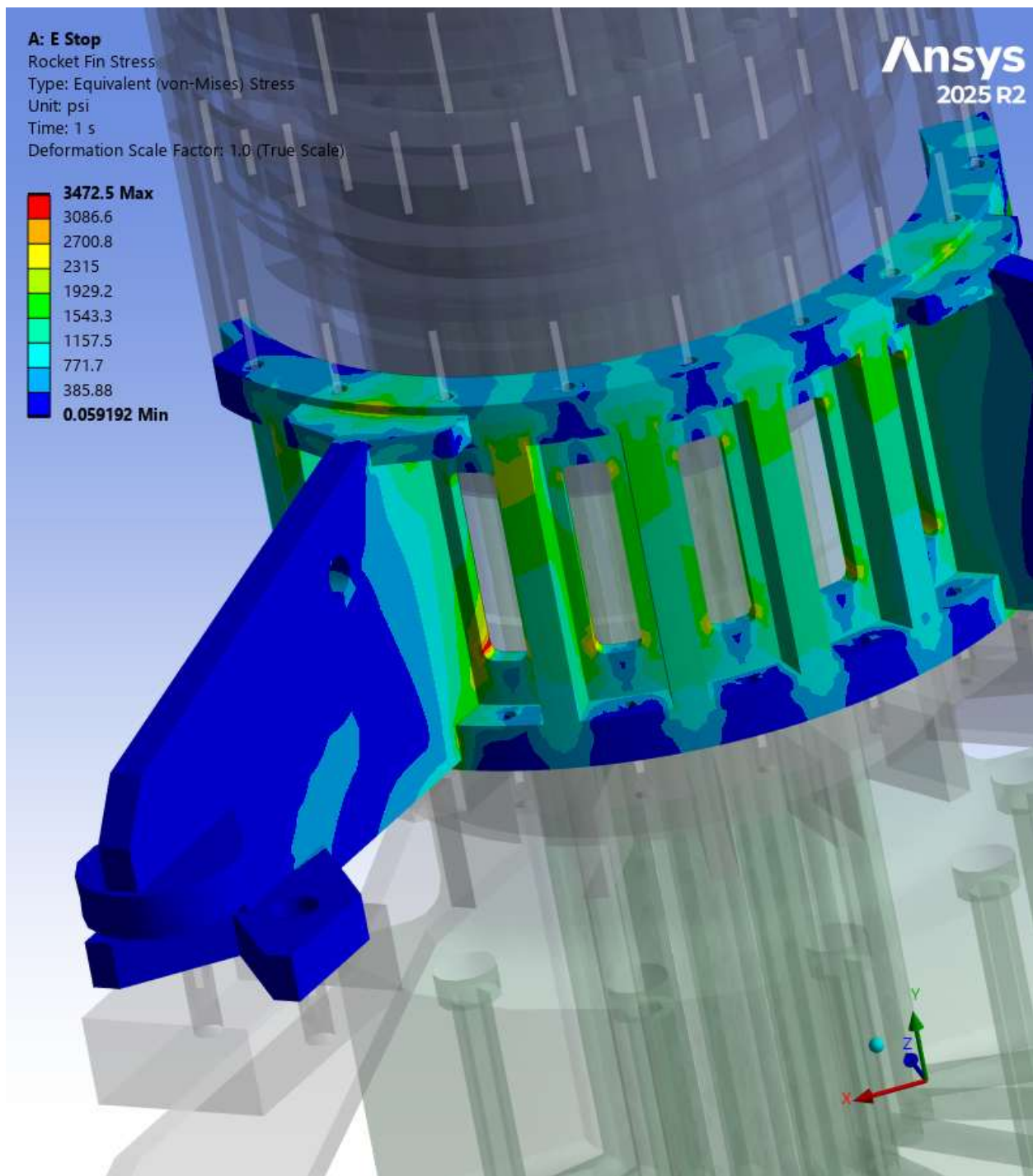


Figure 580 Crown and Drive, E Stop Equivalent Stress, Rocket Fins

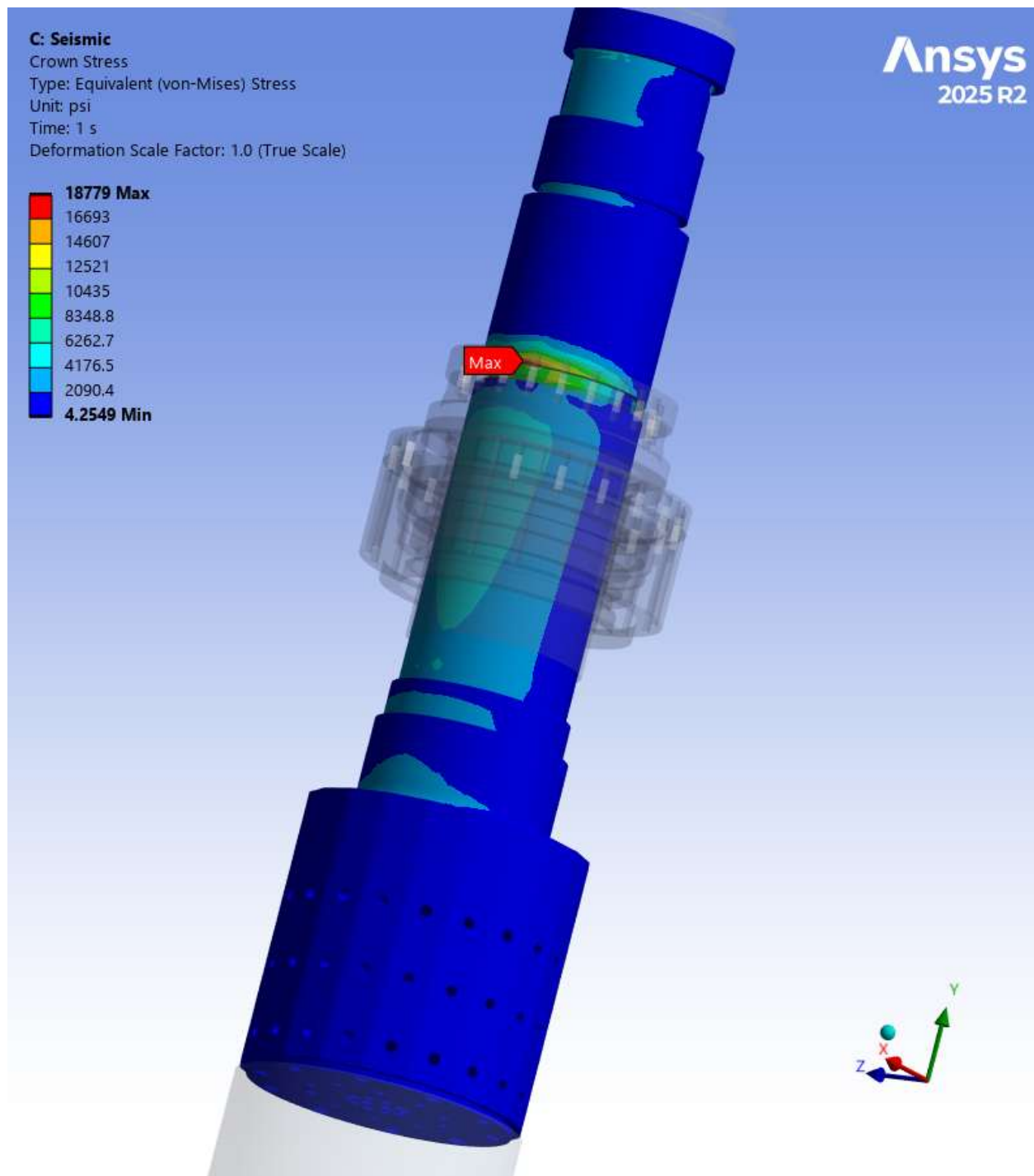


Figure 581 Crown and Drive, Seismic Equivalent Stress, Crown

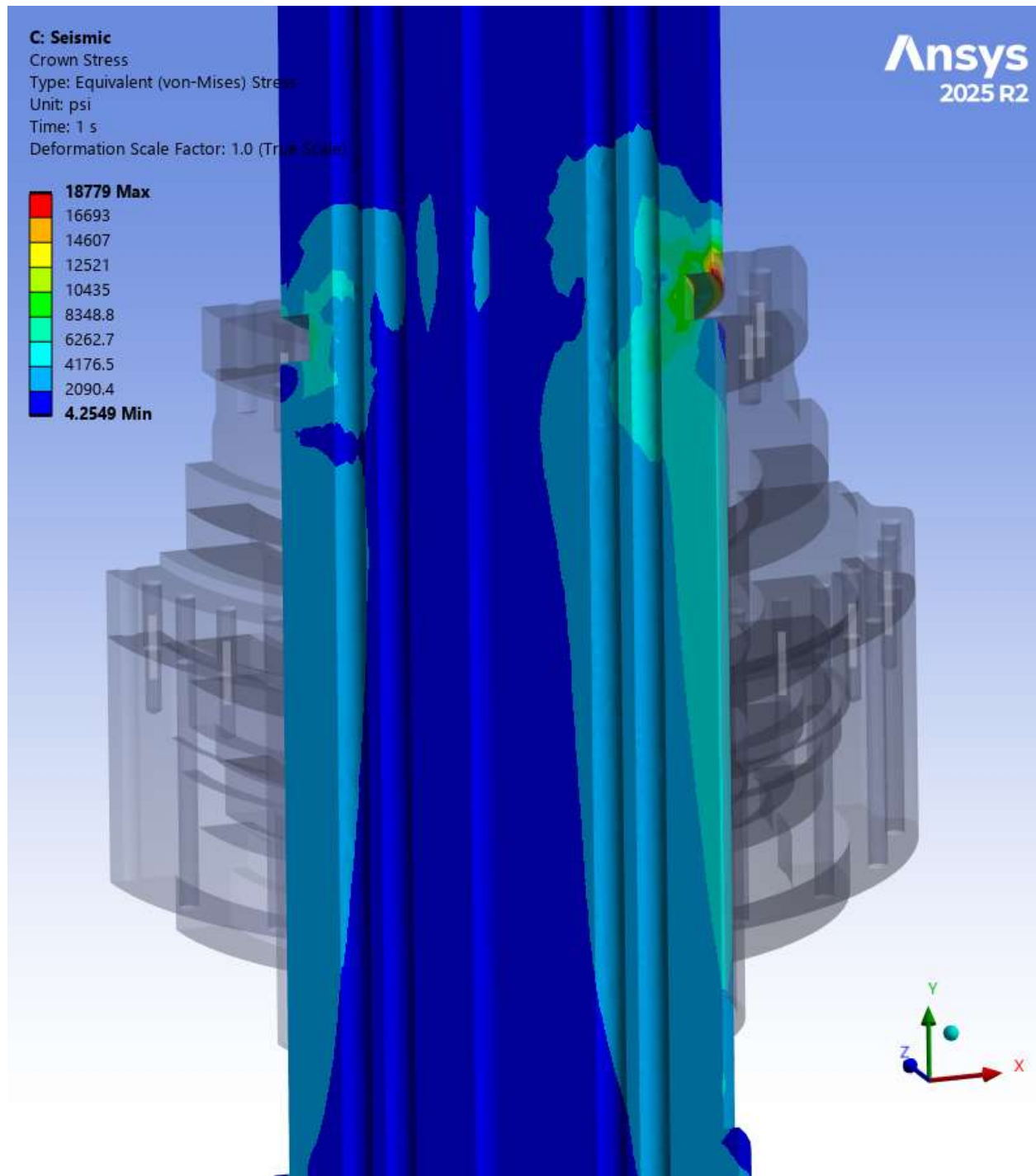


Figure 582 Crown and Drive, Seismic Equivalent Stress, Crown

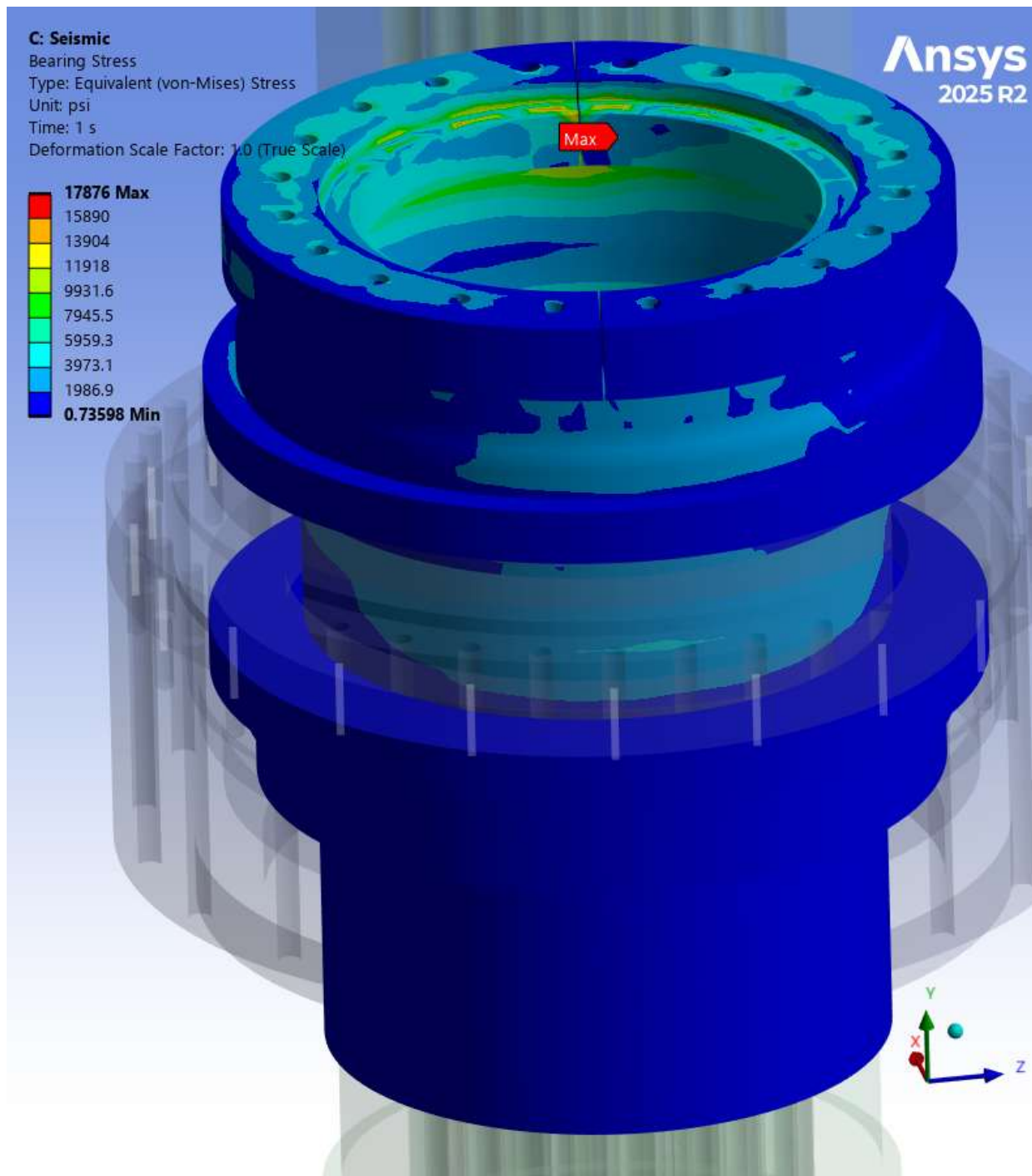


Figure 583 Crown and Drive, Seismic Equivalent Stress, Inner Components

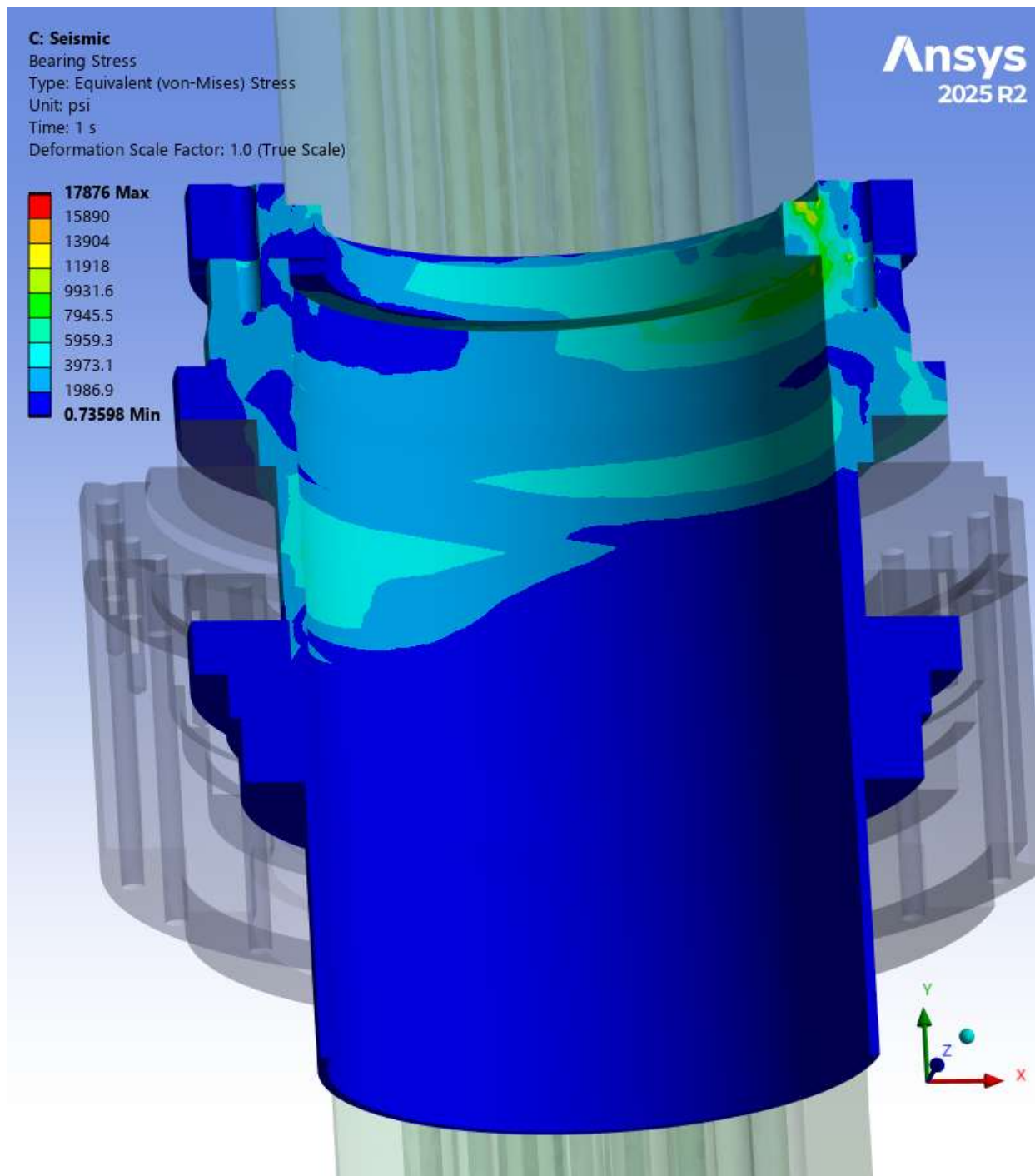


Figure 584 Crown and Drive, Seismic Equivalent Stress, Inner Components

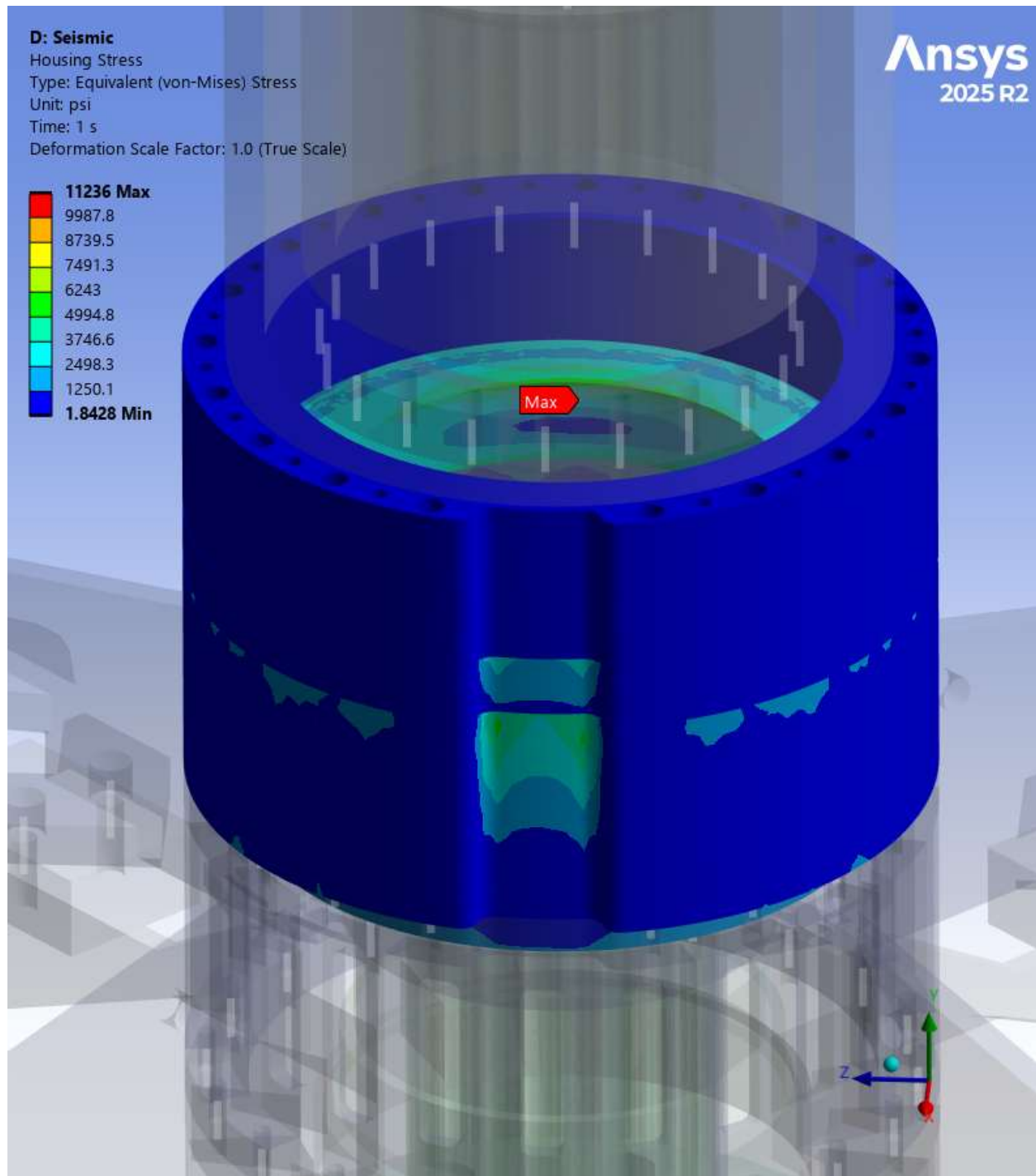


Figure 585 Crown and Drive, Seismic Equivalent Stress, Outer Housing

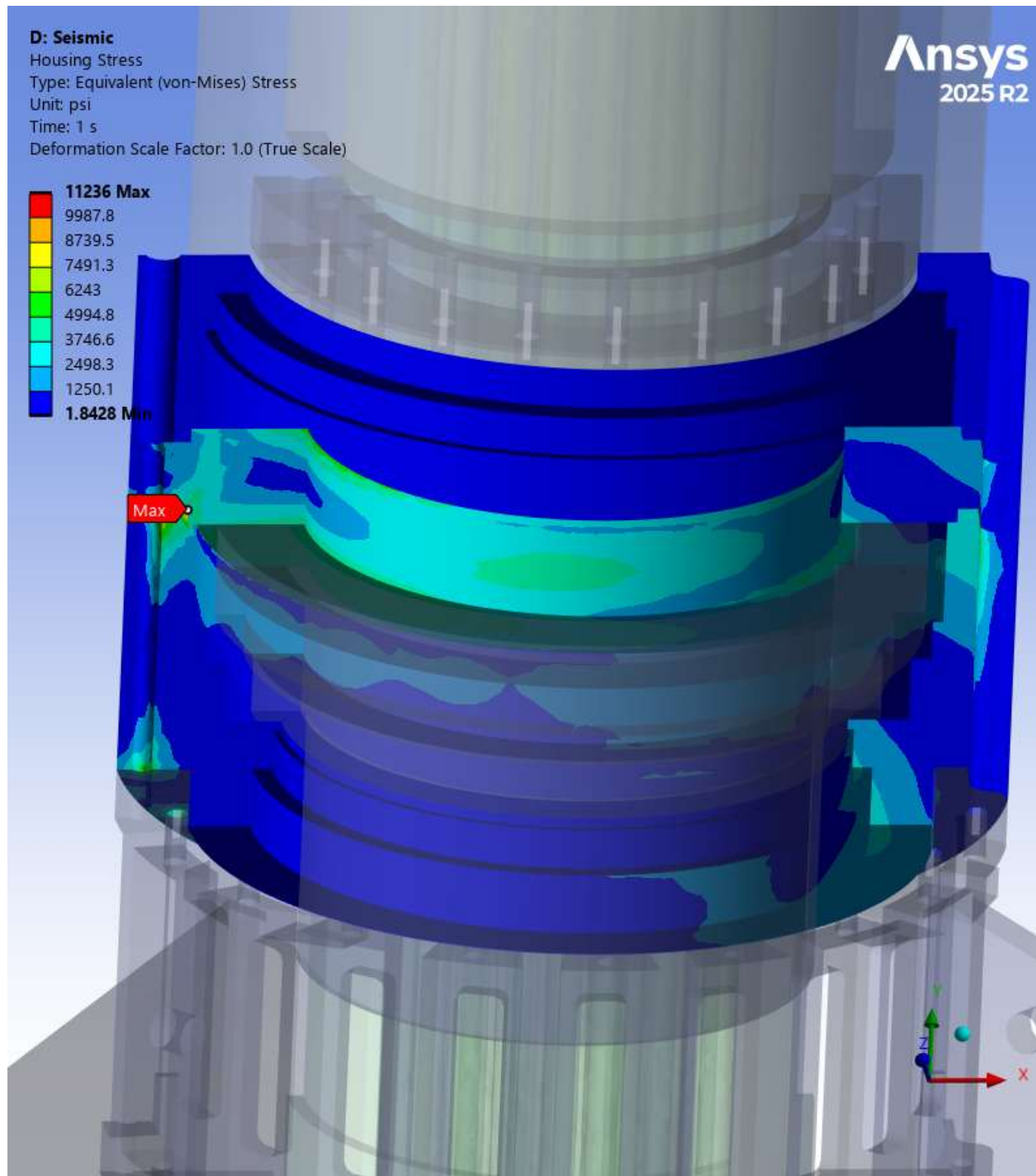


Figure 586 Crown and Drive, Seismic Equivalent Stress, Outer Housing

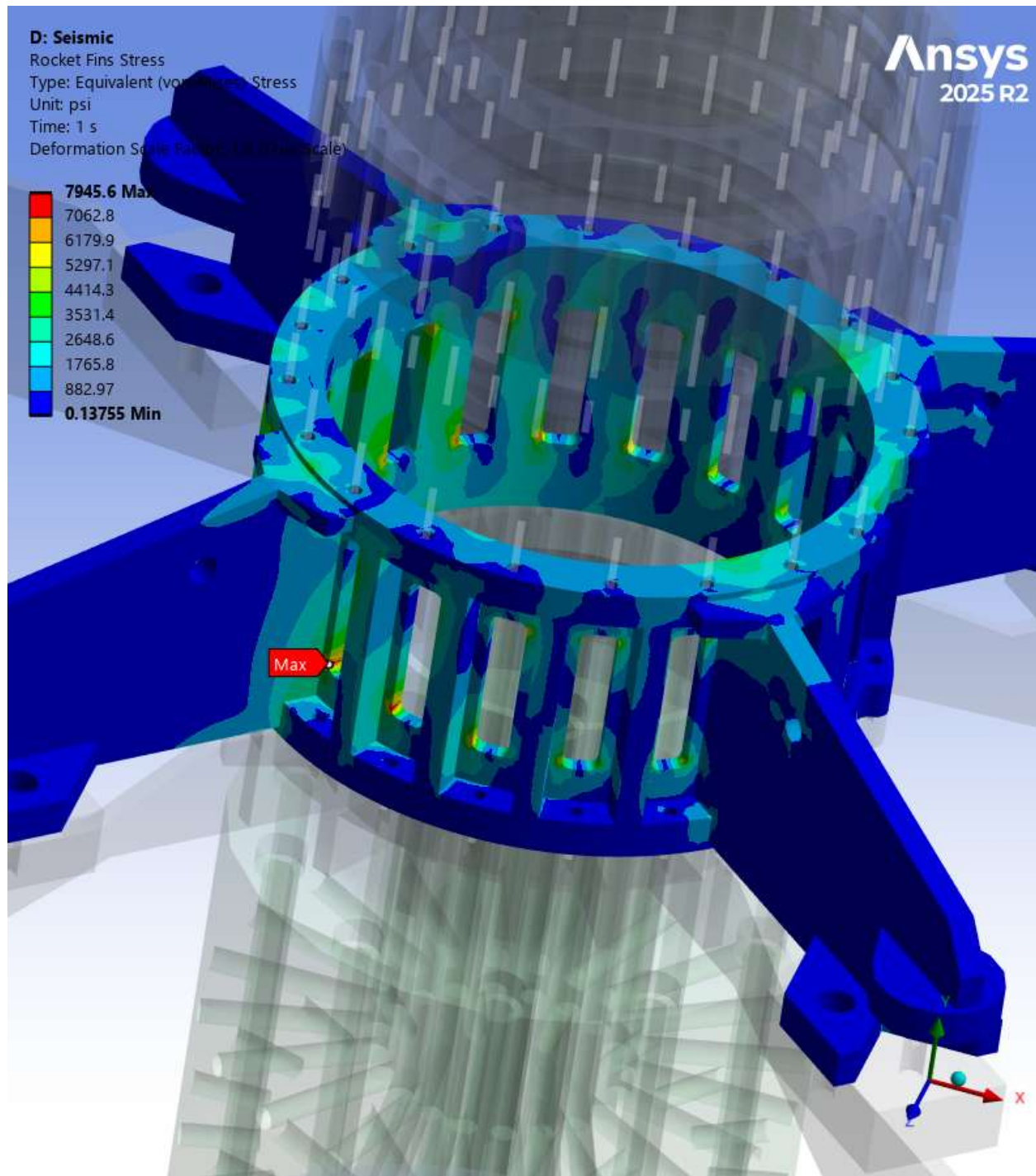


Figure 587 Crown and Drive, Seismic Equivalent Stress, Rocket Fins

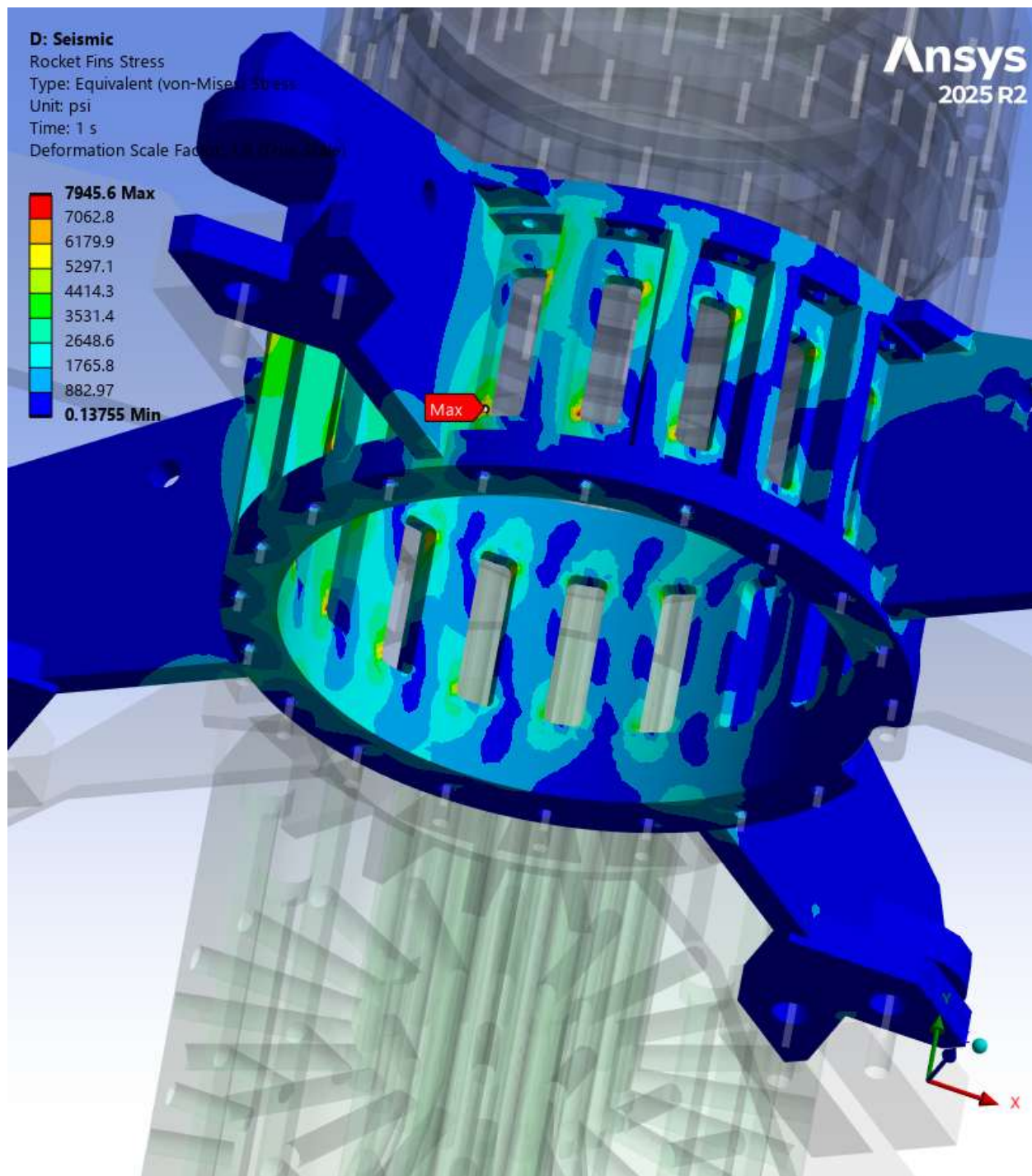


Figure 588 Crown and Drive, Seismic Equivalent Stress, Rocket Fins

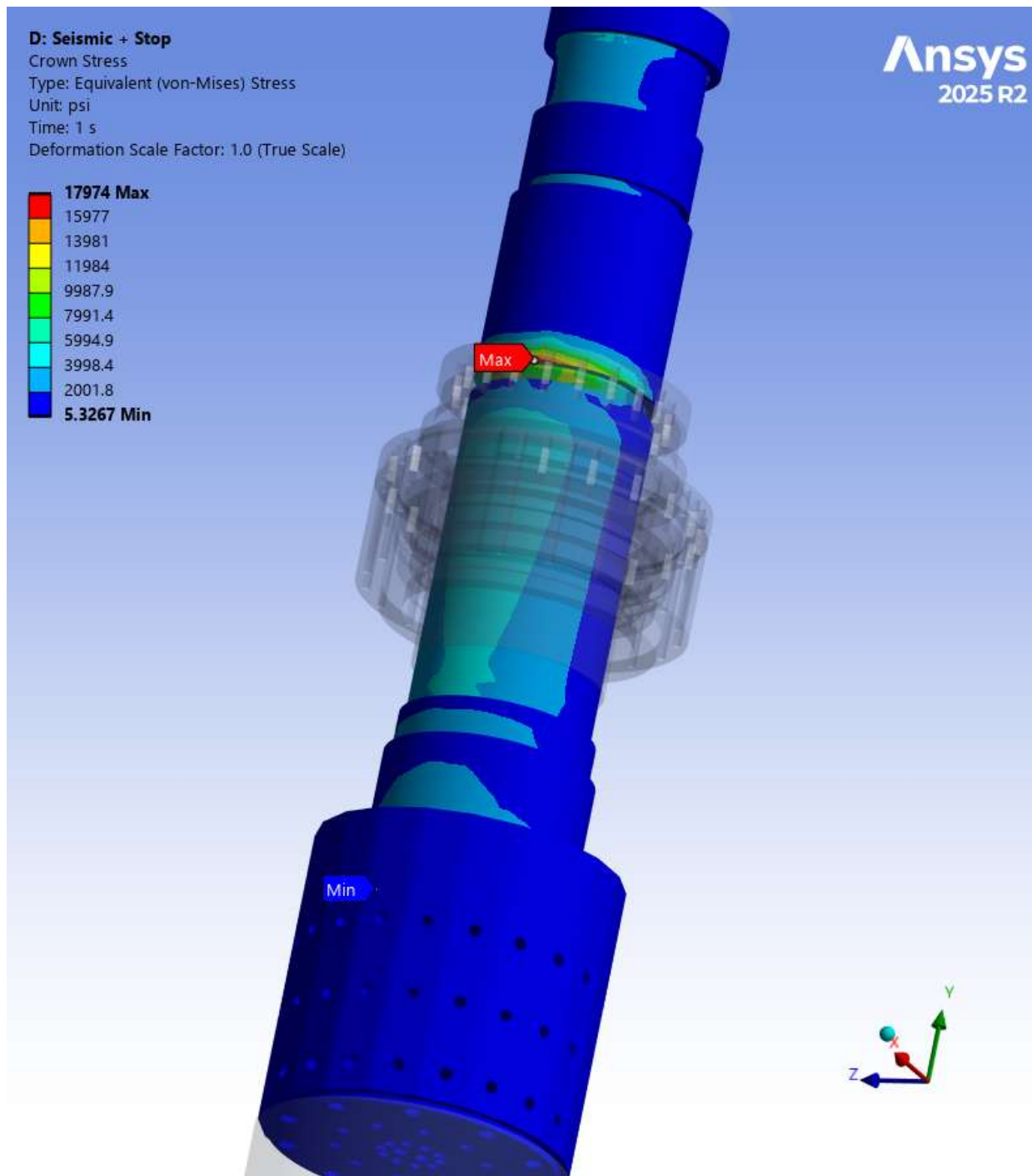


Figure 589 Crown and Drive, Seismic + Stop Equivalent Stress, Crown

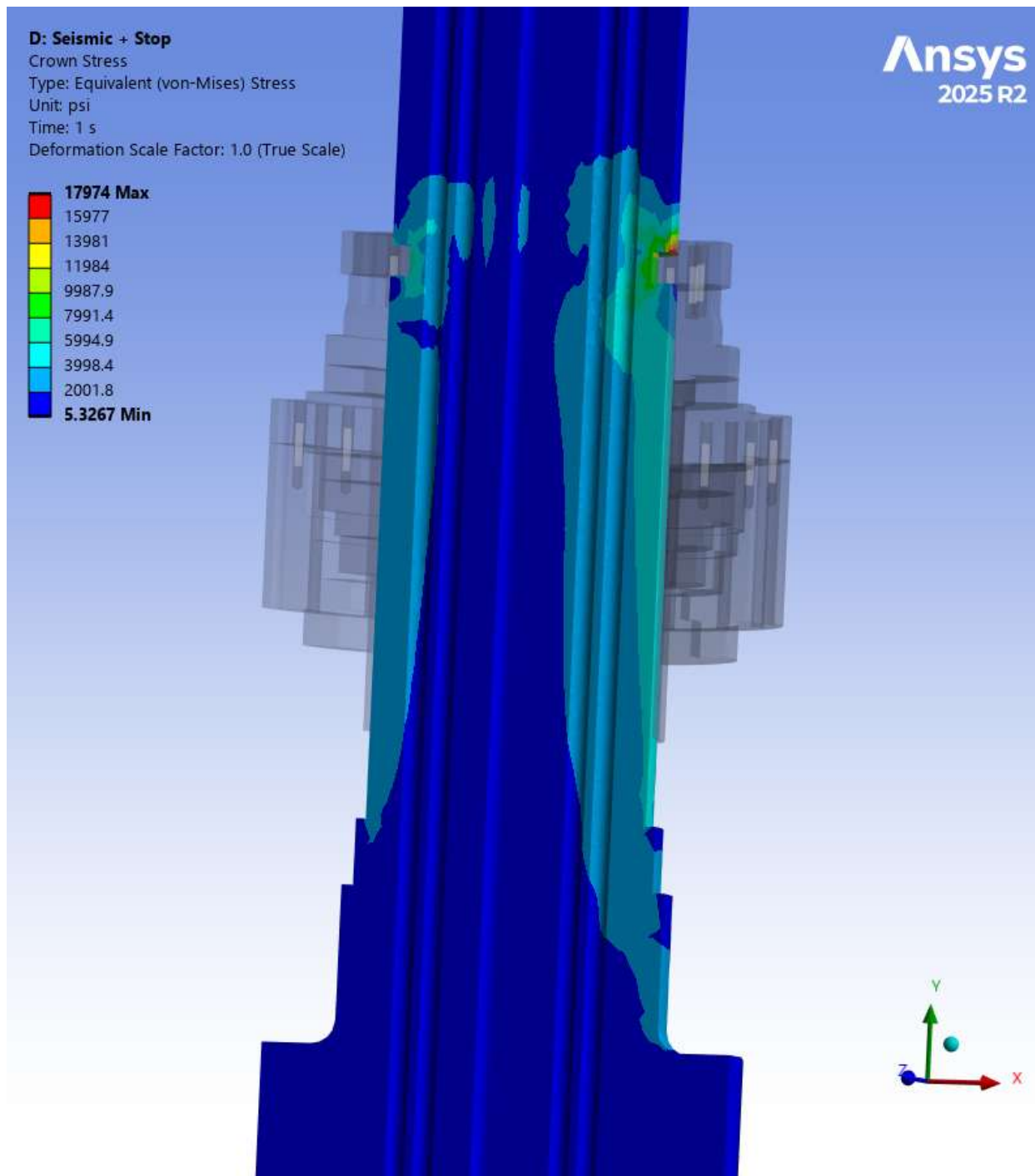


Figure 590 Crown and Drive, Seismic + Stop Equivalent Stress, Crown

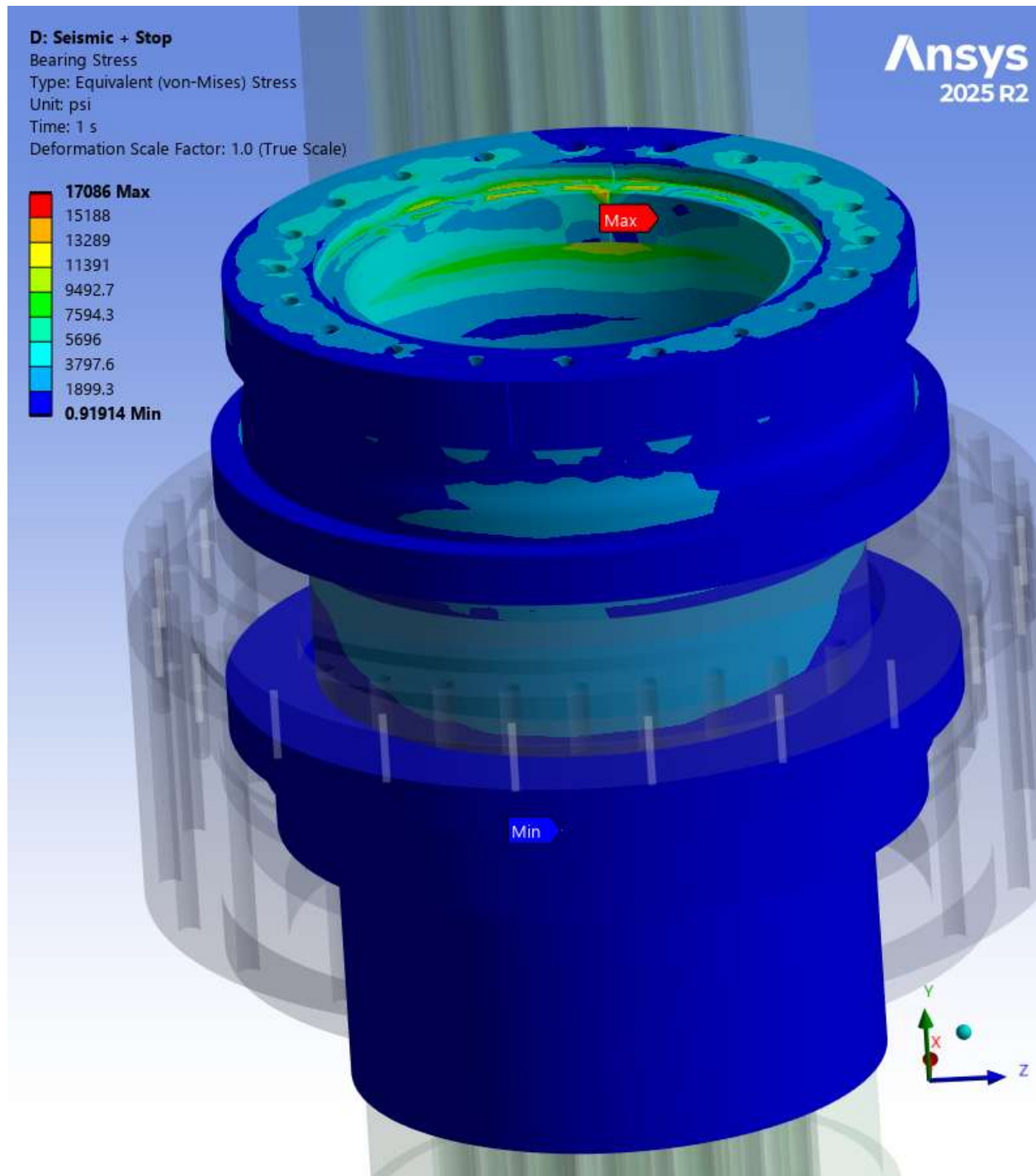


Figure 591 Crown and Drive, Seismic + Stop Equivalent Stress, Inner Components

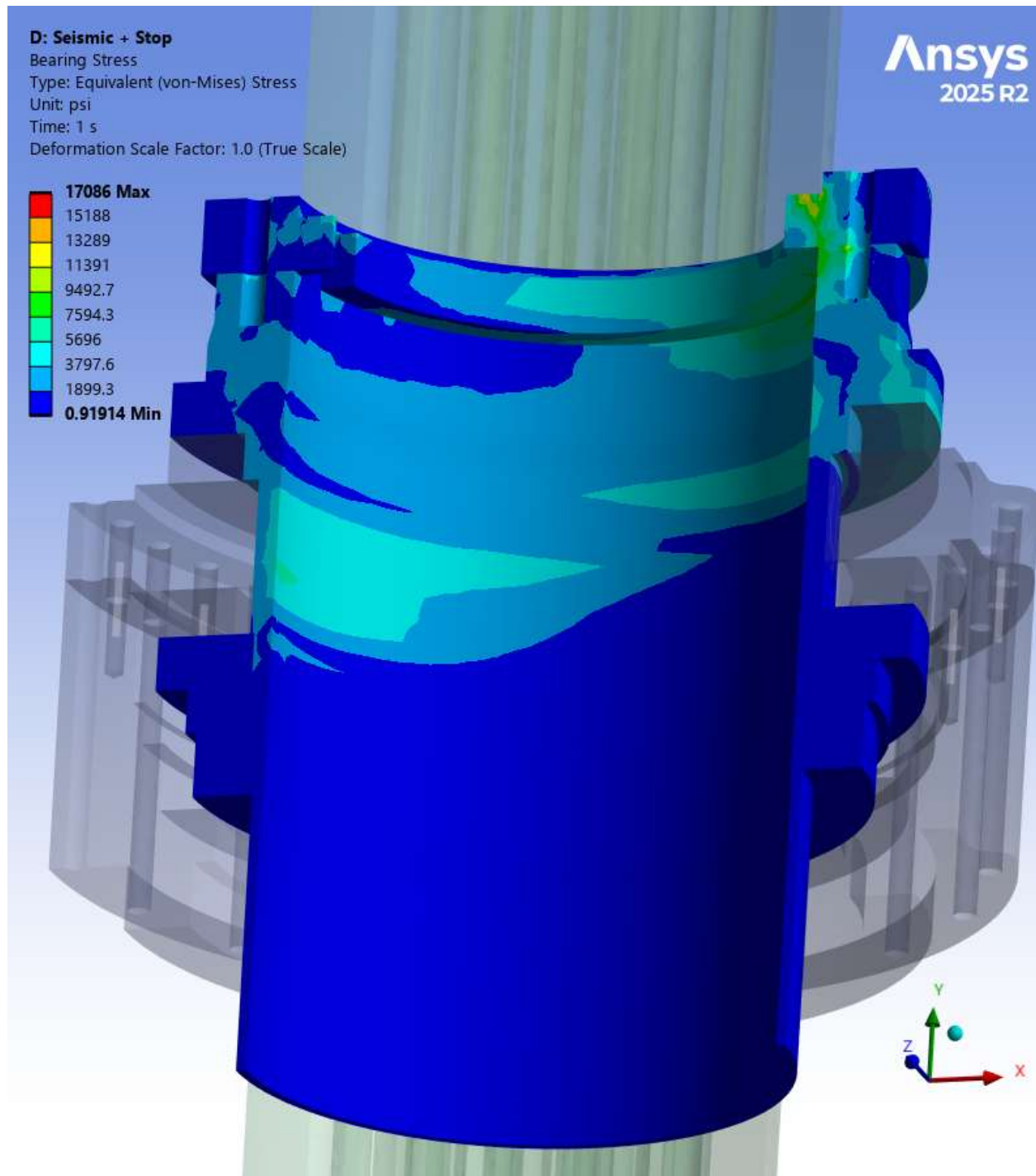


Figure 592 Crown and Drive, Seismic + Stop Equivalent Stress, Inner Components

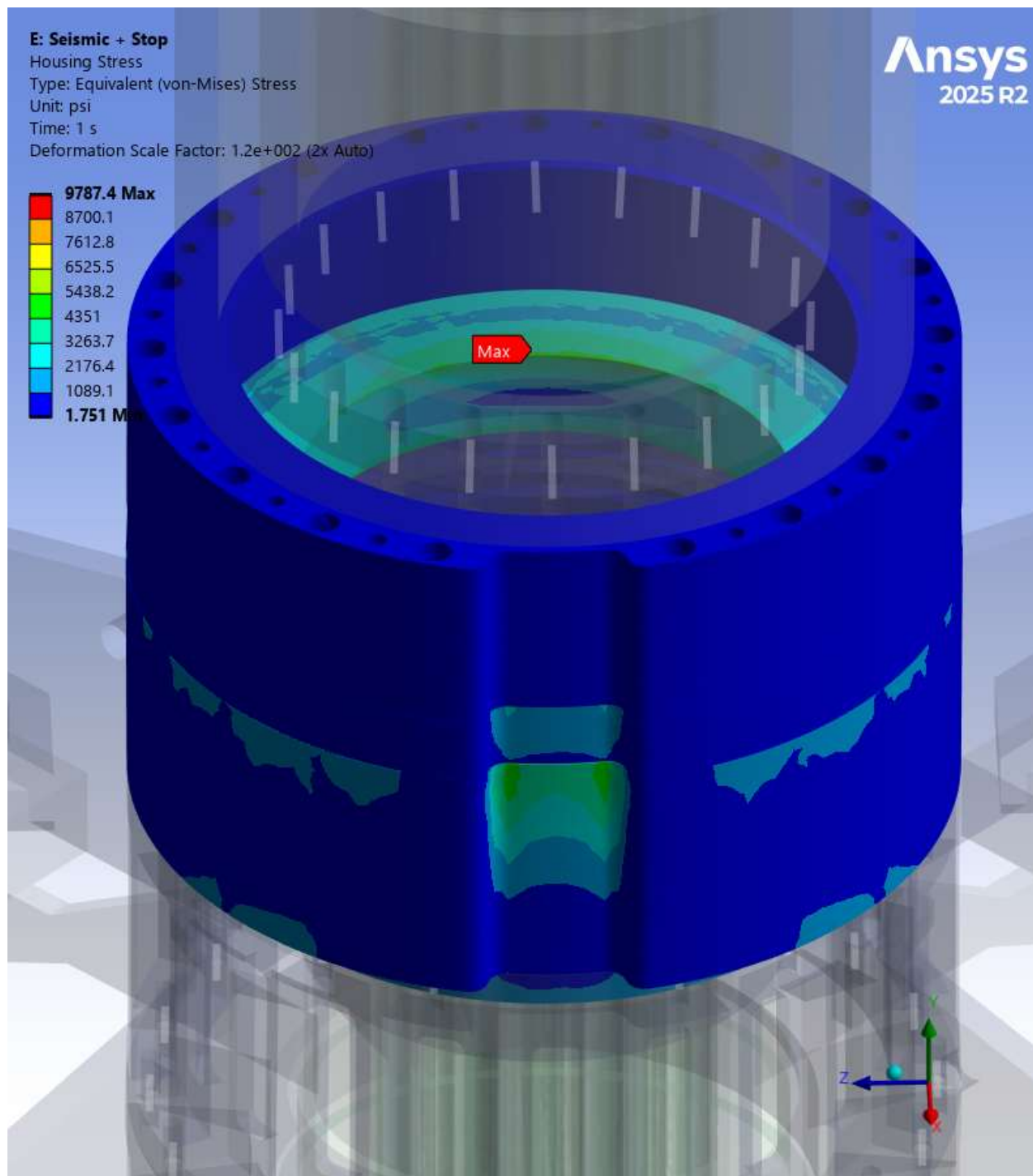


Figure 593 Crown and Drive, Seismic + Stop Equivalent Stress, Outer Housing

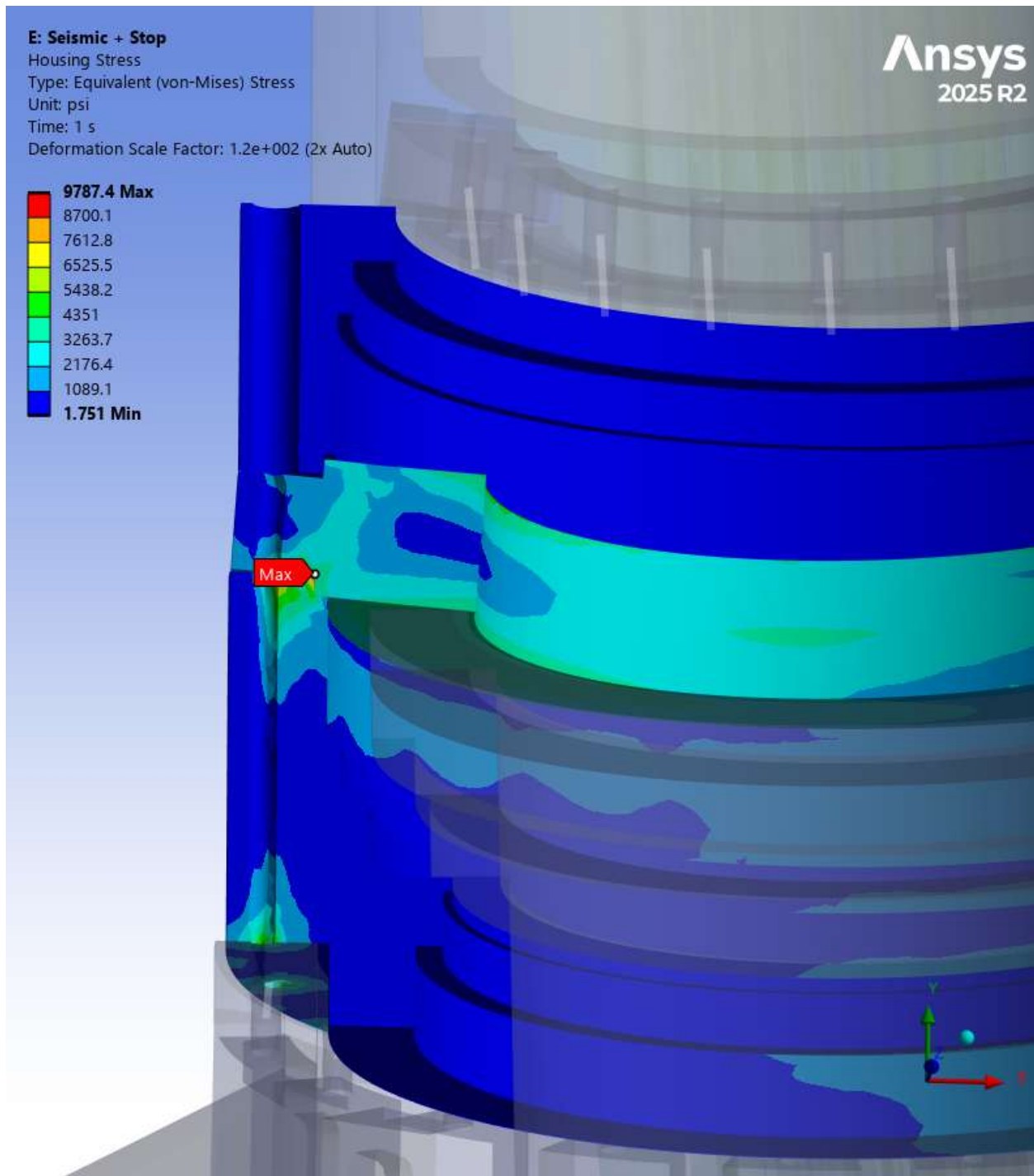


Figure 594 Crown and Drive, Seismic + Stop Equivalent Stress, Outer Housing

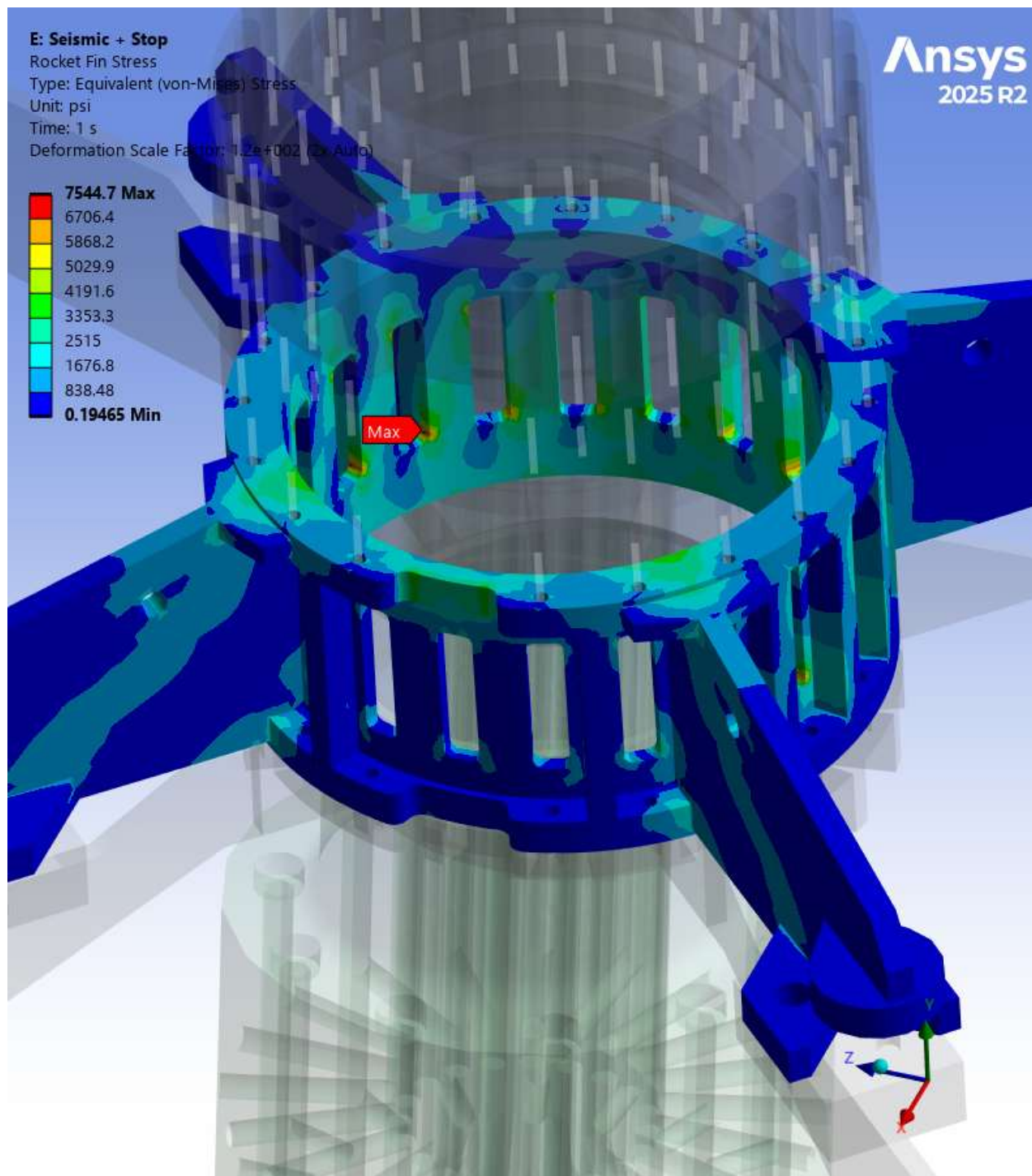


Figure 595 Crown and Drive, Seismic + Stop Equivalent Stress, Rocket Fins

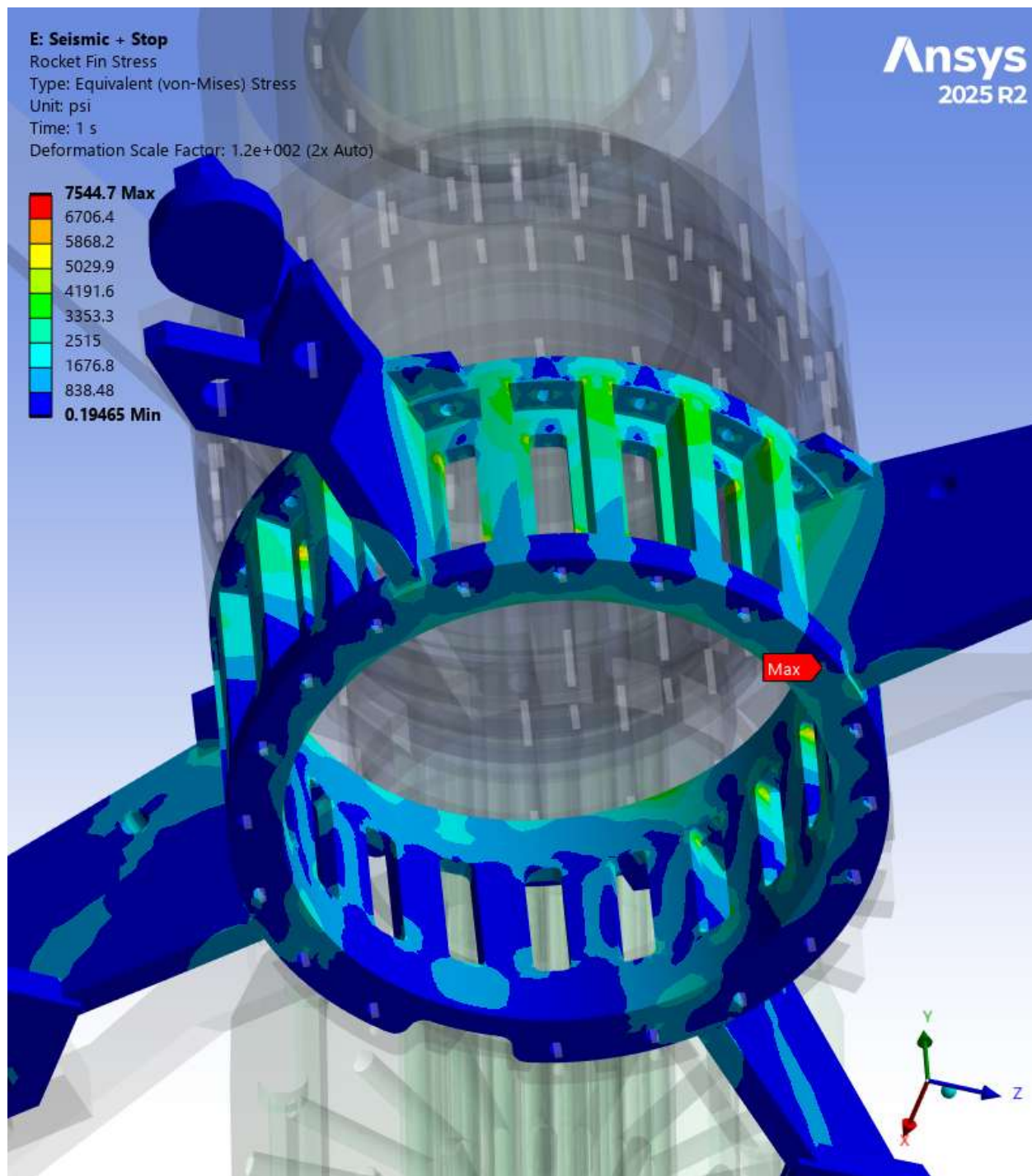


Figure 596 Crown and Drive, Seismic + Stop Equivalent Stress, Rocket Fins

5.1.4.5 Fasteners

The Drive model contains the majority of the fasteners analyzed in this report, only the Shaft Tie Rods and Segment bolts are not in this section. The following figures show the properties of the beam

connectors used, the location on the assembly and the nomenclature used on the results table to help with identification. Notes that no preload is used with these fasteners, the method for fastener calculation only uses axial and shear loads.

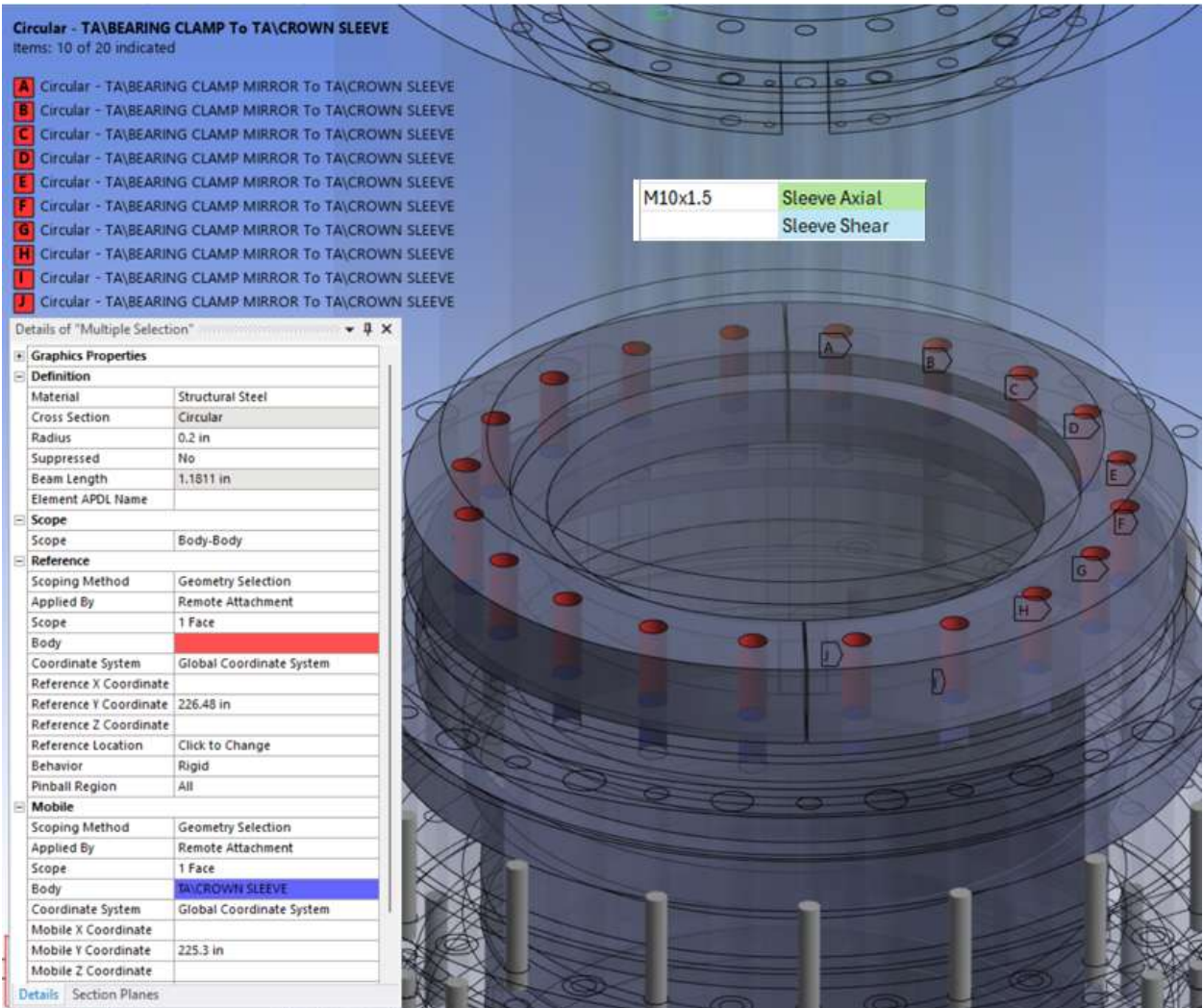


Figure 597 Clamp to Sleeve Fasteners

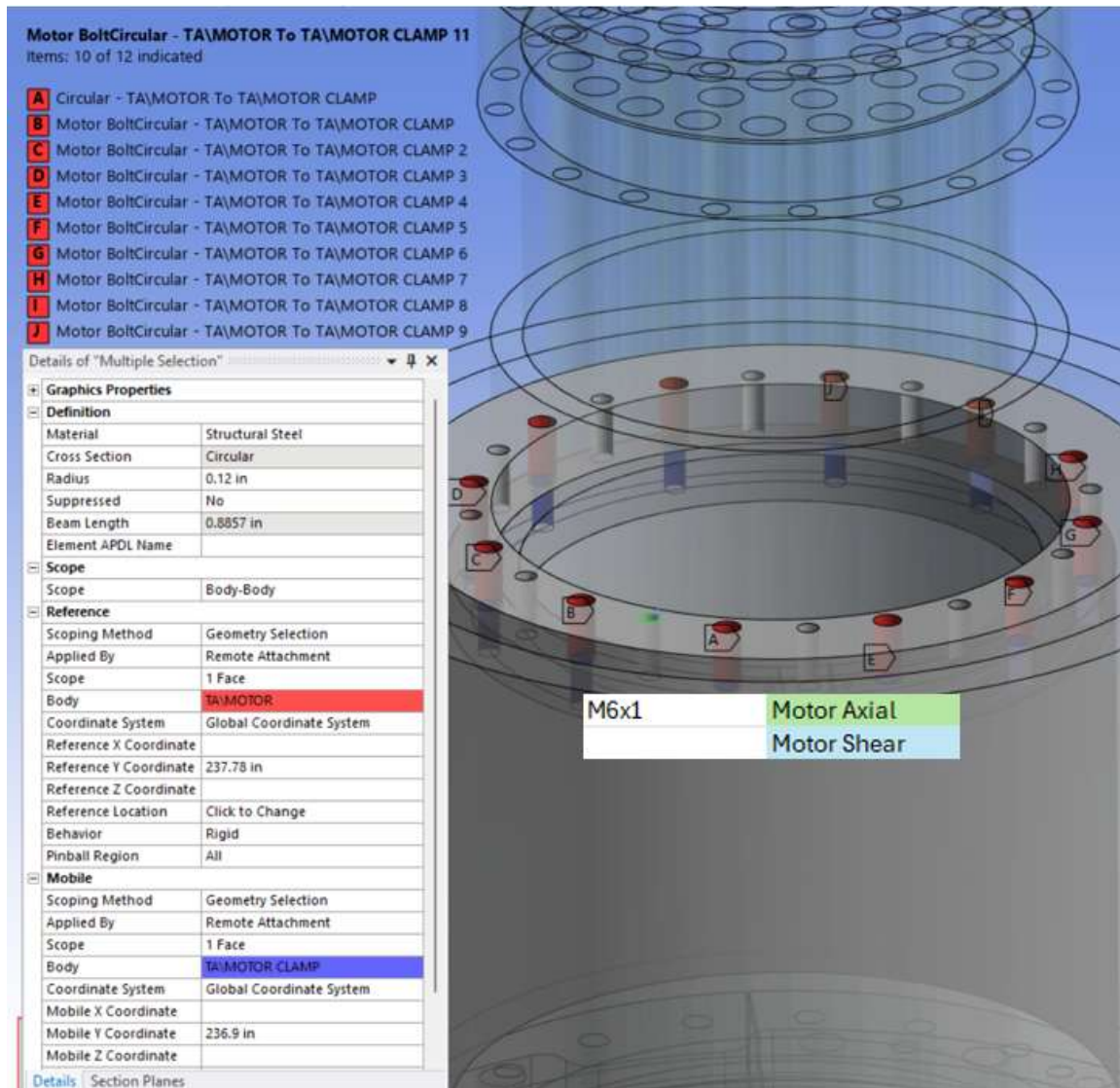


Figure 598 Motor to Motor Clamp Fasteners

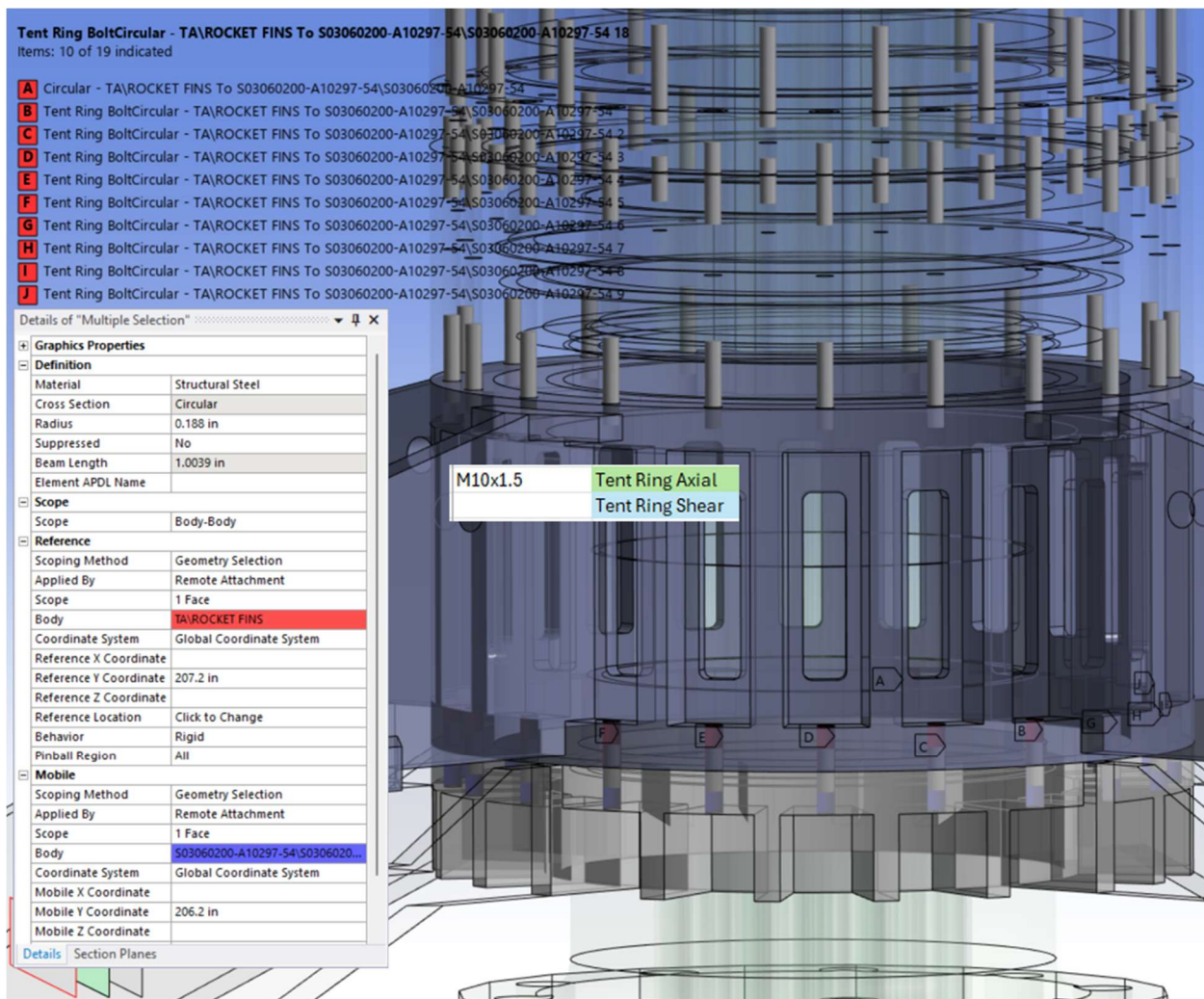


Figure 600 Tent to Rocket Fins Fasteners

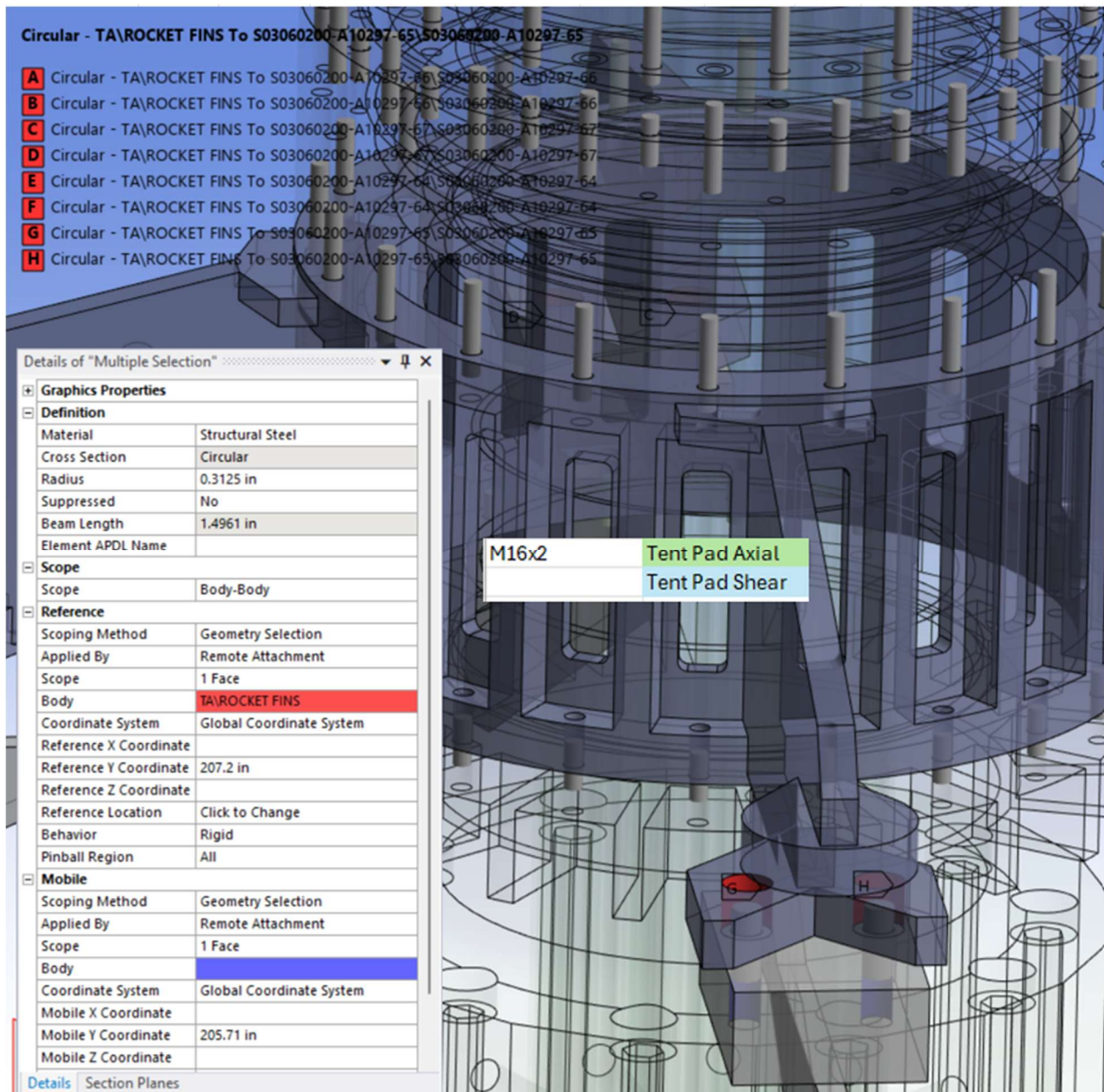


Figure 601 Tent Pad Fasteners

There are two bolted joints with more than two components bolted together, the left figure below shows the bearing race, lower housing and rocket fins fastened with one bolt. The figure on the right shows the upper housing, bearing race and lower housing connected with one bolt.

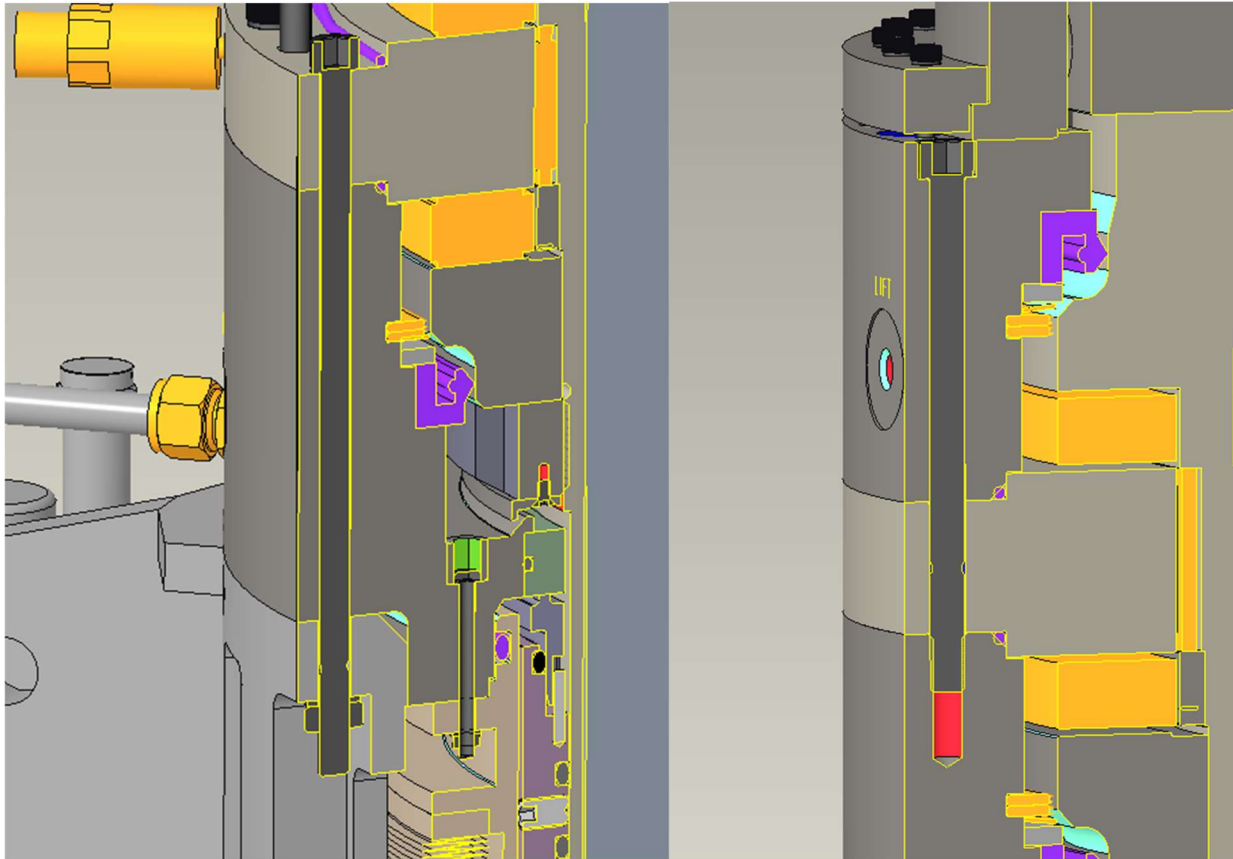


Figure 602 Fasteners for Multiple Components

The typical way of modeling fasteners with beam elements in FEA won't work in these cases. The middle component has no anchor to the beam element and is basically floating in the model, this could be addressed by using solid fastener but that would be computationally expensive. Instead, two beam fasteners are used and the results are combined.

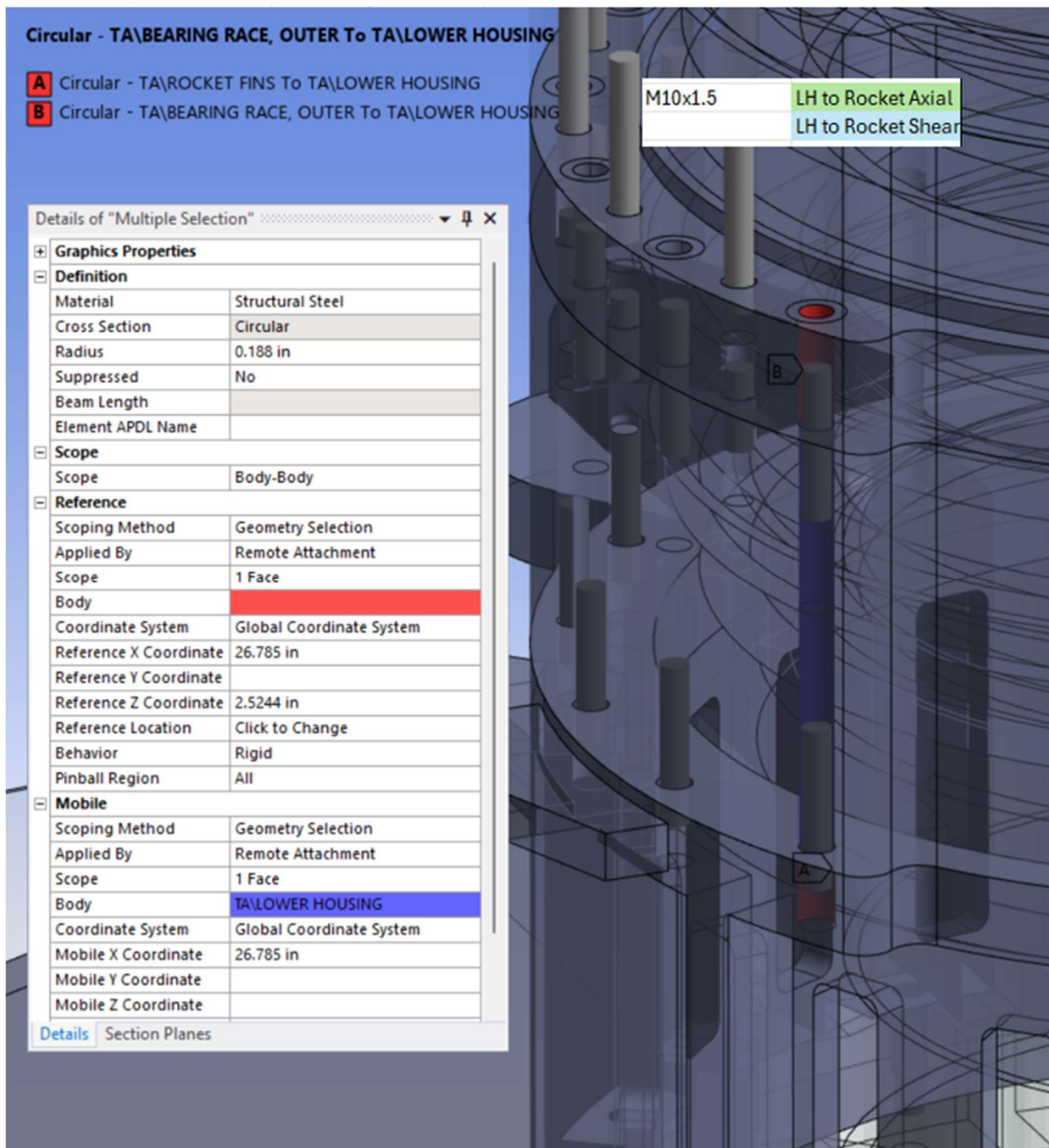
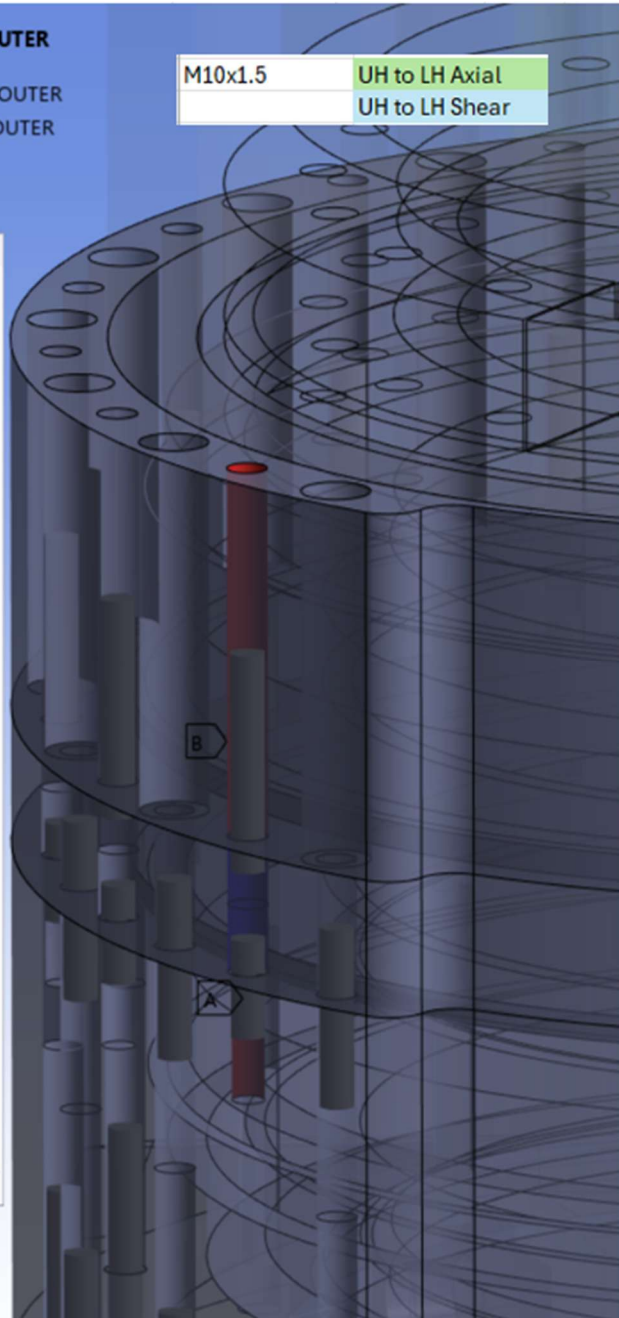
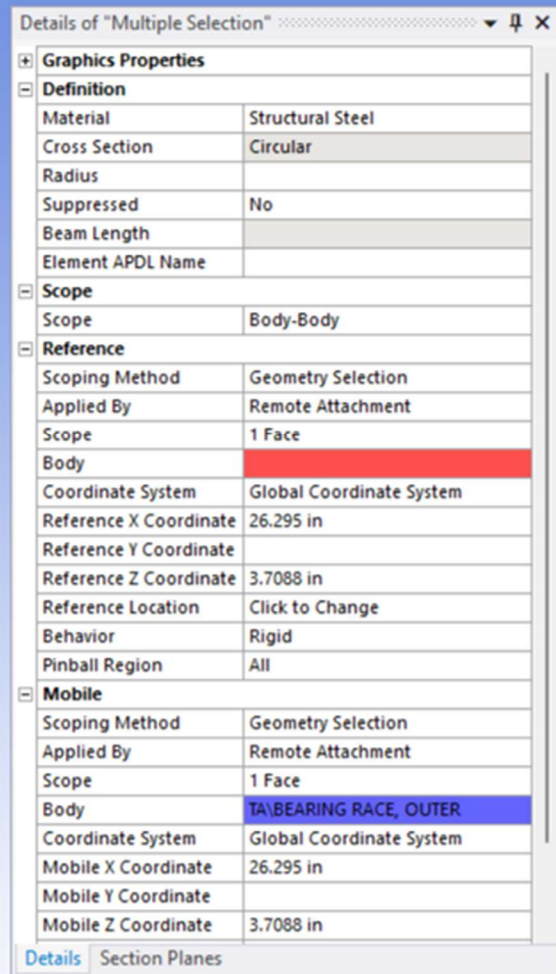


Figure 603 Bearing Race, Lower Housing, Rocket Fin Fastener

A Circular - TA\LOWER HOUSING To TA\BEARING RACE, OUTER
B Circular - TA\UPPER HOUSING To TA\BEARING RACE, OUTER

M10x1.5	UH to LH Axial
	UH to LH Shear



531

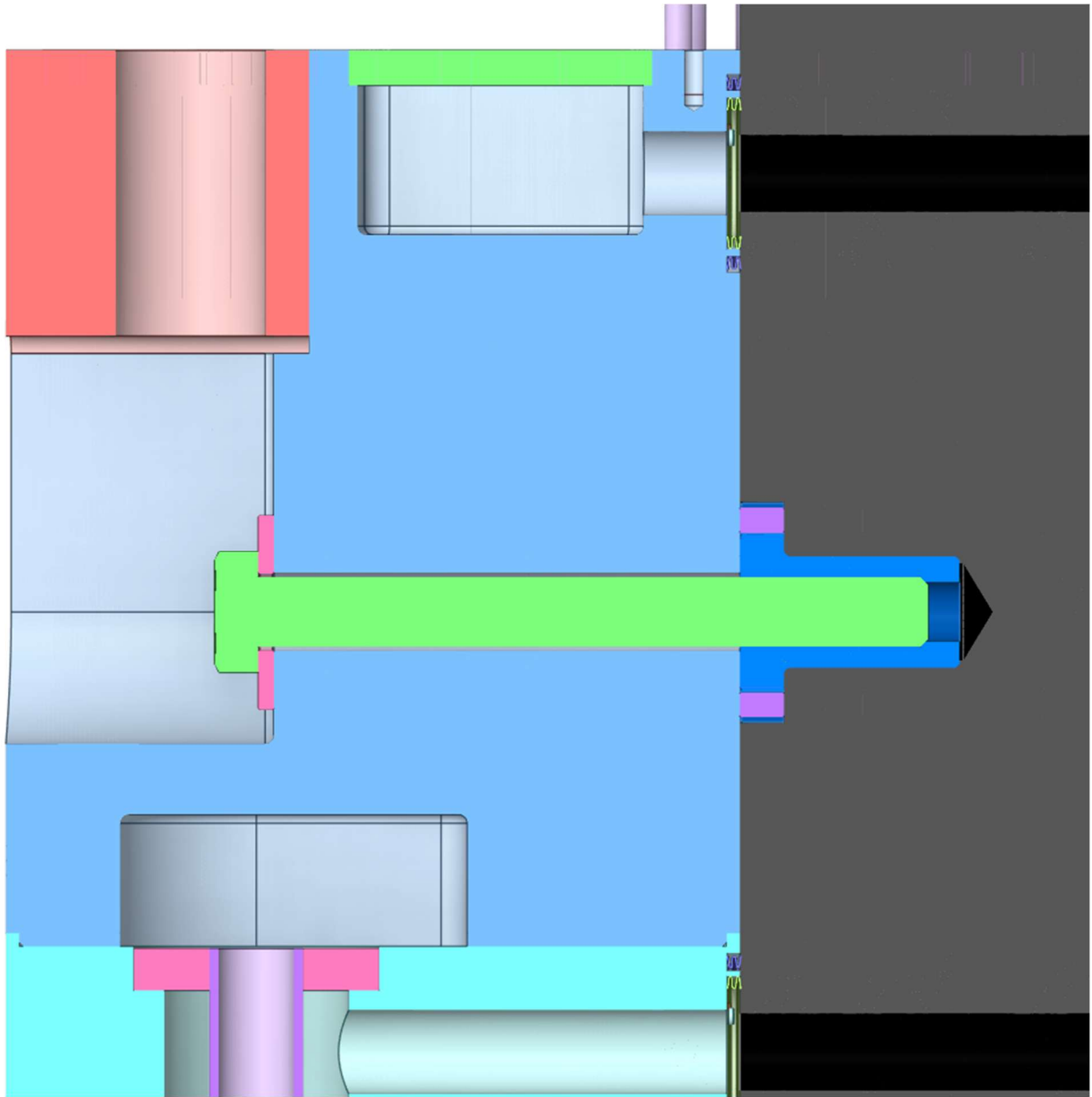


Figure 605 Segment Bolt and Crown Insert

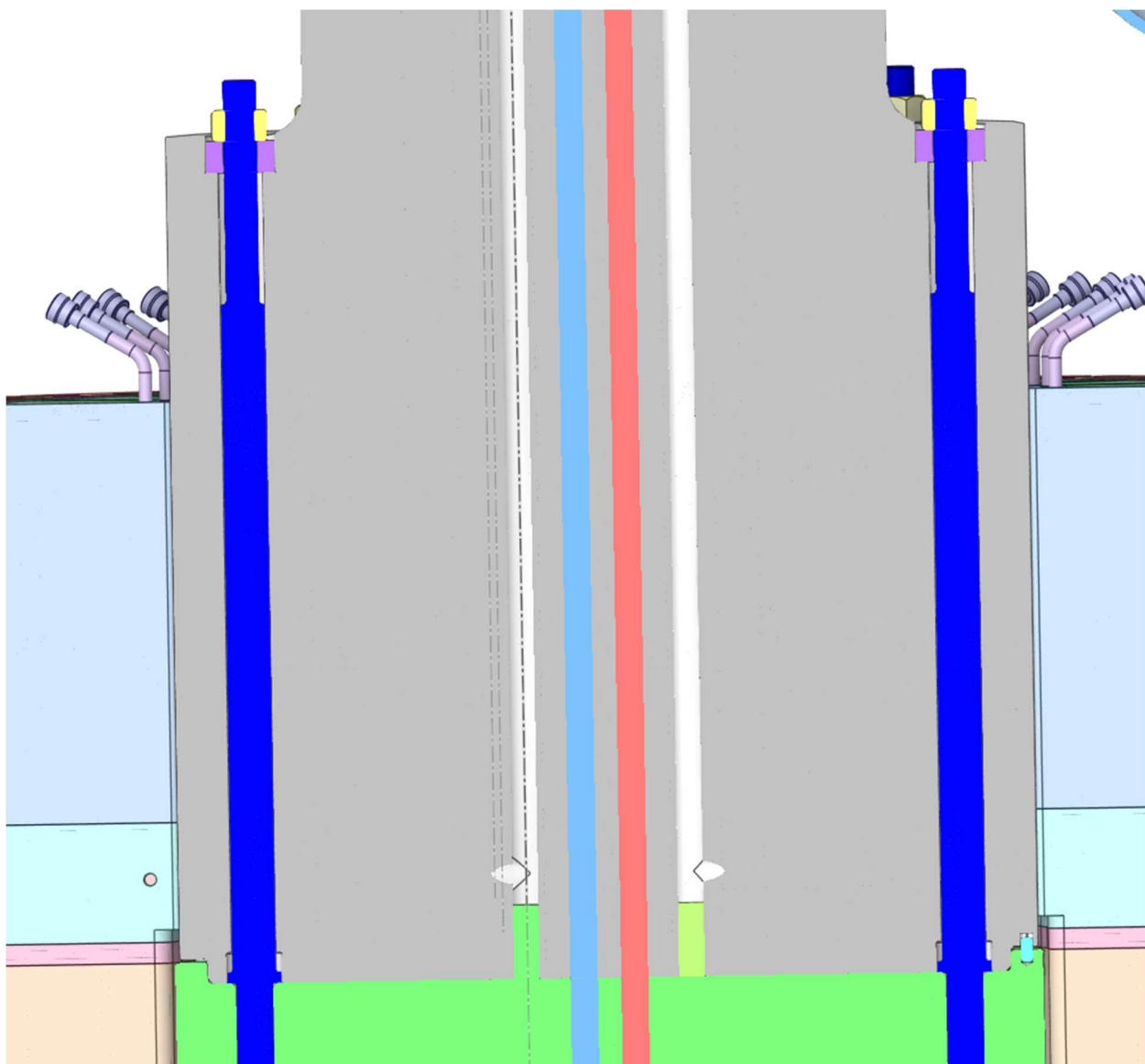


Figure 606 Tie Rods at the Crown

An example calculation of the Combined Tension and Shear stress on one of the fasteners is shown below, the method is Equation 5.2b from RCSC [8].

$$\left[\frac{T_a}{(R_n/\Omega)_t} \right]^2 + \left[\frac{V_a}{(R_n/\Omega)_v} \right]^2 \leq 1 \quad (\text{Equation 5.2b})$$

where

T_a = required strength in tension (service tensile load) per bolt, kips

V_a = required strength in shear (service shear load) per bolt, kips

$(R_n/\Omega)_t$ = allowable strength in tension determined in accordance with Section 5.1, kips

$(R_n/\Omega)_v$ = allowable strength in shear determined in accordance with Section 5.1, kips

Figure 607 Combined Tension and Shear Method

Taking the results from the first fastener in Table 36 the calculation for combined tension and shear is performed here.

Example Calculation for Sleeve Fasteners

Allowable Tensile $F_n := 113 \text{ ksi}$	Allowable Shear $F_v := 68 \text{ ksi}$
$d := 10 \text{ mm}$	M10 x 1.5 Bolt
$A_b := \frac{\pi}{4} \cdot d^2 = 0.122 \text{ in}^2$	
$\Omega := 2.0$	
$R_n := F_n \cdot A_b = 13756 \text{ lbf}$	$T_a := 401 \text{ lbf}$
$R_v := F_v \cdot A_b = 8278 \text{ lbf}$	$V_a := 128 \text{ lbf}$
$\left(\frac{T_a}{\left(\frac{R_n}{\Omega} \right)} \right)^2 + \left(\frac{V_a}{\left(\frac{R_v}{\Omega} \right)} \right)^2 = 0.004$	

Figure 608 Fastener Example Calculation

Next, because this fastener uses a threaded hole instead of a nut, the pullout strength of the threaded hole is calculated and checked against the applied tensile force. Thread shear area comes from NASA torque charts [9].

Crown Sleeve

$$P_{Sleeve} := \frac{\pi \cdot d_{M10} \cdot L_{e_Sleeve} \cdot F_{su_100CrMo73}}{3} = 22638 \text{ lbf}$$

$$T_a := 401 \text{ lbf}$$

$$\frac{T_a}{P_{Sleeve}} = 0.018$$

Figure 609 Thread Pullout Example

Finally, to check fatigue strength, the allowable stress is tabulated in Table 5.3 in the RCSC [8]. The number of cycles is greater than 500,000 so 38ksi is used. Computing the fastener stress from the tensile force the margin on fatigue can be determined.

Allowable Fatigue

$$F_f := 38 \text{ ksi}$$

Applied Stress

$$F_a := \frac{T_a}{A_b} = 3294 \text{ psi}$$

Fatigue Margin

$$\frac{F_a}{F_f} = 0.09$$

Figure 610 Fastener Fatigue Example

The remaining information on the fastener calculations can be found in the Appendix. The following result tables are a summary of the margins just discussed applied to the highest fastener load out of each group of fasteners.

Table 36 E Stop Fastener Results

E Stop	Size	Location	Applied Force	Allowable Force	Combined Tension + Shear	Allowable Pullout Force	Thread Pullout		Fatigue
					Margin <1 OK		Margin <1 OK	Stress Area	
M10x1.5		Sleeve Axial	401	13756	0.004	22304	0.018	0.12	3290
		Sleeve Shear	128	8278					0.09
M6x1		Motor Axial	3	4952	0.000	5442	0.001	0.04	70
		Motor Shear	5	2980					0.00
M10x1.5		Manifold Axial	1	13756	0.002	17377	0.000	0.12	7
		Manifold Shear	177	8278					0.00
M10x1.5		Tent Ring Axial	68	13756	0.000	Nut		0.12	557
		Tent Ring Shear	72	8278					0.01
M16x2		Tent Pad Axial	6	35216	0.0002	11027	0.001	0.31	20
		Tent Pad Shear	141	21192					0.00
M10x1.5		LH to Rocket Axial	35	13756	0.000	Nut		0.12	291
		LH to Rocket Shear	14	8278					0.01
M10x1.5		UH to LH Axial	287	13756	0.002	14381	0.020	0.12	2349
		UH to LH Shear	24	8278					0.06
Tie Rod		Max Tension	1156.9	35216	0.007	33080	0.035	0.31	3708
		Max Shear	557	21192					0.10
Segment Bolt/ Crown Insert		Max Tension	768	35216	0.010	33080	0.023	0.31	2462
		Max Shear	933	21192					0.06
Crown Insert		Max Tension	768			47665	0.016		
External		Max Shear	933		Bound by Internal Thread limit				

Table 37 Seismic Fastener Results

Seismic	Size	Location	Applied Force	Allowable Force	Combined Tension + Shear	Allowable Pullout Force	Thread Pullout
					Margin <1 OK		Margin <1 OK
M10x1.5		Sleeve Axial	2261	13756	0.121	22304	0.101
		Sleeve Shear	466	8278			
M6x1		Motor Axial	1	4952	0.000	5442	0.000
		Motor Shear	3	2980			
M10x1.5		Manifold Axial	123	13756	0.000	17377	0.007
		Manifold Shear	4	8278			
M10x1.5		Tent Ring Axial	118	13756	0.006	Nut	
		Tent Ring Shear	300	8278			
M16x2		Tent Pad Axial	259	35216	0.003	11027	0.023
		Tent Pad Shear	559	21192			
M10x1.5		LH to Rocket Axial	671	13756	0.010	Nut	
		LH to Rocket Shear	80	8278			
M10x1.5		UH to LH Axial	706	13756	0.013	14381	0.049
		UH to LH Shear	202	8278			
Tie Rod		Max Tension	1592	35216	0.012	33080	0.048
		Max Shear	637	21192			
Segment Bolt/ Crown Insert		Max Tension	356	35216	0.014	33080	0.011
		Max Shear	1246	21192			
Crown Insert External		Max Tension	356			47665	0.007
		Max Shear	1246	Bound by Internal Thread limit			

Table 38 Seismic + Stop Fastener Results

Seismic + Stop				Combined Tension + Shear		Thread Pullout
Size	Location	Applied Force	Allowable Force	Margin <1 OK	Allowable Pullout Force	Margin <1 OK
M10x1.5	Sleeve Axial	1485	13756	0.055	22304	0.067
	Sleeve Shear	388	8278			
M6x1	Motor Axial	4	4952	0.000	5442	0.001
	Motor Shear	8	2980			
M10x1.5	Manifold Axial	1444	13756	0.044	17377	0.083
	Manifold Shear	48	8278			
M10x1.5	Tent Ring Axial	1	13756	0.006	Nut	
	Tent Ring Shear	313	8278			
M16x2	Tent Pad Axial	283	35216	0.004	11027	0.026
	Tent Pad Shear	648	21192			
M10x1.5	LH to Rocket Axial	295	13756	0.002	Nut	
	LH to Rocket Shear	78	8278			
M10x1.5	UH to LH Axial	615	13756	0.010	14381	0.043
	UH to LH Shear	186	8278			
Tie Rod	Max Tension	1604	35216	0.012	33080	0.049
	Max Shear	666	21192			
Segment Bolt/ Crown Insert	Max Tension	644	35216	0.014	33080	0.019
	Max Shear	1211	21192			
Crown Insert	Max Tension	644			47665	0.014
External	Max Shear	1211	Bound by Internal Thread limit			

5.1.4.6 Snubber results

There is no failure criteria for the Target weight sitting on the Snubber ring, a plot of total deformation and of equivalent stress are shown.

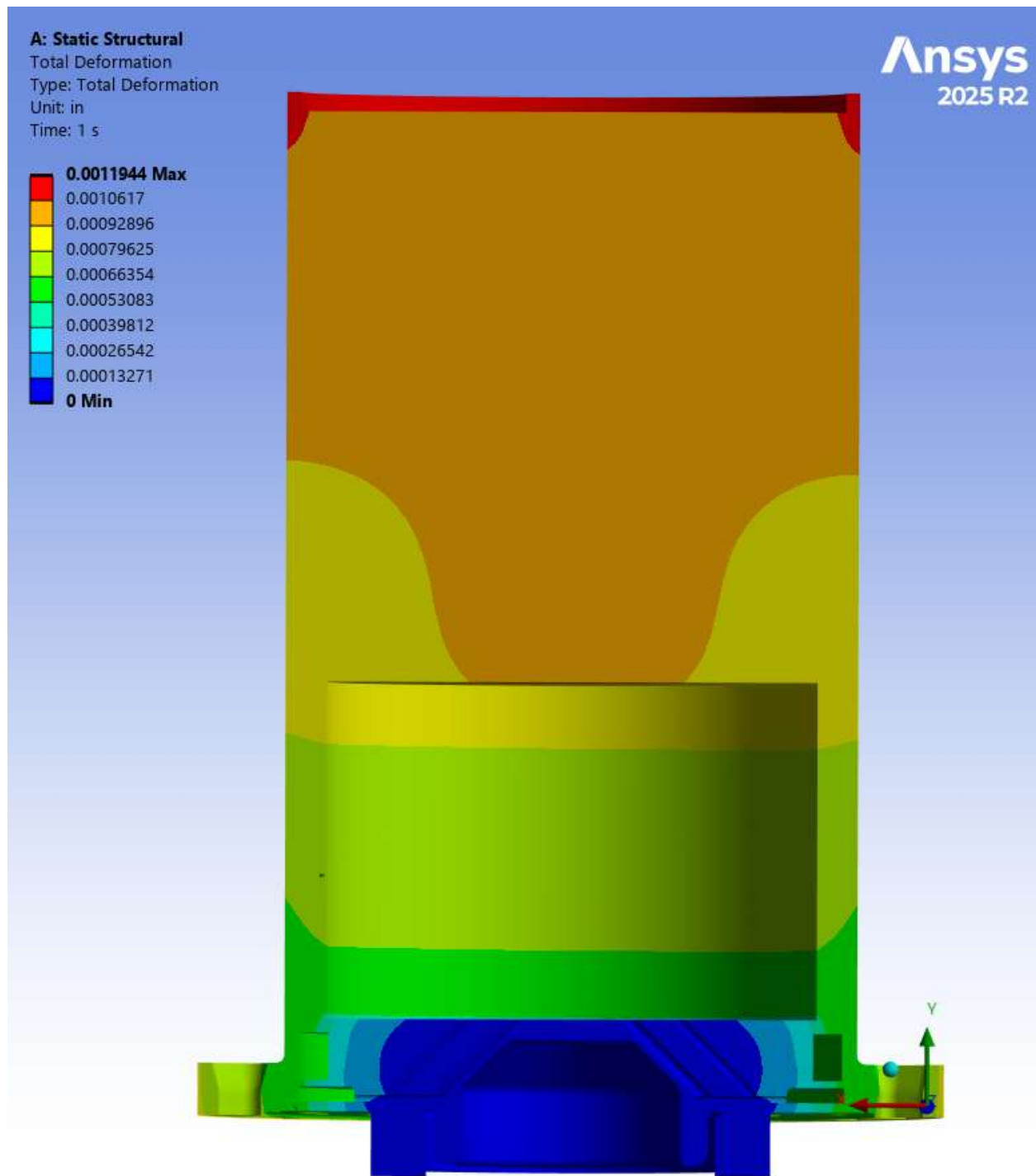


Figure 611 Snubber Deformation

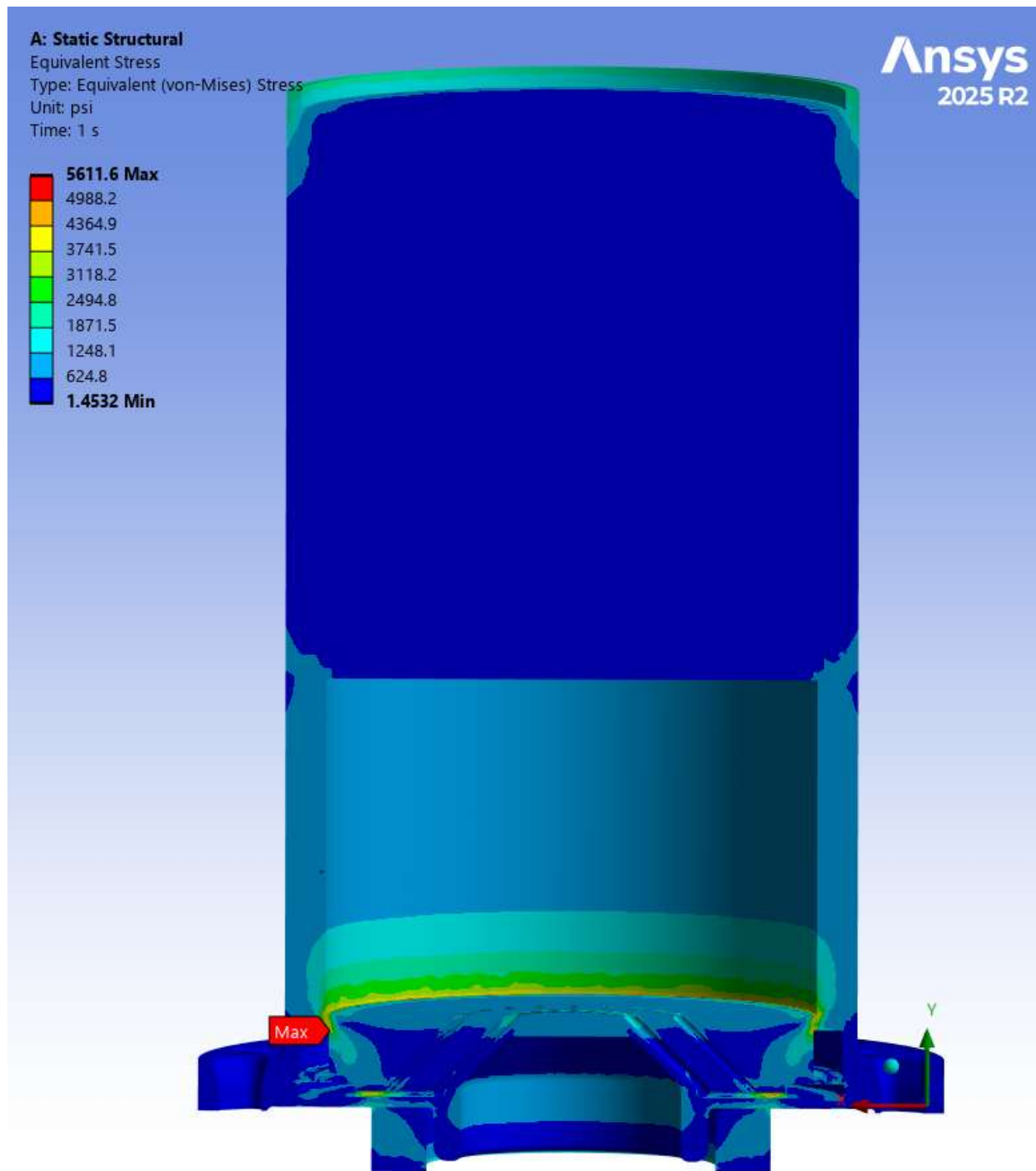


Figure 612 Snubber Equivalent Stress

5.1.5 Result Summary

Table 39 Target Assembly Result Summary

Target Assembly	Load Case	Plot	Requirement
	E Stop	Total Deformation	3297, 2085, 3006
		X Deformation	3297, 2085, 3006
		Y Deformation	3297, 2085, 3006
		Z Deformation	3297, 2085, 3006
	Seismic	Total Deformation	3297, 2085, 3006
		X Deformation	3297, 2085, 3006
		Y Deformation	3297, 2085, 3006
		Z Deformation	3297, 2085, 3006
	Seismic + Stop	Total Deformation	3297, 2085, 3006
		X Deformation	3297, 2085, 3006
		Y Deformation	3297, 2085, 3006
		Z Deformation	3297, 2085, 3006

Table 40 Segment Result Summary

Segment	Load Case	Criteria	Component	Requirement
	E Stop	Ratcheting, Plastic Strain	Segment	1600, 1605, 1693, 1543, 3006
			Foot Pin	1600, 1605, 1543, 3006
	Cyclic		Segment	1574, 3006, 1600
			Foot Pin	1574, 3006, 1600
	Seismic	Ratcheting, Plastic Strain	Segment X	1600, 3006
			Segment Z	1600, 3006
	Seismic + Stop	Ratcheting, Plastic Strain	Segment X	1600, 3006
			Segment Z	1600, 3006
	EP1	Local Failure	Segment	1600, 3006
			Foot Pin	1600, 3006
		Plastic Collapse	Plot	1600, 3006

EP2	Local Failure	Segment	1600, 3006
		Foot Pin	1600, 3006
	Plastic Collapse	Plot	1600, 3006
EP5	Local Failure	Segment X	1600, 3006
		Foot Pin X	1600, 3006
		Segment Z	1600, 3006
		Foot Pin Z	1600, 3006
	Plastic Collapse	Plot X	1600, 3006
		Plot Z	1600, 3006

Table 41 Shaft Result Summary

Shaft	Load Case	Criteria	Component	Requirement
E Stop	Ratcheting		Top Section	1687, 1694, 1543, 3006
			Upper Mid-Section	1687, 1694, 1543, 3006
			Lower Mid-Section	1687, 1694, 1543, 3006
			Bottom Section	1687, 1694, 1543, 3006
	Cyclic		Tie Rods	1677, 1687, 3006, 1447
			Shaft	1677, 1687, 3006, 1447
	Seismic	Ratcheting	Top Section	1687, 3006
			Upper Mid-Section	1687, 3006
			Lower Mid-Section	1687, 3006
			Bottom Section	1687, 3006
Seismic+Stop	Ratcheting		Top Section	1687, 3006
			Upper Mid-Section	1687, 3006
			Lower Mid-Section	1687, 3006
			Bottom Section	1687, 3006
	Local Failure		Shaft	1687, 3006
EP1	Plastic Collapse			

EP2		Plot	1687, 3006
	Local Failure		
EP5		Shaft	1687, 3006
	Plastic Collapse		
		Plot	1687, 3006
	Local Failure		
		Shaft	1687, 3006
	Plastic Collapse		
		Plot	1687, 3006

Table 42 Drive Result Summary

Drive	Load Case	Criteria	Component	Requirement
	Estop	Ratcheting	Crown	3006, 1666, 1543
			Inner Housing	3006, 1666, 1543
			Outer Housing	3006, 1666, 1543
			Rocket Fins	3006, 1666, 1543
		Cyclic	Crown	1447, 3006, 3199
			Inner Housing	1447, 3006, 3199
			Outer Housing	1447, 3006, 3199
			Rocket Fins	1447, 3006, 3199
	Seismic	Ratcheting	Crown	3006
			Inner Housing	3006
			Outer Housing	3006
			Rocket Fins	3006
	Seismic+Stop	Ratcheting	Crown	3006
			Inner Housing	3006
			Outer Housing	3006
			Rocket Fins	3006
	EP1	Local Failure	Crown	3006
			Outer Housing	3006
			Inner Housing	3006
			Rocket Fins	3006

EP2	Plastic Collapse	Plot	3006
	Local Failure	Crown	3006
		Outer Housing	3006
		Inner Housing	3006
		Rocket Fins	3006
EP5	Plastic Collapse	Plot	3006
	Local Failure	Crown	3006
		Inner Housing	3006
		Outer Housing	3006
		Rocket Fins	3006
	Plastic Collapse	Plot	3006

6. CONCLUSIONS

The Target Assembly design has satisfied all failure criteria for both elastic stress and plastic strain analysis. The cyclic analysis results show the components are adequate for their required lifespan. The deflection limits set forth by the project requirements are acceptable by the code-based load combinations. The components are able to survive a sudden stop with no plastic deformation. The requirements of the project are all satisfied.

7. REFERENCES

- [1] RCSC, "Specification for Structural Joints Using High-Strength Bolts," Research Council on Structural Connections, 2020.
- [2] ASCE, Minimum Design Loads for Buildings and Other Structures, ASCE 7, American Society of Civil Engineers, 2016.
- [3] U. D. o. Energy, "Natural Phenomena Hazards Analysis and Design Criteria for Department of Energy Facilities," DOE-STD-1020-2016, Dec. 2016.
- [4] G. & H. Simpson, *Natural Phenomenon Hazard Basis of Design Recommendations for Oak Ridge National Laboratory Second Target Station*, Newport Beach: SGH, 2023.
- [5] M.-T. Kao, "S03020000-DAC10003, Target Assembly Thermo-Fluid Analysis," ORNL, Oak Ridge, 2026.
- [6] ORNL, *Interface Sheet - Target Assembly and Target Viewing Periscope. Tech rep S01020500-IST10212*, Oak Ridge National Lab, 2024.
- [7] A. W. Society, "Structural Welding Code - Stainless Steel," AWS Standard D1.6/D1.6M - AMD1, 2021.
- [8] ASME, ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, American Society of Mechanical Engineers, 2019.
- [9] J. S. P. Hazel T. Rivera-Rosario, "Installation Torque Tables for Noncritical Applications. TM-2017-219475," NASA, 2017.
- [10] ORNL, "Interface Sheet for Proton Beam Parameters, Tech. rep. S01020500-IS0002," Oak Ridge National Laboratory, 2024.
- [11] L. B. Aaron Jacques, *Second Target Station Target Assembly Requirements*, Oak Ridge: ORNL, 2026.
- [12] A. Jacques, *TARGET_SYSTEMS_ASSEMBLY, 0000004343.ASM -.187*, Oak Ridge: ORNL, 2024.
- [13] L. B. Aaron Jacques, *Second Target Station, Target Drive*, Oak Ridge: ORNL, 2026.
- [14] L. B. Aaron Jacques, *Second Target Station, Target Segment*, Oak Ridge: ORNL, 2026.
- [15] L. B. Aaron Jacques, *Second Target Station, Target Shaft*, Oak Ridge: ORNL, 2026.
- [16] S. S. M. S. L. B. Aaron Jacques, *Second Target Station Project: IS - Target Assembly - Remote Handling*, Oak Ridge: ORNL, 2024.
- [17] D. M. L. B. Aaron Jacques, *Second Target Station Project: IS – Target Assembly – Target Process Systems*, Oak Ridge: ORNL, 2024.
- [18] J. Tipton Jr, "Target Segment Thermostructural Analysis," ORNL, Oak Ridge, 2026.

APPENDIX A. SUPPLEMENTAL CALCULATIONS

Simplified Shaft and Segments Weight:

Shaft	$5115 \text{ kg} \cdot g = 11277 \text{ lbf}$
Segment	$543 \text{ kg} \cdot g = 1197 \text{ lbf}$
20 Segments	$1200 \cdot \text{lbf} \cdot 20 = 24000 \text{ lbf}$
Shaft + Segments	$24000 \cdot \text{lbf} + 11300 \cdot \text{lbf} = 35300 \text{ lbf}$
Simplified Part	$16211603 \cdot \text{gm} \cdot g = 35740 \text{ lbf}$

Cycles:

$$t_{\text{year}} := 5000 \cdot \text{hr}$$

$$v_{\text{rpm}} := 45 \cdot \text{rpm} = (2.7 \cdot 10^3) \frac{\text{rev}}{\text{hr}}$$

$$\text{years}_{\text{segment}} := 10 \quad \text{years}_{\text{LoF}} := 40$$

$$\text{Segment} := (t_{\text{year}} \cdot \text{years}_{\text{segment}}) \cdot v_{\text{rpm}} = 8.5 \cdot 10^8$$

$$\text{LoF} := (t_{\text{year}} \cdot \text{years}_{\text{LoF}}) \cdot v_{\text{rpm}} = 3.4 \cdot 10^9$$

Load Values:

	Design Loads	psi	in/s ²	rpm	rad/s ²	F
P	Pressure	125				
D	Dead Load		1g			
L	Live Load			45	4.7	
E	Seismic		.625g			
T	Temperature					mapped
	Operating Loads	psi	in/s ²	rpm	rad/s ²	F
P ₀	Pressure	60				
D ₀	Dead Load		1g			
L ₀	Live Load			45	0.47	
E	Seismic		.625g			
T ₀	Temperature					mapped

Thread Data

Pitch

$$P_{M6} := 1 \cdot \text{mm}$$

$$P_{M10} := 1.5 \cdot \text{mm}$$

$$P_{M16} := 2 \cdot \text{mm}$$

$$P_{M24} := 3 \cdot \text{mm}$$

Nominal Diameter

$$D_{M6} := 6 \cdot \text{mm}$$

$$D_{M10} := 10 \cdot \text{mm}$$

$$D_{M16} := 16 \cdot \text{mm}$$

$$D_{M24} := 24 \cdot \text{mm}$$

Pitch Diameter

Internal Thread

$$d_{M6} := 5.5 \cdot \text{mm}$$

$$d_{M10} := 9.206 \cdot \text{mm}$$

$$d_{M16} := 14.913 \cdot \text{mm}$$

$$d_{M24} := 22.316 \cdot \text{mm}$$

Nominal Area

$$A_{M6} := \frac{\pi}{4} \cdot D_{M6}^2 = 0.044 \cdot \text{in}^2$$

$$A_{M10} := \frac{\pi}{4} \cdot D_{M10}^2 = 0.122 \cdot \text{in}^2$$

$$A_{M16} := \frac{\pi}{4} \cdot D_{M16}^2 = 0.312 \cdot \text{in}^2$$

$$A_{M24} := \frac{\pi}{4} \cdot D_{M24}^2 = 0.701 \cdot \text{in}^2$$

Thread Engagement

$$L_{e_Tent} := 20 \cdot \text{mm}$$

$$L_{e_MotorRing} := 16 \cdot \text{mm}$$

$$L_{e_Sleeve} := 25 \cdot \text{mm}$$

$$L_{e_Manifold} := 29 \cdot \text{mm}$$

$$L_{e_SegmentBolt} := 30 \cdot \text{mm}$$

$$L_{e_TieRod} := 56 \cdot \text{mm}$$

$$L_{e_LowerHousing} := 24 \cdot \text{mm}$$

$$L_{e_CrownInsert} := 38 \cdot \text{mm}$$

Material Strength

Grade 12.9 Steel Alloy

$$F_{12.9_Ult} := 1220 \cdot \text{MPa} = 176946 \cdot \text{psi}$$

$$F_{12.9_Yield} := 1080 \cdot \text{MPa} = 156641 \cdot \text{psi}$$

Group 150 Bolts

$$F_{nt} := 113 \cdot \text{ksi}$$

$$F_{nv} := 68 \cdot \text{ksi}$$

Nominal Tensile

Nominal Shear

Table 5.1
Nominal Strengths per
Unit Area of Bolts

Applied Load Condition			Nominal Strength per Unit Area, F_n , ksi		
			Group 120	Group 144	Group 150
Tension ^a	Static		90	108	113
	Fatigue		See Section 5.5		
Shear ^{a,b}	Threads included in shear plane	$L_s \leq 38 \text{ in.}$	54	65	68
		$L_s > 38 \text{ in.}$	45	54	56
	Threads excluded from shear plane	$L_s \leq 38 \text{ in.}$	68	81	84
		$L_s > 38 \text{ in.}$	56	68	70

^a Except as required in Section 5.2.

^b Reduction for values for $L_s > 38 \text{ in.}$ applies only when the joint is axially end loaded, such as splice plates on a beam or column flange, but it does not apply for web connections in shear.

Allowable Strength

Tensile, Bolt

$$P_{t_M6} := F_{nt} \cdot A_{M6} = 4952 \text{ lbf}$$

$$P_{t_M10} := F_{nt} \cdot A_{M10} = 13756 \text{ lbf}$$

$$P_{t_M16} := F_{nt} \cdot A_{M16} = 35216 \text{ lbf}$$

Shear, Bolt

$$P_{v_M6} := F_{nv} \cdot A_{M6} = 2980 \text{ lbf}$$

$$P_{v_M10} := F_{nv} \cdot A_{M10} = 8278 \text{ lbf}$$

$$P_{v_M16} := F_{nv} \cdot A_{M16} = 21192 \text{ lbf}$$

The *design strength* in shear or tension for a Group 120, 144, or 150 bolt is ϕR_n , where $\phi = 0.75$ and the *allowable strength* in shear or tension is R_n/Ω , where $\Omega = 2.00$ and:

$$R_n = F_n A_b \quad (\text{Equation 5.1})$$

where

R_n = *nominal strength* (shear strength per shear plane or tensile strength) of a bolt, kips

F_n = *nominal strength* per unit area from Table 5.1 for the appropriate applied load conditions, ksi, adjusted for the presence of fillers as required below

A_b = cross-sectional area based upon the nominal diameter of bolt, in.²

Threaded Materials:

Ultimate Strength

$$F_{718} := 160 \cdot \text{ksi}$$

$$F_{316L} := 70 \text{ ksi}$$

$$F_{100CrMo73} := 101 \text{ ksi}$$

$$F_{4130} := 85 \cdot \text{ksi}$$

$$F_{1045} := 85 \text{ ksi}$$

$$F_{N60} := 95 \text{ ksi}$$

$$F_{625} := 110 \cdot \text{ksi}$$

In the absence of specific shear and bearing allowables for materials, the following approximations may be used:

$$\text{Alloy and carbon steels: } F_{su} = 0.6 F_{tu}$$

$$\text{Stainless steels: } F_{su} = 0.55 F_{tu}$$

where F_{su} is ultimate shear stress and F_{tu} is ultimate tensile stress. Since bearing stress allowables are empirical to begin with, the bearing allowable for any given metallic alloy may be approximated as follows:

Ultimate Shear Strength (Thread Pullout)

$$F_{su_718} := .55 \cdot F_{718}$$

$$F_{su_316L} := .55 \cdot F_{316L}$$

$$F_{su_100CrMo73} := .6 \cdot F_{100CrMo73}$$

$$F_{su_4130} := .6 \cdot F_{4130}$$

$$F_{su_1045} := .6 \cdot F_{1045}$$

$$F_{su_N60} := .55 \cdot F_{N60}$$

$$F_{su_625} := .55 \cdot F_{625}$$

Table 5.3
Maximum Applied Tensile
Stress for Fatigue Loading

Number of Cycles	Maximum Bolt Stress for Design at Service Loads ^a , ksi		
	Group 120	Group 144	Group 150
Not more than 20,000	45	45	57
From 20,000 to 500,000	40	40	49
More than 500,000	31	31	38

^a Including the effects of prying action, if any, but excluding the pretension.

Thread Pullout Force:

Shaft Tie Rod Internal Threads, 316L

$$P_{TR} := \frac{\pi \cdot d_{M16} \cdot L_{e_TieRod} \cdot F_{su_316L}}{3} = 52189 \text{ lbf}$$

Tent Pads

$$P_{Tent} := \frac{\pi \cdot d_{M16} \cdot L_{e_Tent} \cdot F_{su_316L}}{3} = 18639 \text{ lbf}$$

Crown Sleeve

$$P_{Sleeve} := \frac{\pi \cdot d_{M10} \cdot L_{e_Sleeve} \cdot F_{su_100CrMo73}}{3} = 22638 \text{ lbf}$$

Motor Ring

$$P_{MotorRing} := \frac{\pi \cdot d_{M6} \cdot L_{e_MotorRing} \cdot F_{su_4130}}{3} = 7285 \text{ lbf}$$

Lower Housing

$$P_{LowerHousing} := \frac{\pi \cdot d_{M10} \cdot L_{e_LowerHousing} \cdot F_{su_1045}}{3} = 18290 \text{ lbf}$$

Manifold Nutplate

$$P_{Manifold} := \frac{\pi \cdot d_{M10} \cdot L_{e_Manifold} \cdot F_{su_4130}}{3} = 22100 \text{ lbf}$$

Crown Insert, Internal

$$P_{CrownInsert} := \frac{\pi \cdot d_{M16} \cdot L_{e_SegmentBolt} \cdot F_{su_N60}}{3} = 37943 \text{ lbf}$$

Crown Insert, External

$$P_{CrownInsert_Ext} := \frac{\pi \cdot d_{M24} \cdot L_{e_CrownInsert} \cdot F_{su_625}}{3} = 83275 \text{ lbf}$$

Calculating Pullout Load for Threaded Hole

In many cases a bolt of one material may be installed in a tapped hole in a different (and frequently lower strength) material. If the full strength of the bolt is required, the depth of the tapped hole must be determined for the weaker material by using the formula

$$P = \frac{\pi d_m F_s L}{3}$$

where

P pullout load, lb

d_m mean diameter of threaded hole, in. ($\approx$ pitch diameter of threads)

F_s material ultimate or yield shear stress

L length of thread engagement, in.

The $\frac{1}{3}$ factor is empirical. If the threads were perfectly mated, this factor would be $\frac{1}{2}$, since the total cylindrical shell area of the hole would be split equally between the bolt threads and the tapped hole threads. The $\frac{1}{3}$ is used to allow for mismatch between threads.

Further information on required tapped hole lengths is given in reference 19.

Fatigue, ANSYS Data

Stainless Steel 316L

$$S_a := \begin{bmatrix} 13000 \\ 13700 \\ 14000 \\ 14500 \\ 20000 \\ 30000 \\ 40000 \end{bmatrix} \cdot \text{psi}$$

$$Y_{316} := \log \left(28300 \cdot \left(\frac{S_a}{28300 \cdot \text{psi}} \right) \right) = \begin{bmatrix} 1.114 \\ 1.137 \\ 1.146 \\ 1.161 \\ 1.301 \\ 1.477 \\ 1.602 \end{bmatrix}$$

$$Y_x := 10^{Y_{316}} = \begin{bmatrix} 13 \\ 13.7 \\ 14 \\ 14.5 \\ 20 \\ 30 \\ 40 \end{bmatrix}$$

$$X_{SS1} := \frac{17.0181 - 19.8713 \cdot Y_{316} + 4.21366 \cdot Y_{316}^2}{1 - .1720606 \cdot Y_{316} - .633592 \cdot Y_{316}^2} = \begin{bmatrix} 5.025 \\ 8.788 \\ 7.521 \\ 6.921 \\ 5.746 \\ 4.933 \\ 4.438 \end{bmatrix} \quad 10^Y > 14.4$$

$$X_{SS2} := \frac{1}{-.331096 + \frac{4.3261 \cdot \ln(Y_{316})}{Y_{316}^2}} = \begin{bmatrix} 22.172 \\ 10.21 \\ 8.469 \\ 6.724 \\ 2.929 \\ 2.261 \\ 2.159 \end{bmatrix} \quad 10^Y < 14.4$$

$$N_{SS1} := 10^{X_{SS1}} = \begin{bmatrix} 105951 \\ 613323664 \\ 33219094 \\ 8341636 \\ 557213 \\ 85777 \\ 27405 \end{bmatrix} \quad N_{SS2} := 10^{X_{SS2}} = \begin{bmatrix} 14849175495644000000000 \\ 16210324723 \\ 294624164 \\ 5291273 \\ 848 \\ 182 \\ 144 \end{bmatrix}$$

	A	B
1	Cycles	Alternating Stress (psi)
2	27405	40000
3	85777	30000
4	5.5721E+05	20000
5	8.3416E+06	14500
6	2.9462E+08	14000
7	1.621E+10	13700
8	1.4849E+22	13000

$$N_{SS} := \begin{bmatrix} 1.485^{22} \\ 16210324723 \\ 294624164 \\ 8341636 \\ 557213 \\ 85777 \\ 27405 \end{bmatrix}$$

Stainless Steel 316L, 200F

$$E_{SS_200F} := 27500 \cdot \text{ksi}$$

$$Y_{316_200F} := \log \left(28300 \cdot \left(\frac{S_a}{E_{SS_200F}} \right) \right) = \begin{bmatrix} 1.126 \\ 1.149 \\ 1.159 \\ 1.174 \\ 1.313 \\ 1.49 \\ 1.615 \end{bmatrix} \quad Y_x := 10^{Y_{316_200F}} = \begin{bmatrix} 13.378 \\ 14.099 \\ 14.407 \\ 14.922 \\ 20.582 \\ 30.873 \\ 41.164 \end{bmatrix}$$

$$X_{SS1} := \frac{17.0181 - 19.8713 \cdot Y_{316_200F} + 4.21366 \cdot Y_{316_200F}^2}{1 - .1720606 \cdot Y_{316_200F} - .633592 \cdot Y_{316_200F}^2} = \begin{bmatrix} -8.109 \\ 7.342 \\ 6.992 \\ 6.689 \\ 5.682 \\ 4.882 \\ 4.391 \end{bmatrix} \quad 10^Y > 14.4$$

$$X_{SS2} := \frac{1}{-.331096 + \frac{4.3261 \cdot \ln(Y_{316_200F})}{Y_{316_200F}^2}} = \begin{bmatrix} 13.38 \\ 8.039 \\ 6.978 \\ 5.811 \\ 2.836 \\ 2.243 \\ 2.156 \end{bmatrix} \quad 10^Y < 14.4$$

$$N_{SS1} := 10^{X_{SS1}} = \begin{bmatrix} 0 \\ 21960664 \\ 9821852 \\ 4883583 \\ 480315 \\ 76142 \\ 24607 \end{bmatrix} \quad N_{SS2} := 10^{X_{SS2}} = \begin{bmatrix} 23991645204971 \\ 109436933 \\ 9513994 \\ 646893 \\ 685 \\ 175 \\ 143 \end{bmatrix}$$

$$N_{SS_200F} := \begin{bmatrix} 9821852 \\ 4883583 \\ 480315 \\ 76142 \\ 24607 \end{bmatrix}$$

Table of Properties Row 25: S-N Curve

	A	B
1	Cycles	Alternating Stress (psi)
2	24607	40000
3	76142	30000
4	4.8032E+05	20000
5	4.8836E+06	14500
6	9.8219E+06	14000

Steel

$$S_{a_steel} := \begin{bmatrix} 12000 \\ 15000 \\ 20000 \\ 25000 \\ 30000 \end{bmatrix} \cdot \text{psi} \quad Y_{steel} := \log \left(28300 \cdot \left(\frac{S_{a_steel}}{29200 \text{ ksi}} \right) \right)$$

$$Y_{steel} = \begin{bmatrix} 1.066 \\ 1.162 \\ 1.287 \\ 1.384 \\ 1.464 \end{bmatrix} \quad 10^{Y_{steel}} = \begin{bmatrix} 11.63 \\ 14.538 \\ 19.384 \\ 24.229 \\ 29.075 \end{bmatrix}$$

$$10^{Y_{steel}} > 20$$

$$X_1 := -4706.5245 + 1813.6228 \cdot Y_{steel} + \frac{6785.5644}{Y_{steel}} - 368.12404 \cdot Y_{steel}^2 - \frac{5133.7345}{Y_{steel}^2} + 30.708204 \cdot Y_{steel}^3 + \frac{1596.1916}{Y_{steel}^3} = \begin{bmatrix} 11.124 \\ 6.834 \\ 5.088 \\ 4.623 \\ 4.374 \end{bmatrix}$$

$$10^{Y_{steel}} < 20$$

$$X_2 := \frac{38.1309 - 60.1705 \cdot Y_{steel}^2 + 25.0352 \cdot Y_{steel}^4}{1 + 1.80224 \cdot Y_{steel}^2 - 4.68904 \cdot Y_{steel}^4 + 2.26536 \cdot Y_{steel}^6} = \begin{bmatrix} 6.578 \\ 5.481 \\ 5.052 \\ 4.647 \\ 4.298 \end{bmatrix}$$

$$N_{steel1} := 10^{X_1} = \begin{bmatrix} 133038241096 \\ 6829877 \\ 122396 \\ 41941 \\ 23652 \end{bmatrix} \quad N_{steel2} := 10^{X_2} = \begin{bmatrix} 3786320 \\ 302618 \\ 112811 \\ 44404 \\ 19866 \end{bmatrix}$$

$$N_{steel} := \begin{bmatrix} 3786320 \\ 302618 \\ 112811 \\ 41641 \\ 23652 \end{bmatrix}$$

Inconel 625

$$S_{a_625} := \begin{bmatrix} 15000 \\ 25000 \\ 35000 \\ 45000 \\ 55000 \end{bmatrix} \cdot \text{psi} \quad Y_{625} := \log \left(28300 \cdot \left(\frac{S_{a_625}}{27800 \cdot \text{ksi}} \right) \right) \quad 10^{Y_{625}} = \begin{bmatrix} 15.27 \\ 25.45 \\ 35.629 \\ 45.809 \\ 55.989 \end{bmatrix}$$

$$10^{Y_{625}} > 14.4$$

$$X_{625_1} := \frac{17.0181 - 19.8713 \cdot Y_{625} + 4.21366 \cdot Y_{625}^2}{1 - .1720606 \cdot Y_{625} - .633592 \cdot Y_{625}^2} = \begin{bmatrix} 6.557 \\ 5.242 \\ 4.631 \\ 4.22 \\ 3.915 \end{bmatrix}$$

$$10^{Y_{625}} < 14.4$$

$$X_{625_2} := \frac{1}{-.331096 + \frac{4.3261 \cdot \ln(Y_{625})}{Y_{625}^2}} = \begin{bmatrix} 5.268 \\ 2.413 \\ 2.182 \\ 2.153 \\ 2.176 \end{bmatrix}$$

$$N_{625_1} := 10^{X_{625_1}} = \begin{bmatrix} 3606214 \\ 174716 \\ 42769 \\ 16611 \\ 8221 \end{bmatrix} \quad N_{625_2} := 10^{X_{625_2}} = \begin{bmatrix} 185262 \\ 259 \\ 152 \\ 142 \\ 150 \end{bmatrix}$$

$$N_{625} := \begin{bmatrix} 29241441 \\ 3606214 \\ 507851 \\ 174716 \\ 79641 \end{bmatrix}$$

Table of Properties Row 22: S-N Curve		
	A	B
1	Cycles	Alternating Stress (psi)
2	79641	30000
3	1.7472E+05	25000
4	5.0785E+05	20000
5	3.6062E+06	15000
6	2.9241E+07	14000

Inconel 718

Table of Properties Row 15: S-N Curve		
	A	B
1	Cycles	Alternating Stress (psi)
2	1E+06	1.3198E+05
3	1E+07	1.0095E+05
4	1E+08	91954
5	1E+09	90068
*		

INCONEL® alloy 718

Table 33 - High-Temperature Fatigue Strength of Hot-Rolled Bar (Annealed 1750°F/1 hr, A.C. and Aged)^a

Test Temperature, °F	Fatigue Strength, ksi			
	10 ⁵ Cycles	10 ⁶ Cycles	10 ⁷ Cycles	10 ⁸ Cycles
Room	132.0	101.0	92.0	90.0
600	115.0	110.0	110.0	110.0
1000	111.0	102.0	95.0	90.0
1200	100.0	94.0	88.0	72.0

<https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-718.pdf>

Triaxial Strain Limit, ANSYS Data

316L

$$\sigma_{ys_316L} := 25 \text{ ksi}$$

$$\alpha_{sl} := .6$$

$$\sigma_{uts_316L} := 70 \text{ ksi}$$

$$R_{316L} := \frac{\sigma_{ys_316L}}{\sigma_{uts_316L}}$$

$$m_{2_316L} := .75 \cdot (1.00 - R_{316L}) = 0.482$$

$$\varepsilon_{Lu_316L} := m_{2_316L}$$

Example stresses
to check equation:

$$\sigma_1 := 5000 \text{ psi}$$

$$\sigma_3 := 5000 \cdot \text{psi}$$

$$\sigma_2 := 5000 \text{ psi}$$

$$\sigma_{vm} := 5000 \text{ psi}$$

$$\varepsilon_L := \varepsilon_{Lu_316L} \cdot \left(e^{-\left(\frac{\alpha_{sl}}{1 + m_{2_316L}} \right) \cdot \left(\frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3 \cdot \sigma_{vm}} \right) - \frac{1}{3}} \right) = 0.368$$

$$\frac{\alpha_{sl}}{1 + m_{2_316L}} = 0.405$$

$$\text{Acceptance : } \varepsilon_p \leq \varepsilon_L$$

ANSYS User Defined Equation:

$$\text{"PS}/(.482*(2.7128^{((- .405)*(((S1+S2+S3)/VM)-(1/3)))))\text{"}$$

Inconel 625

$$\sigma_{ys_625} := 60 \text{ ksi}$$

$$\alpha_{sl} := .6$$

$$\sigma_{uts_625} := 120 \text{ ksi}$$

$$R_{625} := \frac{\sigma_{ys_625}}{\sigma_{uts_625}} = 0.5$$

$$m_{2_625} := .75 \cdot (1.00 - R_{625}) = 0.375$$

$$\frac{\alpha_{sl}}{1 + m_{2_625}} = 0.436$$

$$\text{"PS}/(.375*(2.7128^{(-.436)*(((S1+S2+S3)/(3*VM))-(1/3))}))"$$

Steel

$$\sigma_{ys_steel} := 36 \text{ ksi}$$

$$\alpha_{sl_steel} := 2.2$$

$$\sigma_{uts_steel} := 58 \text{ ksi}$$

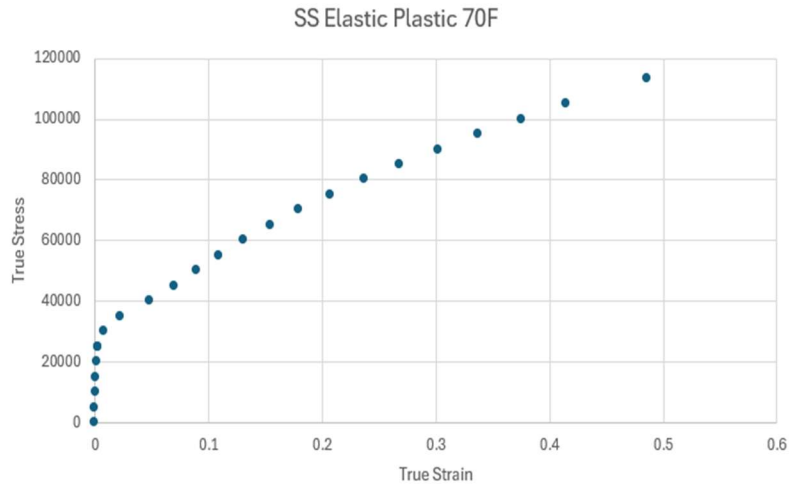
$$R_{steel} := \frac{\sigma_{ys_steel}}{\sigma_{uts_steel}} = 0.62$$

$$m_{2_steel} := .6 \cdot (1.00 - R_{steel}) = 0.228$$

$$\frac{\alpha_{sl_steel}}{1 + m_{2_steel}} = 1.792$$

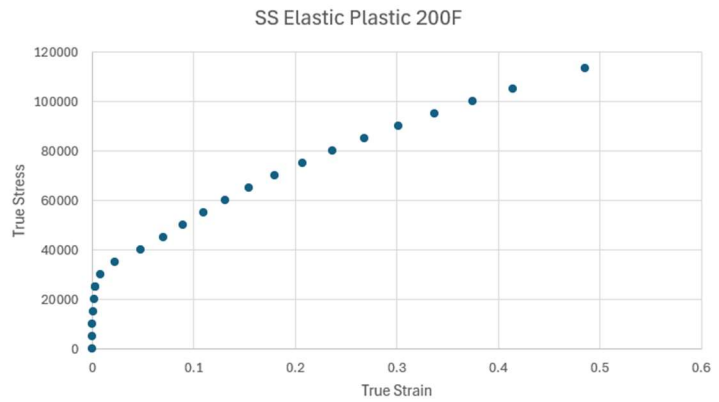
$$\text{"PS}/(.228*(2.7128^{((-1.792)*(((S1+S2+S3)/VM)-(1/3))}))"$$

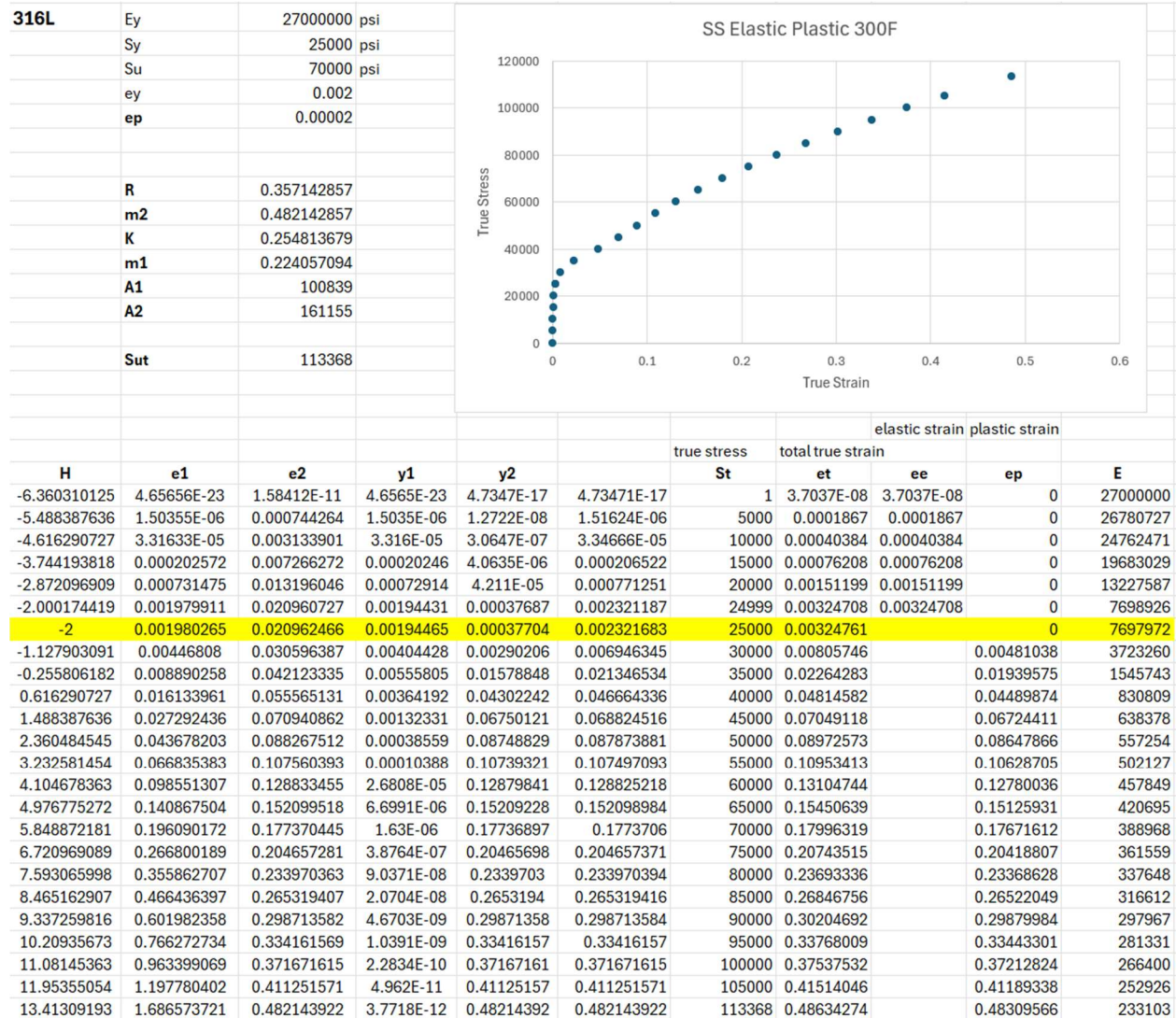
316L	Ey	28300000 psi
	Sy	25000 psi
	Su	70000 psi
	ey	0.002
	ep	0.00002
	R	0.357142857
	m2	0.482142857
	K	0.254813679
	m1	0.224057094
	A1	100839
	A2	161155
	Sut	113368

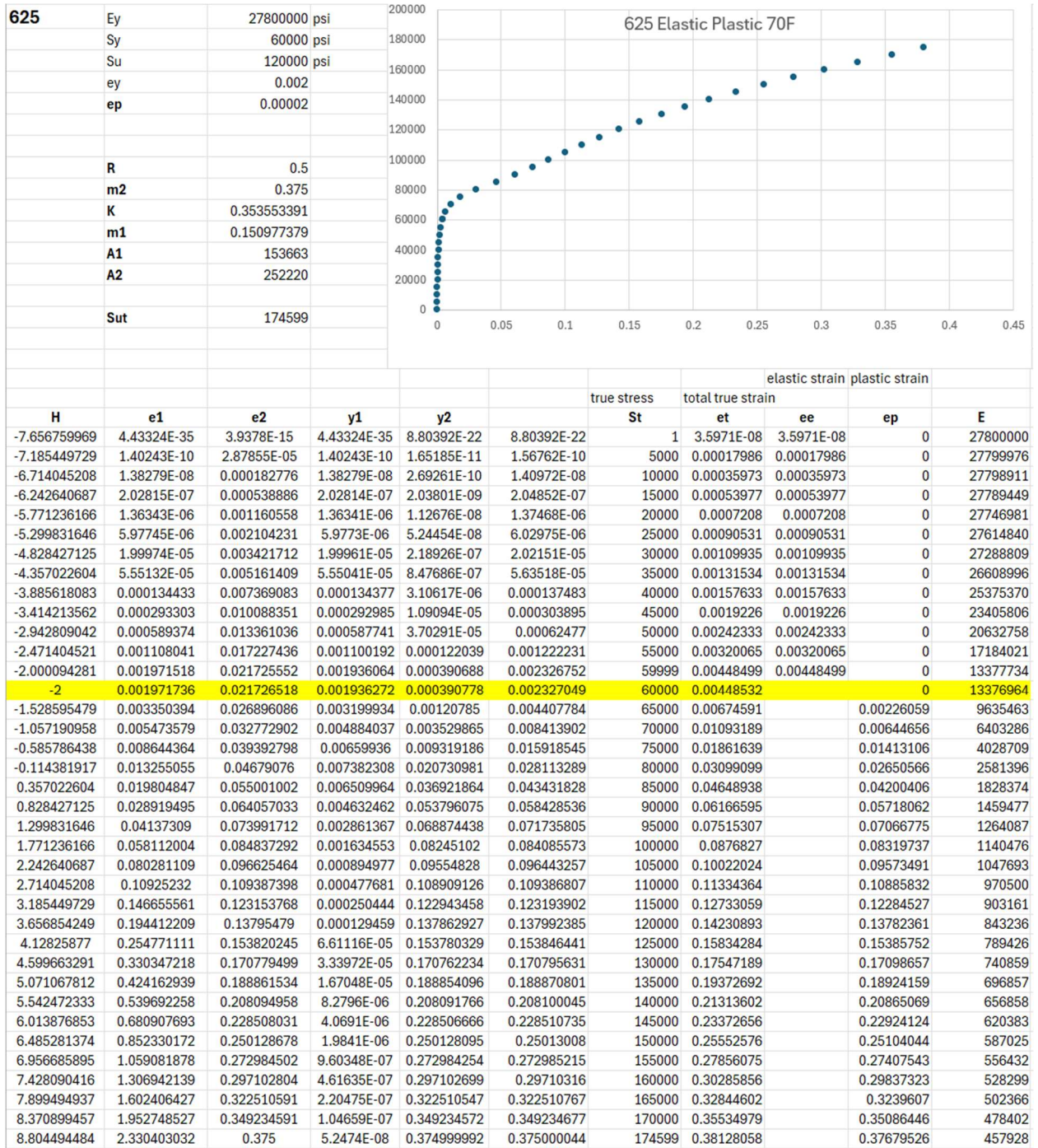


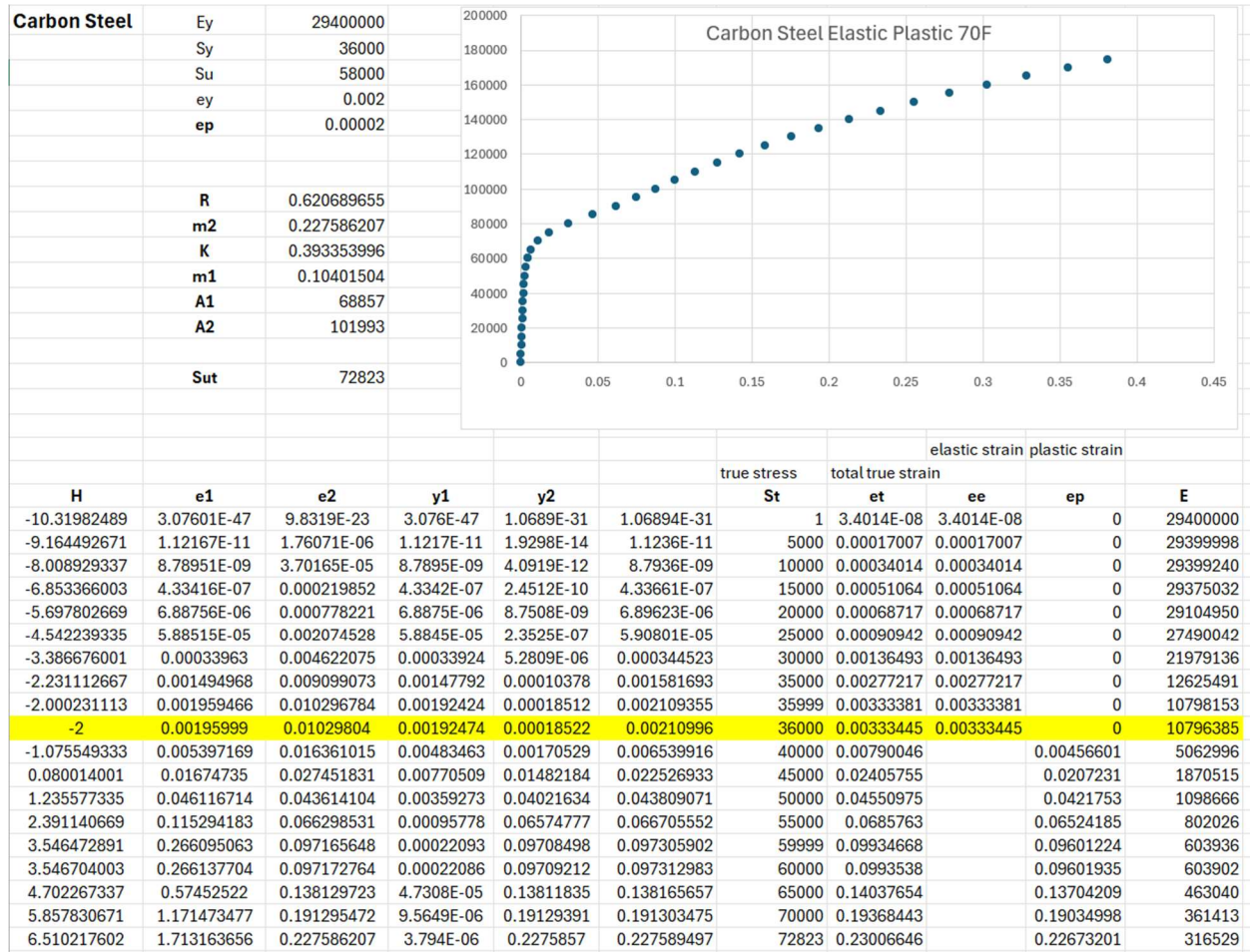
						elastic strain		plastic strain			
						true stress	total true strain				
H	e1	e2	y1	y2		St	et	ee	ep	E	
-6.360310125	4.65656E-23	1.58412E-11	4.65655E-23	4.7347E-17	4.73471E-17	1	3.5336E-08	3.5336E-08	0	28300000	
-5.488387636	1.50355E-06	0.000744264	1.50352E-06	1.27223E-08	1.51624E-06	5000	0.00017819	0.00017819	0	28059198	
-4.616290727	3.31633E-05	0.003133901	3.31601E-05	3.06467E-07	3.34666E-05	10000	0.00038682	0.00038682	0	25851587	
-3.744193818	0.000202572	0.007266272	0.000202459	4.06353E-06	0.000206522	15000	0.00073656	0.00073656	0	20365006	
-2.872096909	0.000731475	0.013196046	0.000729141	4.21099E-05	0.000771251	20000	0.00147796	0.00147796	0	13532124	
-2.000174419	0.001979911	0.020960727	0.001944313	0.000376875	0.002321187	24999	0.00320454	0.00320454	0	7801109	
-2	0.001980265	0.020962466	0.001944647	0.000377035	0.002321683	25000	0.00320507		0	7800129	
-1.127903091	0.00446808	0.030596387	0.004044283	0.002902062	0.006946345	30000	0.00800642		0.00480187	3746995	
-0.255806182	0.008890258	0.042123335	0.00555805	0.015788484	0.021346534	35000	0.02258328		0.01937874	1549819	
0.616290727	0.016133961	0.055565131	0.003641918	0.043022418	0.046664336	40000	0.04807776		0.04487322	831985	
1.488387636	0.027292436	0.070940862	0.001323306	0.06750121	0.068824516	45000	0.07041462		0.06721008	639072	
2.360484545	0.043678203	0.088267512	0.000385588	0.087488294	0.087873881	50000	0.08964067		0.08643612	557783	
3.232581454	0.066835383	0.107560393	0.000103883	0.10739321	0.107497093	55000	0.10944056		0.10623601	502556	
4.104678363	0.098551307	0.128833455	2.68081E-05	0.12879841	0.128825218	60000	0.13094536		0.12774081	458206	
4.976775272	0.140867504	0.152099518	6.69913E-06	0.152092285	0.152098984	65000	0.1543958		0.15119126	420996	
5.848872181	0.196090172	0.177370445	1.63E-06	0.17736897	0.1773706	70000	0.1798441		0.17663955	389226	
6.720969089	0.266800189	0.204657281	3.87638E-07	0.204656984	0.204657371	75000	0.20730755		0.204103	361781	
7.593065998	0.355862707	0.233970363	9.0371E-08	0.233970304	0.233970394	80000	0.23679725		0.2335927	337842	
8.465162907	0.466436397	0.265319407	2.07036E-08	0.265319395	0.265319416	85000	0.26832295		0.26511841	316782	
9.337259816	0.601982358	0.298713582	4.67028E-09	0.29871358	0.298713584	90000	0.3018938		0.29868925	298118	
10.20935673	0.766272734	0.334161569	1.03908E-09	0.334161569	0.33416157	95000	0.33751846		0.33431392	281466	
11.08145363	0.963399069	0.371671615	2.28338E-10	0.371671615	0.371671615	100000	0.37520518		0.37200064	266521	
11.95355054	1.197780402	0.411251571	4.96198E-11	0.411251571	0.411251571	105000	0.41496182		0.41175727	253035	
13.41309193	1.686573721	0.482143922	3.77182E-12	0.482143922	0.482143922	113368	0.48614986		0.48294531	233196	

316L	Ey	27500000	psi
	Sy	25000	psi
	Su	70000	psi
	ey	0.002	
	ep	0.00002	
	R	0.357142857	
	m2	0.482142857	
	K	0.254813679	
	m1	0.224057094	
	A1	100839	
	A2	161155	
	Sut	113368	









Target Assembly Deflection Requirements

To capture updates to the Target Assembly deflection requirements this document serves as an addendum to the Target Assembly Structural Analysis S03020000-DAC10002. This document serves to highlight the results for the specified load cases based upon the models described in S03020000-DAC10002.

S.03.02-10698 Structural capacity during relative motion

The target assembly shall be capable of maintaining structural integrity under a horizontal relative motion between base and lower extremity (snubber ring) of up to: 13mm.

- L - Live loads (centrifugal target rotation)
- P - Operational pressures (Core Vessel and component operating pressures)
- T - Operating thermal loads (beam on, cooling water)
- E - Seismic loads (Unfactored, per ASCE 7) + 13mm Displacement

Loads used:

L - Live loads (imbalance target rotation)	45rpm, 1mm offset
P - Operational pressures (Core Vessel and component operating pressures) and pressure testing (MAWP)	75psi
T - Operating thermal loads (beam on, cooling water)	CFD mapped
E - Seismic loads (Unfactored, per ASCE 7)	.65g, (6mm displacement constraint to move snubber into contact)

-

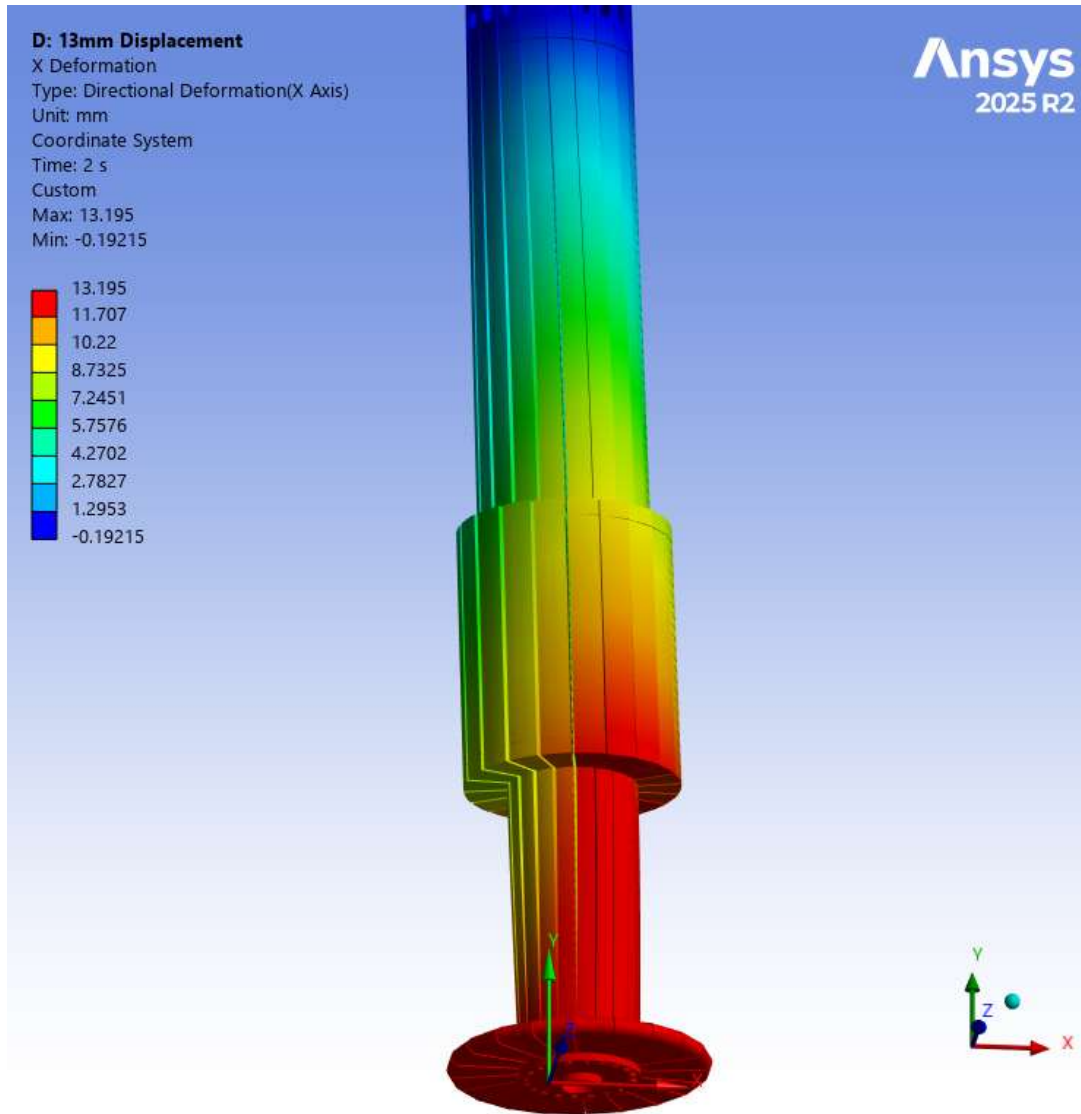


Figure 1 13mm Displacement

Table 1 Tie Rod Preload (lbf) with 13mm Displacement

Tie Rod	1	2	3	4	5	6	7	8	9	10
0.2	4806.5	4806.7	4806.7	4806.7	4806.7	4806.7	4806.7	4806.7	4806.7	4806.7
0.4	9606.5	9606.7	9606.7	9606.7	9606.7	9606.7	9606.7	9606.7	9606.7	9606.7
0.7	16806	16807	16807	16807	16807	16807	16807	16807	16807	16807
1	24006	24007	24007	24007	24007	24007	24007	24007	24007	24007
1.2	23874	23912	23986	24068	24126	24139	24102	24028	23946	23887
1.4	23742	23817	23966	24130	24248	24274	24199	24050	23886	23768
1.7	23567	23703	23971	24268	24481	24529	24392	24123	23826	23614
2	23450	23652	24050	24493	24811	24881	24677	24277	23835	23519

The pretension results show Tie Rod 6 with 881lbf additional force over the initial pretension value, which is 70% of yield strength. The 881lbf is an additional 5% and still within acceptable pretension range.

S.03.02-10733 Mid-Height locations - Radial deflections during normal operation

The outer profile of the target assembly (above the target) shall not deflect in the radial direction more than +/-4.5mm during normal operation and pressure testing operations

Normal operations include the worst case combinations of:

- L - Live loads (imbalance target rotation)
- P - Operational pressures (Core Vessel and component operating pressures) and pressure testing (MAWP)
- T - Operating thermal loads (beam on, cooling water)

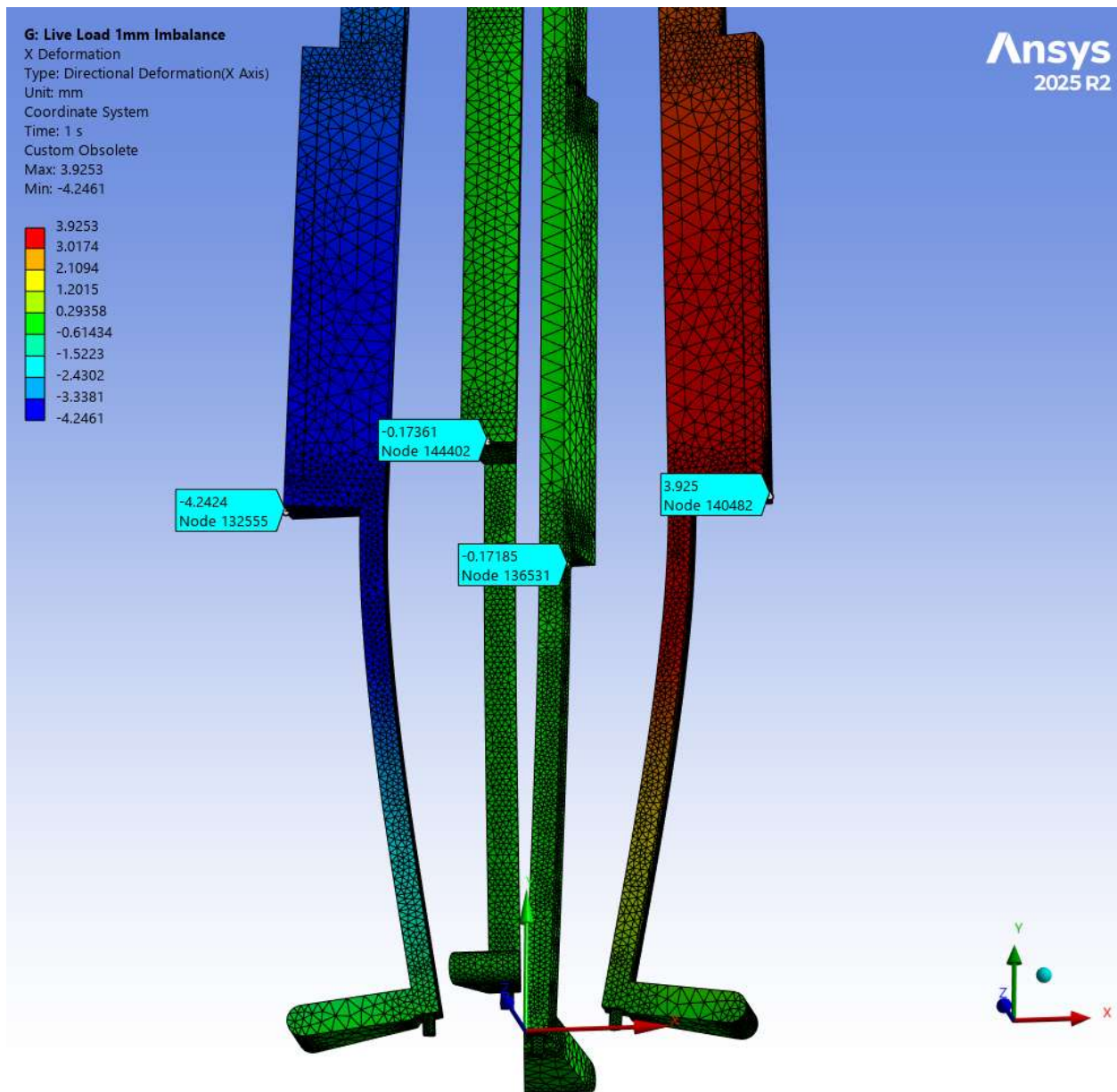


Figure 2 X Deformation, Mid Segment

Table 2 Radial X Deformation, Mid Segment

Requirement < +/-4.5mm				
Node ID	X	Y	Z	X Deformation (mm)
132555	-145.895	1293.687	-0.24909	-4.2424
144402	476.2521	1292.912	623.3245	-0.1736
136531	476.3205	1292.914	-623.281	-0.1719
140482	1099.559	1292.268	-0.06984	3.9250

Note Highlighted Cells are Radial Directions

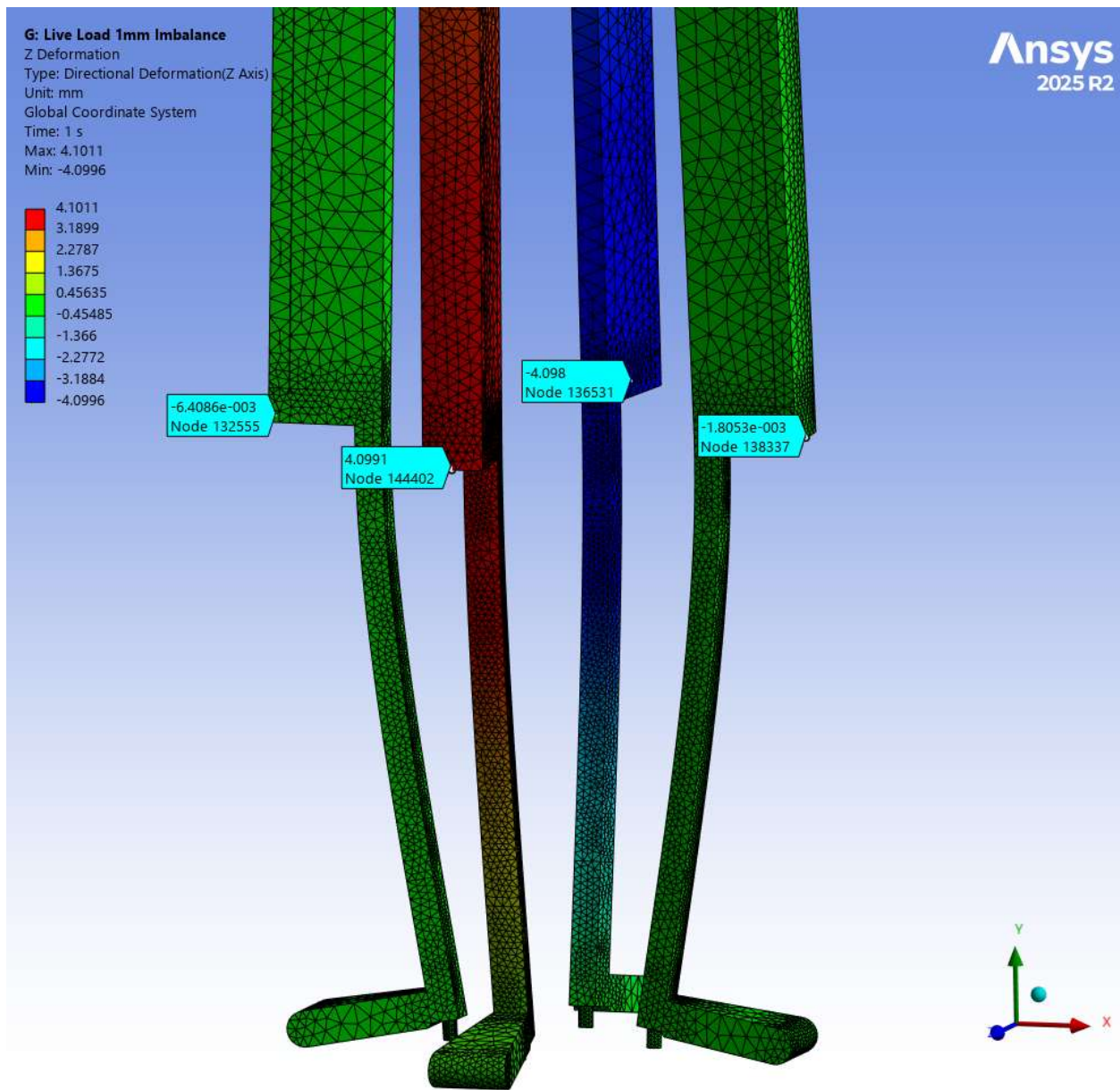


Figure 3 Z Deformation, Mid Segment

Table 3 Radial Z Deformation, Mid Segment

Requirement < +/-4.5mm				Z Deformation (mm)
Node ID	X	Y	Z	
144402	476.2521	1292.912	623.3245	4.0991
132555	-145.895	1293.687	-0.24909	-0.0064
138337	1099.344	1292.262	14.00466	-0.0018
136531	476.3205	1292.914	-623.281	-4.0980

Note Highlighted Cells are Radial Directions

S.03.02-10693 Mid-height locations - Radial deflections during seismic operation

Any portion of the target assembly shall not deflect in the radial direction more than 7mm during a seismic lateral force; displacement is that beyond an imposed relative displacement between mounting flange and lower extremity.

Seismic conditions include worst case combinations of:

- L - Live loads (centrifugal target rotation)
- P - Operational pressures (Core Vessel and component operating pressures)
- T - Operating thermal loads (beam on, cooling water)
- E - Seismic loads (Unfactored, per ASCE 7)

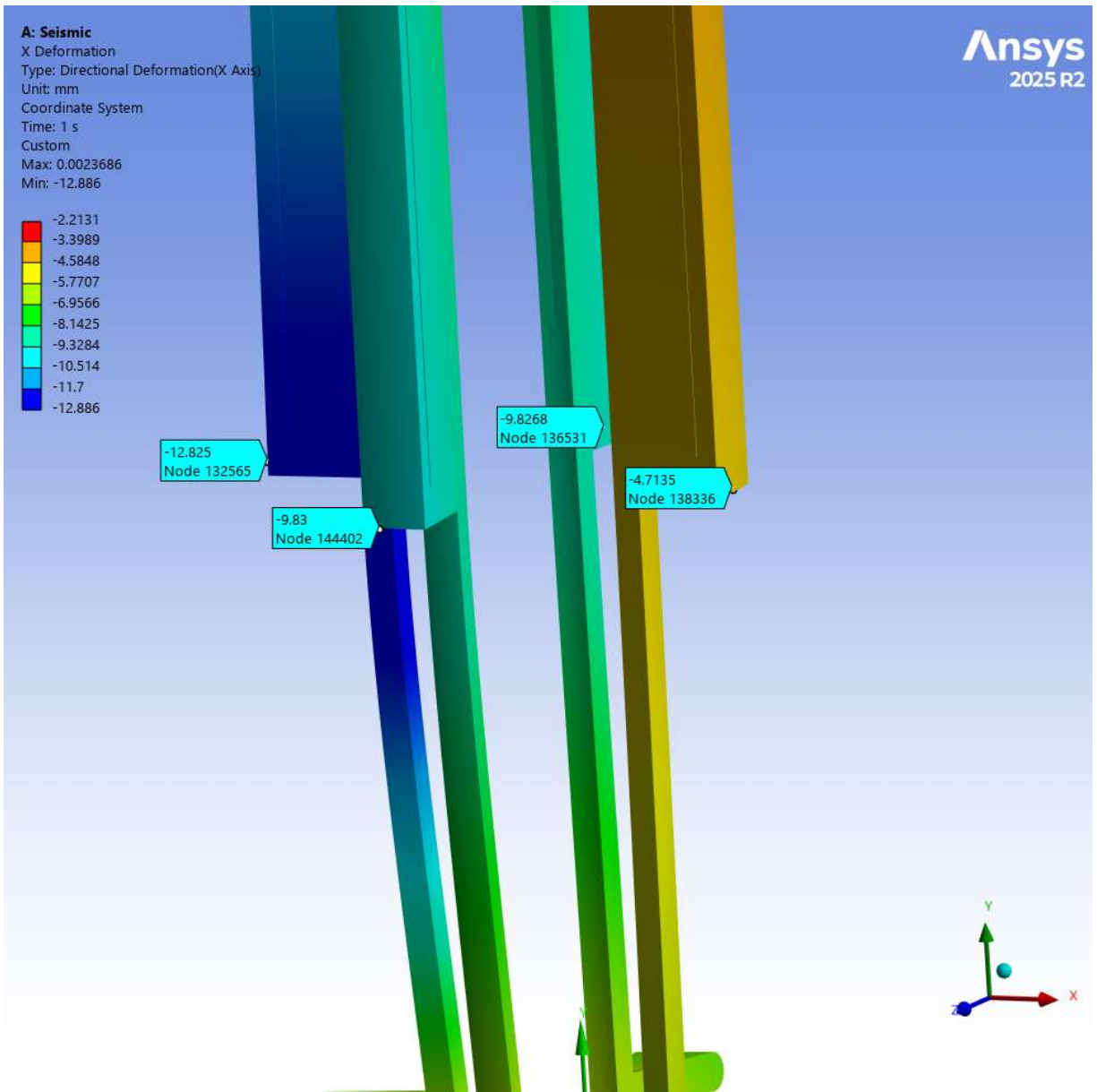


Figure 4 X Deformation, Mid Segment Seismic

Table 4 Radial X Deformation, Mid Segment Seismic

Requirement < 7mm Relative					
Node ID	X	Y	Z	Total X Deformation (mm)	Relative X Deformation (mm)
132565	-145.219	1315.054	-6.34533	-12.825	-6.825
136531	357.1438	1297.65	-516.46	-9.8268	-3.8268
138336	886.4183	1290.18	-14.1274	-4.7135	1.2865
144402	357.1024	1297.641	516.4323	-9.83	-3.83

Note Highlighted Cells are Radial Directions

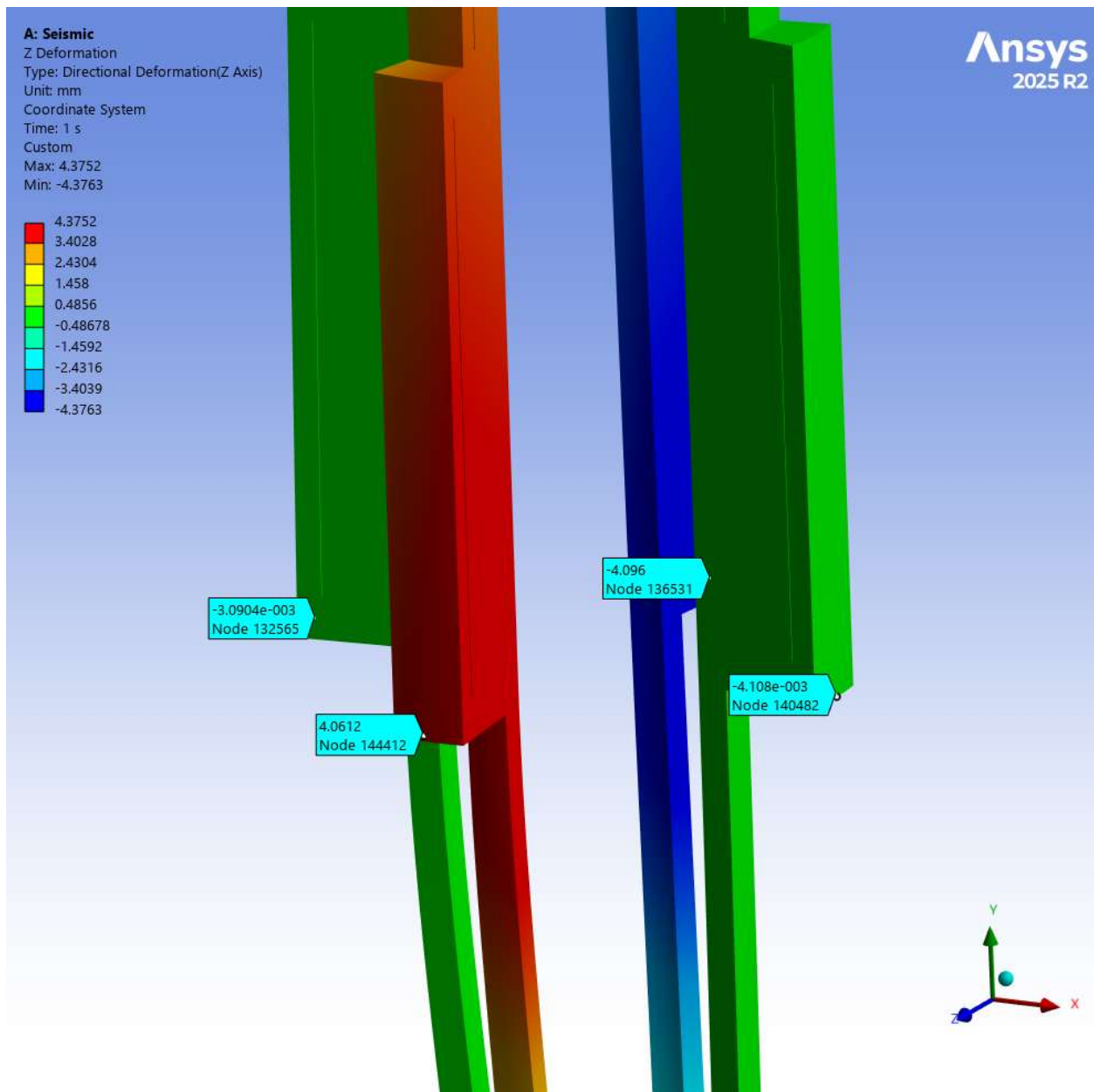


Figure 5 Z Deformation, Mid Segment Seismic

Table 5 Radial Z Deformation, Mid Segment Seismic

Requirement < 7mm Relative				
Node ID	X	Y	Z	Z Deformation (mm)
144412	350.825	1307.653	515.9712	4.0612
140482	886.632	1290.179	-0.05261	-0.0041
132565	-145.219	1315.054	-6.34533	-0.0031
136531	357.1438	1297.65	-516.46	-4.0960

Note Highlighted Cells are Radial Directions

S.03.02-10732 Foot location - Radial deflections during normal operations

The outer boundary of the target assembly at the foot elevation shall deflect <0.5mm radially during the worst case combination of:

- L - Live loads (imbalance target rotation)
- P - Operational pressures (Core Vessel and component operating pressures) and pressure testing (MAWP)
- T - Operating thermal loads (beam on, cooling water)

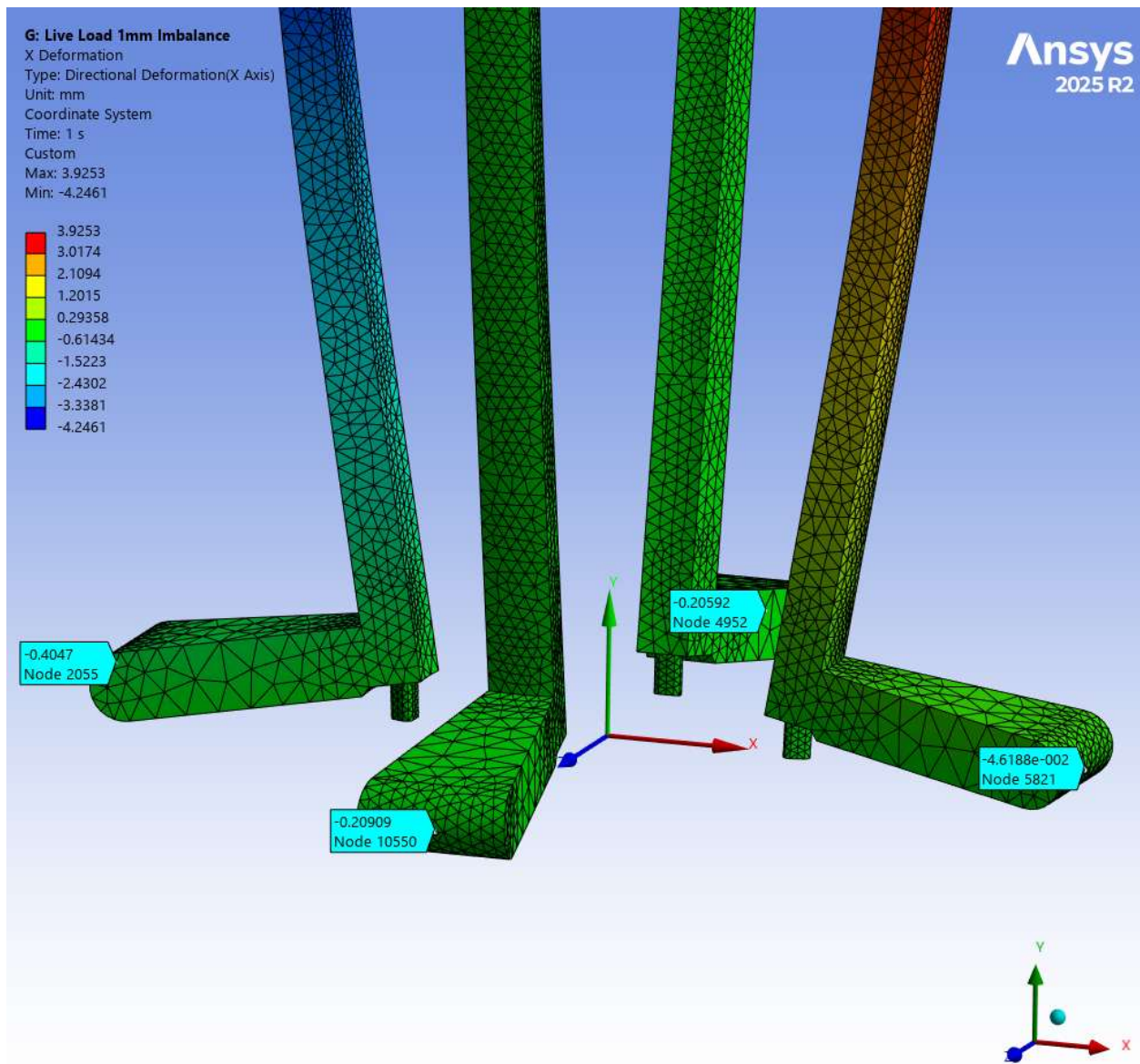


Figure 6 X Deformation, Foot

Table 6 Radial X Deformation, Foot

Requirement < 0.5mm				
Node ID	X	Y	Z	X Deformation (mm)
2055	-115.805	-61.2102	-7.99176	-0.4047
10550	480.452	-72.4517	590.1992	-0.2091
5821	1065.181	-73.2984	4.752222	-0.0462
4952	469.417	-72.3734	-590.269	-0.2059

Note Highlighted Cells are Radial Directions

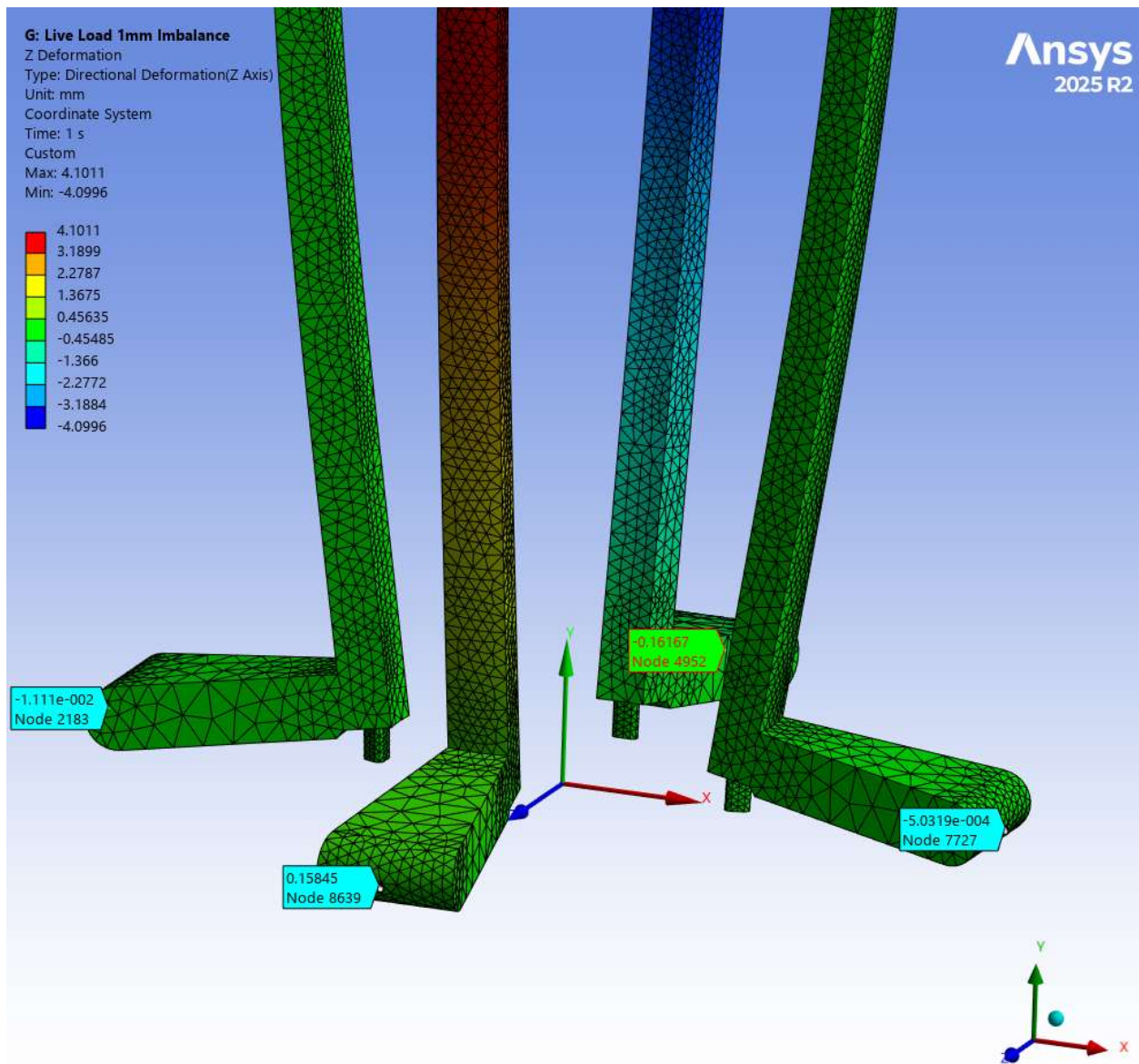


Figure 7 Z Deformation, Foot

Table 7 Radial Z Deformation, Foot

Requirement < 0.5mm				
Node ID	X	Y	Z	Z Deformation (mm)
8639	470.9338	-65.4205	589.5043	0.1585
7727	1065.42	-65.6324	-5.59668	-0.0005
4952	470.2373	-65.0656	-589.625	-0.1617
2183	-113.68	-63.8211	5.191574	-0.0111

Note Highlighted Cells are Radial Directions

S.03.02-10702 Foot location - Vertical Deflections During Normal Operations

The outer boundary of the target assembly at the foot elevation shall not deflect in the vertical direction more than 3.25mm (down) or more than 0.25mm (up) during the worst case combination of:

- L - Live loads (imbalance target rotation)
- P - Operational pressures (Core Vessel and component operating pressures) and pressure testing (MAWP)
- T - Operating thermal loads (beam on, cooling water)

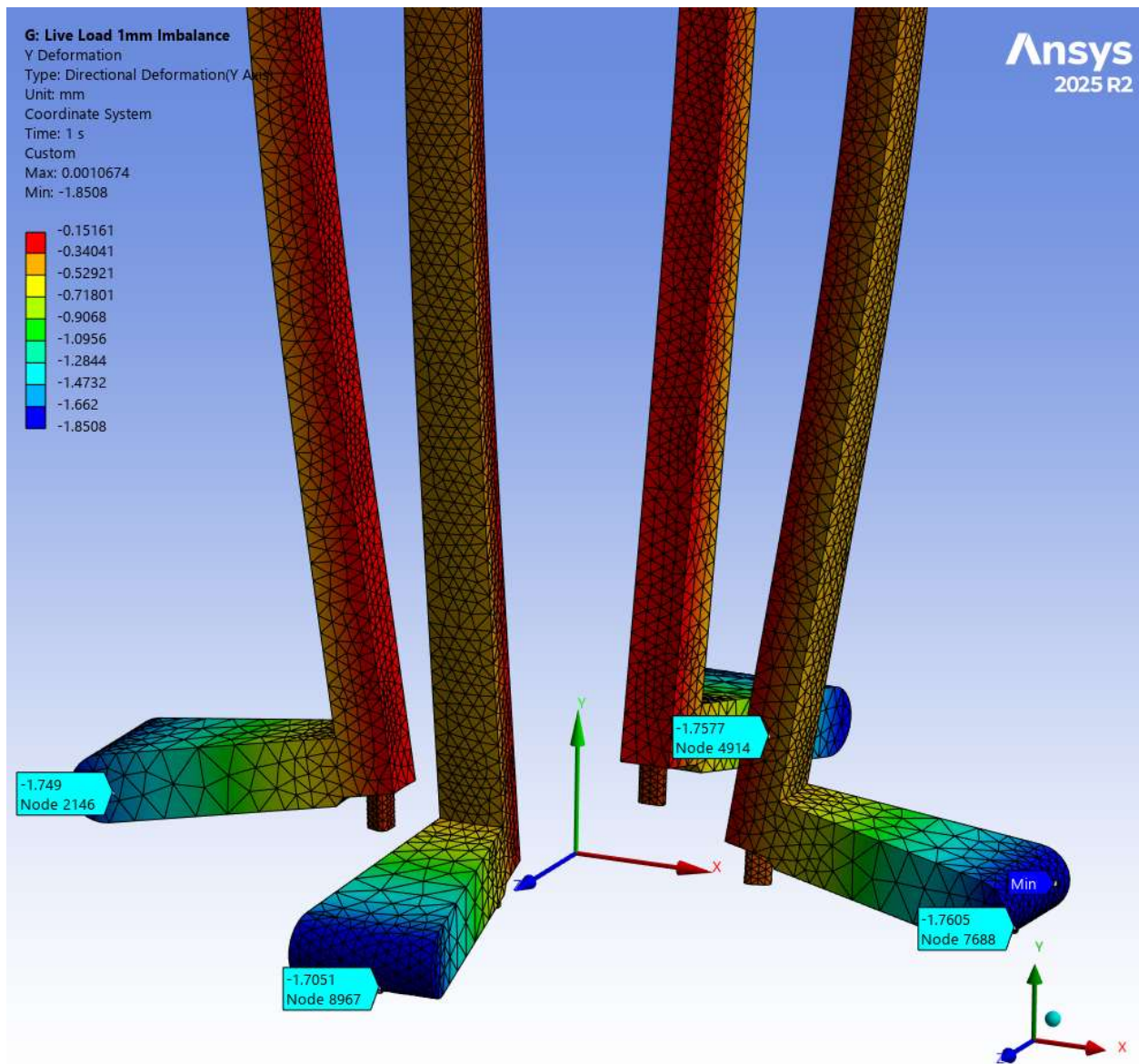


Figure 8 Y Deformation, Foot

Table 8 Y Deformation, Foot

Requirement < -3.25mm				
Node ID	X	Y	Z	Y Deformation (mm)
8967	483.9672	-105.063	553.6025	-1.7051
7688	1038.831	-103.441	3.841708	-1.7605
4914	472.9223	-101.522	-567.164	-1.7577
2146	-98.9889	-96.187	1.264174	-1.749

S.03.02-10713 Foot location - Radial Deflections During Seismic Event

The outer boundary of the target assembly at the foot elevation shall deflect in the radial direction <0.25mm beyond any imposed displacements between mounting flange and lower extremity.

Seismic loads include worst case combinations of:

- L - Live loads (centrifugal target rotation)
- P - Operational pressures (Core Vessel and component operating pressures)
- T - Operating thermal loads (beam on, cooling water)
- E - Seismic loads (Unfactored, per ASCE 7)

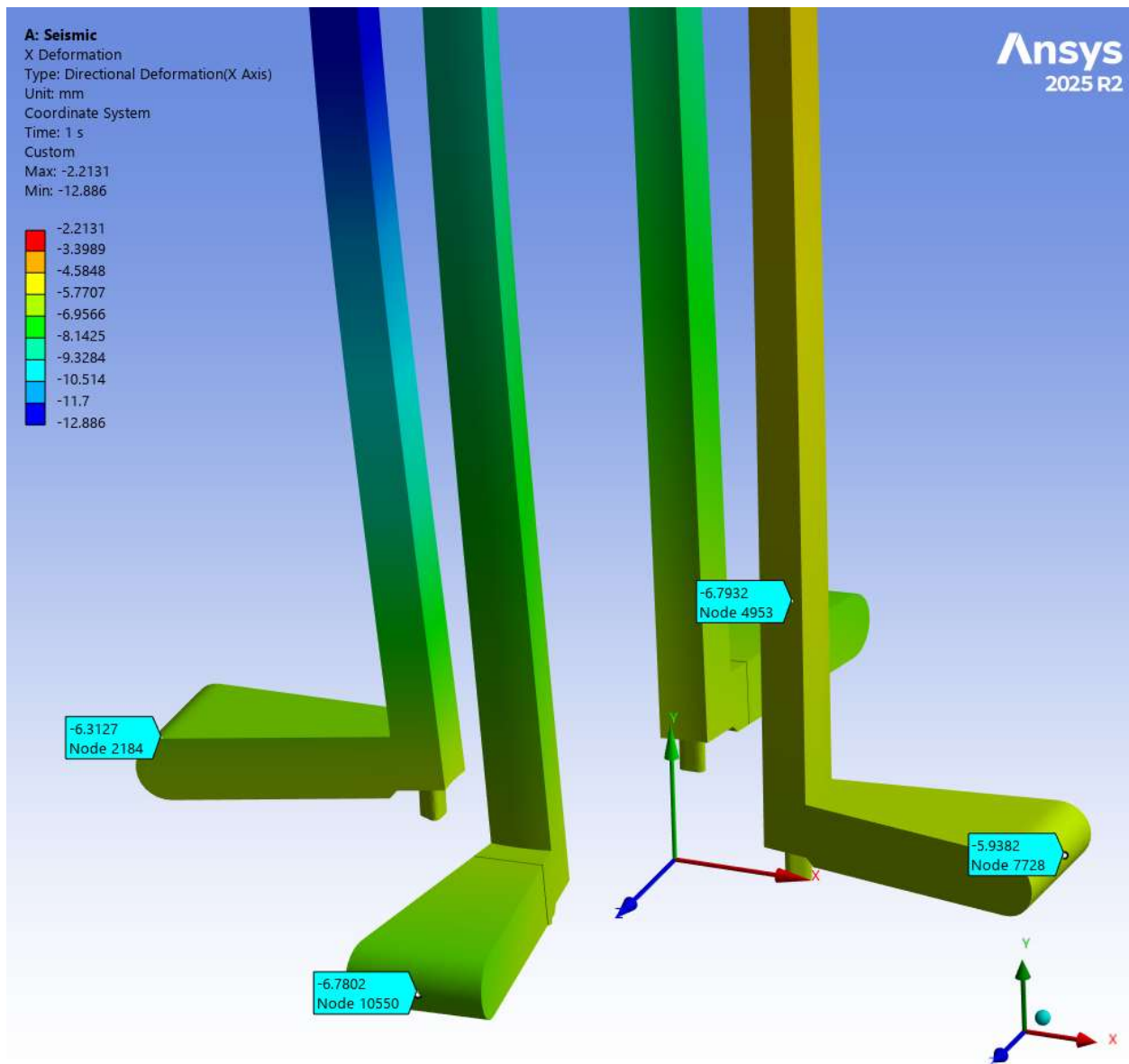


Figure 9 X Deformation, Foot Seismic

Table 9 Radial X Deformation, Foot Seismic

Requirement < 0.5mm Relative				Total X Deformation (mm)	Relative Deformation (mm)
Node ID	X	Y	Z		
7728	990.5558	-7.89725	-10.4377	-5.9382	0.0618
4953	385.6222	-18.2497	-585.828	-6.7932	-0.7932
2184	-181.459	-27.5053	10.26863	-6.3127	-0.3127
10550	401.7421	-24.3978	586.1153	-6.7802	-0.7802

Note Highlighted Cells are Radial Directions

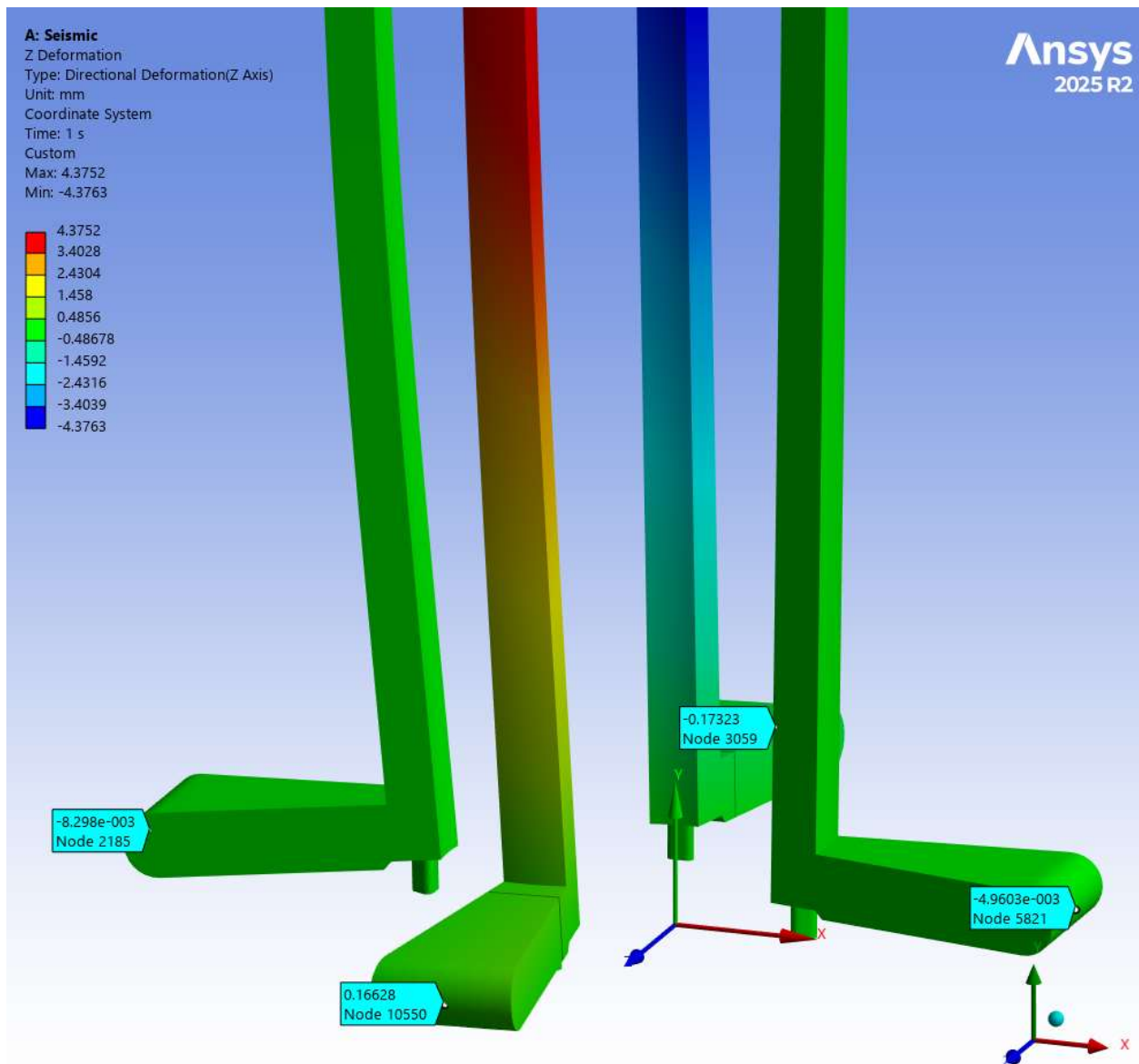


Figure 10 Z Deformation, Foot Seismic

Table 10 Radial Z Deformation, Foot Seismic

Requirement < 0.5mm				
Node ID	X	Y	Z	Z Deformation (mm)
10550	401.7421	-24.3978	586.1153	0.1663
5821	990.8169	-14.8509	4.708168	-0.0050
3059	401.0104	-24.6695	-586.195	-0.1732
2185	-179.869	-40.6663	1.042715	-0.0083

Note Highlighted Cells are Radial Directions

S.03.02-10731 Foot location - Vertical Deflection during seismic event

The outer boundary of the target assembly at the foot elevation shall deflect in the vertical direction < 3.65mm (down) and <0.55mm (up) during a seismic vertical force.

Seismic conditions include the worst case combinations of:

- L - Live loads (centrifugal target rotation)
- P - Operational pressures (Core Vessel and component operating pressures)
- T - Operating thermal loads (beam on, cooling water)
- E - Seismic loads (Unfactored, per ASCE 7)

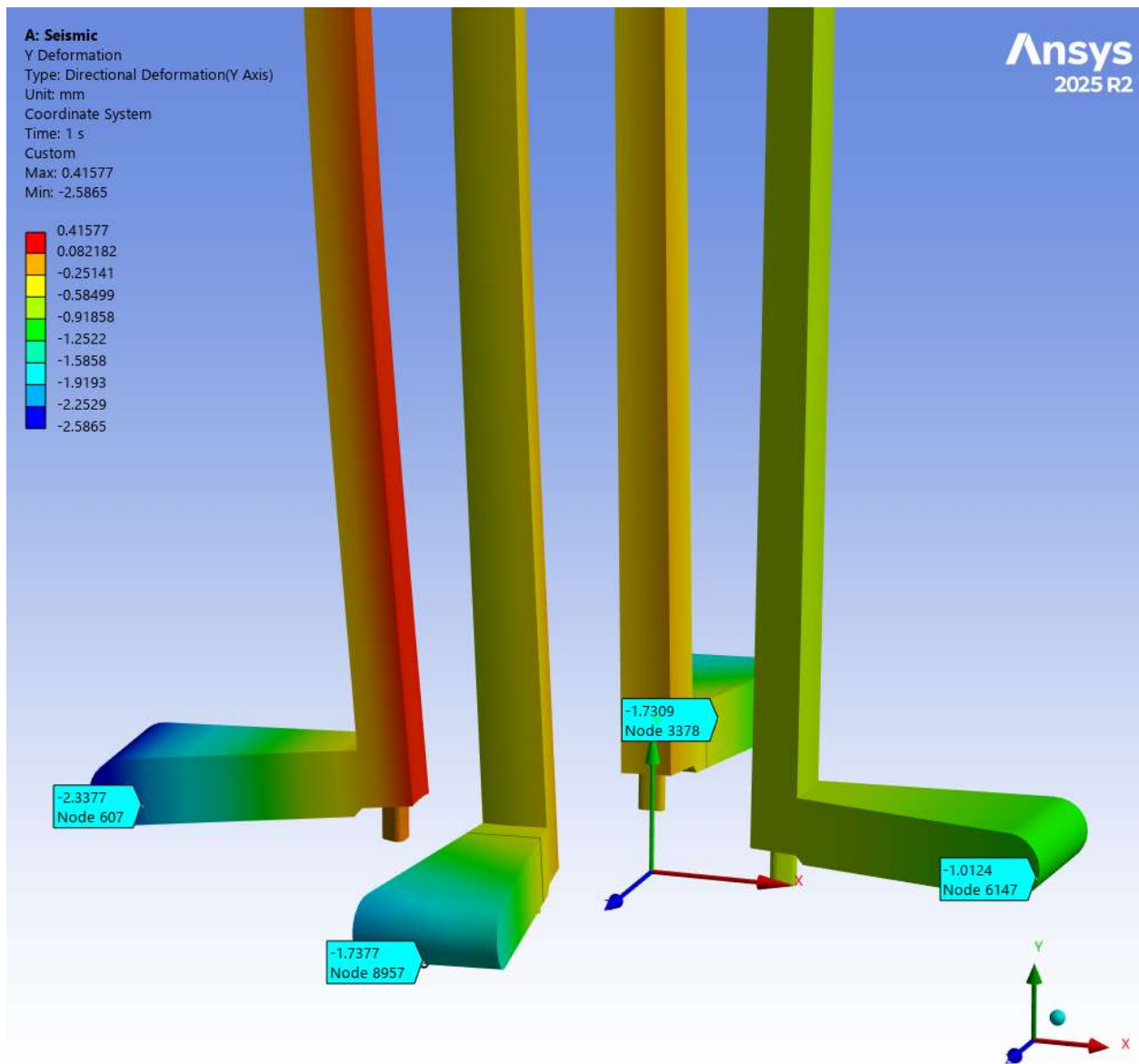


Figure 11 Y Deformation, Foot Seismic

Table 11 Y Deformation, Foot Seismic

Node ID	X	Requirement < -3.65mm			Y Deformation (mm)
		Y	Z		
8957	384.3691	-61.4425	551.5287		-1.7377
607	-143.944	-69.4307	3.113335		-2.3377
6147	956.6136	-52.4573	-3.28		-1.0124
3378	383.3298	-61.6252	-550.165		-1.7309

S.03.02-10676 Radial Deflections During Normal Operation

The lower extremity (snubber) shall not deflect in the radial direction more than +/-0.5mm during the worst case combination of:

- L - Live loads (imbalance target rotation)
- P - Operational pressures (Core Vessel and component operating pressures)
- T - Operating thermal loads (beam on, cooling water)

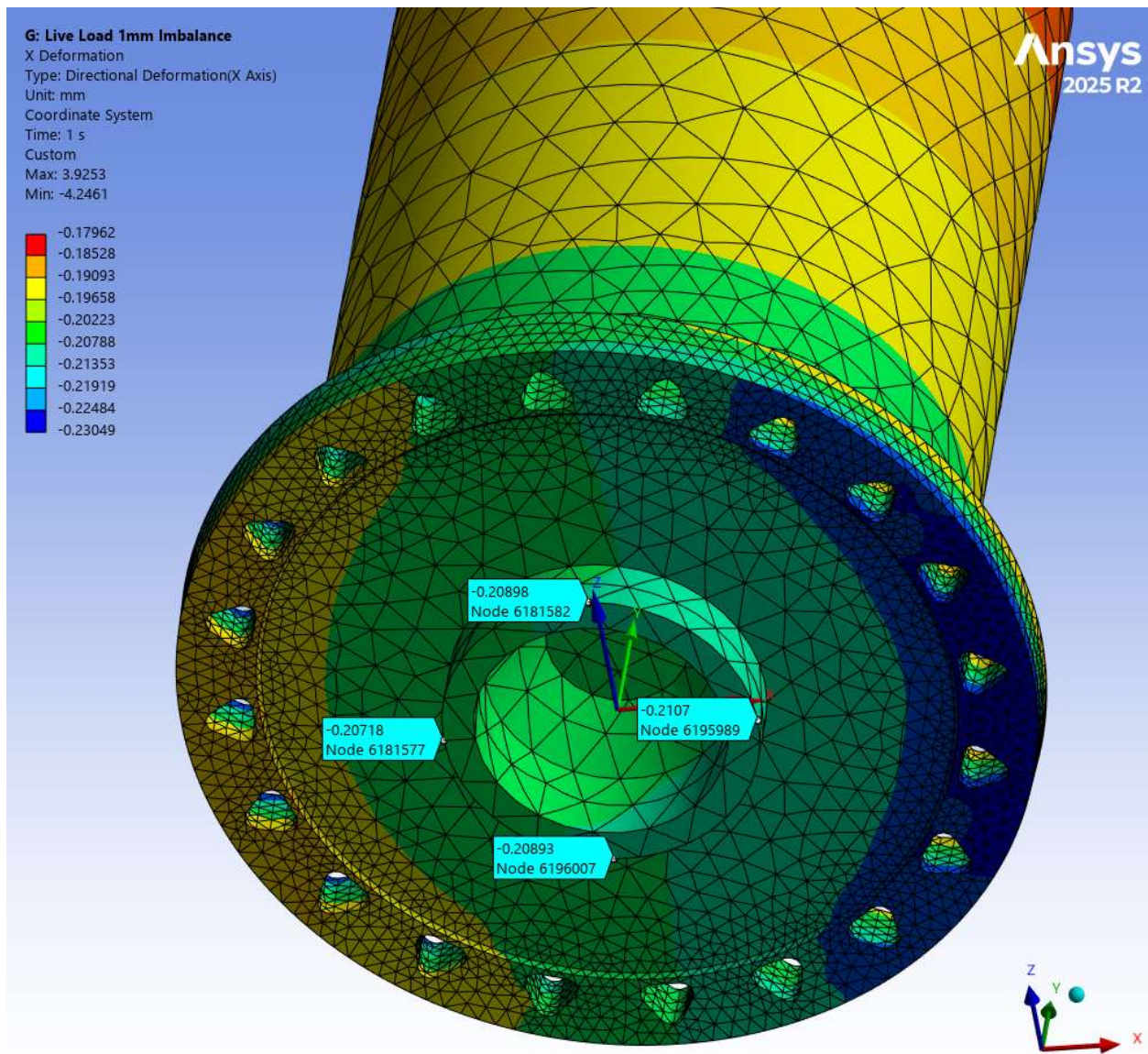


Figure 12 X Deformation, Snubber

Table 12 Radial X Deformation, Snubber

Requirement < +/-0.5mm				
Node ID	X	Y	Z	X Deformation (mm)
6181582	483.1353	-108.122	99.55235	-0.2090
6196007	466.6213	-108.096	-99.6298	-0.2089
6181577	374.9472	-107.964	-0.03355	-0.2072
6195989	574.8106	-108.254	-0.04343	-0.2107

Note Highlighted Cells are Radial Directions

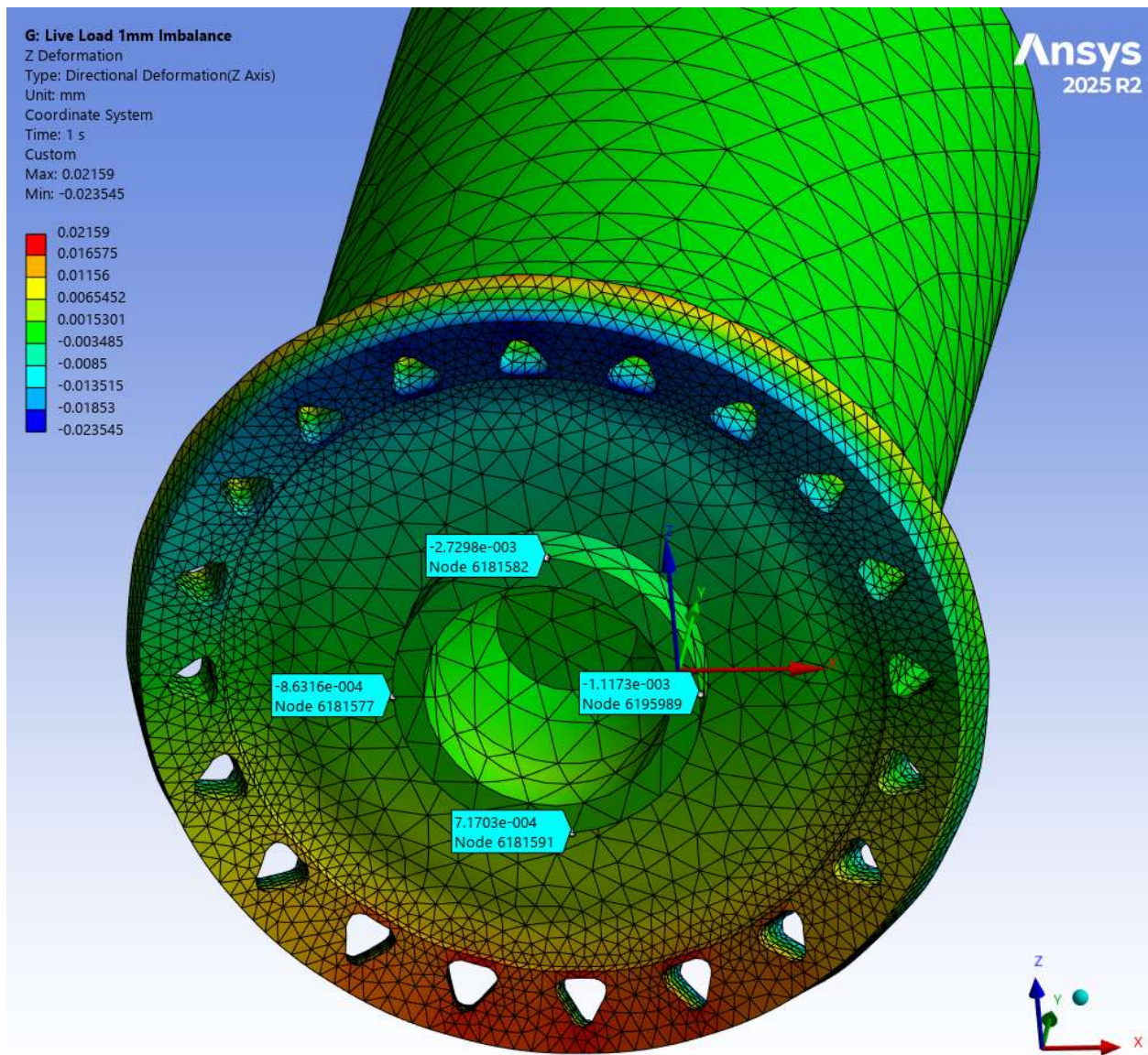


Figure 13 Z Deformation, Snubber

Table 13 Radial Z Deformation, Snubber

Requirement < +/-0.5mm				Z Deformation (mm)
Node ID	X	Y	Z	
6181582	410.3545	-118.172	98.60166	-0.0027
6195989	501.4319	-119.487	-0.43256	-0.0011
6181577	302.792	-116.599	-0.33416	-0.0009
6181591	410.263	-118.156	-99.3809	0.0007

Note Highlighted Cells are Radial Directions

S.03.02-10677 Vertical Deflections During Normal Operation

The lower extremity shall deflect in the vertical direction <2mm (down) and < 0.2mm (up) during the worst case combination of:

- L - Live loads (imbalance target rotation)
- P - Operational pressures (Core Vessel and component operating pressures) and pressure testing (MAWP)
- T - Operating thermal loads (beam on, cooling water)

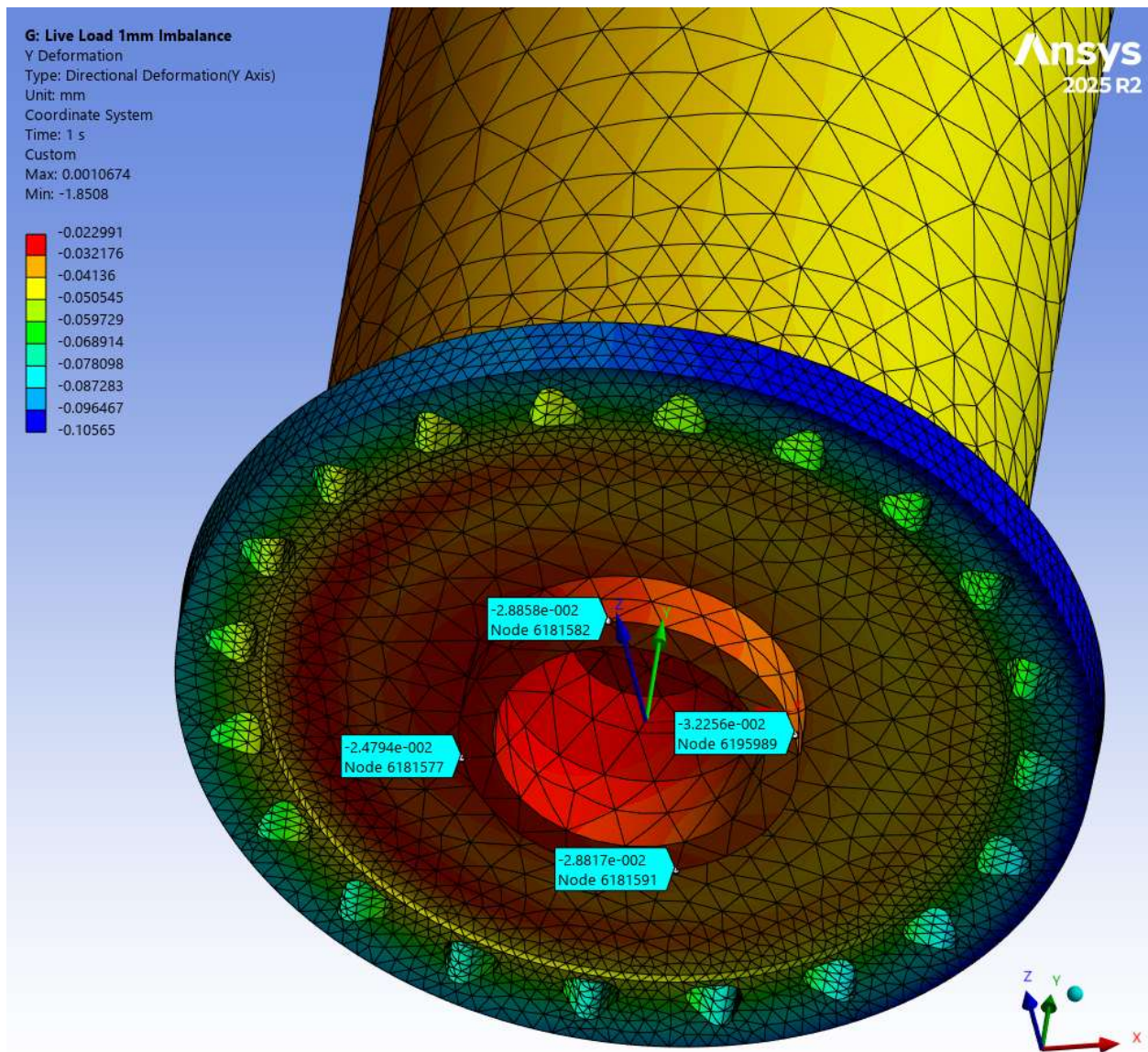


Figure 14 Y Deformation, Snubber

Table 14 Y Deformation, Snubber

Node ID	X	Requirement < -2mm			Y Deformation (mm)
		Y	Z		
6195989	574.8106	-108.254	-0.04343		-0.0323
6181577	374.9472	-107.964	-0.03355		-0.0248
6181582	483.1353	-108.122	99.55235		-0.0289
6181591	483.1261	-108.12	-99.6306		-0.0288