OAK RIDGE National Laboratory

Core Vessel Dual Channel Nozzle Extension Preliminary Analysis

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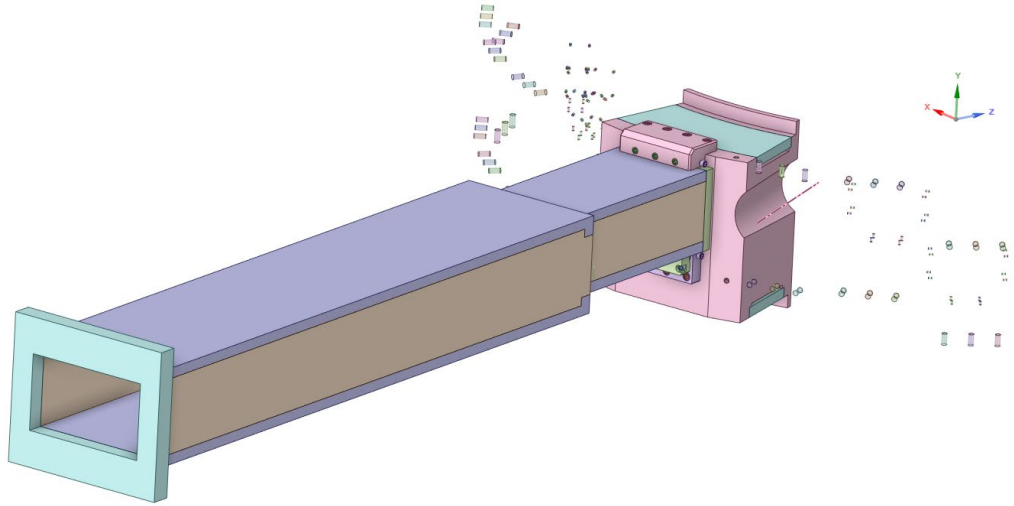
SpaceClaim model and changes

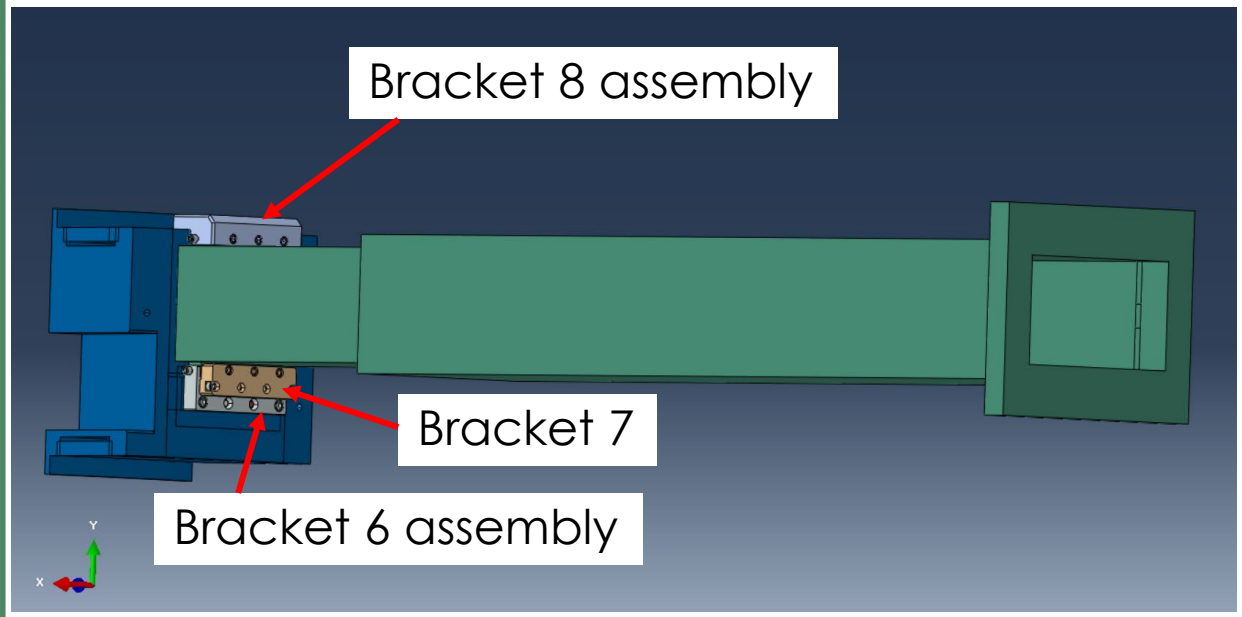
Main changes made for Abaqus model

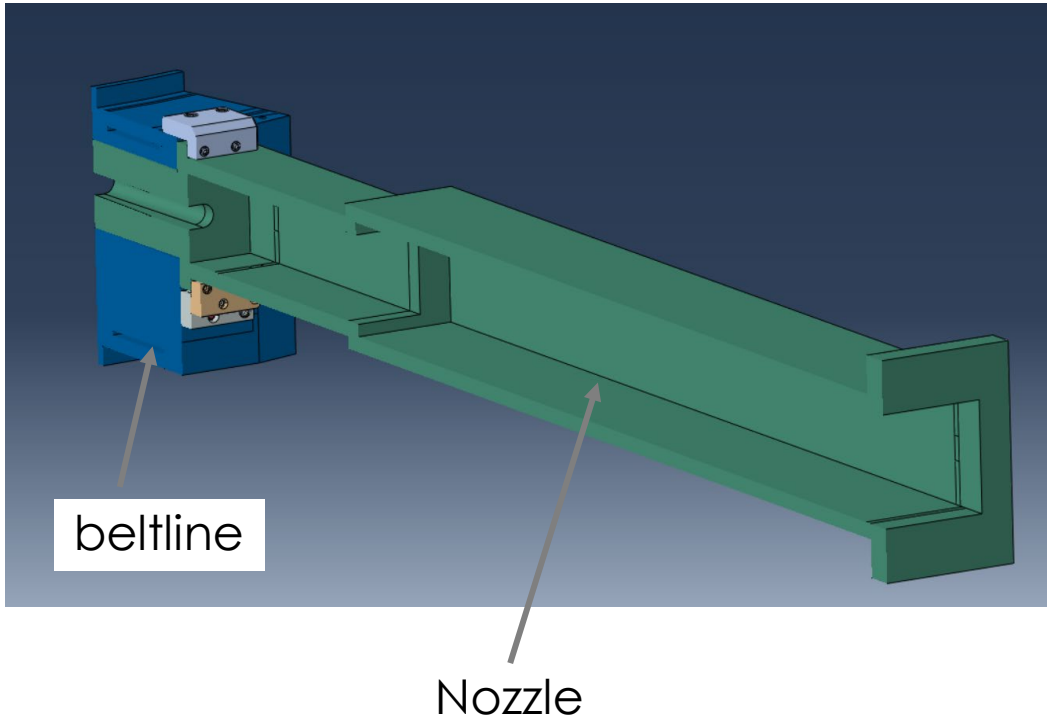
- Nozzle plate and flange parts merged
- Bolt thread areas deleted, and holes enlarged to match bolt diameters
- Lower bracket two center bolts changed to shear pins with the same diameter

SpaceClaim model



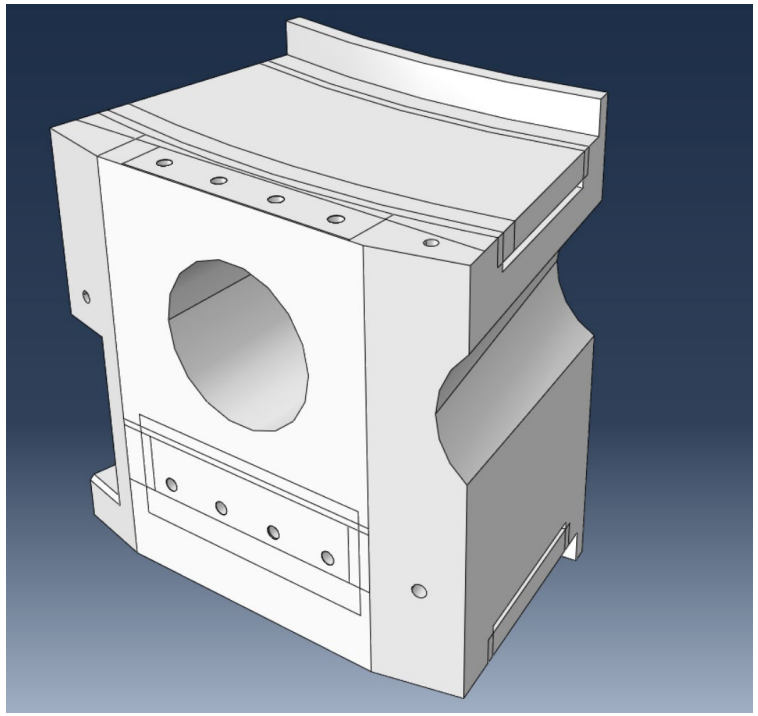
Dual Port Nozzle Abaqus Assembly



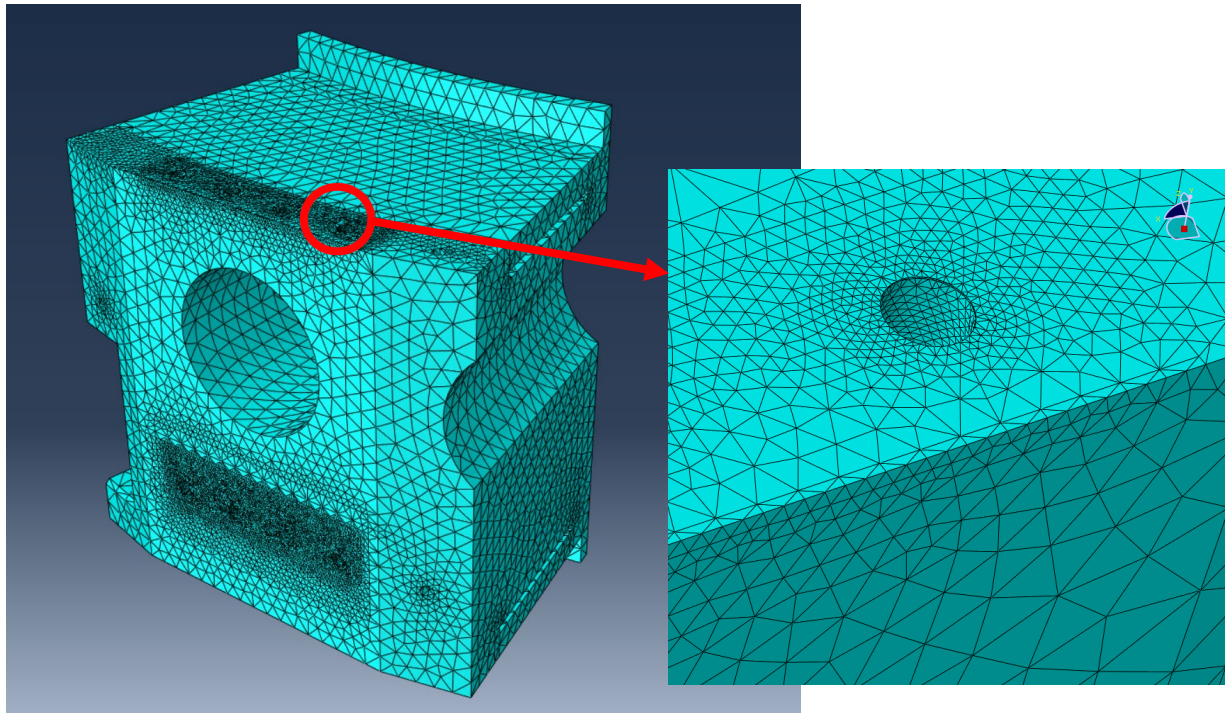


Beltline part with partitions added to define contact zones and merged water manifold plates

Beltline Part

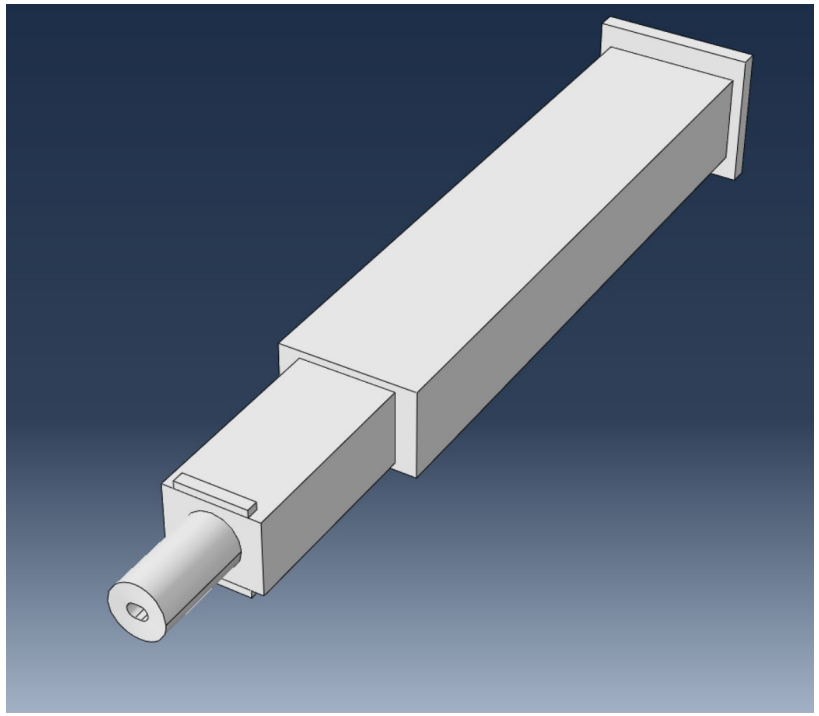


C3D10 Mesh

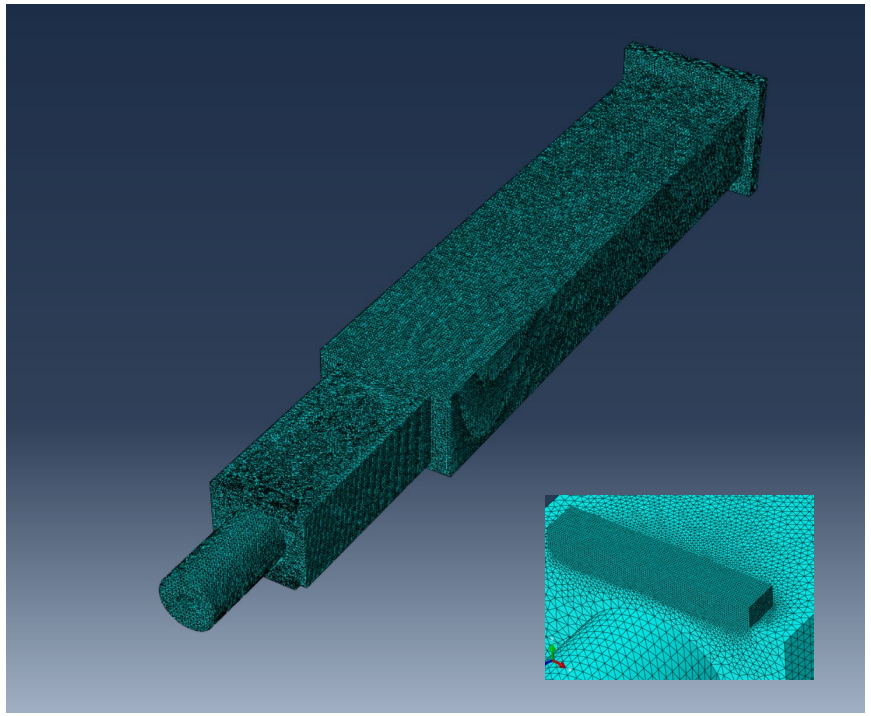


Nozzle

Parts all merged

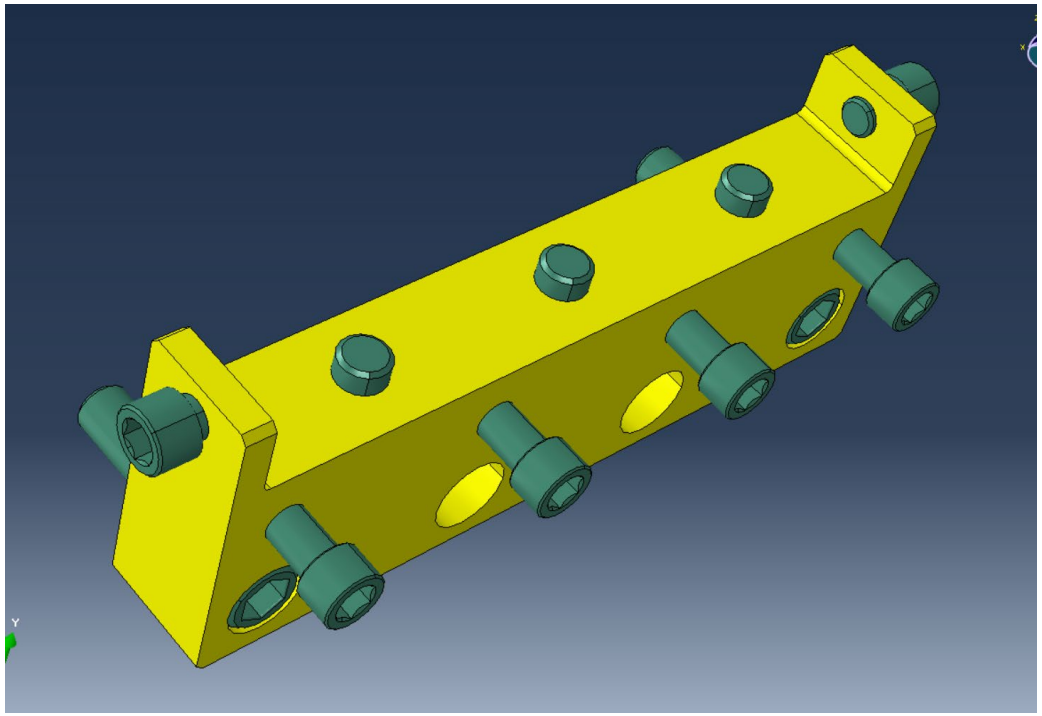


C3D10 Mesh

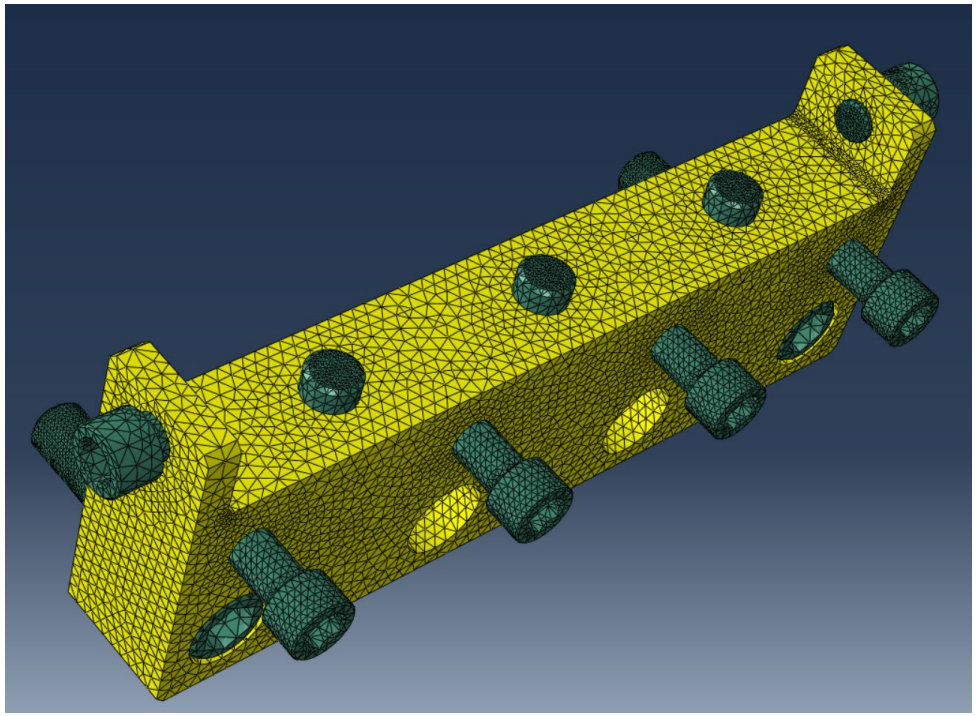


Bracket 6 Assembly

Bolts merged with body in threaded regions – separate material assigned

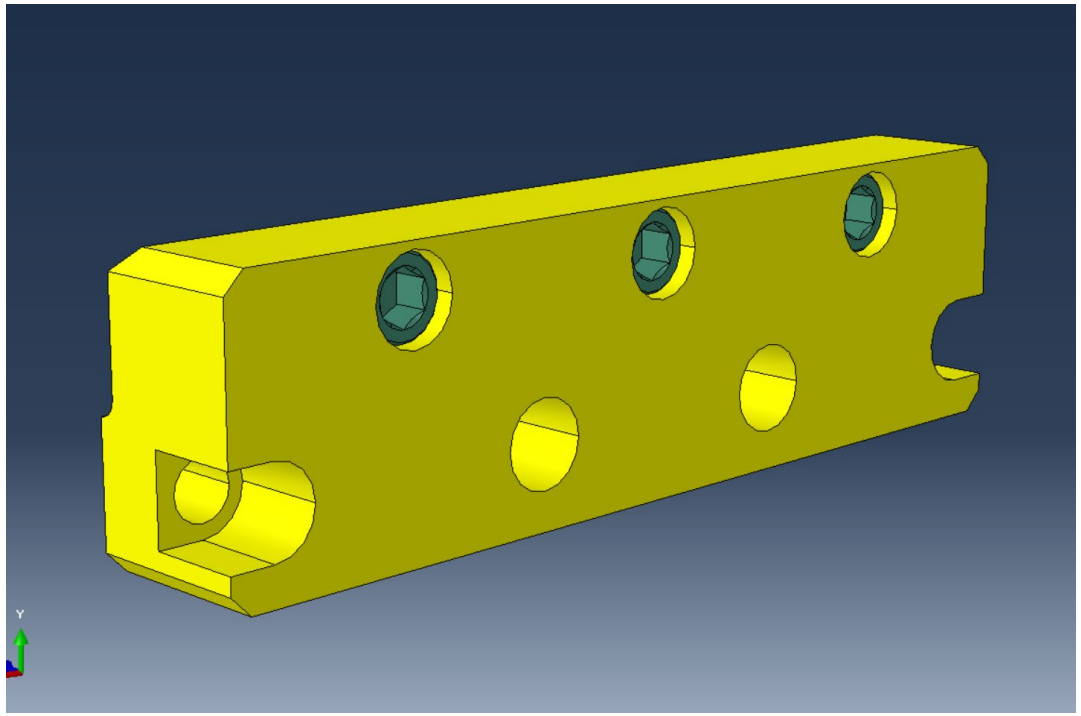


C3D10 Tet mesh

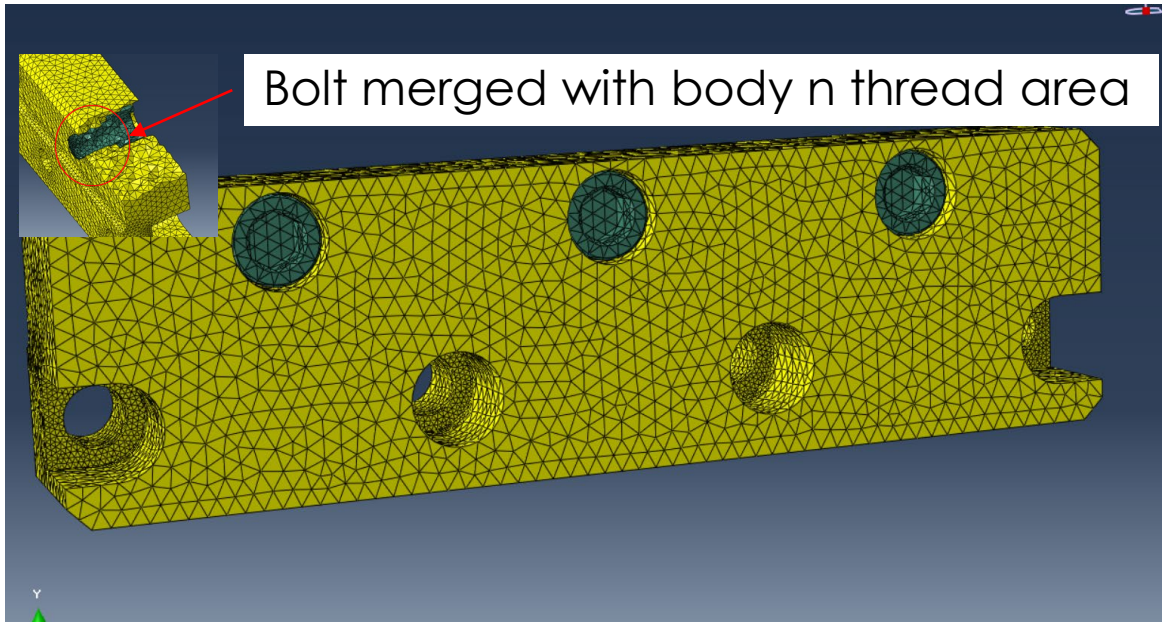


Bracket 7 with body and bolts

Part with bolts merged in contact area of heads

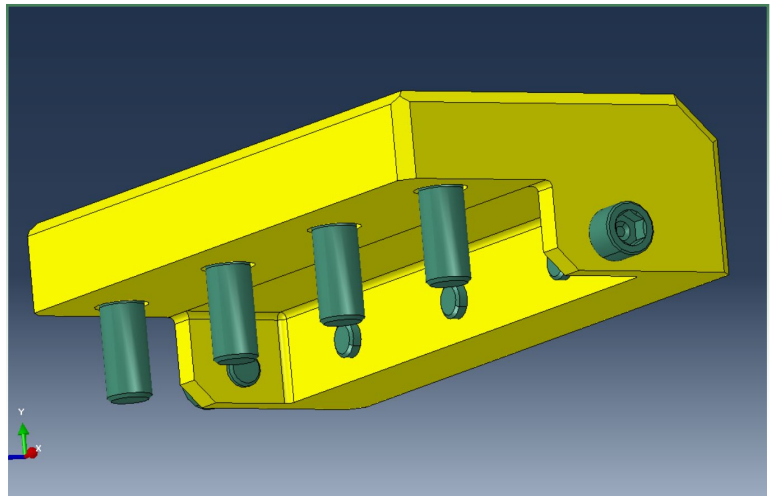


C3D10 Mesh

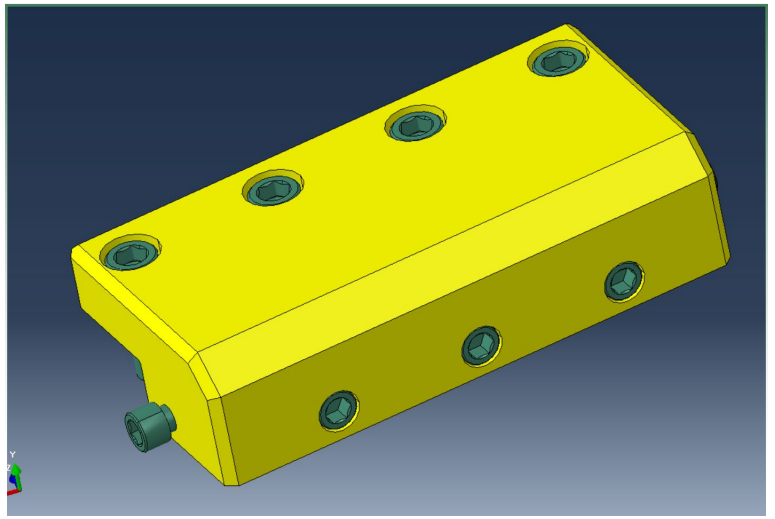


Bracket 8 Assembly

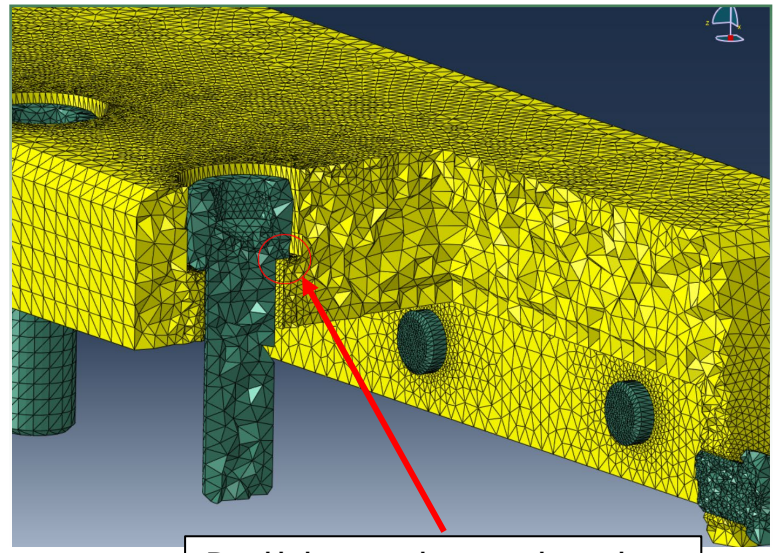
Threaded area of bolts merged with body



Top view



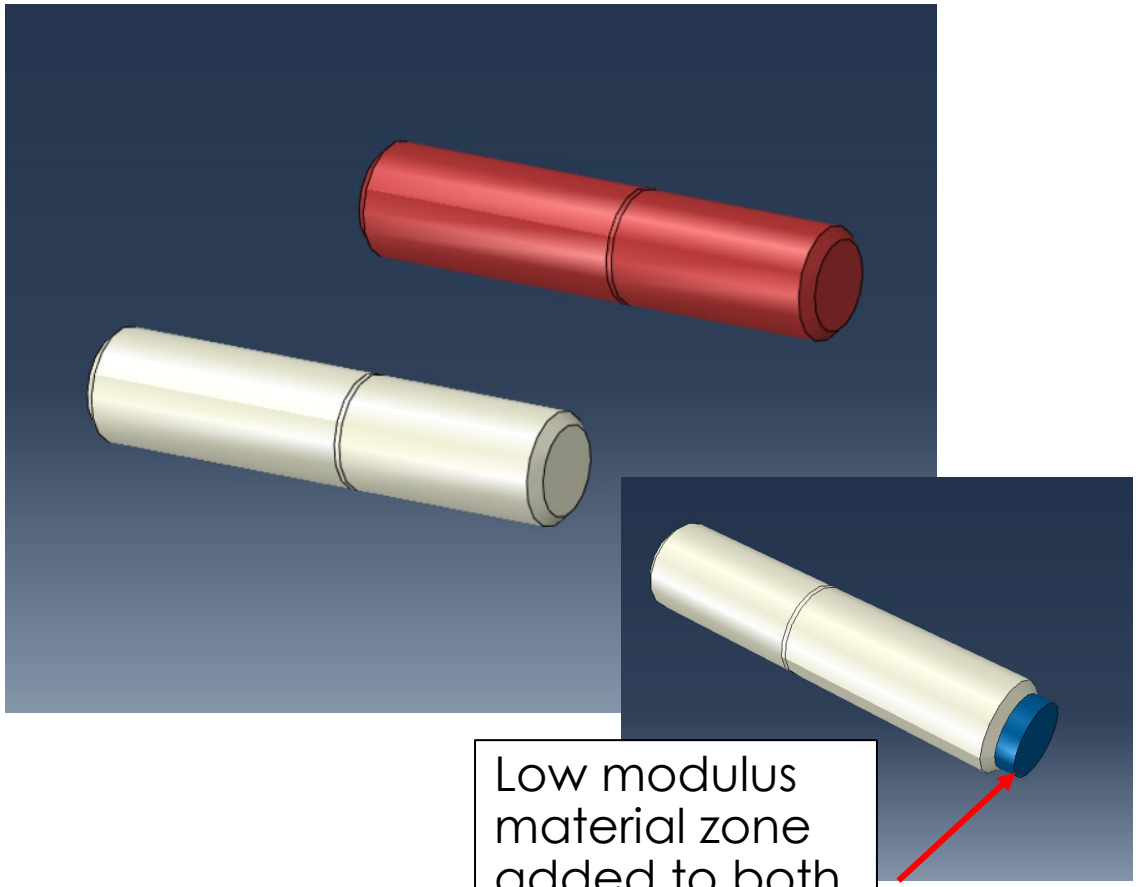
Bolt head merged



Bolt head contact area merged with body

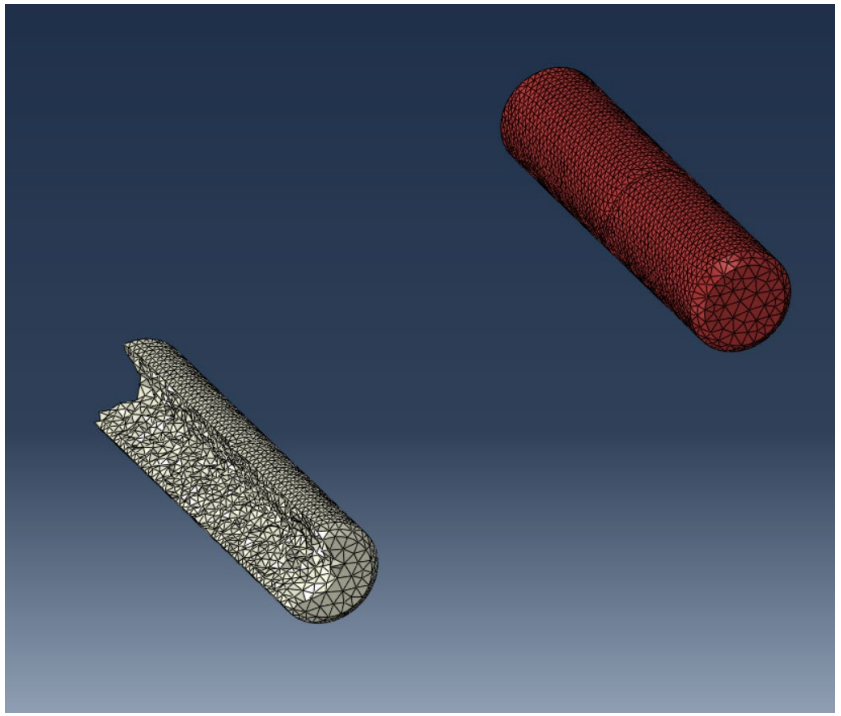
20 mm diameter shear pins used in bracket 6

parts



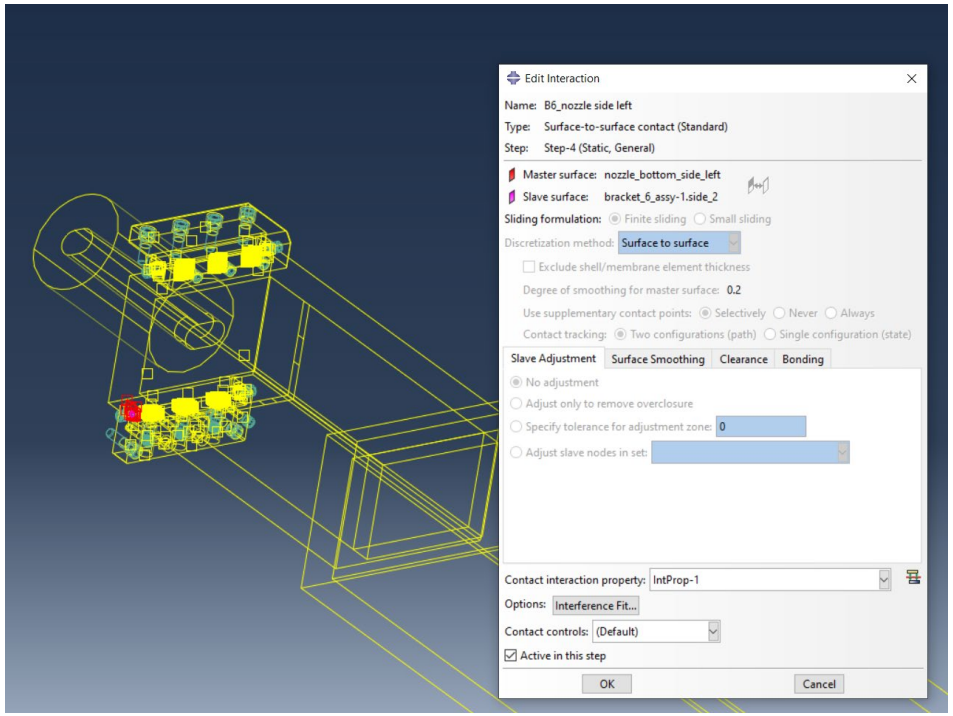
Low modulus material zone added to both to make weak ties to beltline

C3D10 mesh

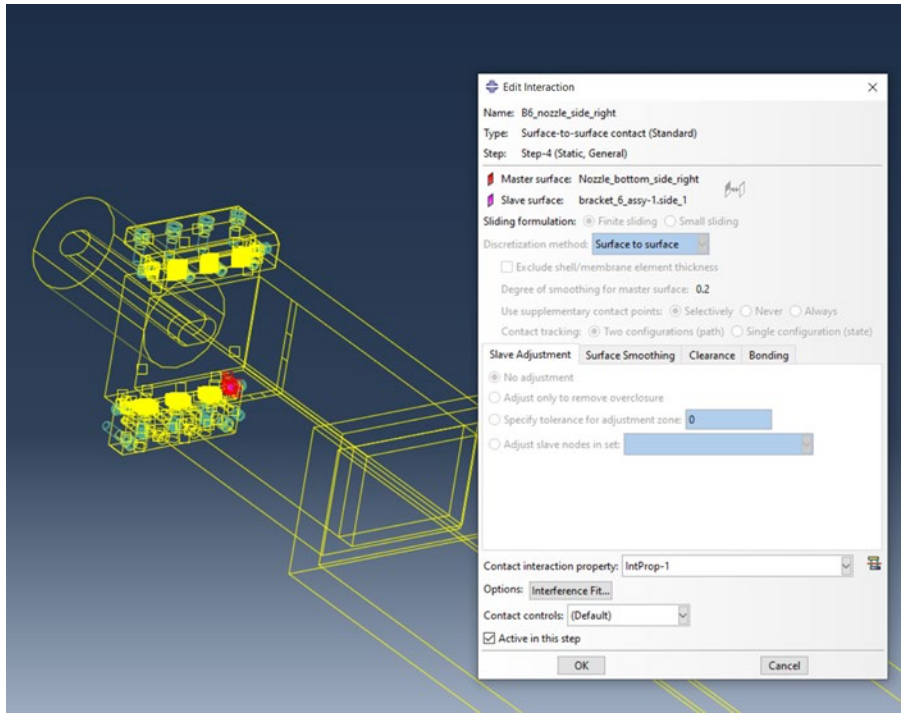


Surface to Surface Interactions

Bracket 6 left side to Nozzle bottom

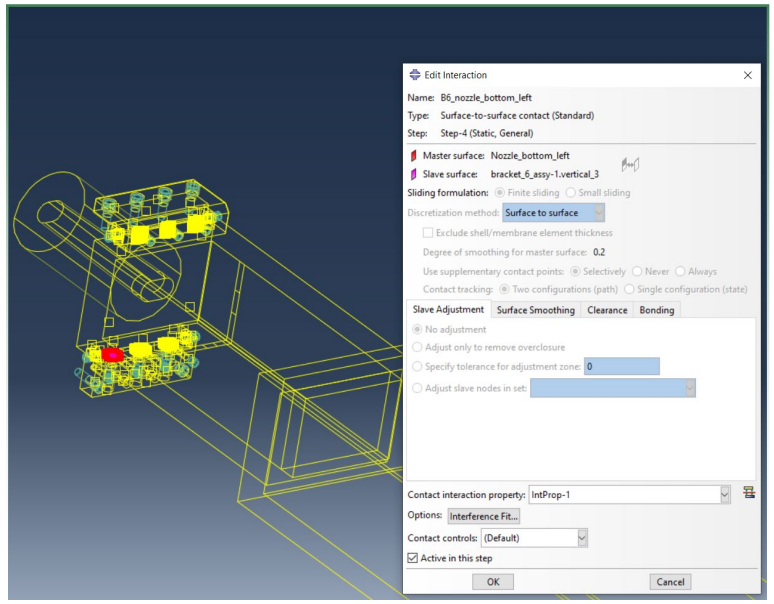


Bracket 6 right side to Nozzle bottom

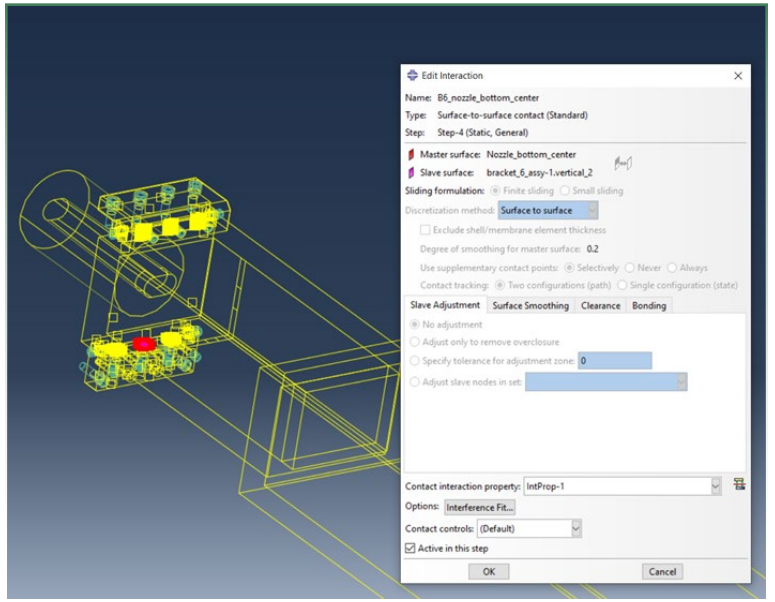


Surface to Surface Interactions – bracket 6 bottom vertical

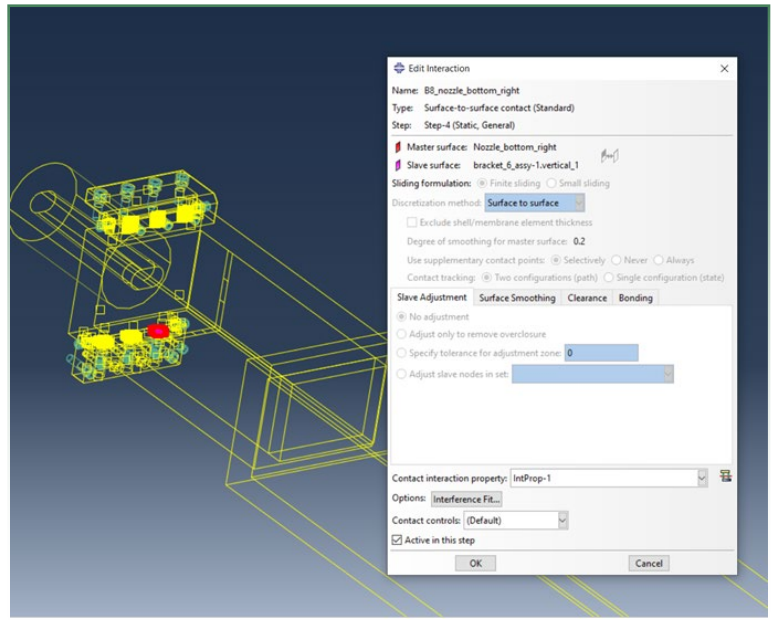
Left bolt to nozzle



Center bolt to nozzle

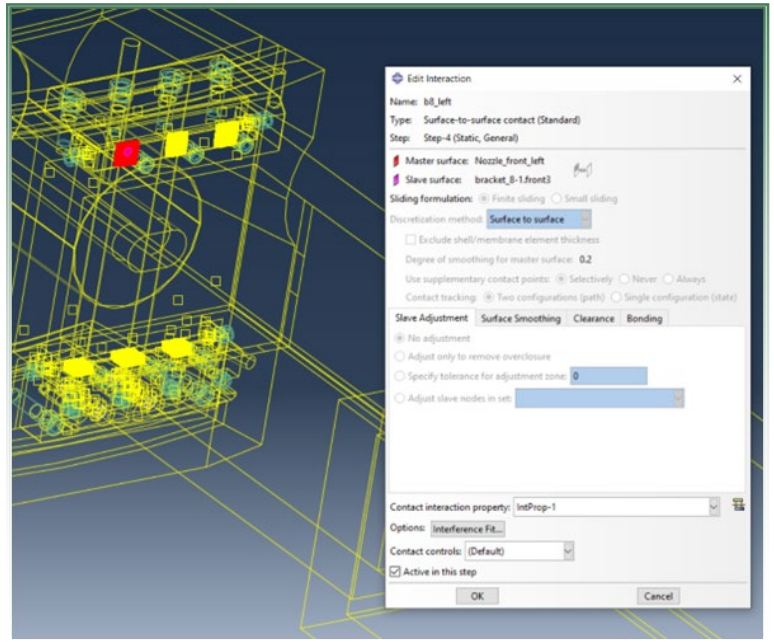


Right bolt to nozzle

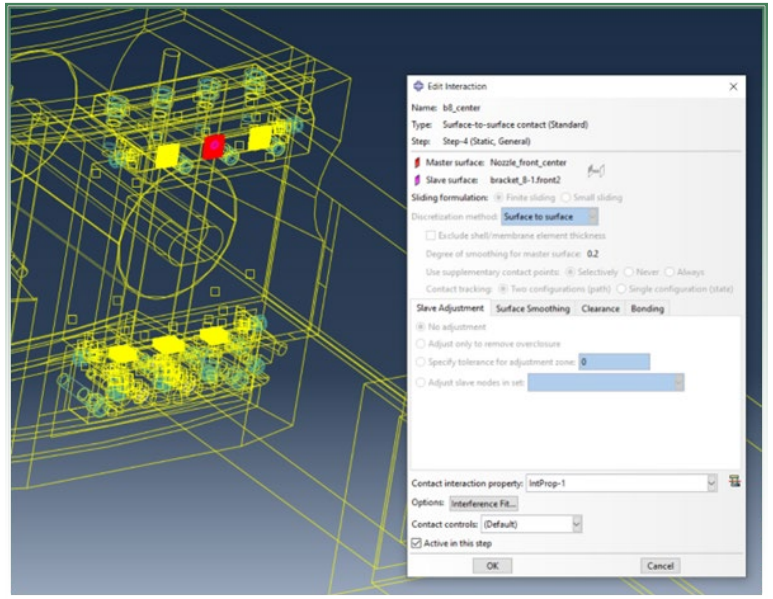


Surface to Surface Interactions – bracket 8 top horizontal

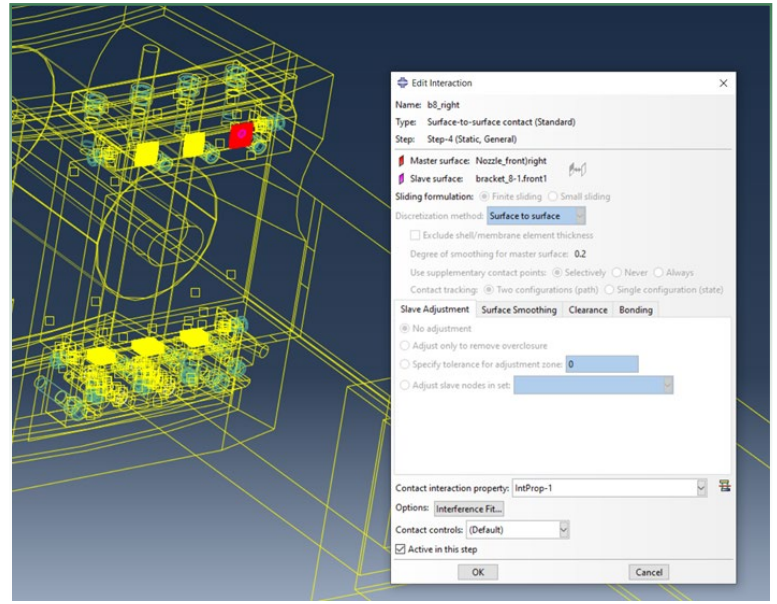
left



center

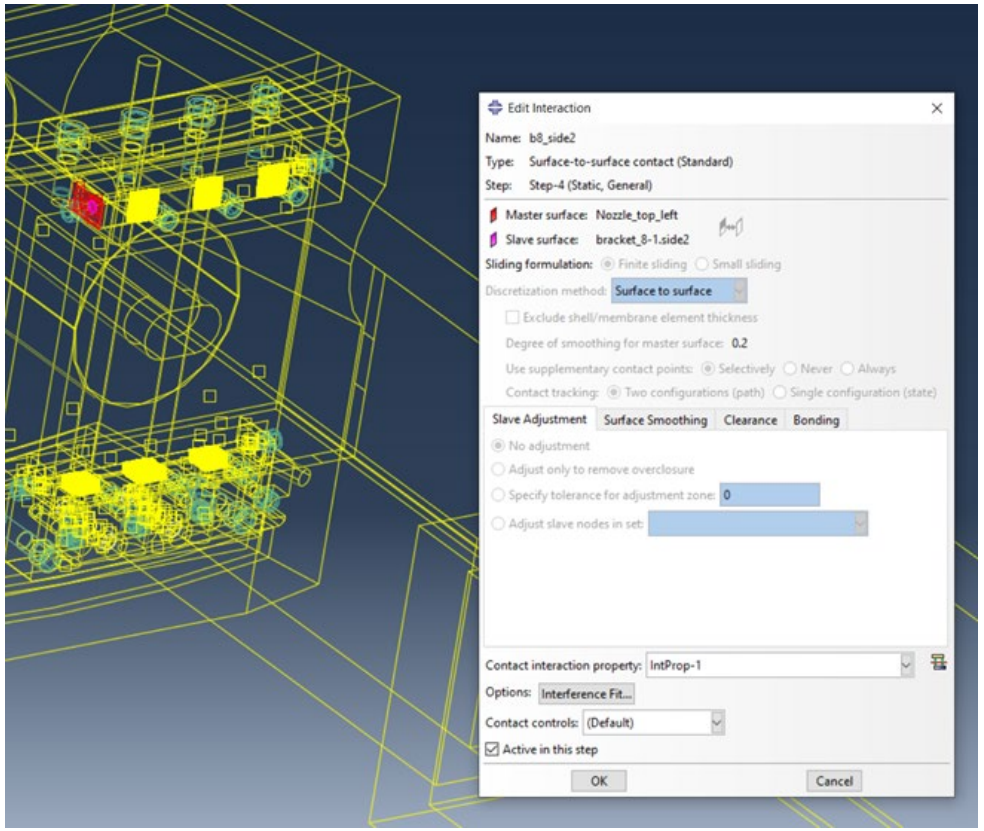


right

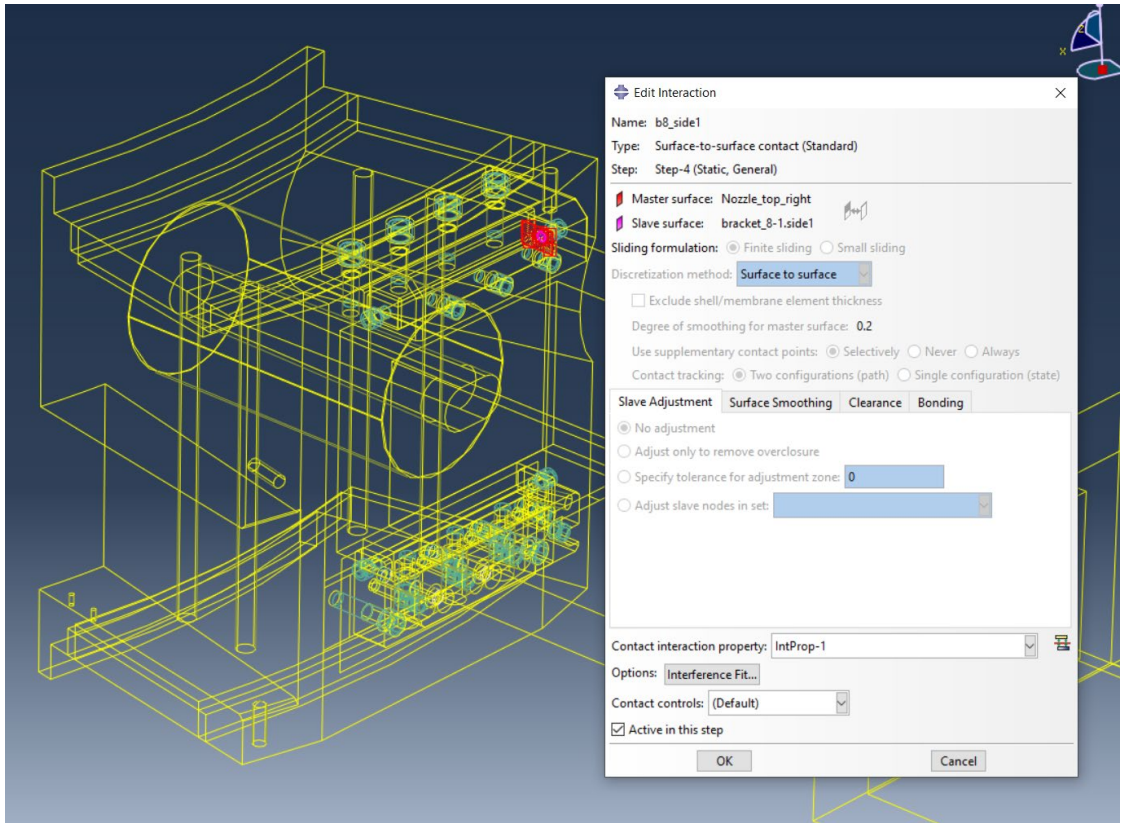


Surface to Surface Interactions –bracket 8 top lateral

Left side to nozzle

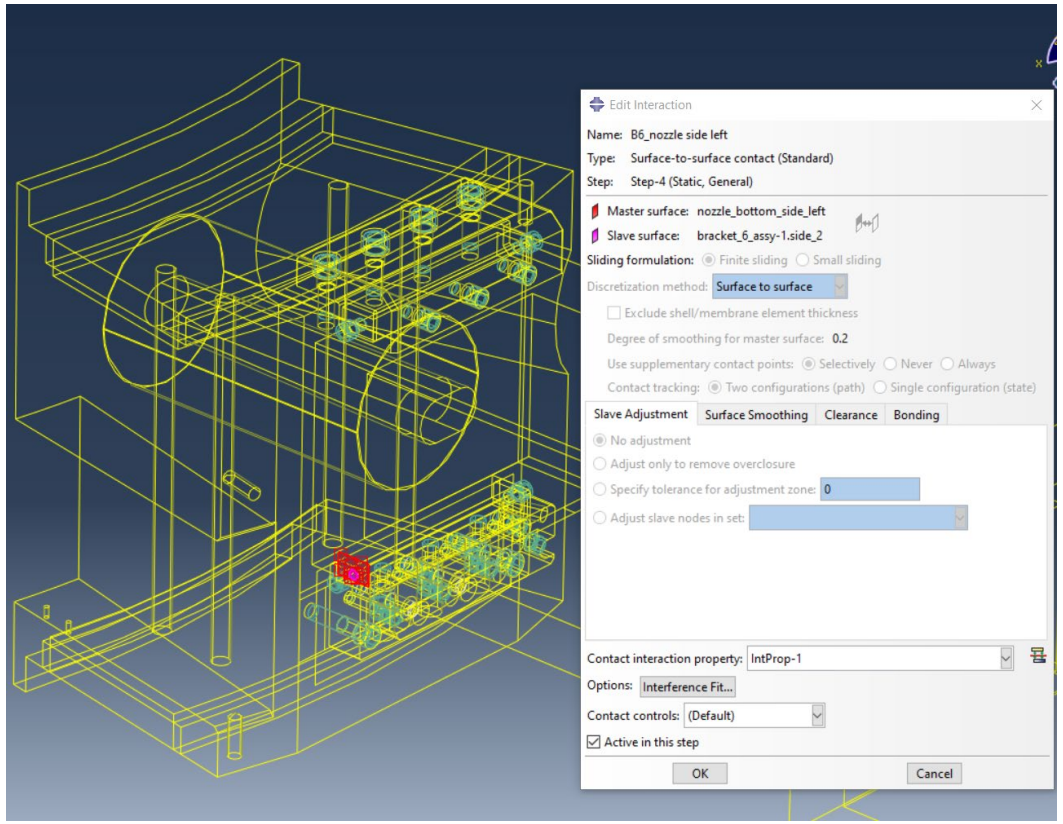


Right side to nozzle



Surface to Surface Interactions – bracket 6 bottom lateral

Left side to nozzle



Right side to nozzle

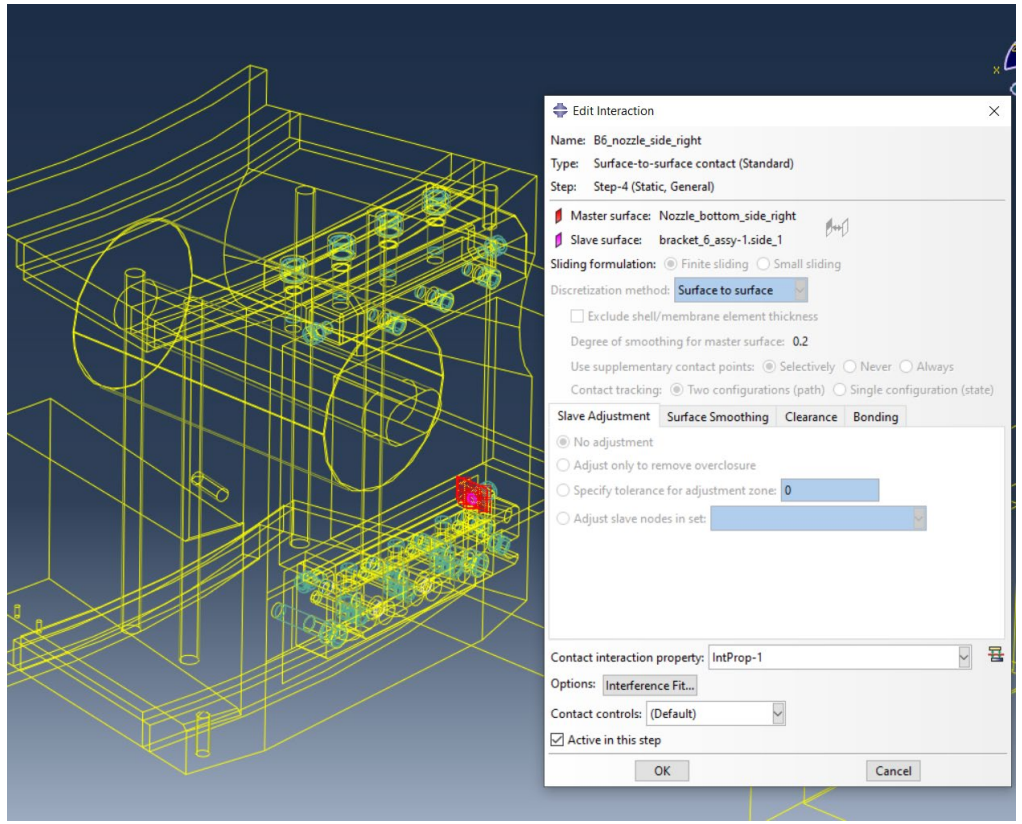
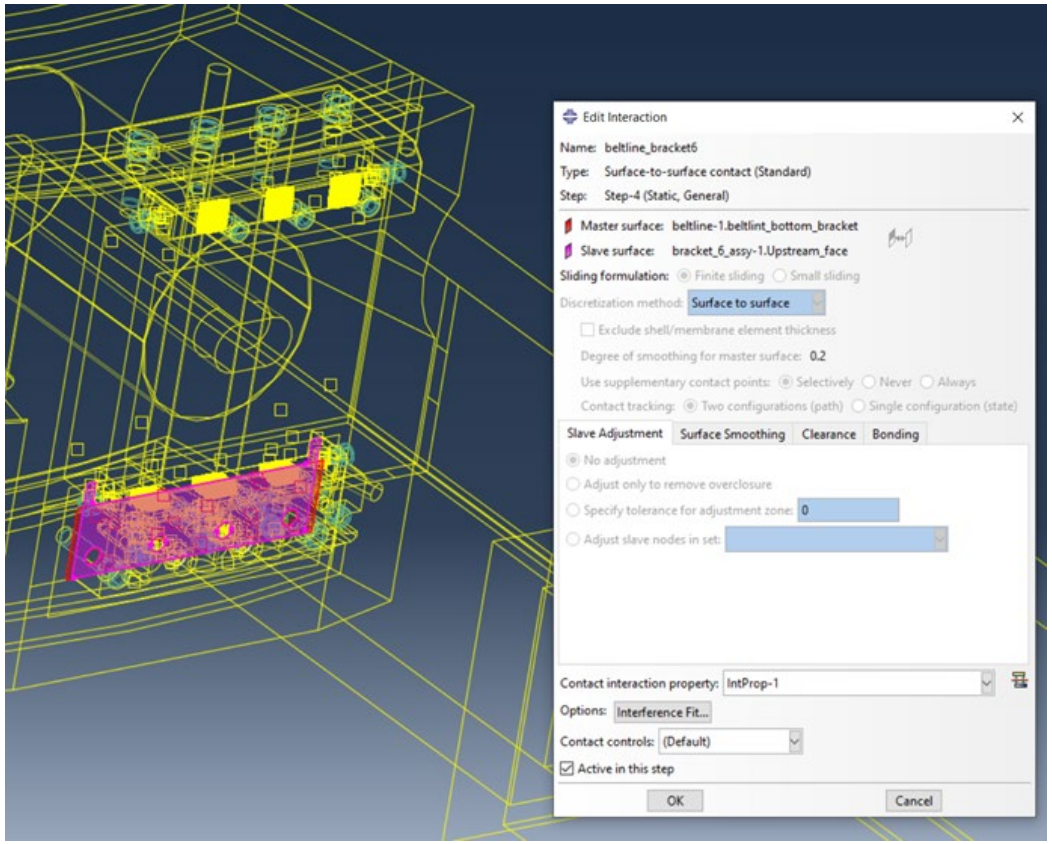


Plate surface to surface interaction

Bracket 6 upstream face to beltline



Bracket 8 bottom to beltline

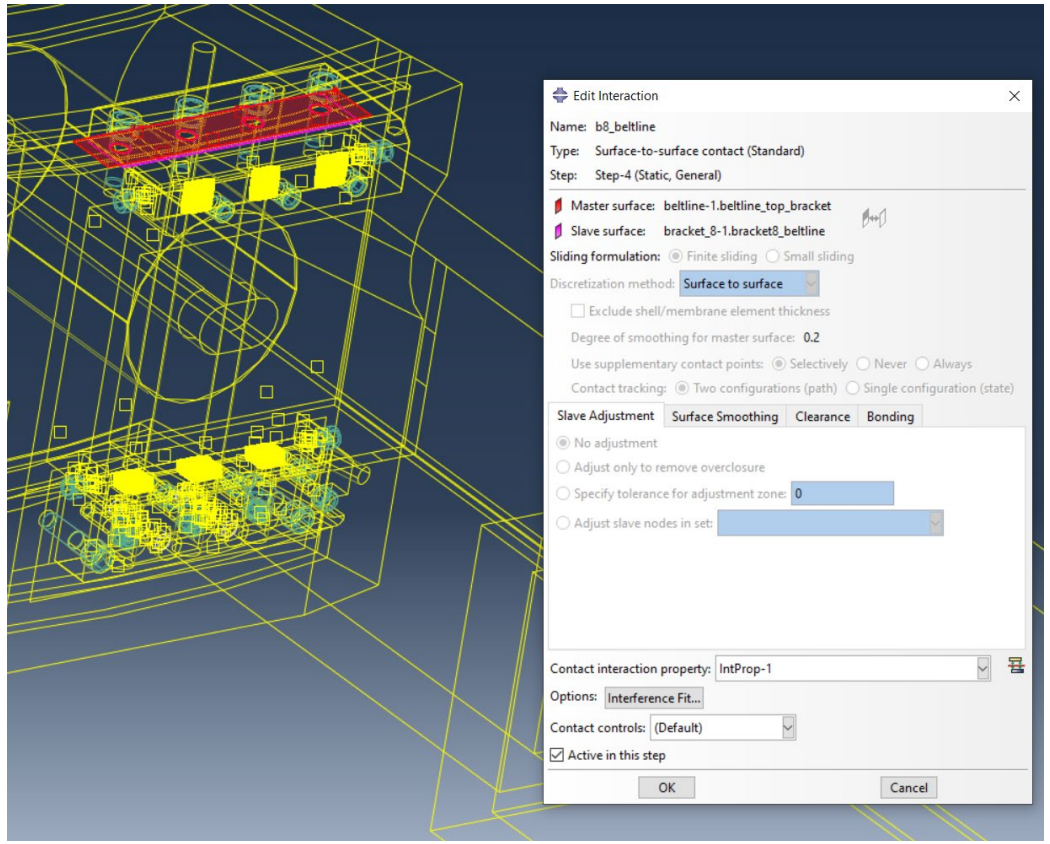
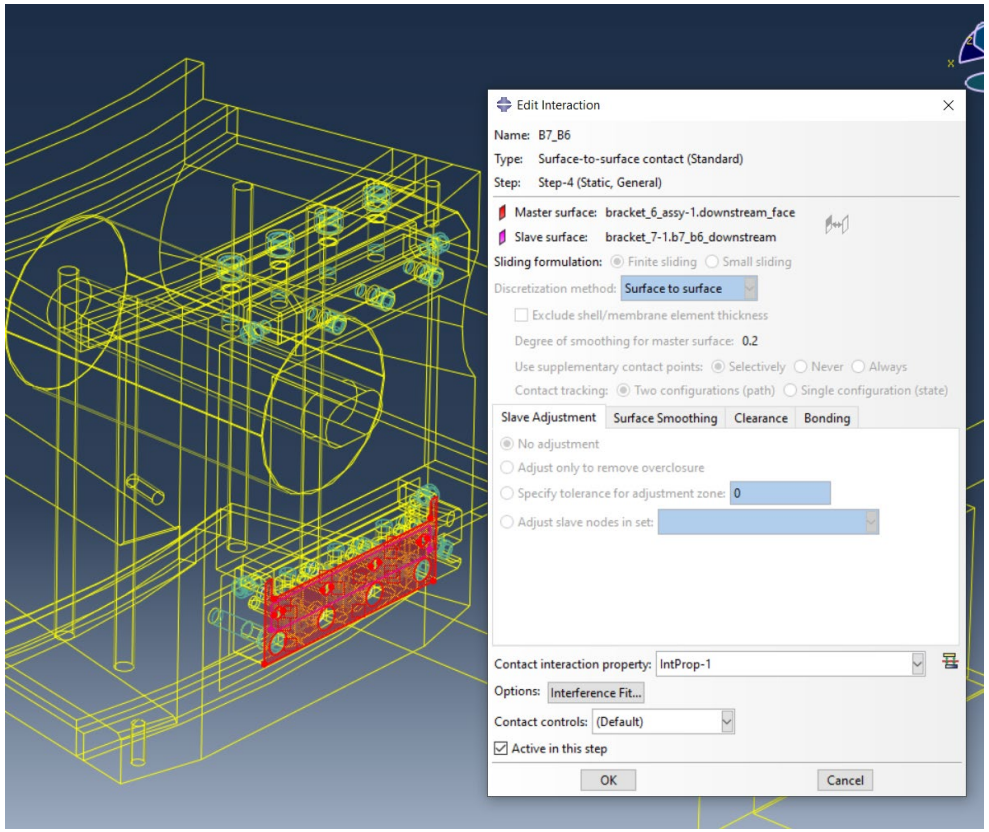
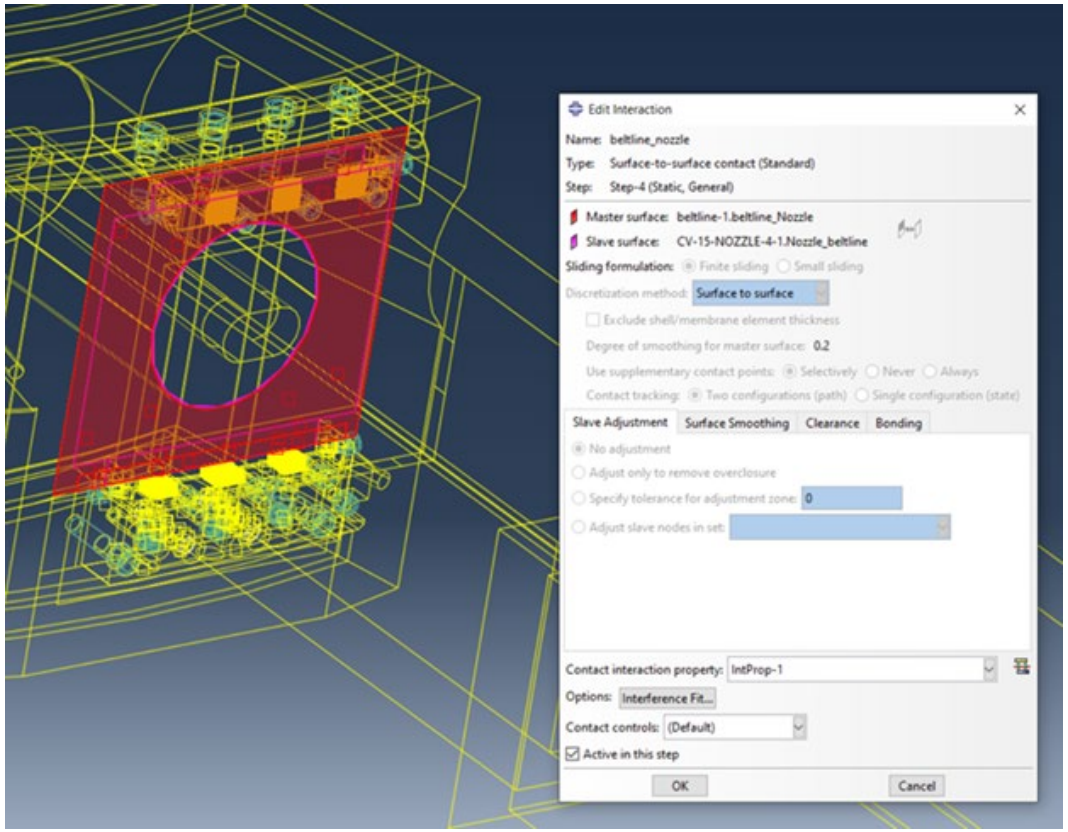


Plate surface to surface interaction

Bracket 7 upstream face to bracket 6

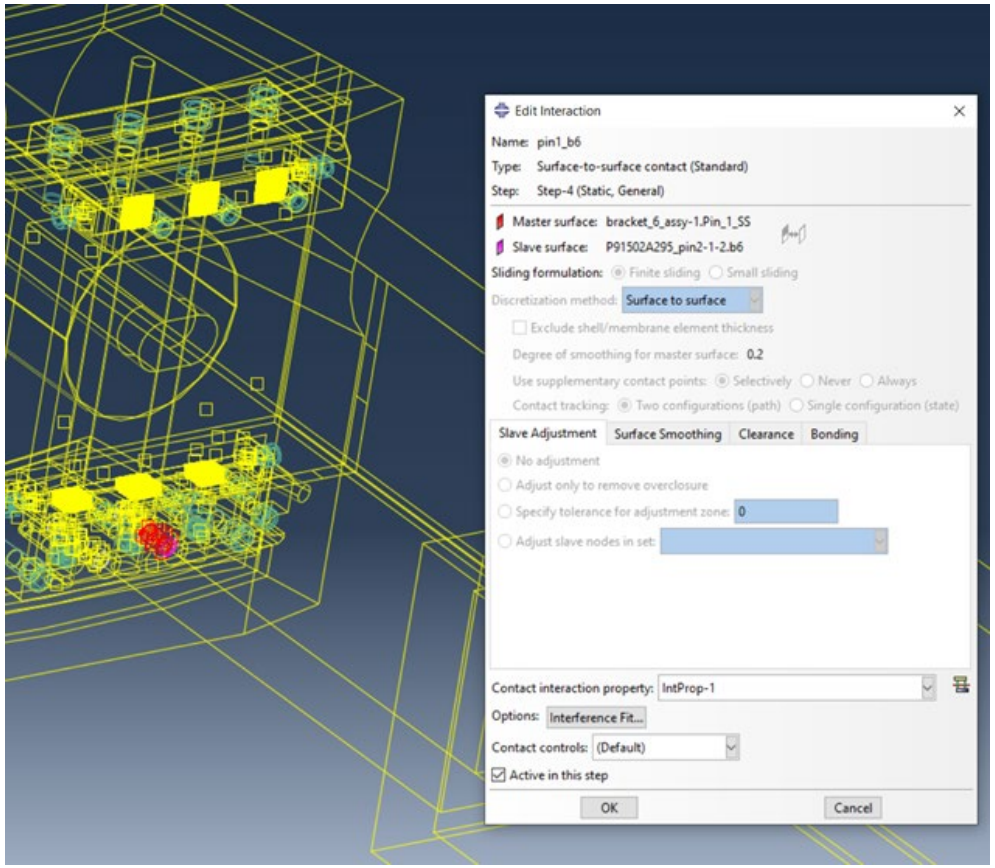


Nozzle upstream face to beltline

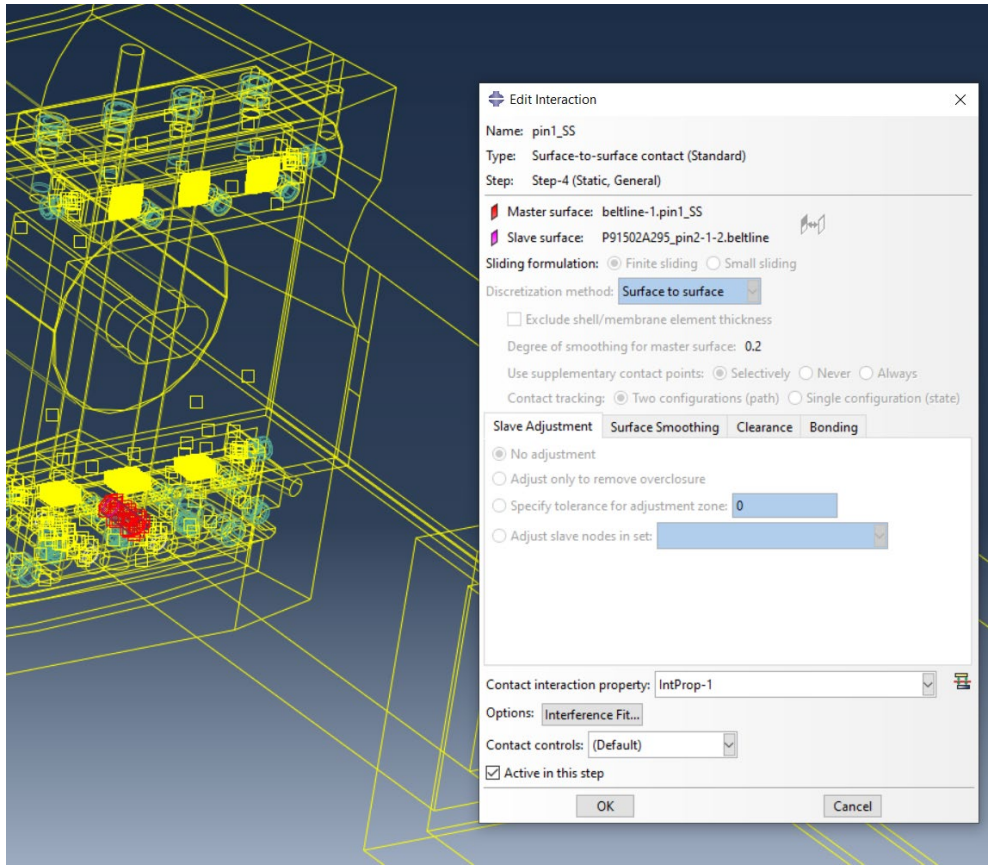


Shear pin surface to surface interactions

Pin 1 to bracket 6

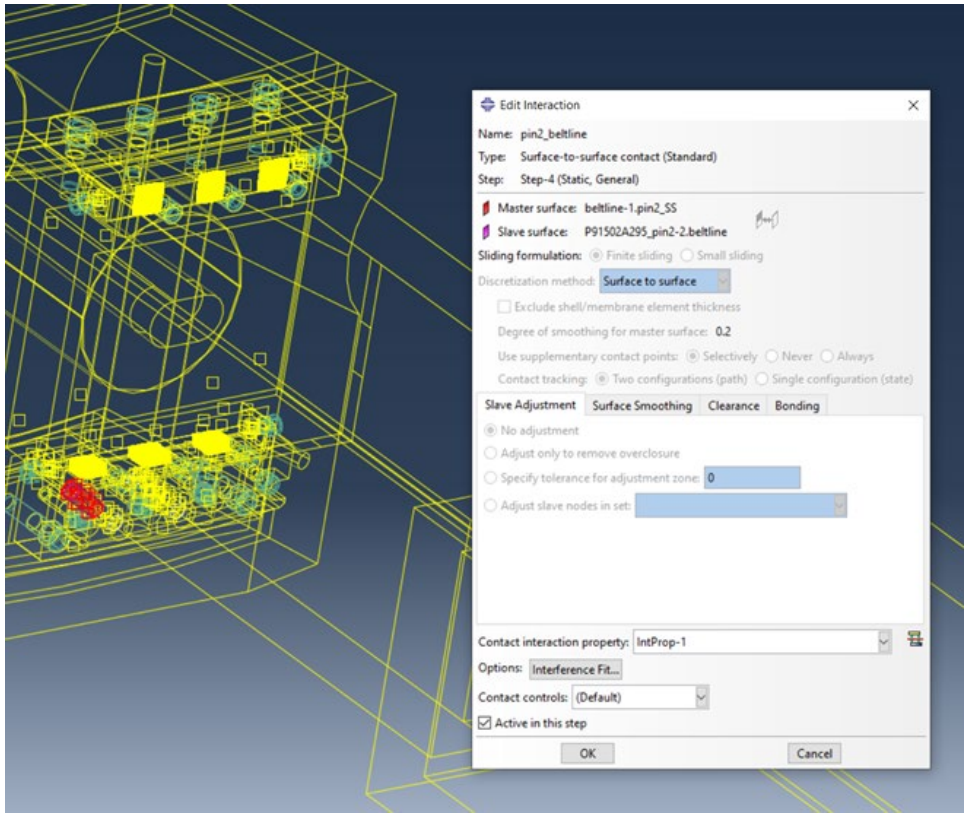


Pin 1 to beltline

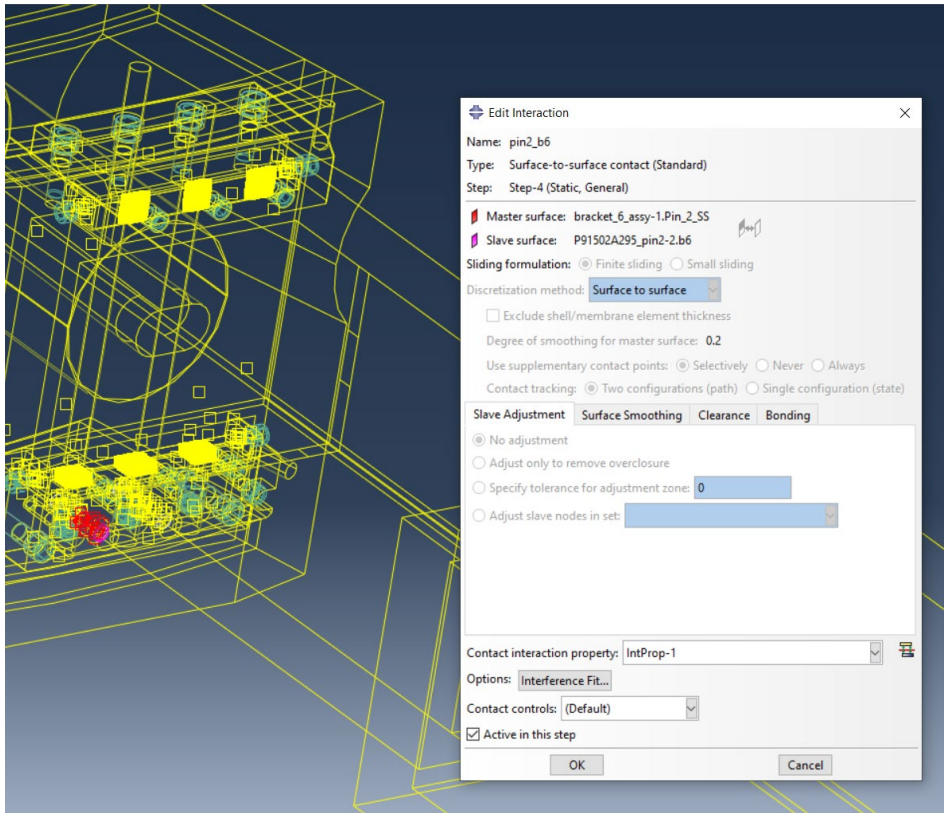


Shear pin surface to surface interactions

Pin 2 to beltline

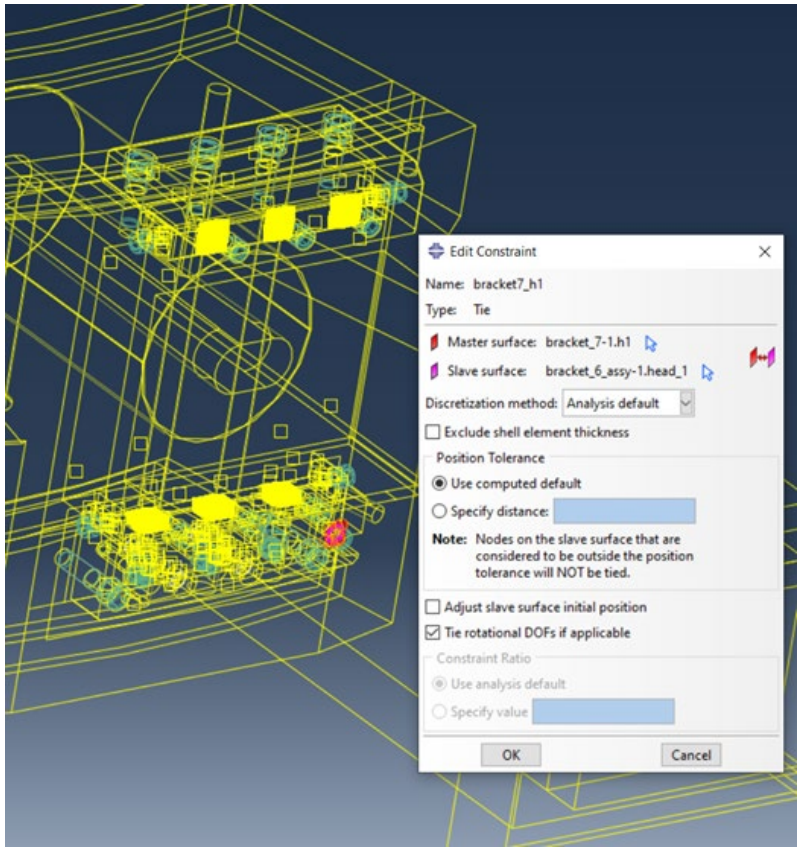


Pin 2 to bracket 6

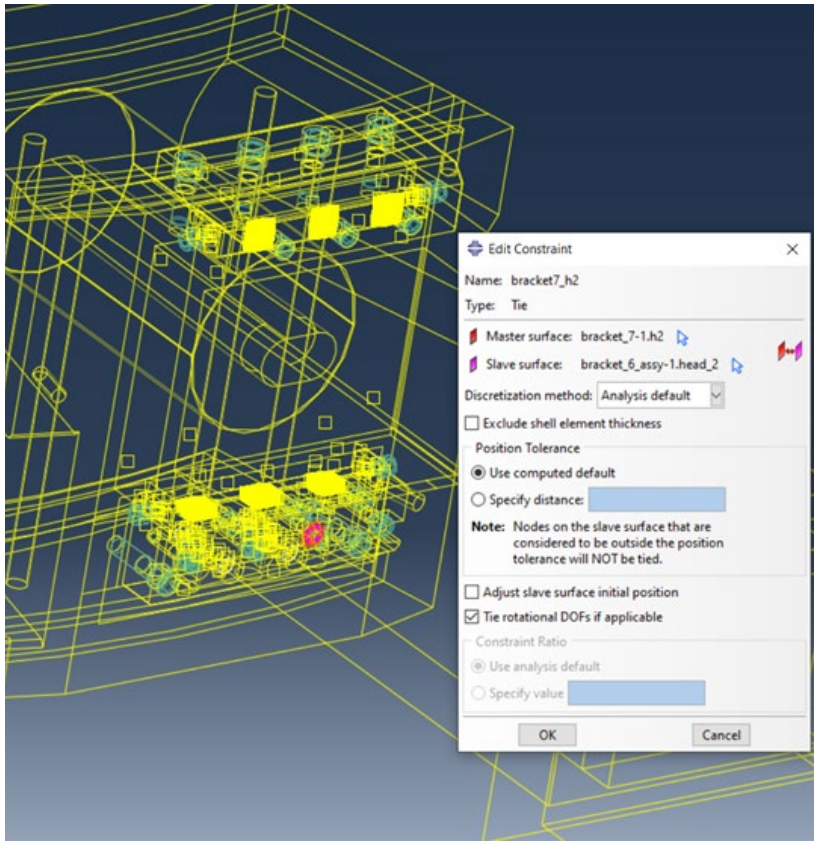


Bracket 6 Tie Constraints

Bracket 6 bolt 1 head to bracket 7

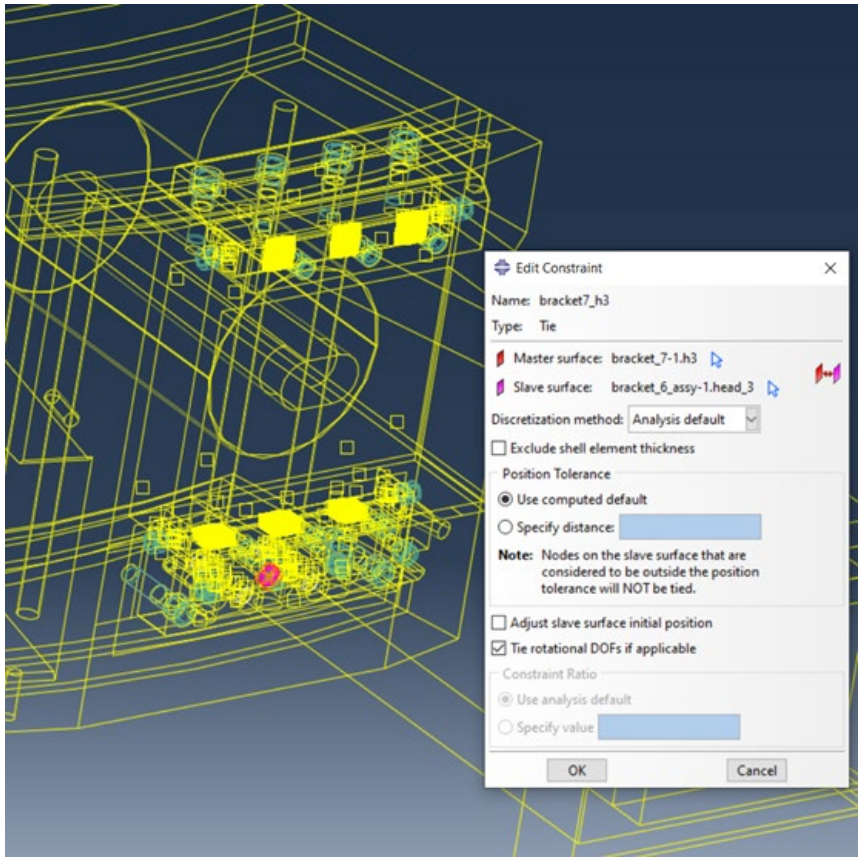


Bracket 6 bolt 2 head to bracket 7

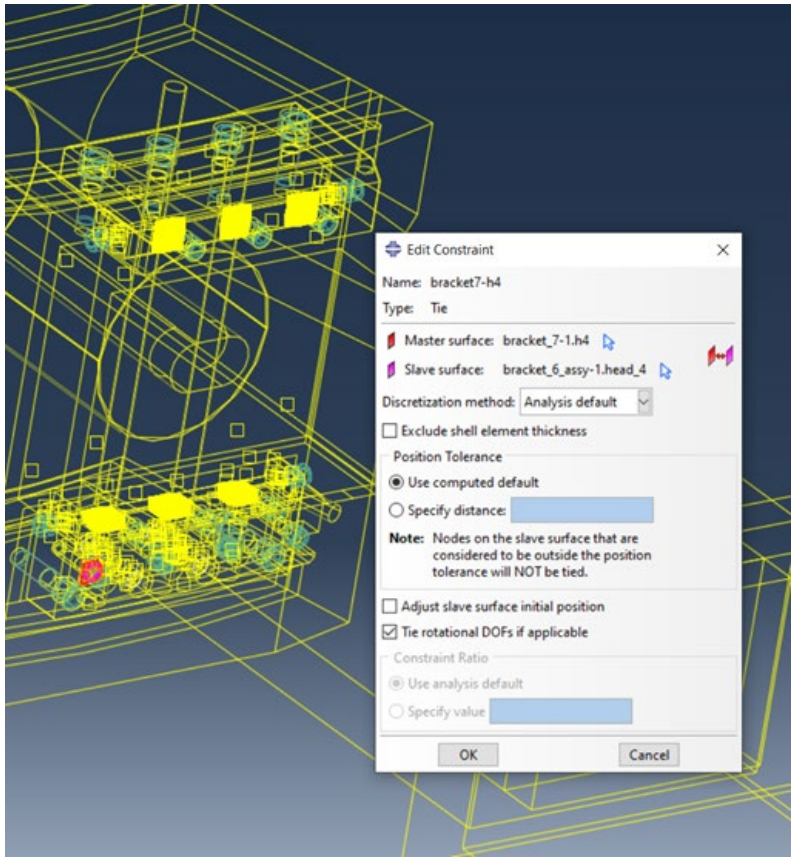


Bracket 6 Tie Constraints

Bracket 6 bolt 3 head to bracket 7

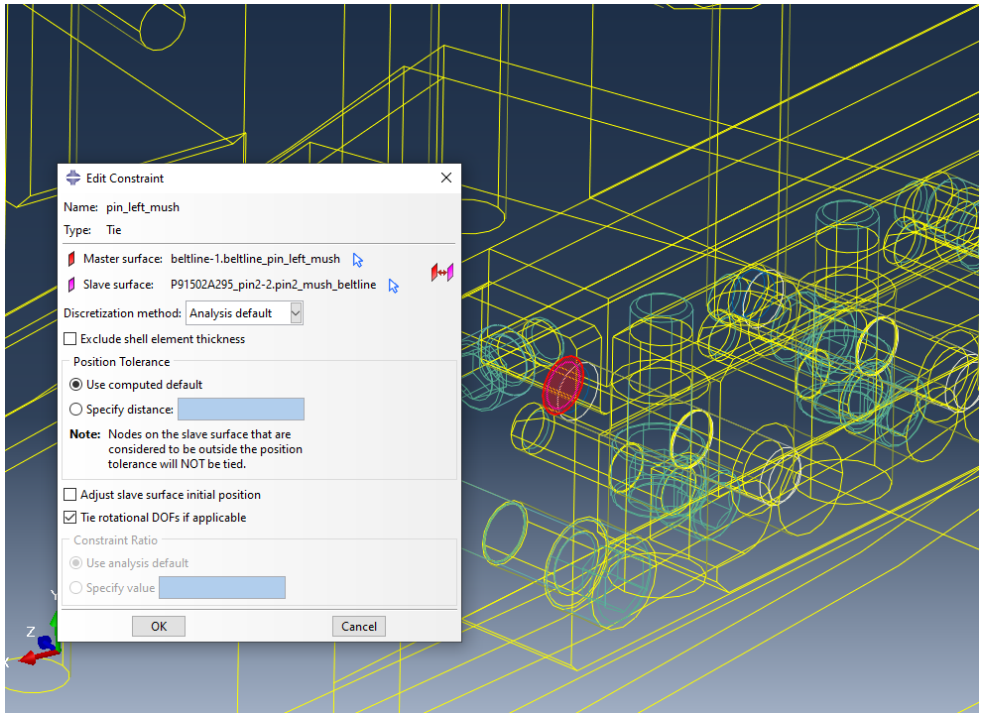


Bracket 6 bolt 4 head to bracket 7

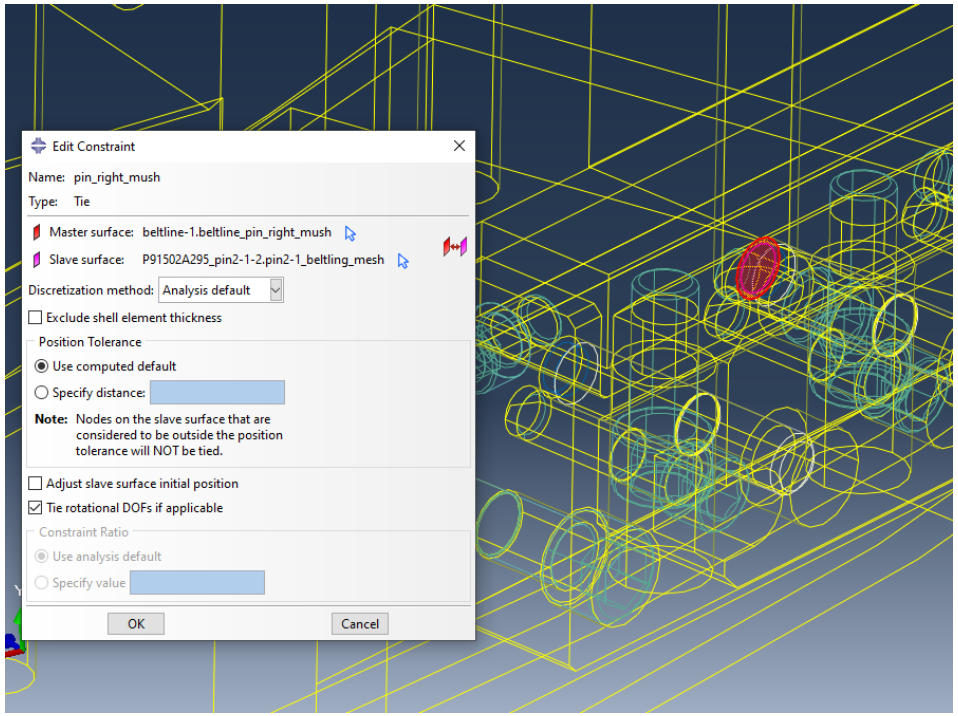


Shear pin ties to beltline for numerical stability

Left pin “mush” tie to beltline



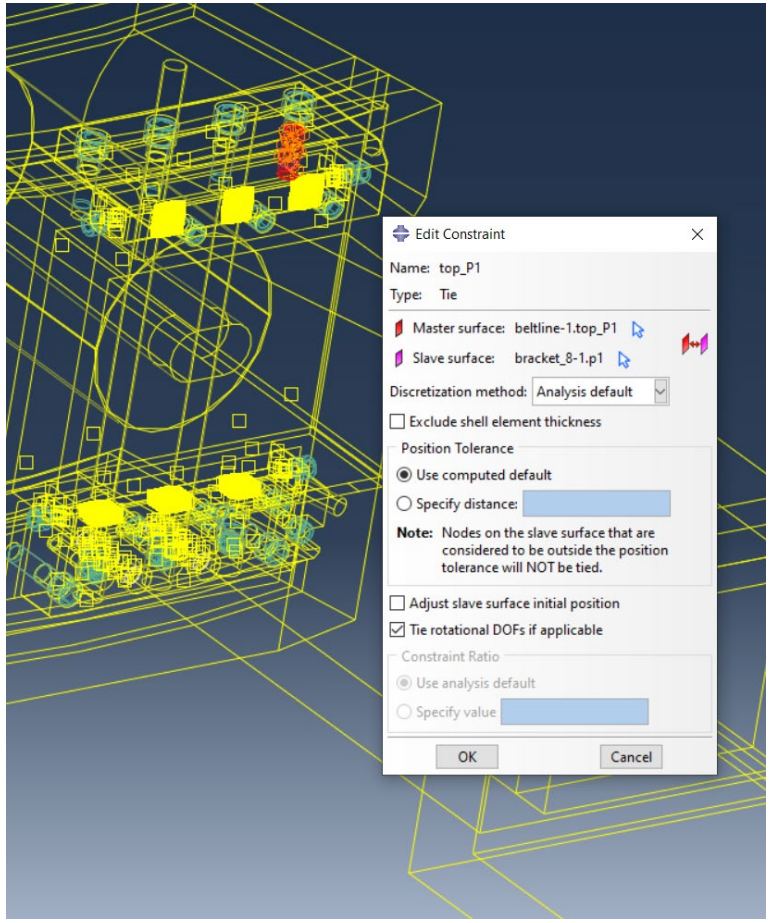
Right pin “mush” tie to beltline



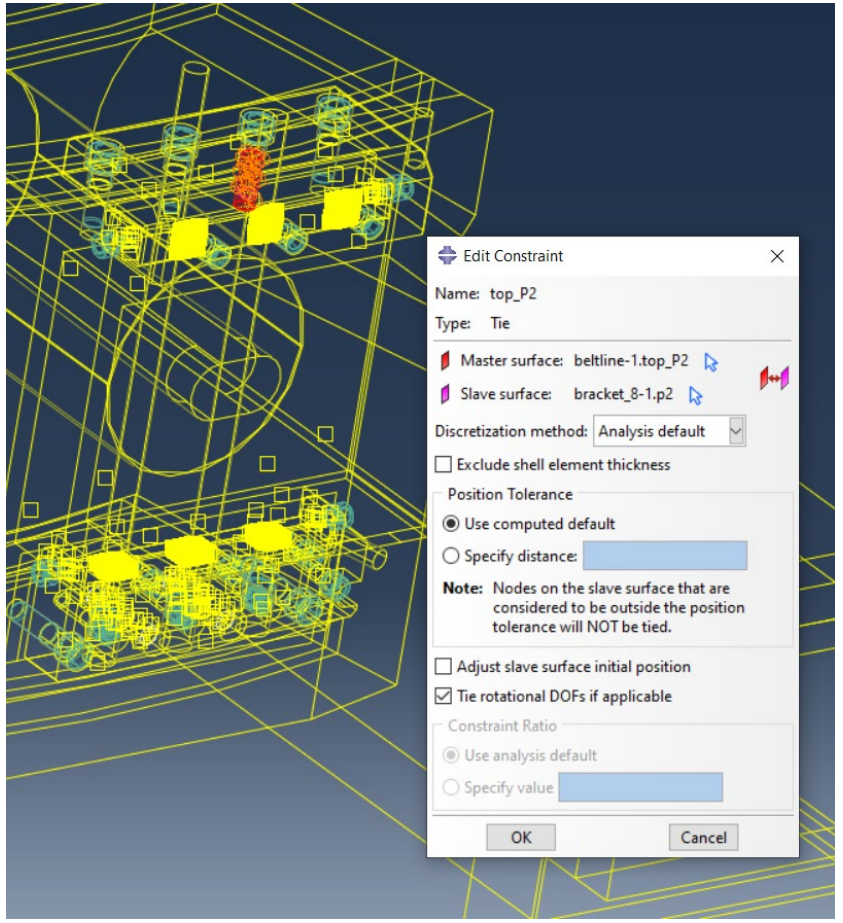
“mush” modulus = 2 MPa

Bracket 8 bolt tie constraints

Vertical Bolt 1 to beltline

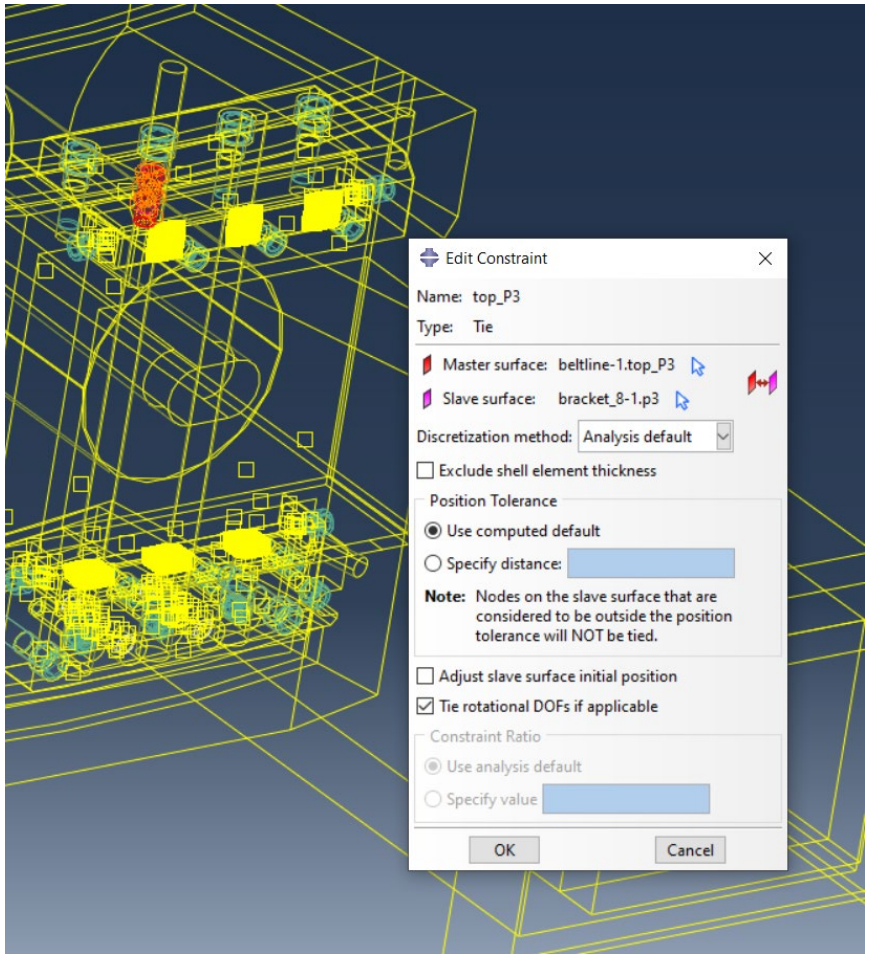


Vertical Bolt 2 to beltline

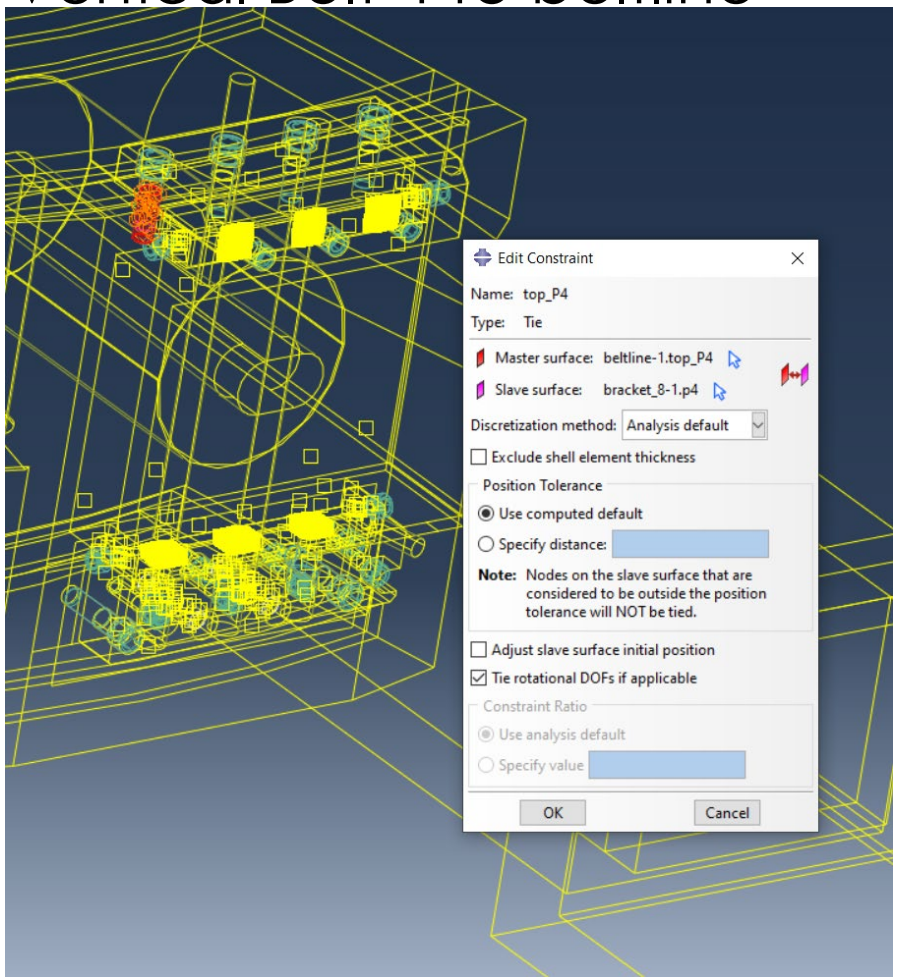


Bracket 8 bolt tie constraints

Vertical Bolt 3 to beltline

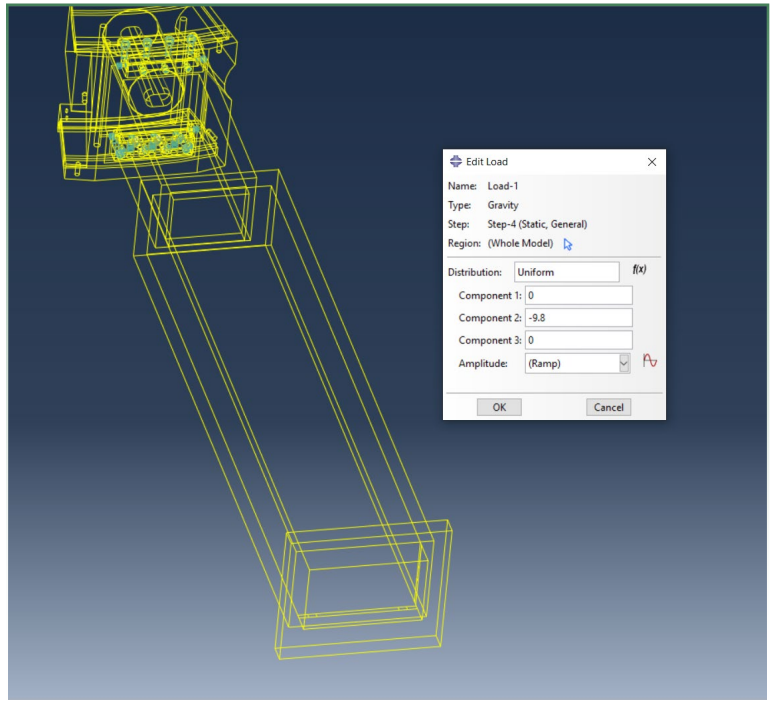


Vertical Bolt 4 to beltline

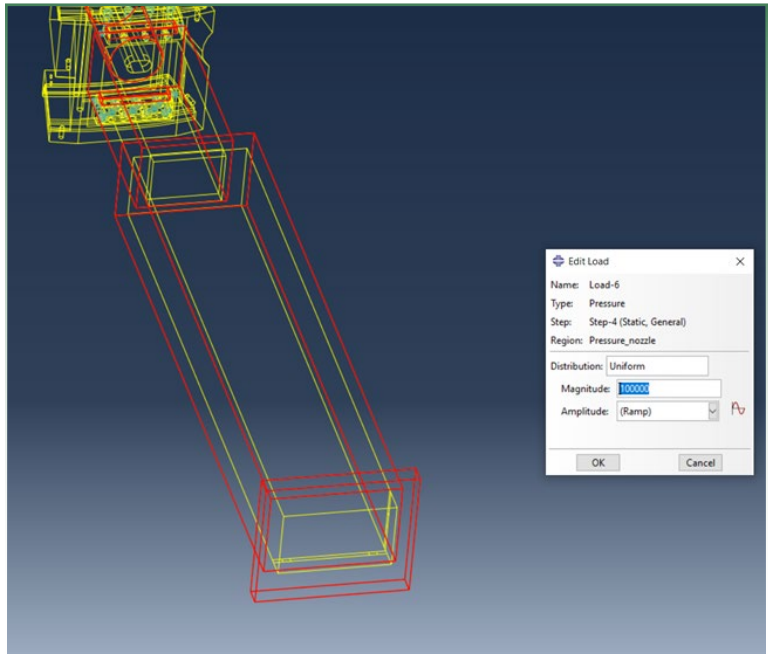


Gravity and Pressure Loads

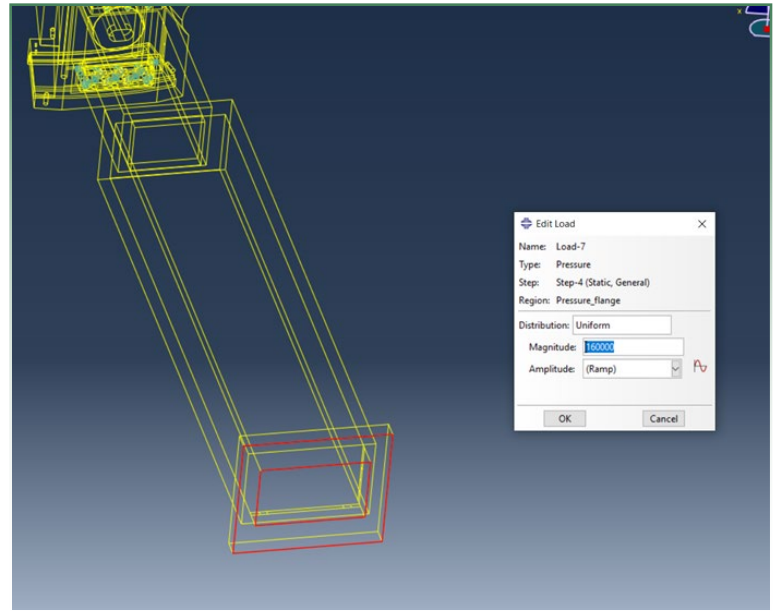
1 G vertical gravity



1 bar side external pressure

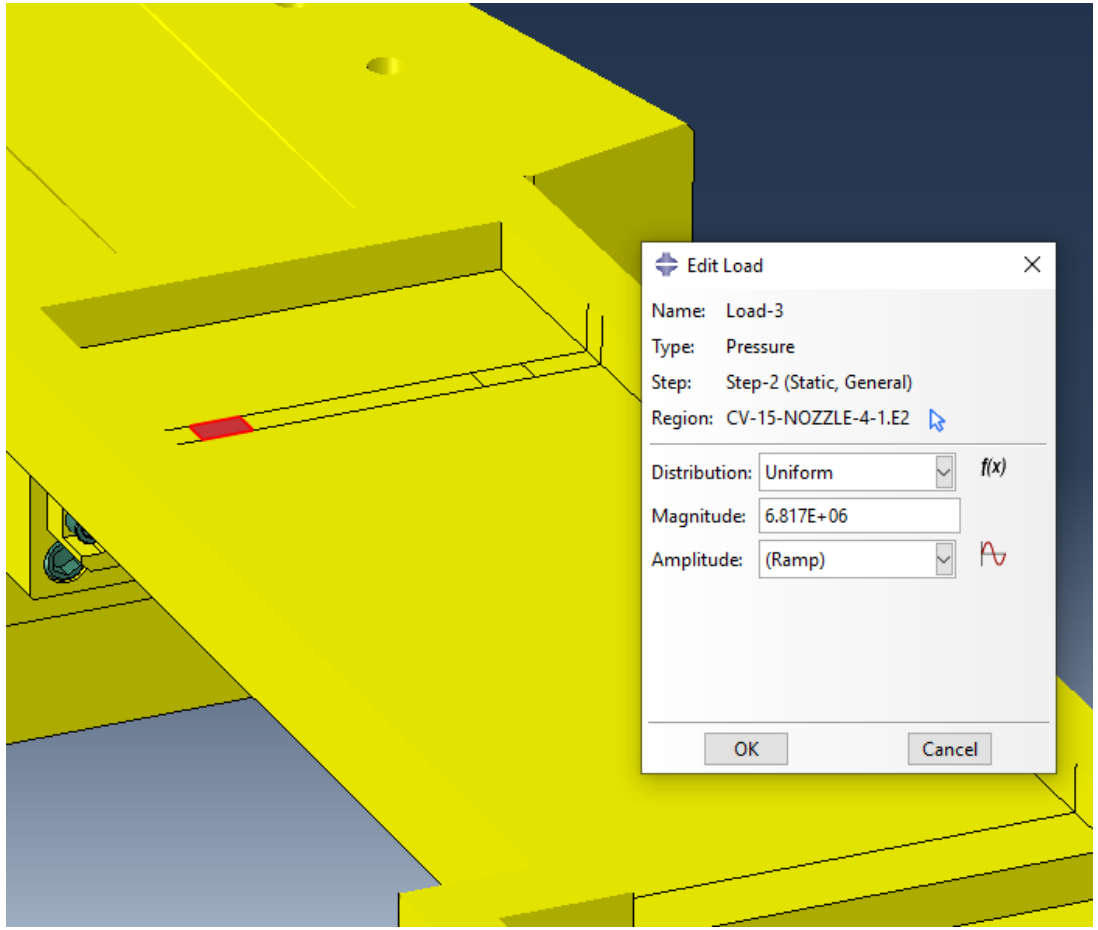


Axial pressure on flange for 1 bar axial pressure

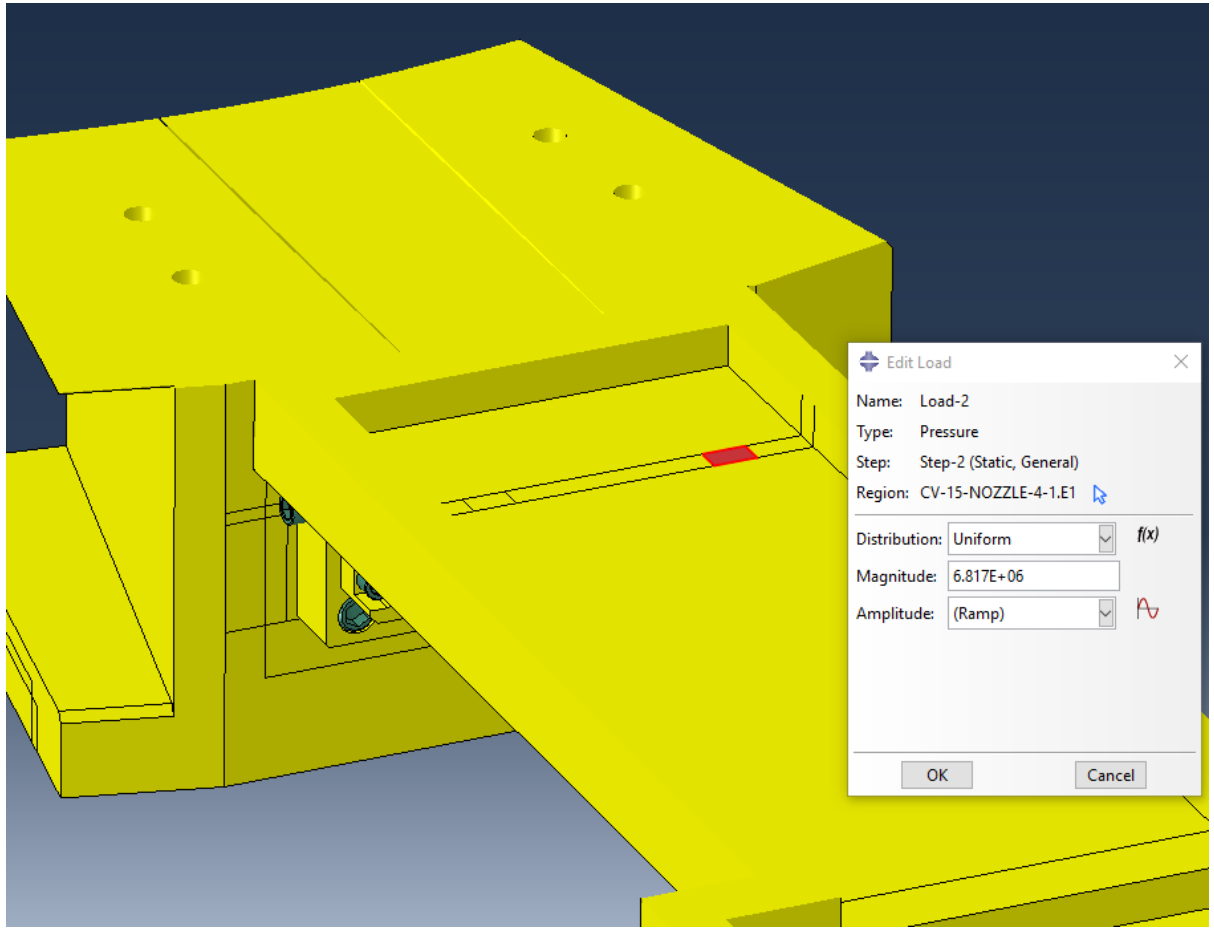


Insert Gravity loads as pressures on pad areas

Left front pad area

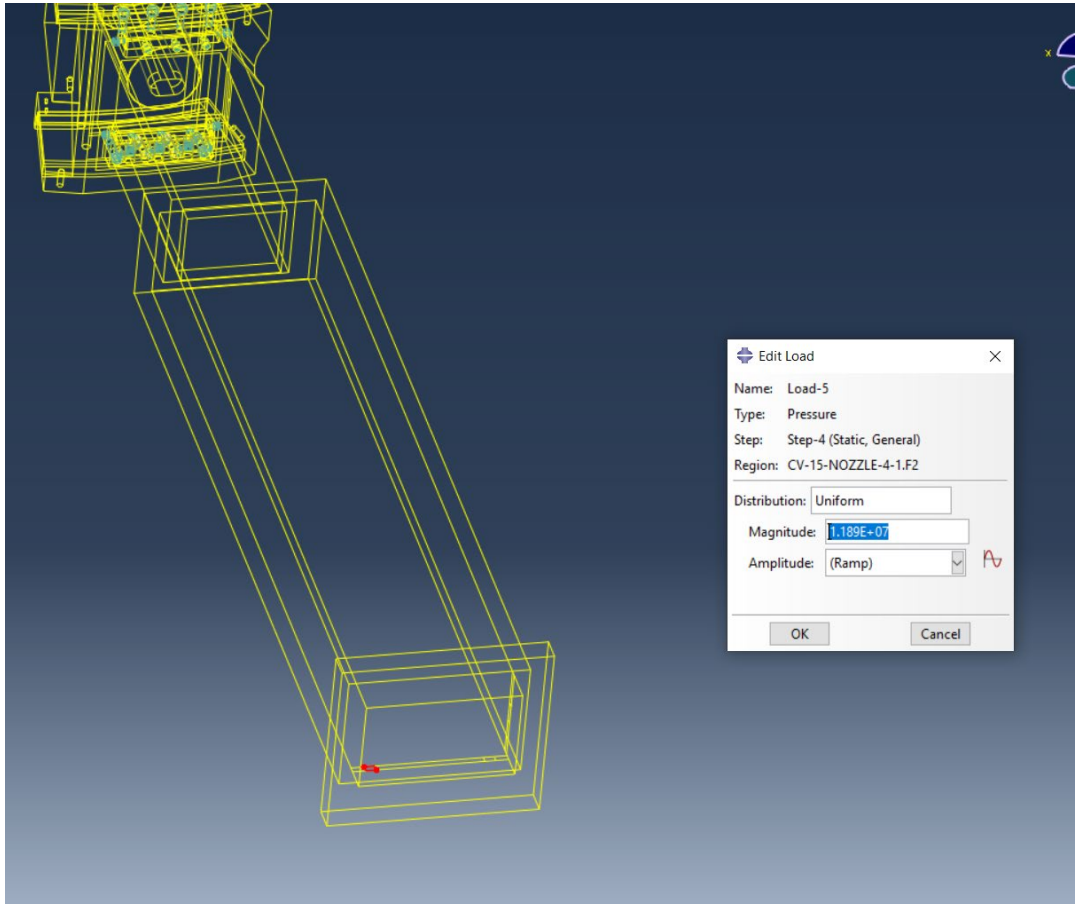


Right front pad area

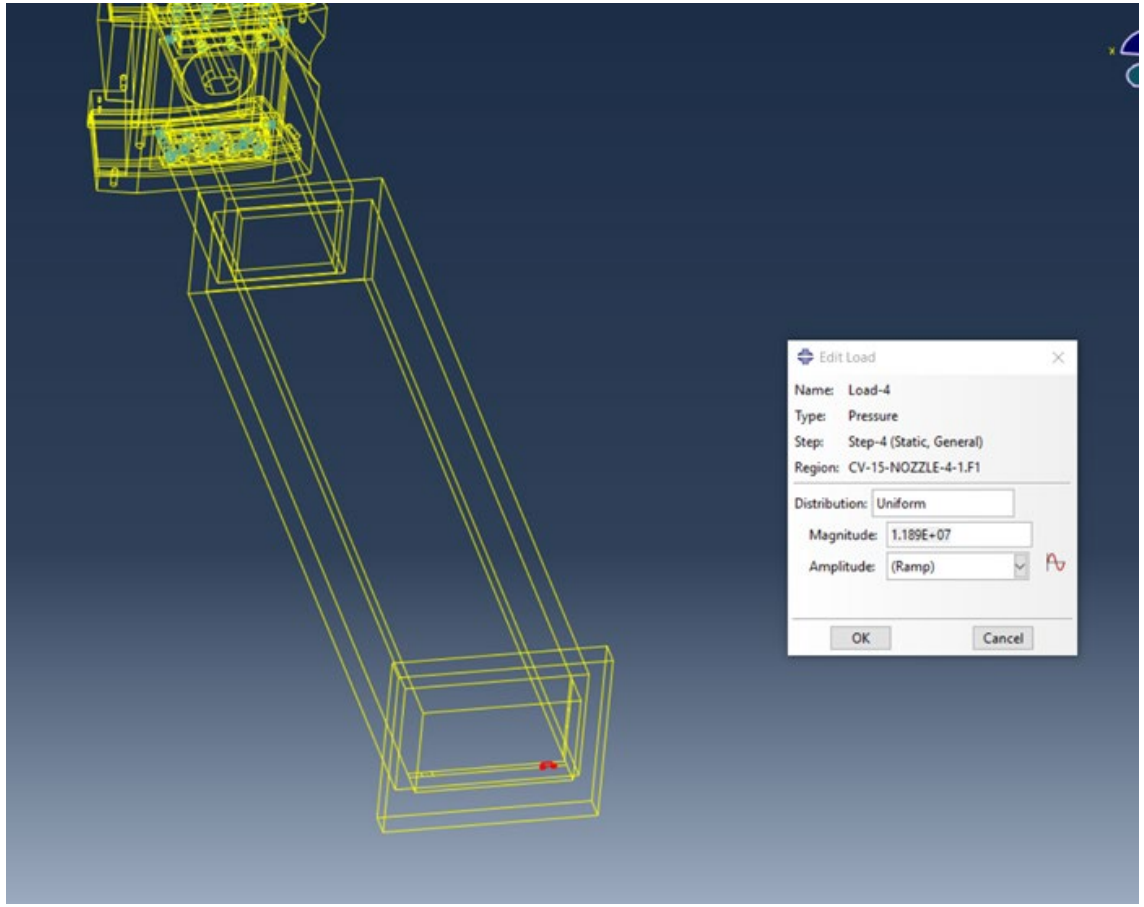


Insert Gravity load as pressure

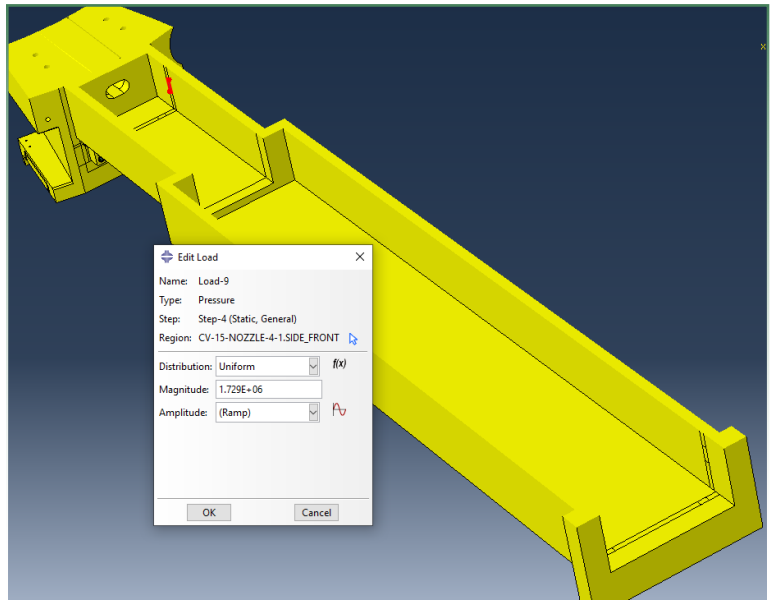
Left rear pad

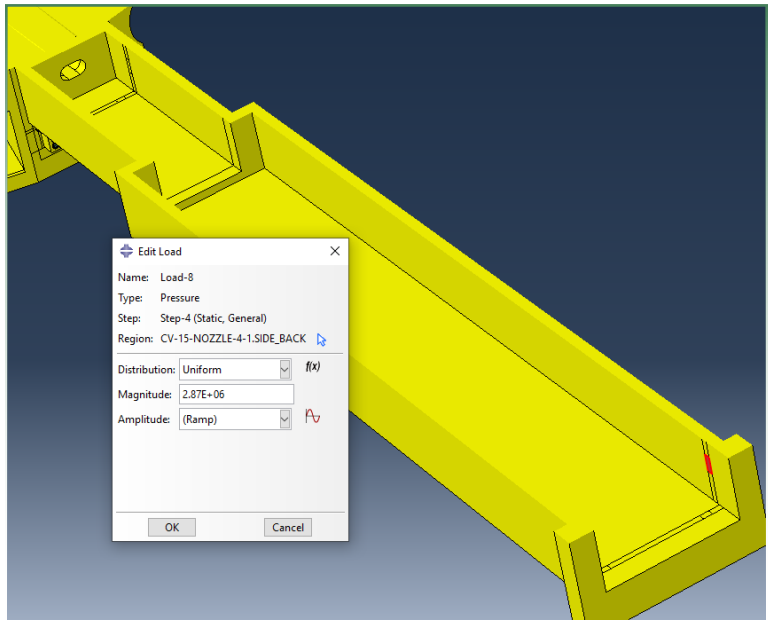


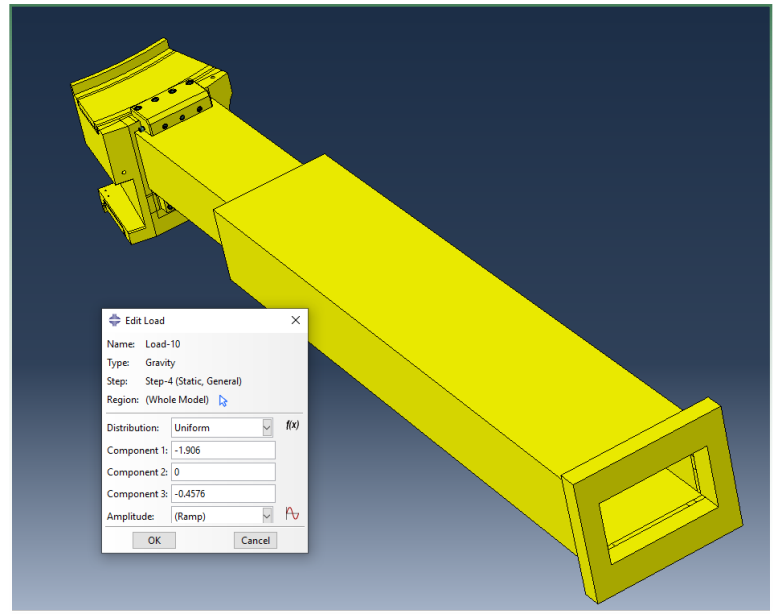
Right rear pad



Seismic .231 g side loads for insert and structure

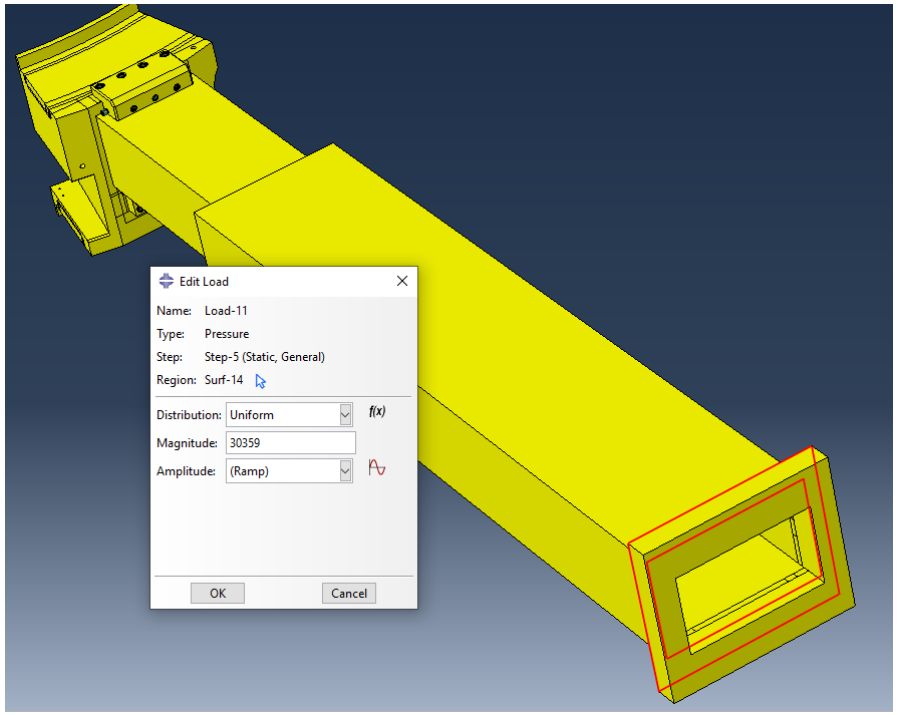




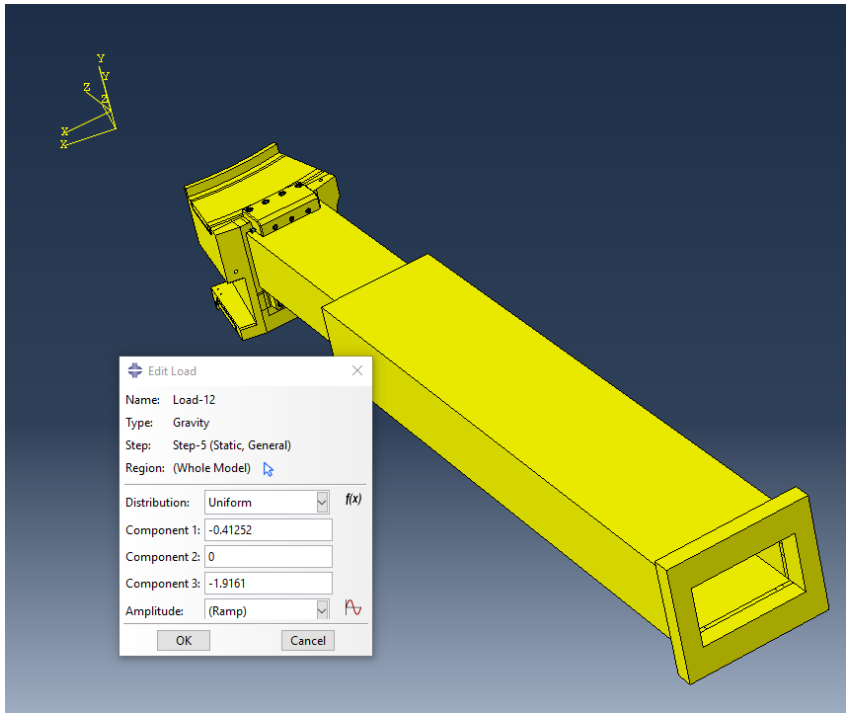


Axial loads from .231 G seismic load in nozzle axial direction (STEP 5)

Axial load from insert .231 g seismic as pressure on upstream flange face

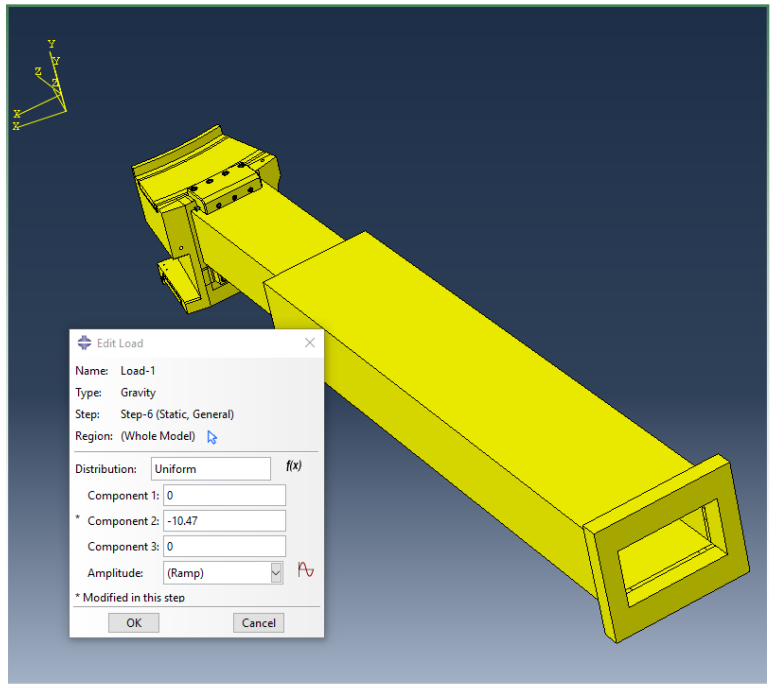


Axial load on structure from .231 g seismic in axial direction

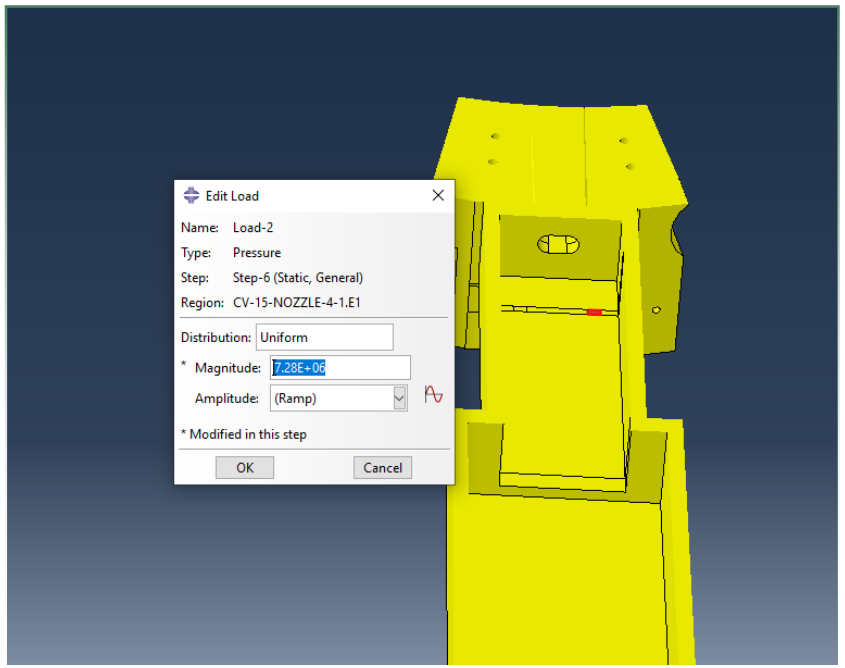


Gravity loads modified to include 0.068 G vertical seismic load

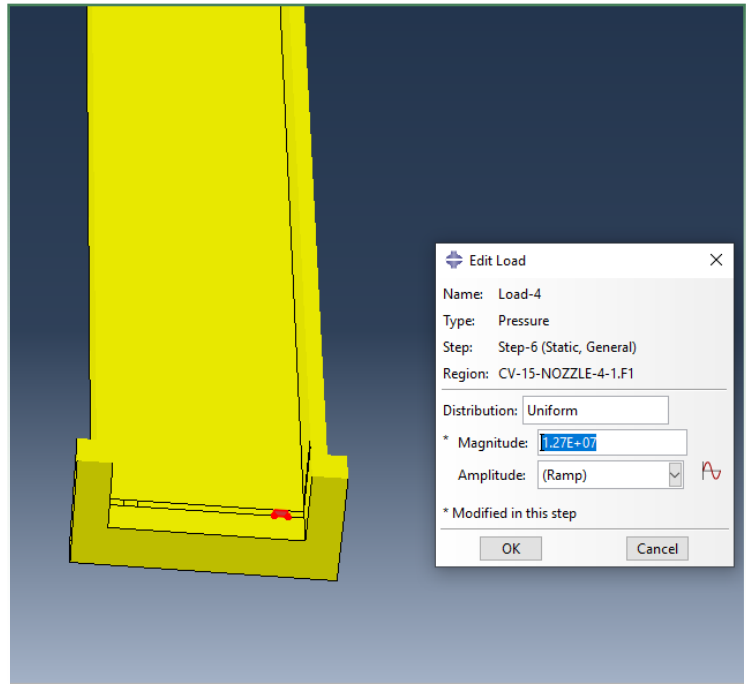
Structure



Front insert load (typ)

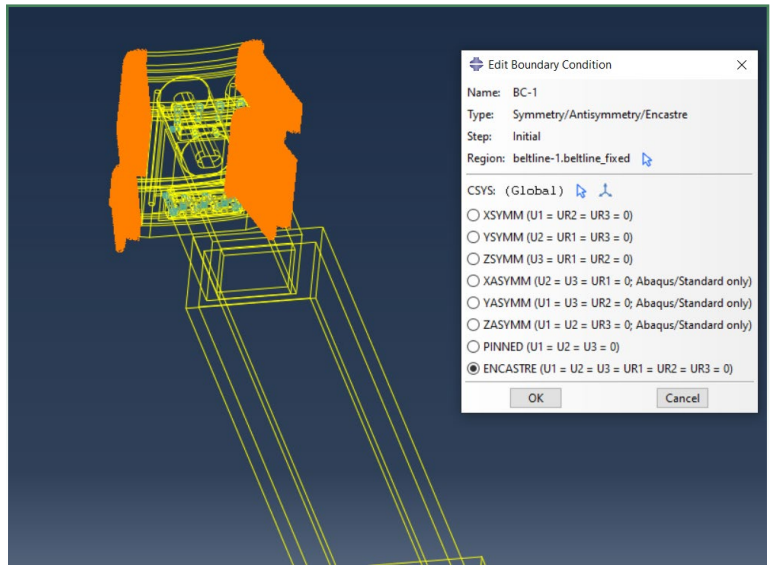


Rear insert load (typ)

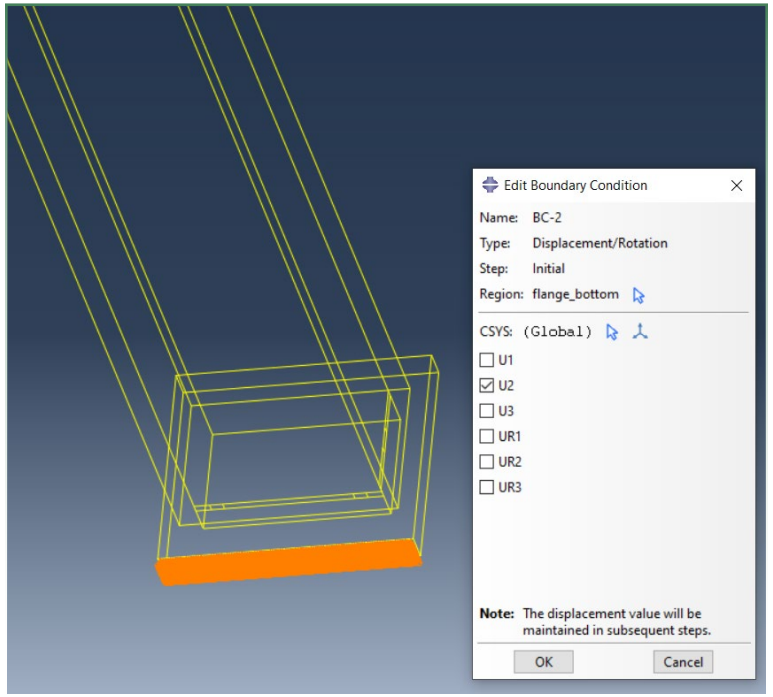


Boundary Conditions

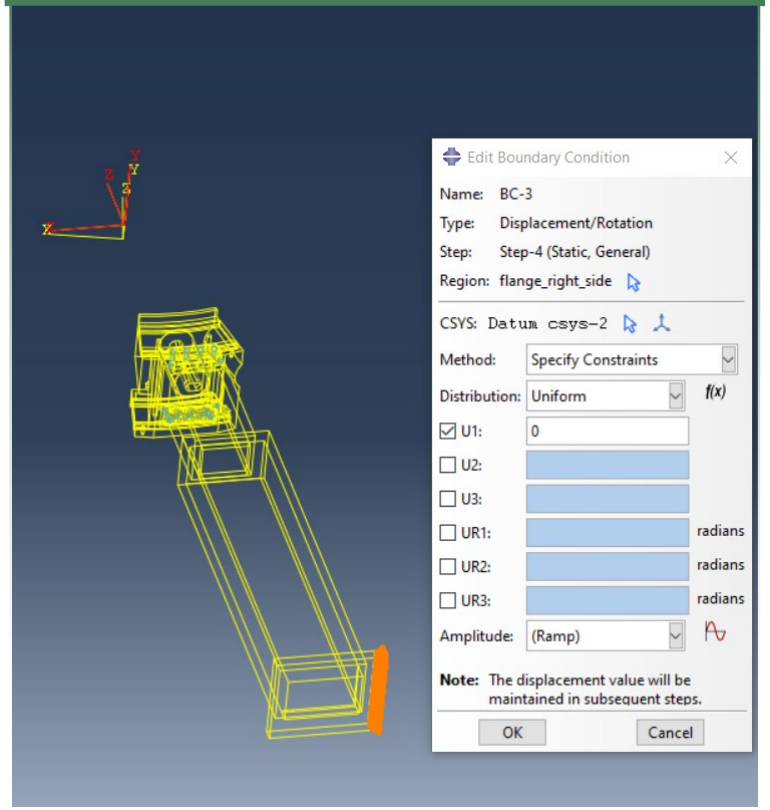
Beltline fixed



Flange Bottom displacement



Flange right side displacement

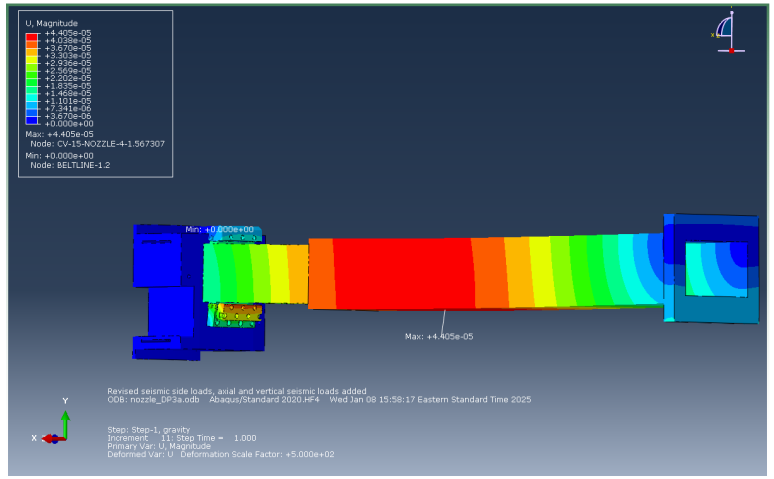


Analysis Step Loads and Boundary Conditions

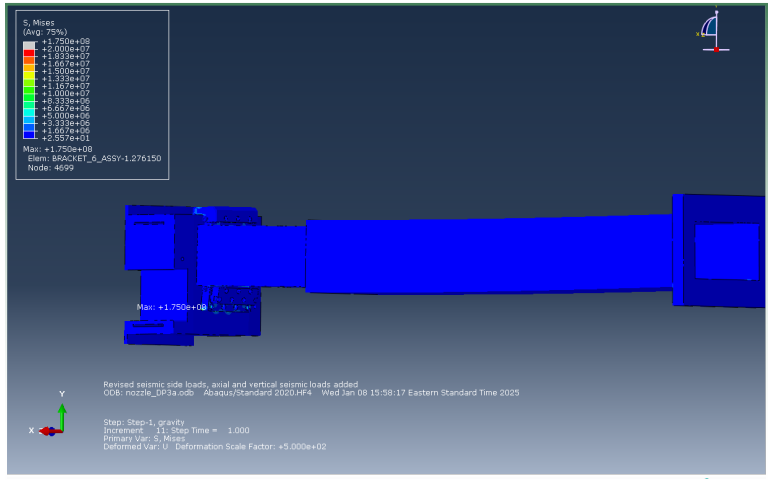
	Loads						Boundary Conditions		
Step	Structure 1 g vertical	Insert mass 1 g vertical	1 bar pressure	Seisimic side load	Seismic axial load	Seismic vertical load	1- Beltline fixed	2- Flange bottom	3 - Flange side
1	X						X	X	
2	X	X					X	X	
3	X	X	X				X	X	
4	X	X	X	X			X	X	
5	X	X	X		X		X	X	X
6			X			X	X	X	

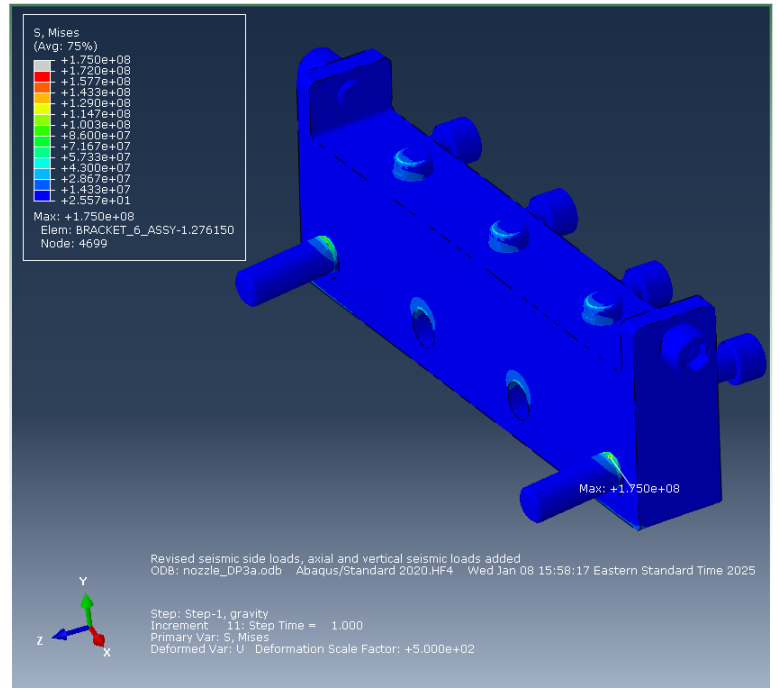
Step 1 Gravity

U



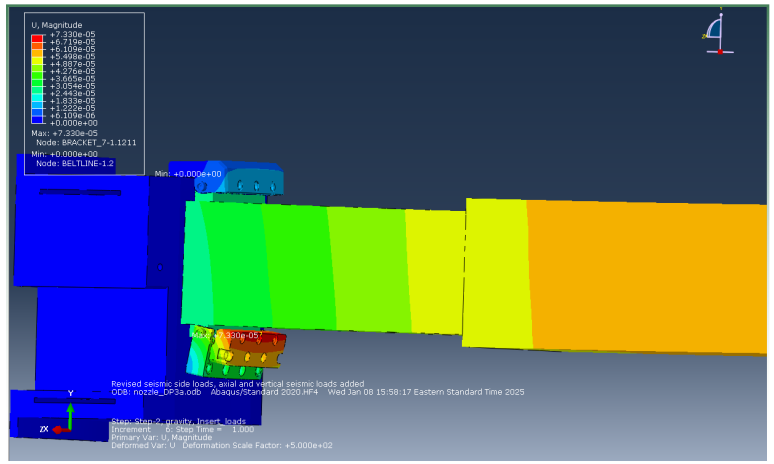
S peak 175 MPa



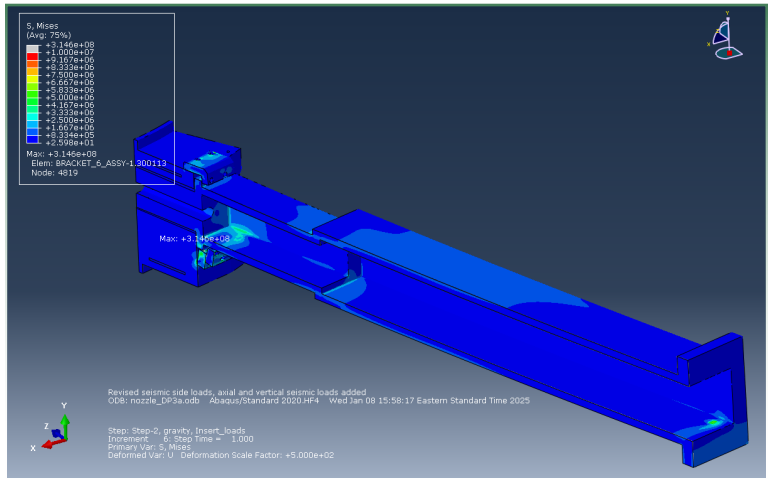


Step 2 Insert loads added

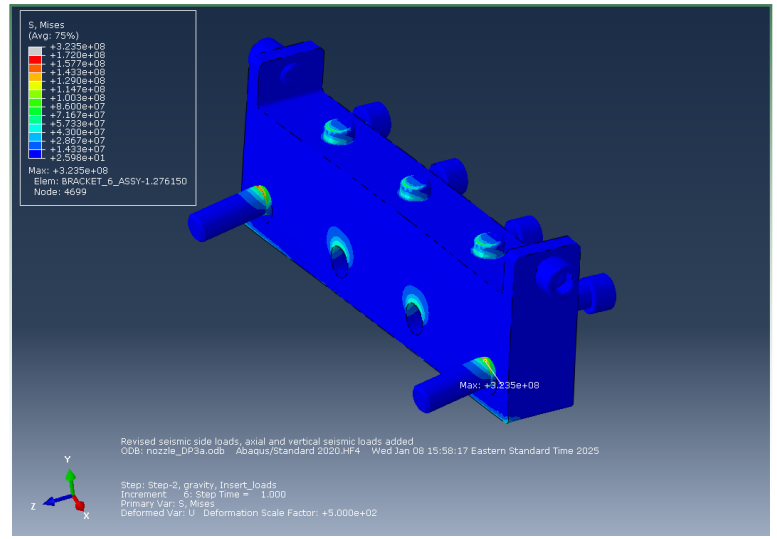
U



S 10 MPa scale max

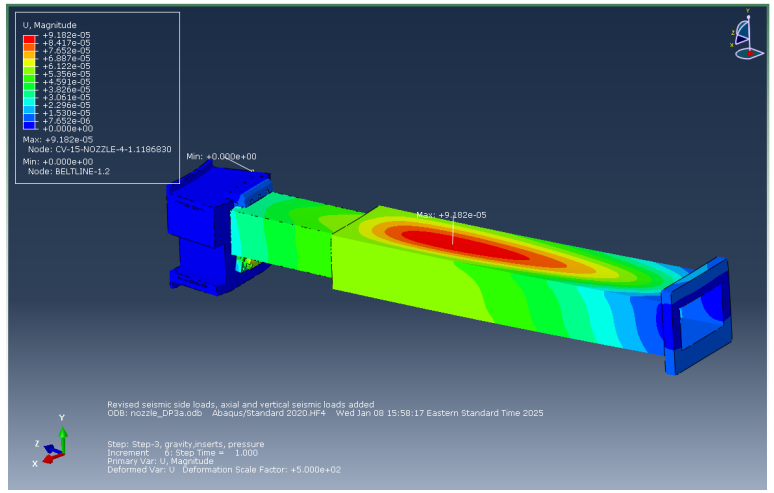


S peak 324 MPa

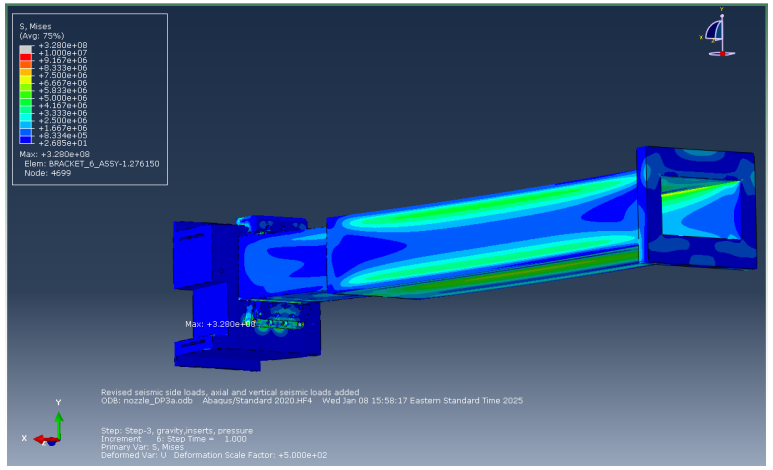


Step 3 gravity inserts and pressure

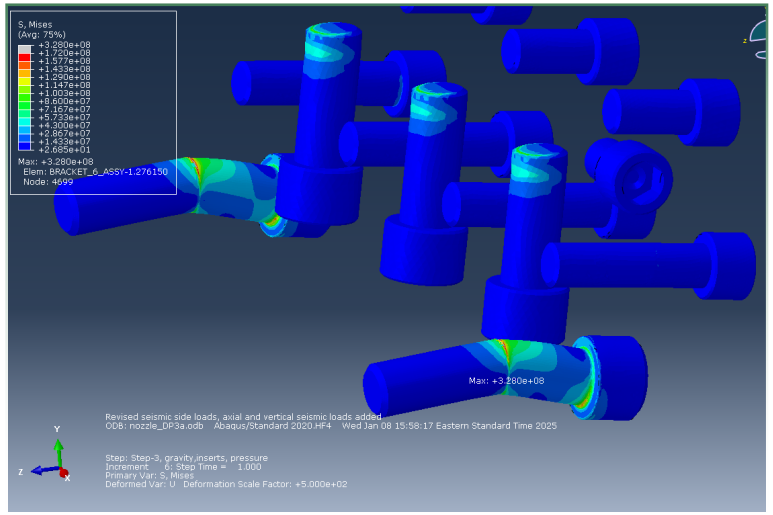
U



S max 328 MPa in bracket bolt

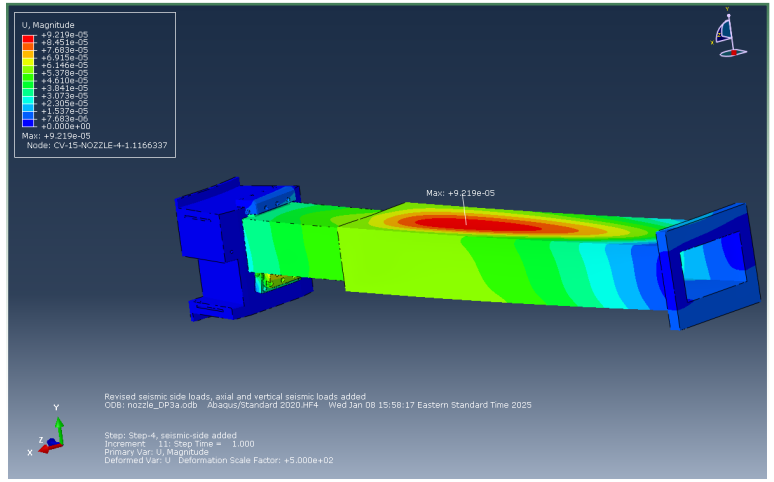


Bracket bolt stresses

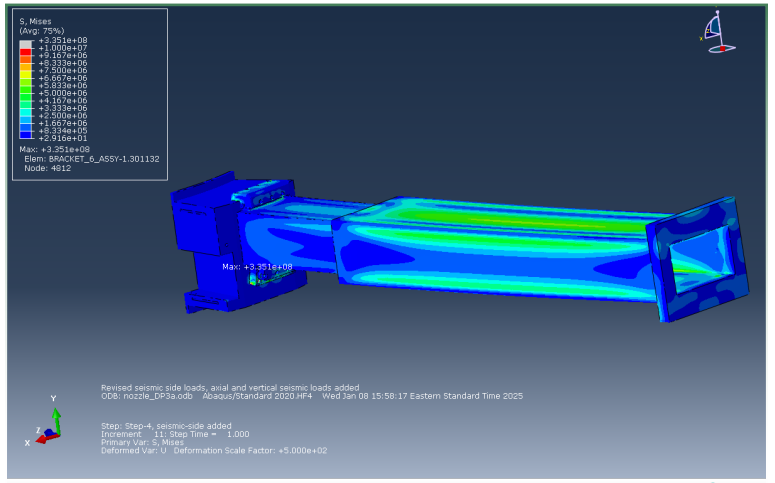


Step 4 gravity, inserts, vacuum and seismic side load

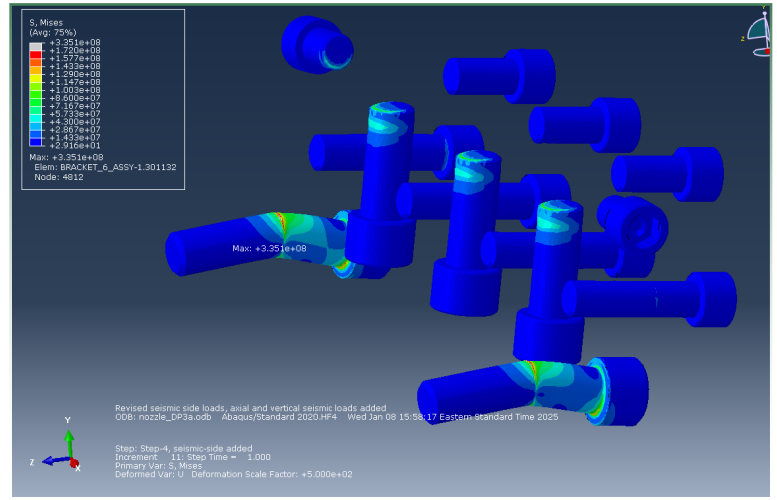
U



Peak 335 MPa in bracket 6 bolts

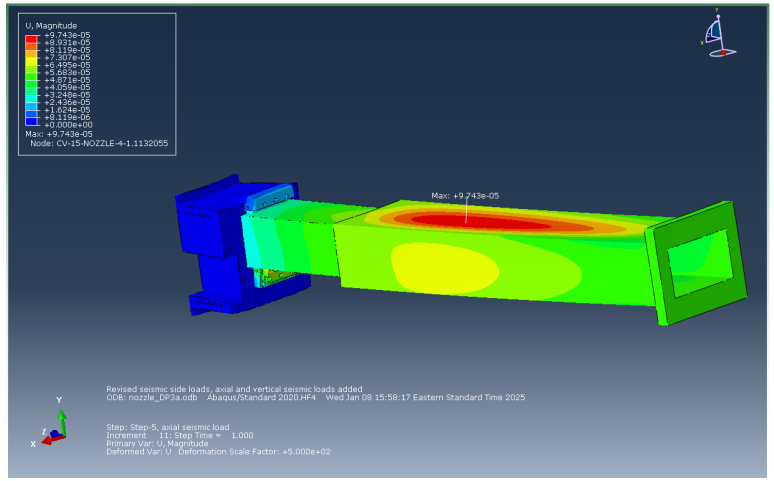


Bracket 6 bolts

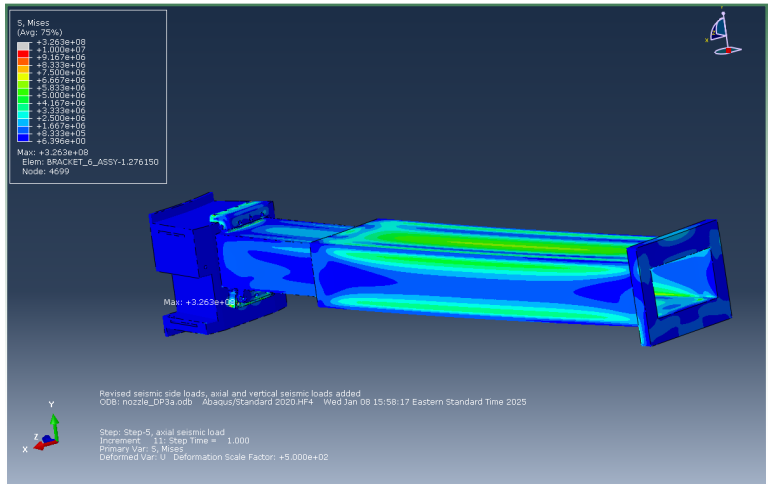


Step 5 gravity, inserts, vacuum and axial seismic load

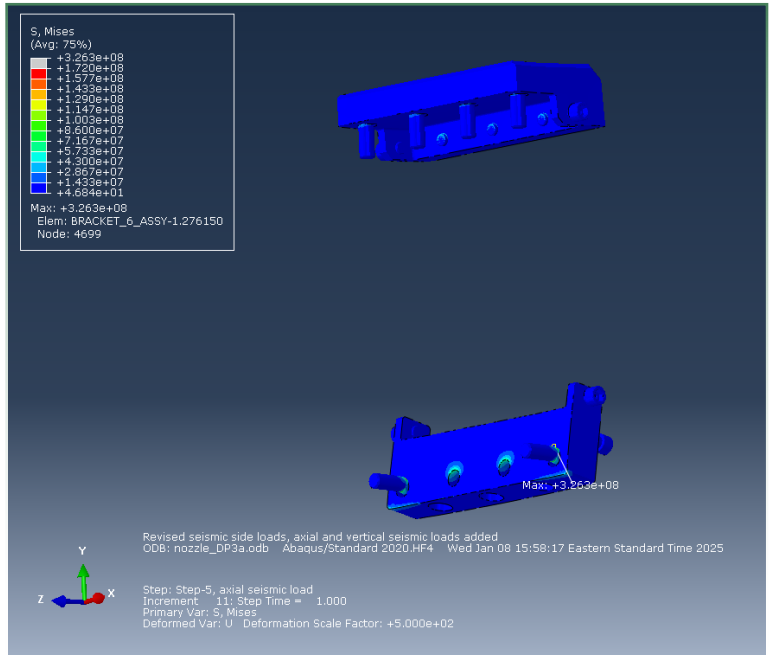
u



S peak 326 MPa in bracket 6 bolt 10 MPa scale max

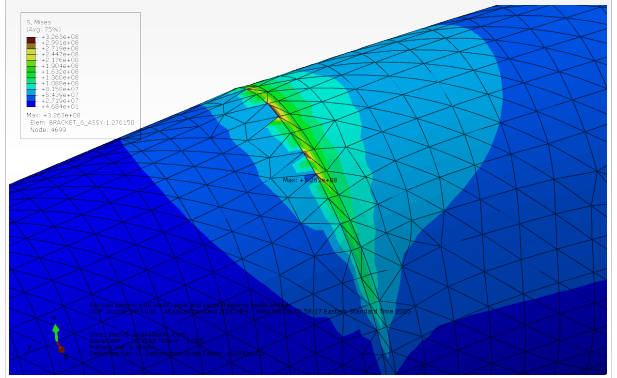


Brackets 6 and 8 172 MPa scale maximum 326 Mpa peak

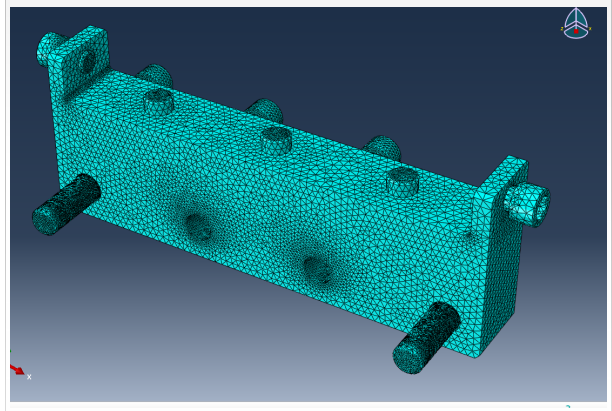


Bolt high stress and refined mesh used in next submission

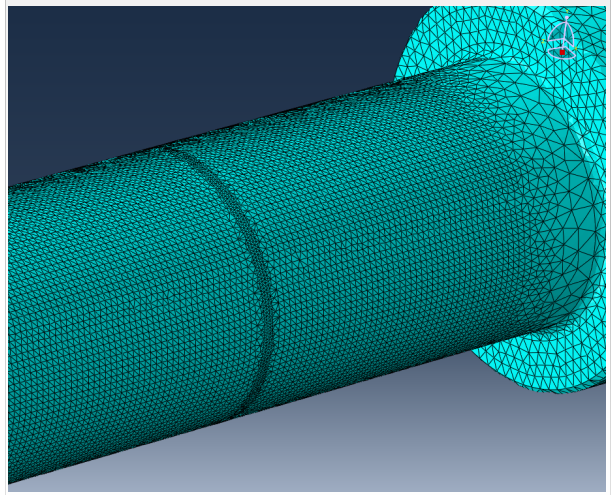
Original bolt mesh and stress



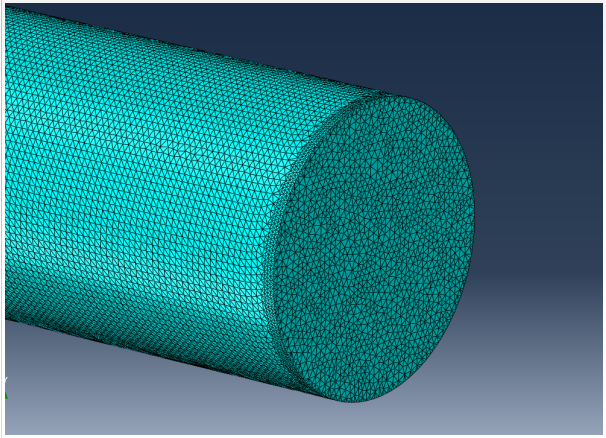
Bracket 6 with bolts



.25 mm mesh around high stress zone

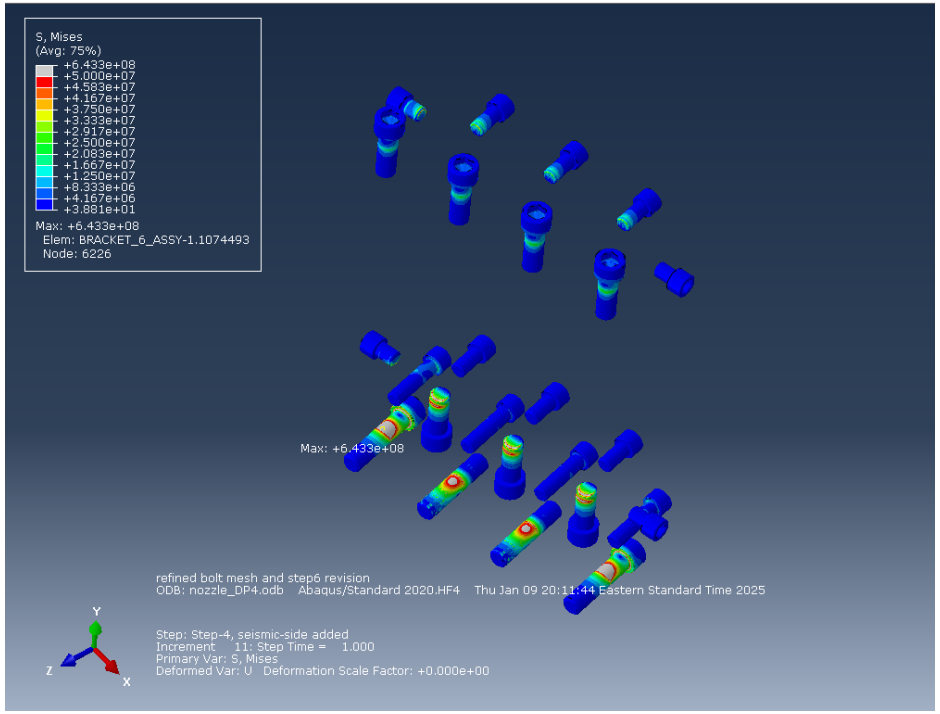


Internal mesh

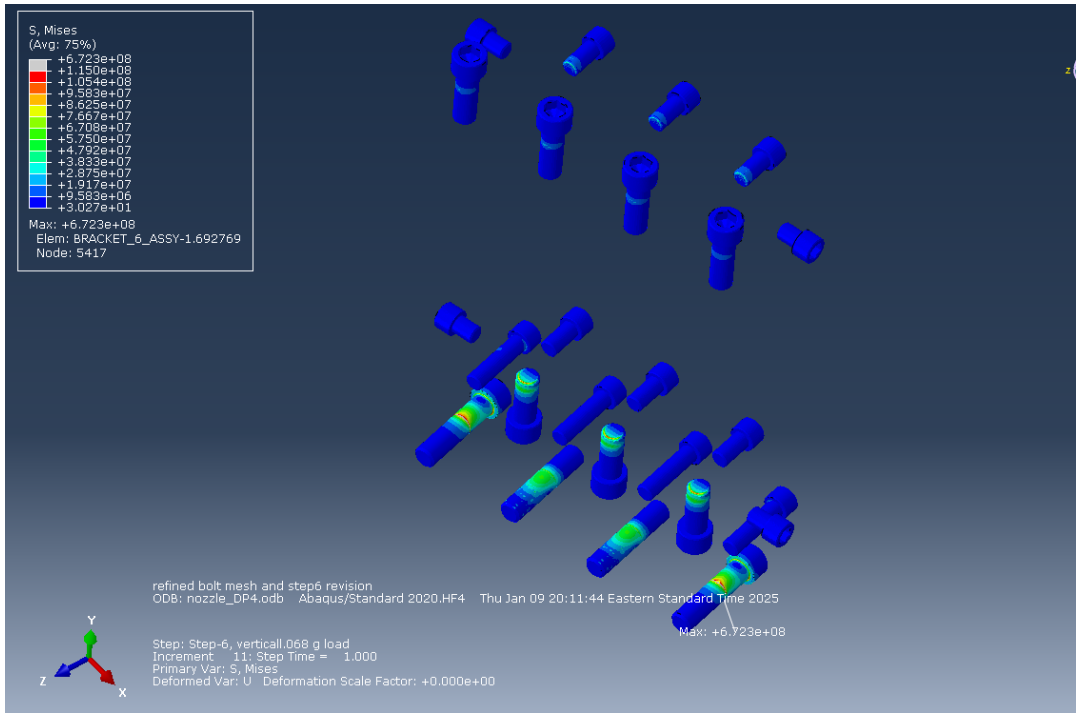


Bolt and Pin Stresses

Bolt and Pin stress Step 4 643 MPa peak 50 MPa scale

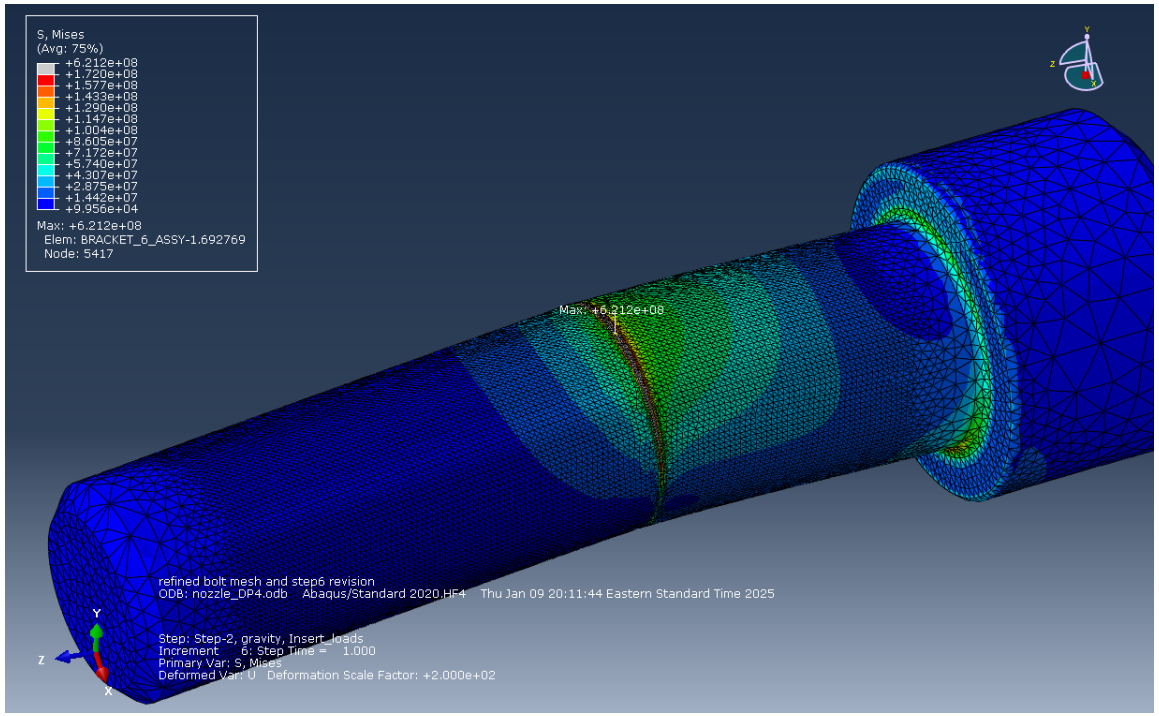


Bolt and Pin stress Step 6 672 MPa peak 115 MPa scale

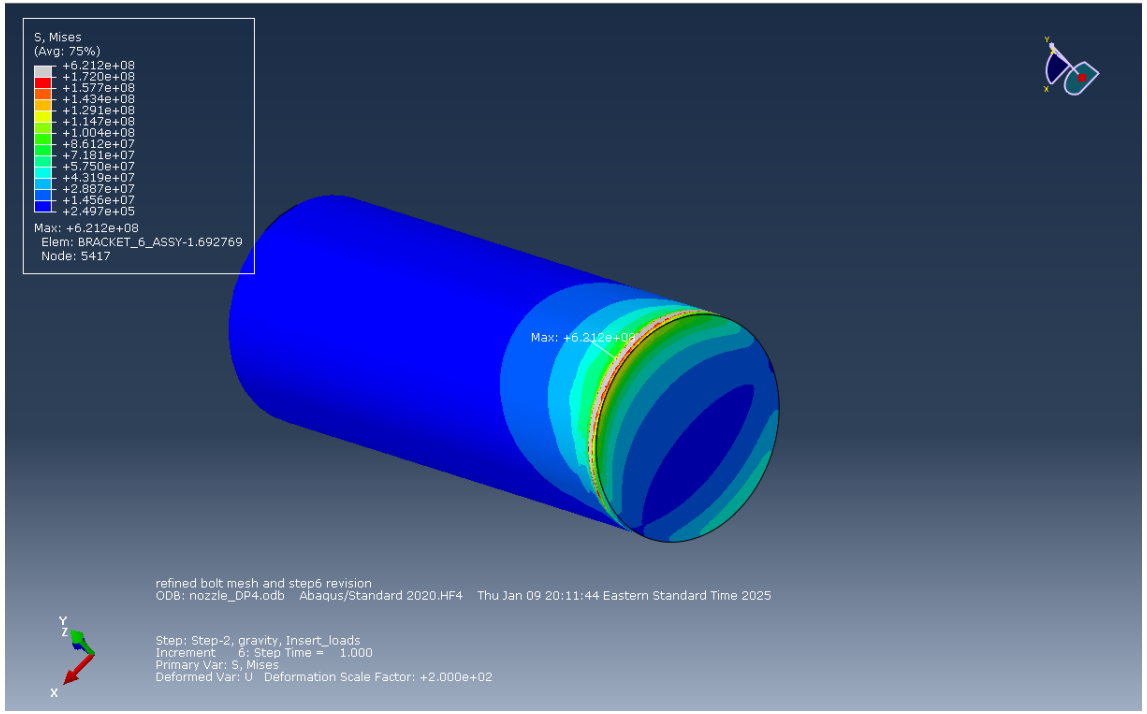


Step 2 Bolt stresses

Bolt peak stress Step 2 621 MPa

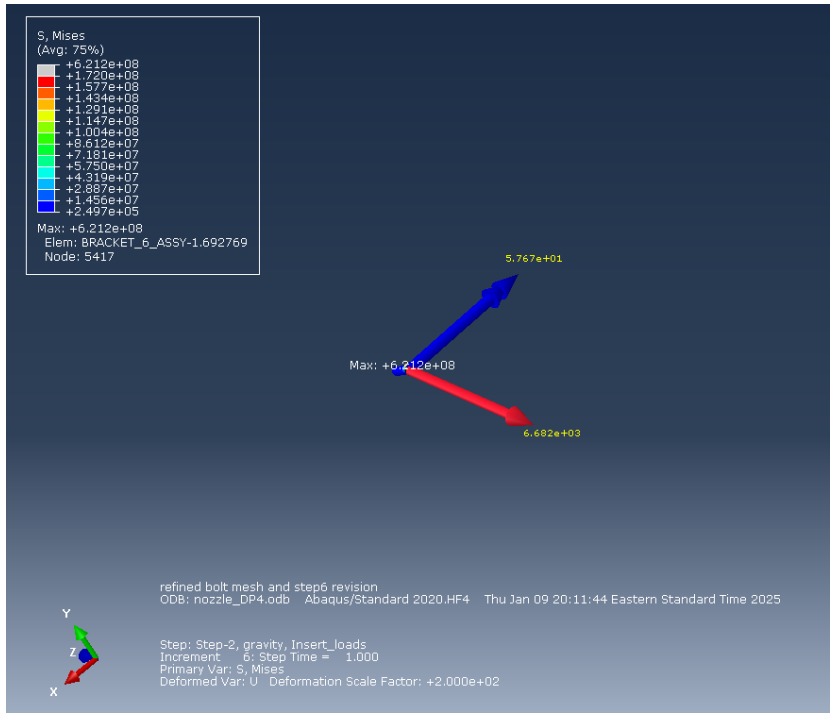


Bolt cross section just downstream of tie to beltline

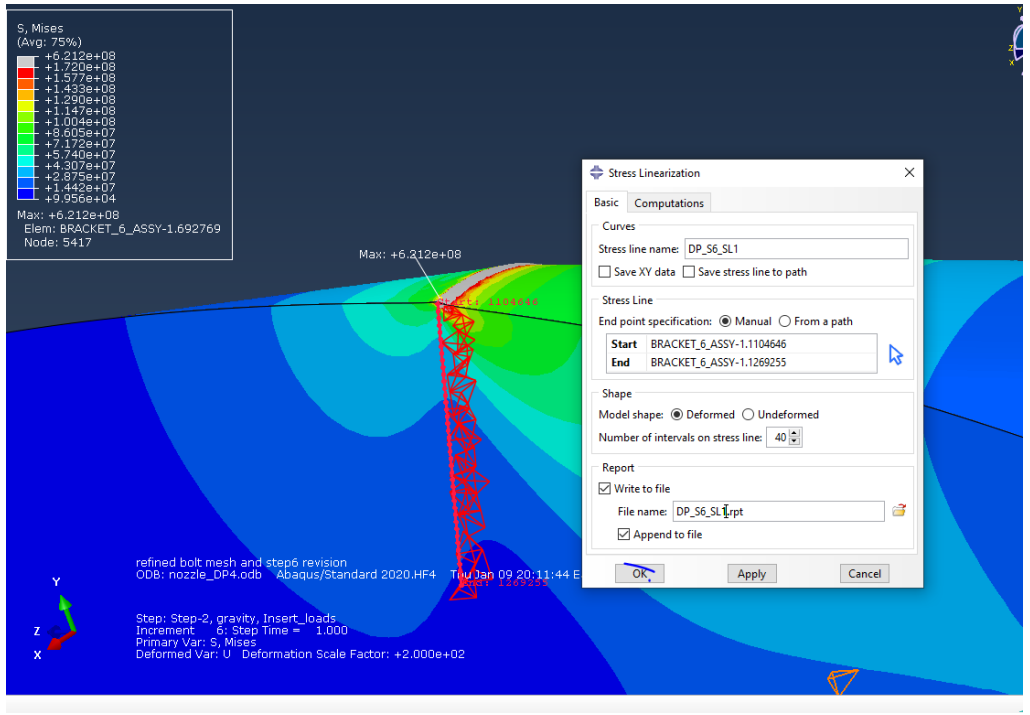


Step 2 bolt cross section loads

Load on cross section primarily in axial direction 6.6e3 N

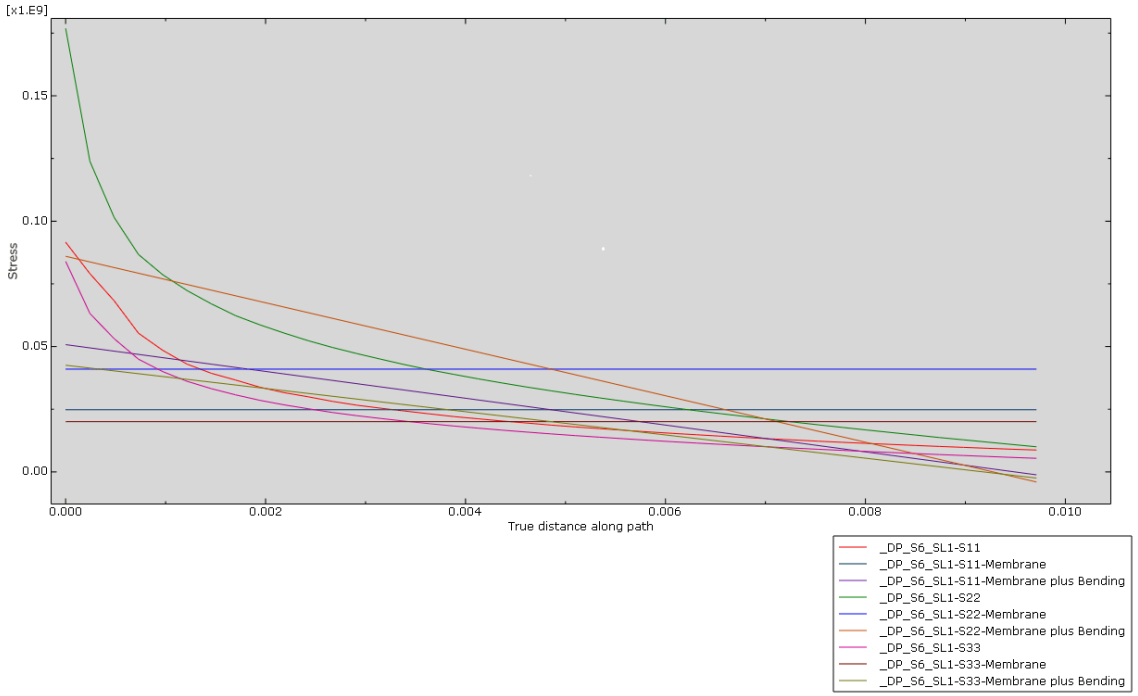


Stress linearization path



Step 2 Stress linearization path 1 ~normal to surface

Stress component plots along path



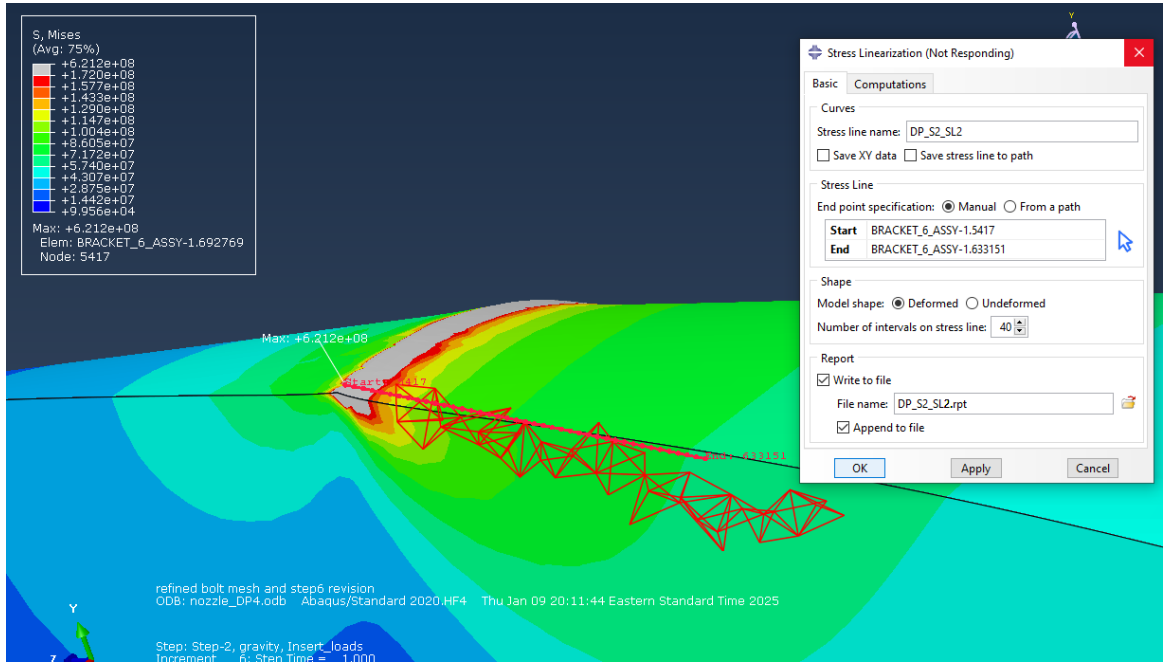
Mises Membrane + Bending well below 172 MPa limit

Bending components in equation for computing membrane plus bending stress invariants are: S11, S22, S33, S12, S13, S23

	Max. Prin.	Mid. Prin.	Min. Prin.	Tresca Stress	Mises Stress
Membrane (Average) Stress	4.50465e+07	2.397e+07	1.68146e+07	2.82319e+07	2.5421e+07
Membrane plus Bending, Point 1	9.16743e+07	5.09364e+07	3.66877e+07	5.49866e+07	4.94273e+07
Membrane plus Bending, Point 2	8.14907e+06	-3.06693e+06	-1.27184e+07	2.08675e+07	1.80887e+07
Peak Stress, Point 1	1.12659e+08	3.70211e+07	2.34531e+07	8.92055e+07	8.32549e+07
Peak Stress, Point 2	1.64539e+07	8.2149e+06	7.14416e+06	9.30969e+06	8.82318e+06

Step 2 Stress linearization path 2 ~parallel to surface

Path 2



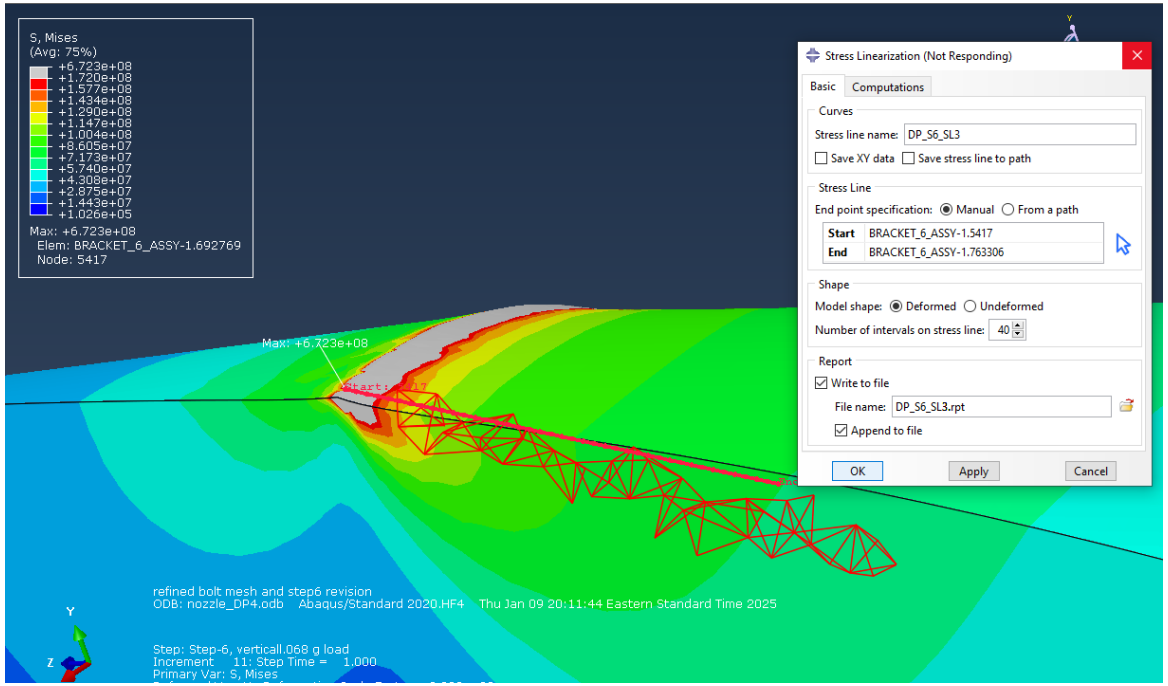
Membrane plus Bending peak 154 MPa

Bending components in equation for computing membrane plus bending stress invariants are: S11, S22, S33, S12, S13, S23

	Max. Prin.	Mid. Prin.	Min. Prin.	Tresca Stress	Mises Stress
Membrane (Average) Stress	1.07829e+08	1.66243e+07	2.17056e+06	1.05659e+08	9.92244e+07
Membrane plus Bending, Point 1	1.76307e+08	4.29358e+07	8.11872e+06	1.68189e+08	1.53765e+08
Membrane plus Bending, Point 2	4.18686e+07	-6.18459e+06	-9.79781e+06	5.16664e+07	4.99579e+07
Peak Stress, Point 1	3.19407e+08	1.03548e+08	5.34196e+07	2.65987e+08	2.44803e+08
Peak Stress, Point 2	3.37888e+07	1.25284e+07	2.87543e+06	3.09134e+07	2.73936e+07

Linearized Stress for Mises Membrane + Bending just below 172 MPa limit for Step 6 with vertical seismic load

Stress linearization path



Membrane + Bending 165 MPa

```
------------------------------------ INVARIANT RESULTS ------------------------------

Bending components in equation for computing
membrane plus bending stress invariants are:   S11, S22, S33, S12, S13, S23

                        Max.          Mid.          Min.         Tresca        Mises
                        Prin.         Prin.         Prin.        Stress        Stress
     Membrane
(Average) Stress   1.15706e+08   1.85194e+07   3.09464e+06   1.12612e+08   1.05746e+08

  Membrane plus
Bending, Point 1   1.91302e+08   4.72327e+07   1.15477e+07   1.79754e+08   1.64835e+08

  Membrane plus
Bending, Point 2   4.28968e+07  -8.12843e+06  -1.02103e+07   5.31071e+07   5.20974e+07

   Peak Stress,
     Point 1       3.37837e+08   1.11243e+08   6.24541e+07   2.75383e+08   2.5452e+08

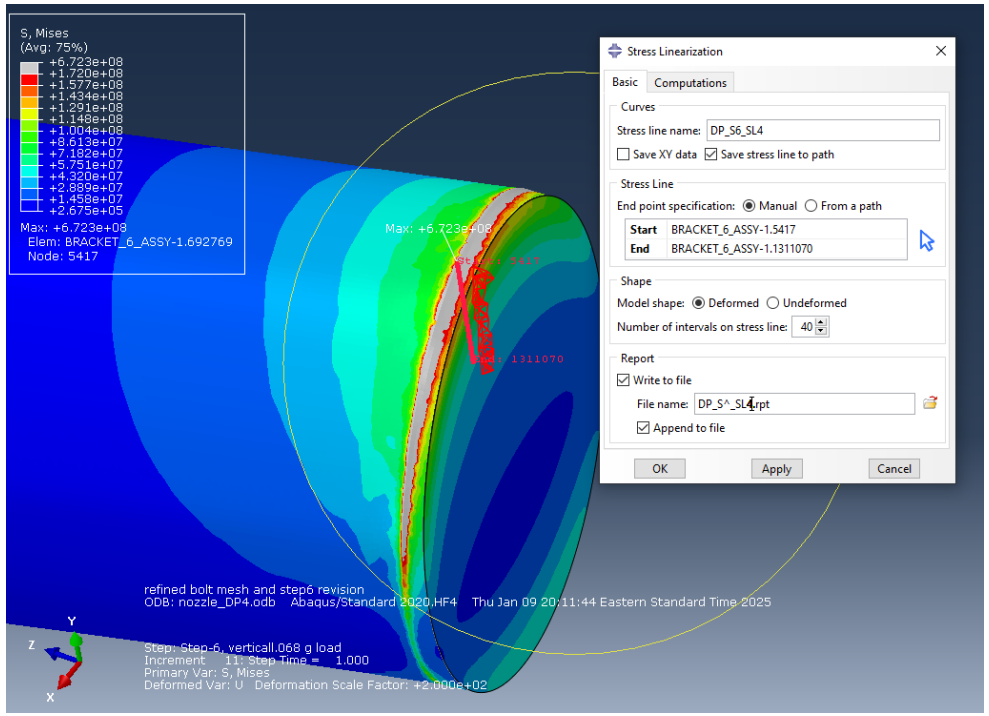
   Peak Stress,
     Point 2       3.61125e+07   1.35838e+07   4.11398e+06   3.19985e+07   2.84704e+07
```

```
ODB: E:/CV 2023_2024/Nozzle_dual_port/nozzle_DP4.odb
Step: Step-6
Frame: Increment     11: Step Time =    1.000


inearized Stresses for stress line 'DP_S6_SL3'
 Start point, Point 1 - (-0.2916299700737, -0.14190374314785, -1.71695816516876)
 End point, Point 2   - (-0.292371213436127, -0.142926007509232, -1.7225593328476)
 Number of intervals  - 40
```

Step 6 Stress linearization Path 2

Stress SL4 path



Mises mebrane + bending 99.6 MPa

```
------------------------------------ INVARIANT RESULTS ------------------------------

Bending components in equation for computing
membrane plus bending stress invariants are:   S11, S22, S33, S12, S13, S23

                      Max.        Mid.        Min.       Tresca       Mises
                      Prin.       Prin.       Prin.      Stress      Stress
    Membrane
(Average) Stress  9.20399e+07  4.9585e+07  3.62583e+07  5.57816e+07  5.04559e+07

  Membrane plus
Bending, Point 1  1.76165e+08  8.66837e+07  6.88391e+07  1.07326e+08  9.96099e+07

  Membrane plus
Bending, Point 2  2.45693e+07  3.62892e+06  -4.11999e+06  2.86893e+07  2.57062e+07

   Peak Stress,
     Point 1       3.0069e+08  8.9398e+07  3.98405e+07  2.60849e+08  2.3994e+08

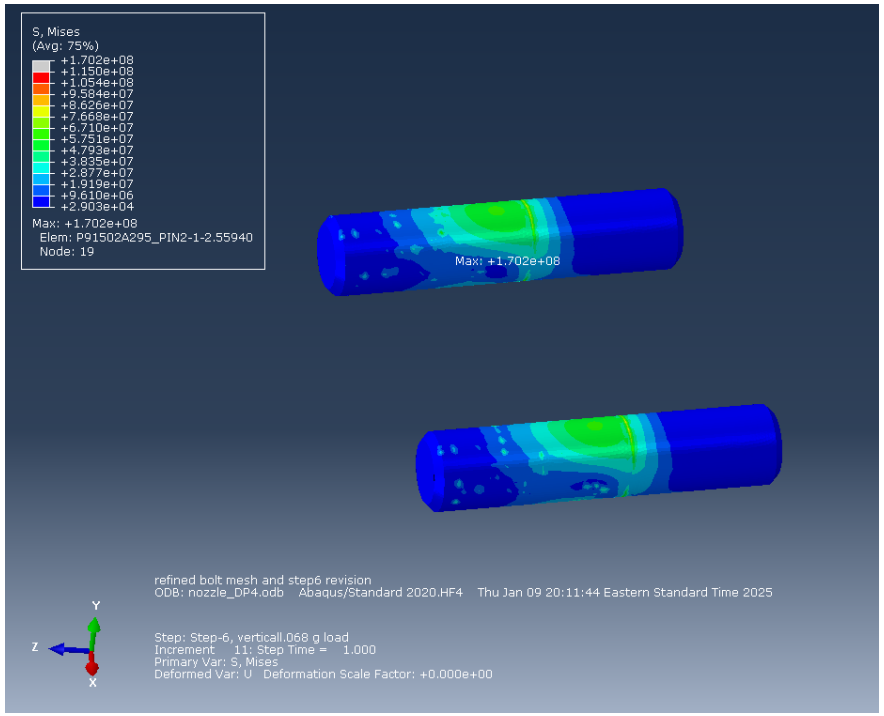
   Peak Stress,
     Point 2       3.84861e+07  1.44351e+07  1.28711e+07  2.56151e+07   2.487e+07

******************************************************************************
Statically Equivalent Linear Stress Distribution across a Section,
written on Tue Jan 14 13:33:34 2025
```

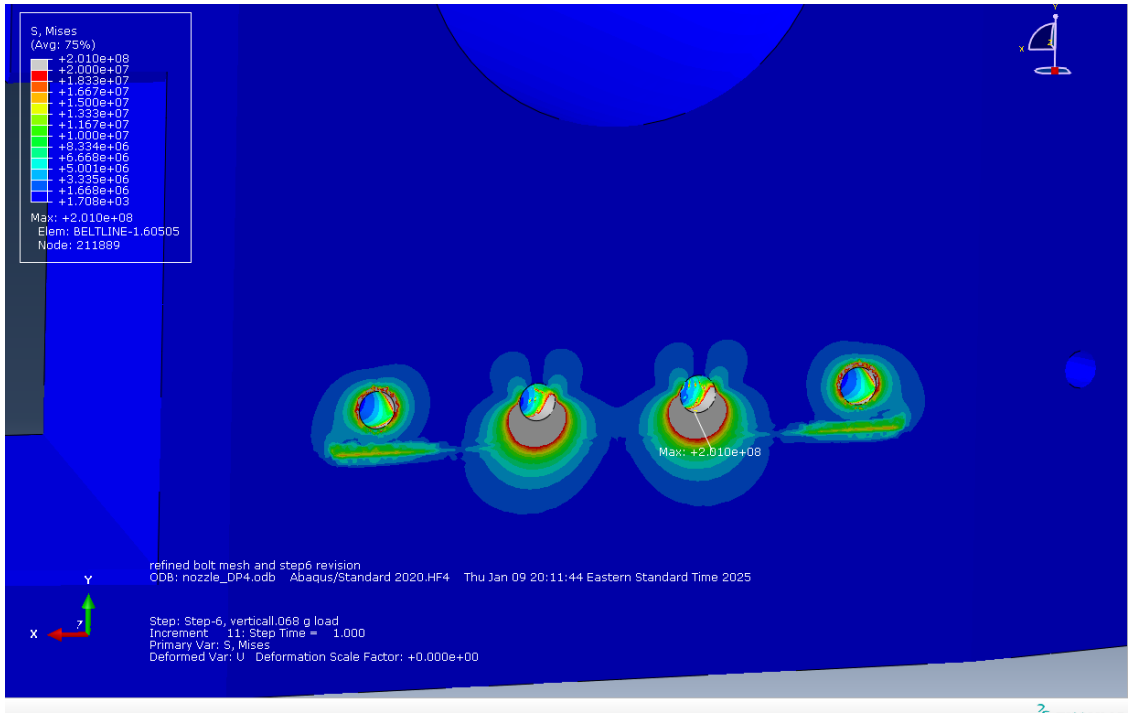
```
Linearized Stresses for stress line 'DP_S6_SL4'
  Start point, Point 1 - (-0.2916299700737, -0.14190374314785, -1.71695816516876)
  End point, Point 2   - (-0.291449248790741, -0.14552815258503, -1.71590042114258)
  Number of intervals  - 40
```

Beltline and shear pin stresses

Shear Pin peak stress 170 MPa



Step 6 peak stress 201 MPa



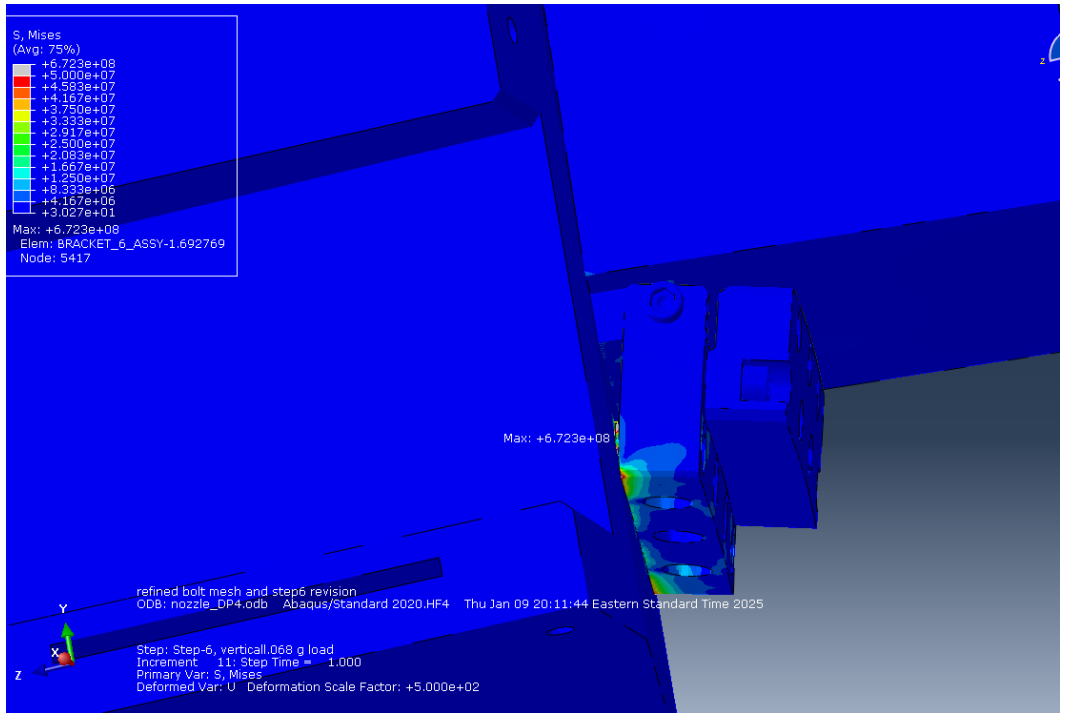
Peak membrane + bending
80 MPa from stress
linearization around peak

Option to reduce lower bolt stress

Option to add margin

- The vertical gravity and seismic loads near the beltline are carried by the vertical pins in the lower bracket
- The moment created around the beltline from these pins is resisted by the bolt tension with bending and lower bracket edge in compression against the beltline
- Extending the bracket lower edge should reduce the loads on the bolts
- Using 25 mm bolts in the lower bracket would also help

Lower Bracket Stress 50 MPa scale



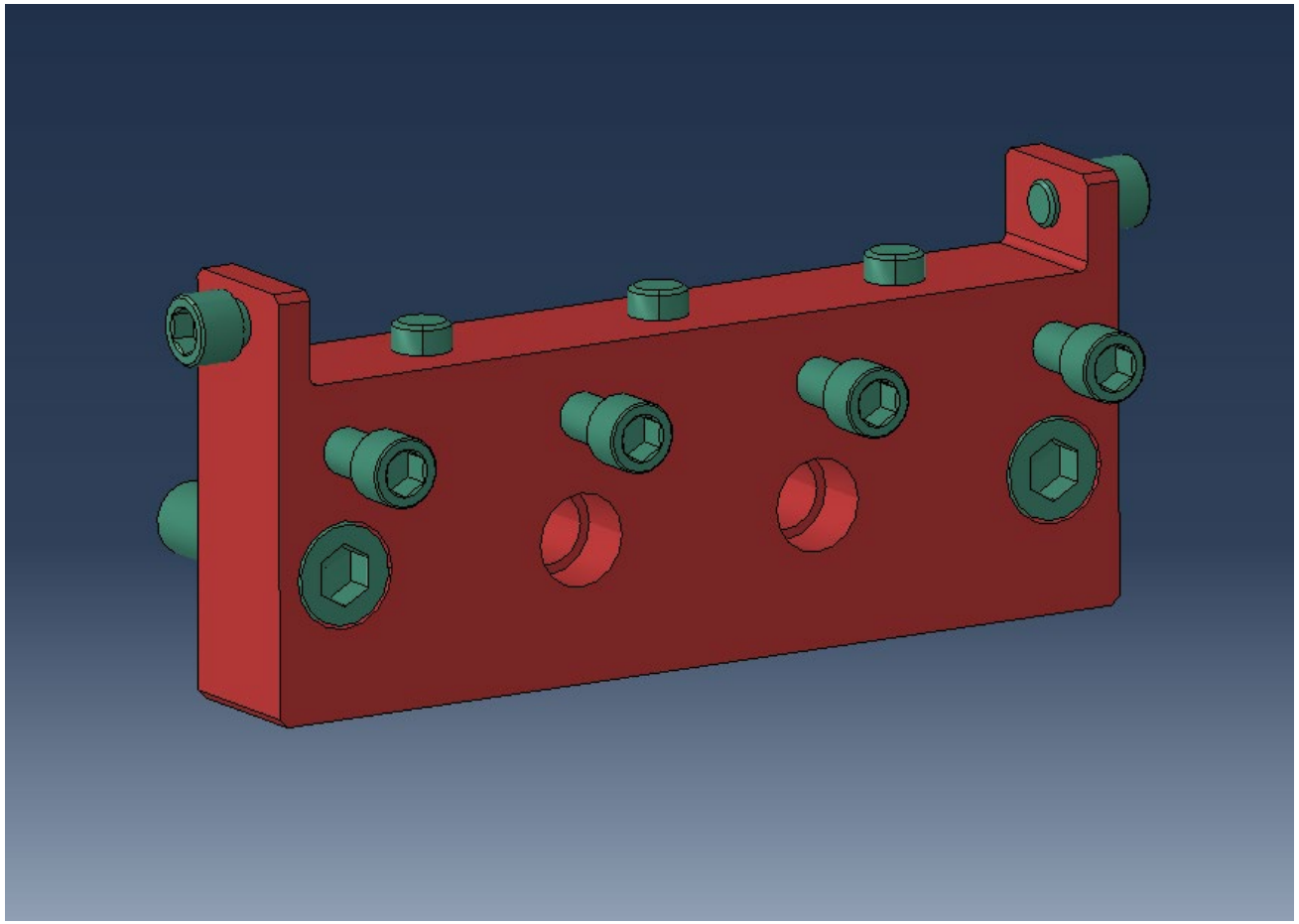
Displacement x 500

Summary- model DP4

- The peak stresses were on the lower bracket bolts from vertical loads and resulting bending moment
- The peak of 167 MPa in Step 6 was very localized just downstream of where the bolt entered the beltline thread area
- Stress linearization Mises peak membrane plus bending was 165 MPa close but below the 1.5 Sm limit of 172.5 MPa
- The bolt load on the 20 mm diameter bolts was approximately 6.5 kN which would give an average axial stress of about 21 MPa
- Design changes such as enlarging the lower bracket increasing the distance from the lower bracket edge to the bolt centerline should reduce the bolt loads

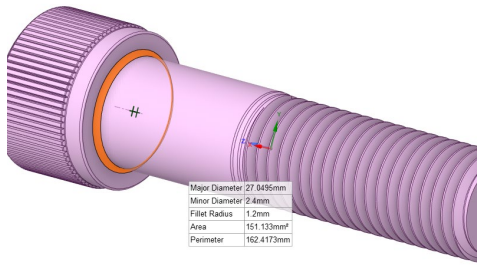
DP5 Proposed design changes to reduce stresses

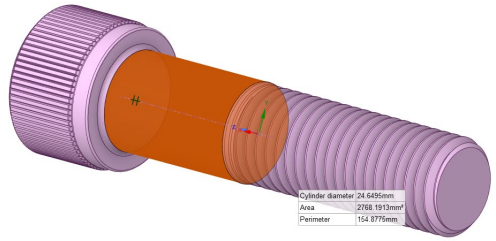
- **Bracket 6 holes enlarged to 24.65 mm Diameter for shank and pins**
- **Bracket bottom extended 25 mm down**



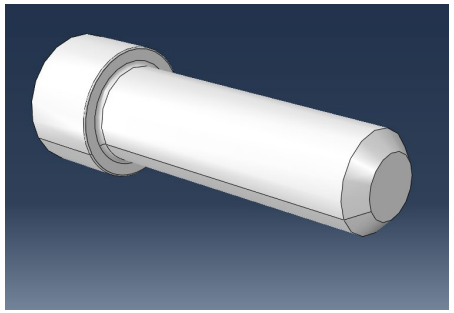
24 mm 316L bolt

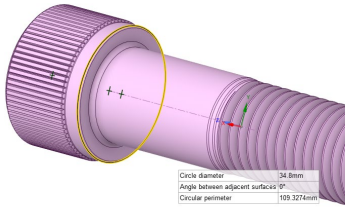
- Shank diameter 24.4649 mm
- Radii near head 1.2 mm
- Head diameter without grooves – 34.8 mm
- Threads not included in model





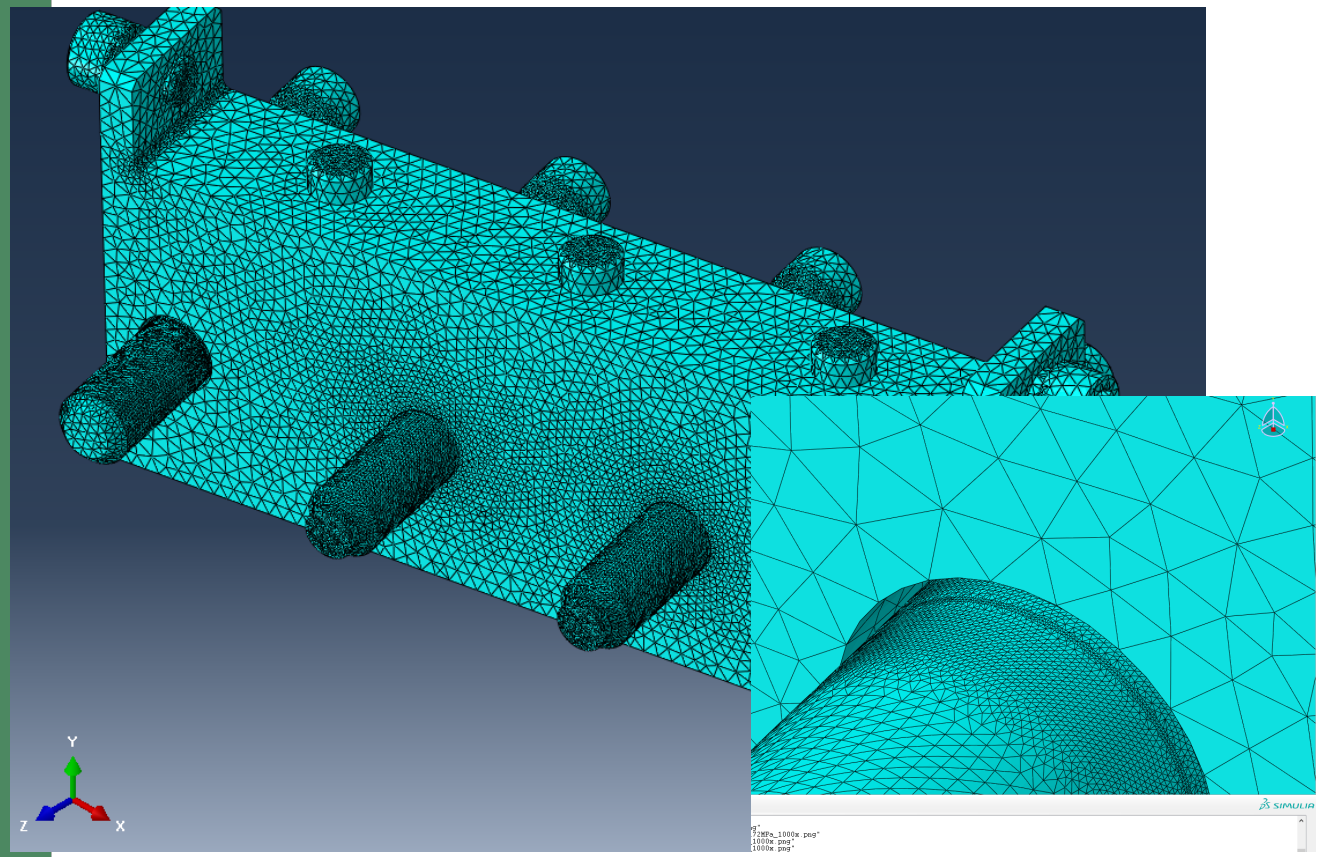
Simulated bolt modeled



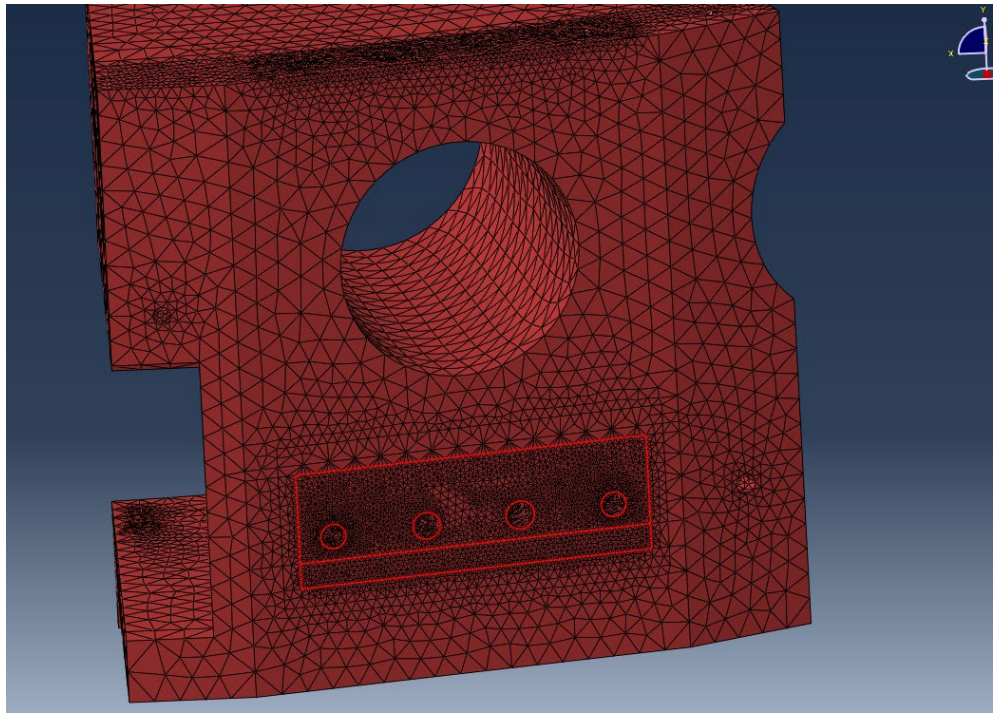


Lower bracket model similar to previous DP4 model with changes to bolt and pin diameters and 25 mm extension

Bracket bolts use .25 mm mesh around tie contact to beltline

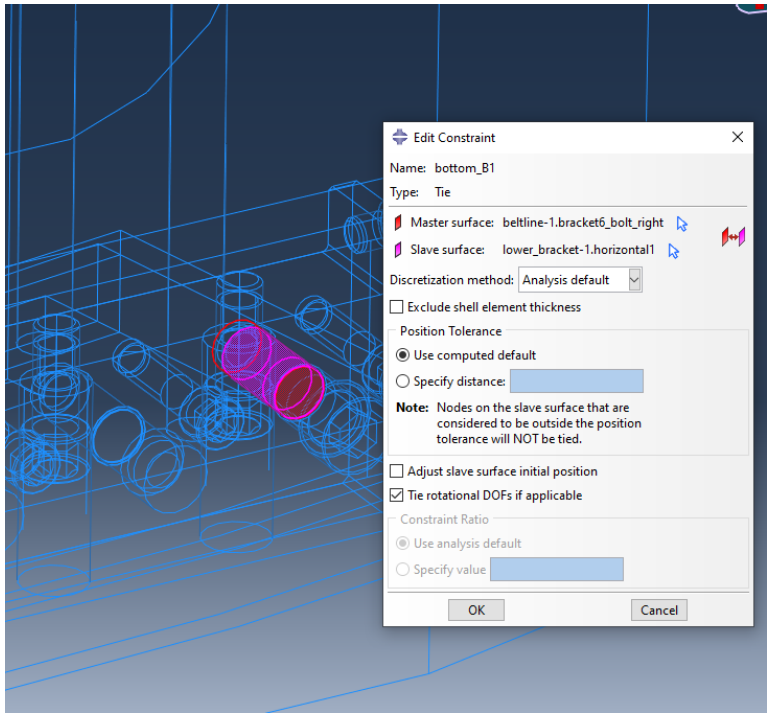


Beltline mesh refined and contact area with lower bracket defined

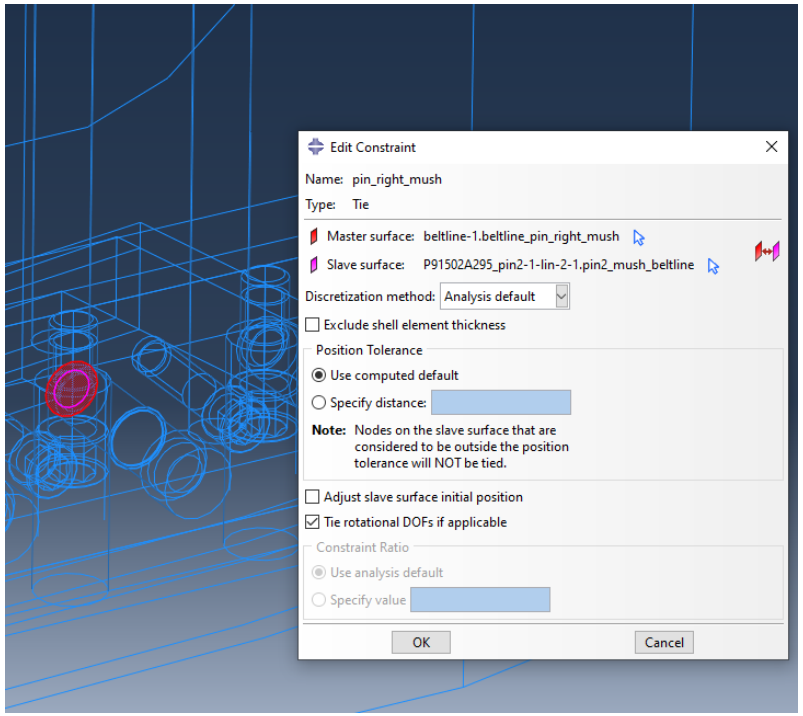


Revised Tie constraints with 24.65 mm diameter bolts/pins

Lower bolt tie to beltline (typ)

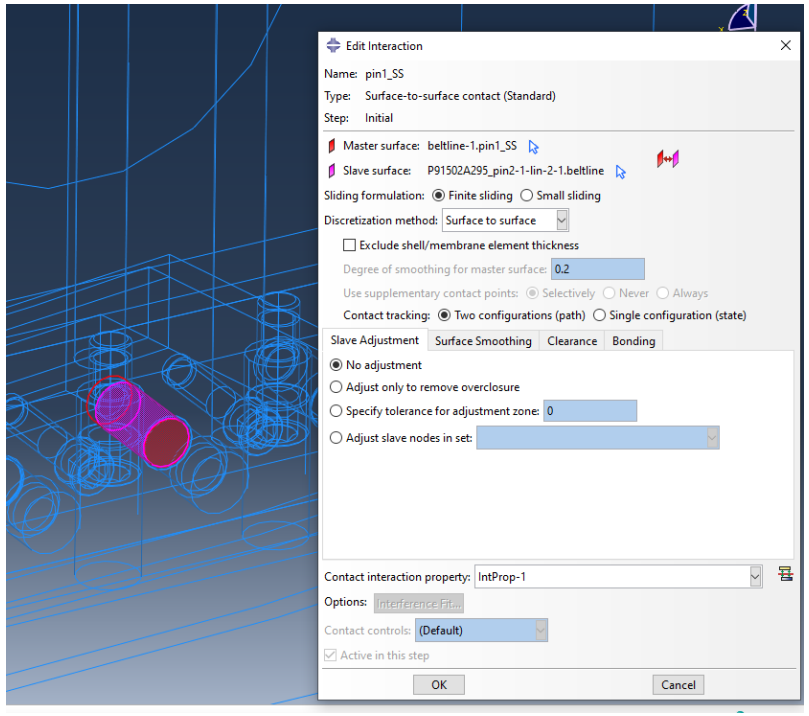


Shear pin soft tie to beltline (typ)

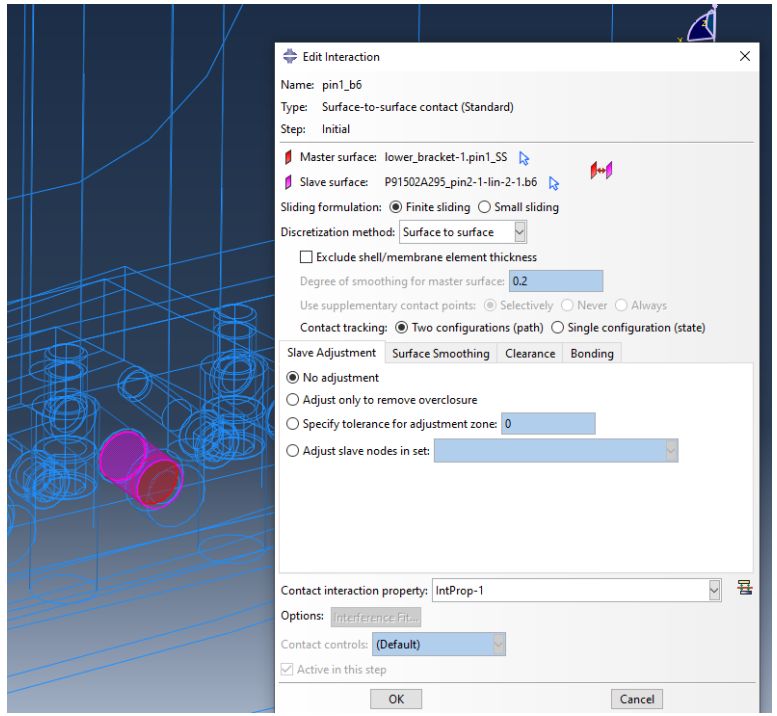


Revised pin Interactions

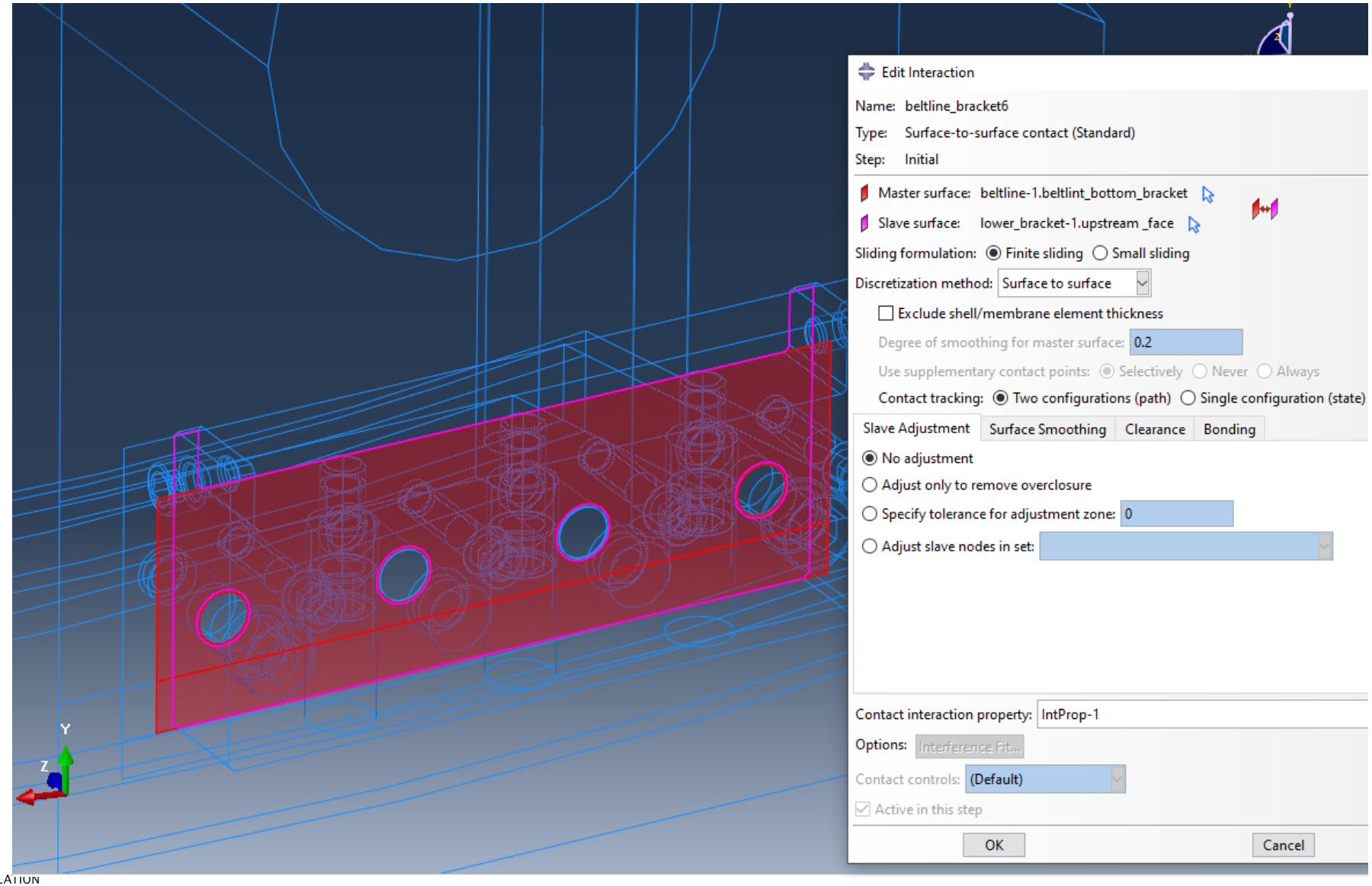
Shear pin surface to surface contact with beltline (typ)



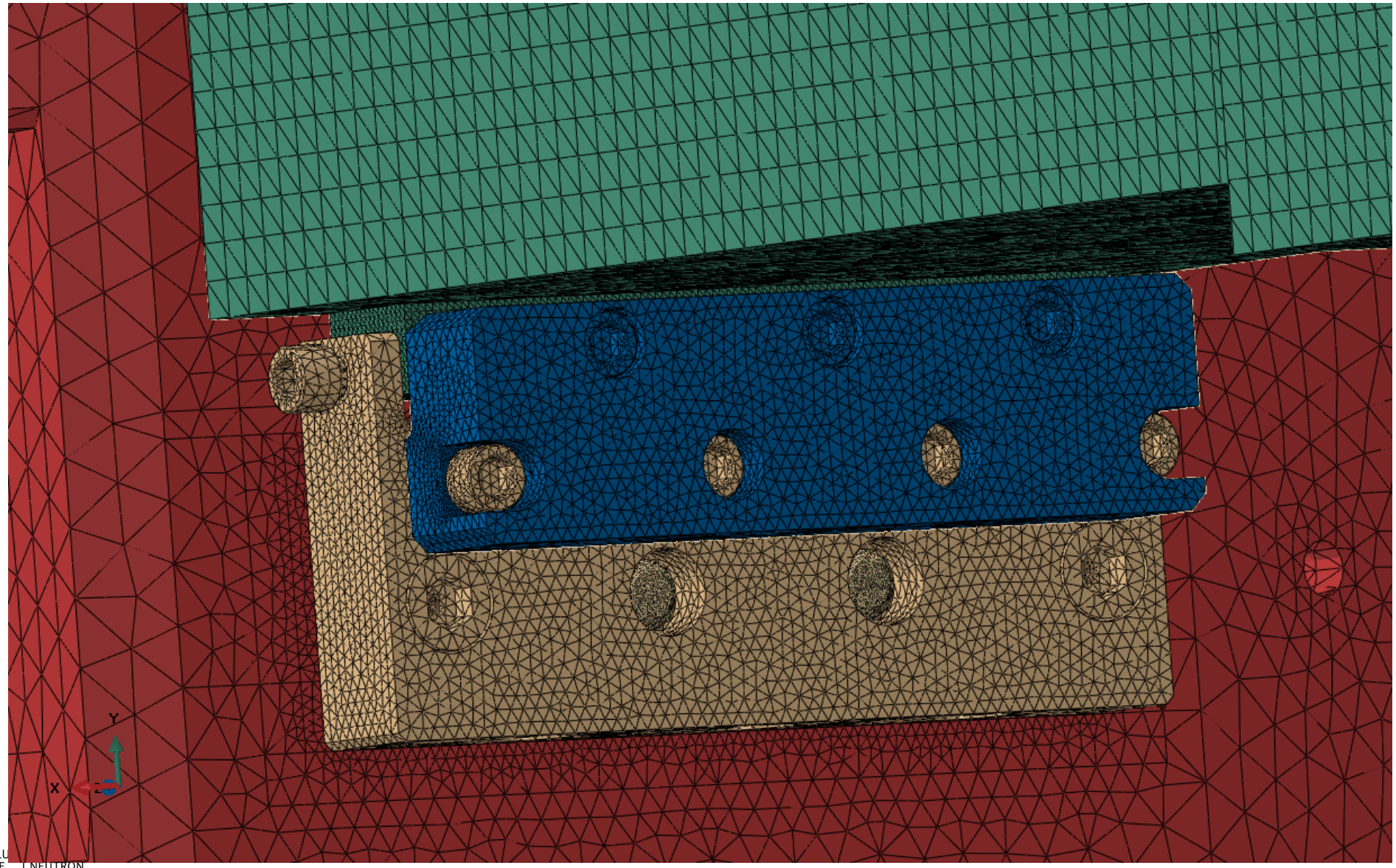
Shear pin surface to surface contact with lower bracket (typ)



Revised surface to surface contact lower bracket to beltline



DP5 model Assembly mesh around lower bracket

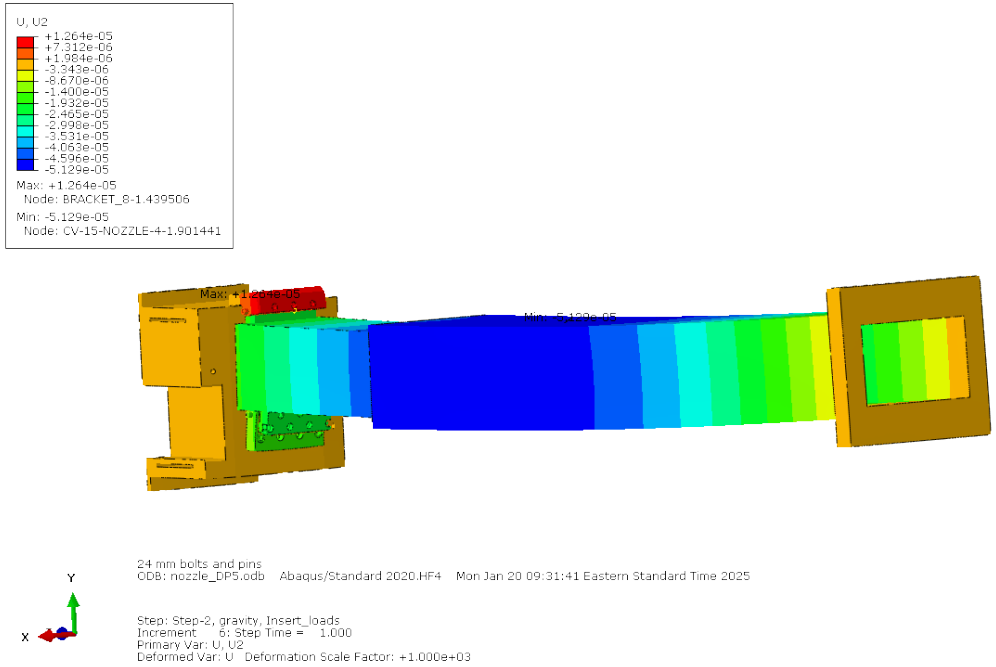


Analysis Step Loads and Boundary Conditions – same as for DP4 model

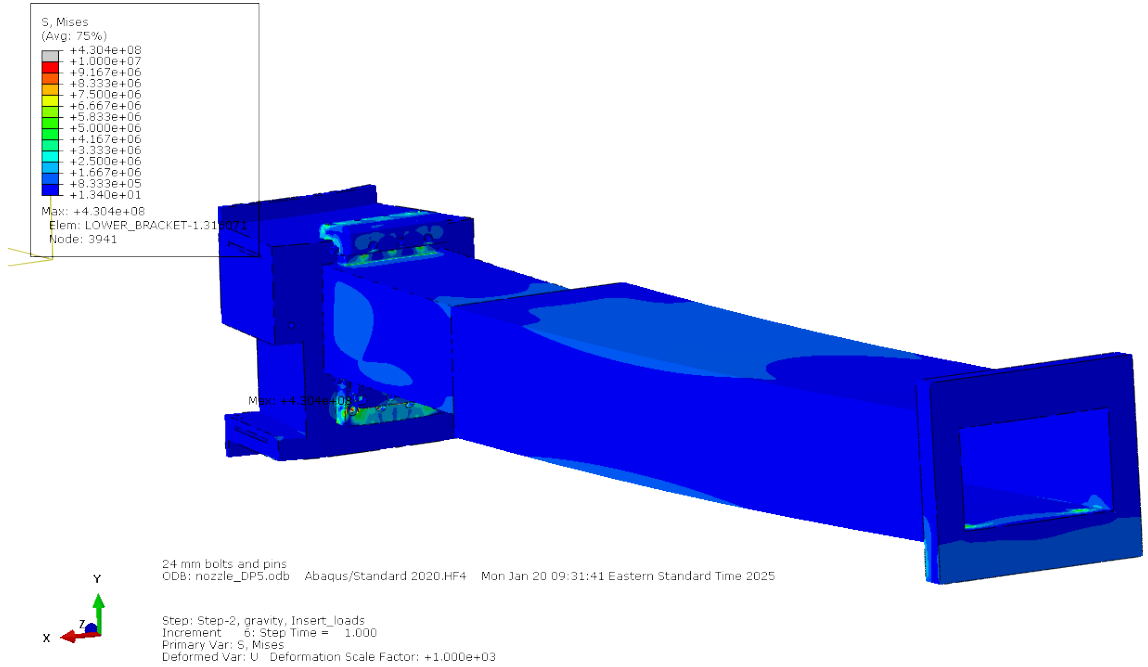
	Loads						Boundary Conditions		
Step	Structure 1 g vertical	Insert mass 1 g vertical	1 bar pressure	Seisimic side load	Seismic axial load	Seismic vertical load	1- Beltline fixed	2- Flange bottom	3 - Flange side
1	X						X	X	
2	X	X					X	X	
3	X	X	X				X	X	
4	X	X	X	X			X	X	
5	X	X	X		X		X	X	X
6			X			X	X	X	

Step2 Gravity with Insert mass

Displacement peak -.05 mm down

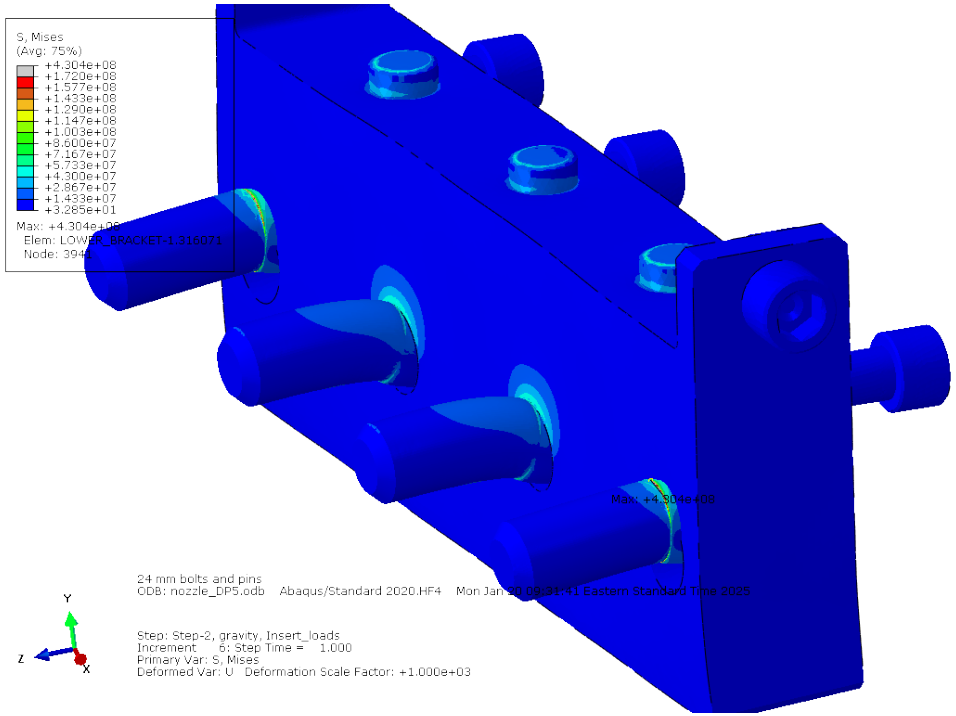


S Mises peak 430 MPa

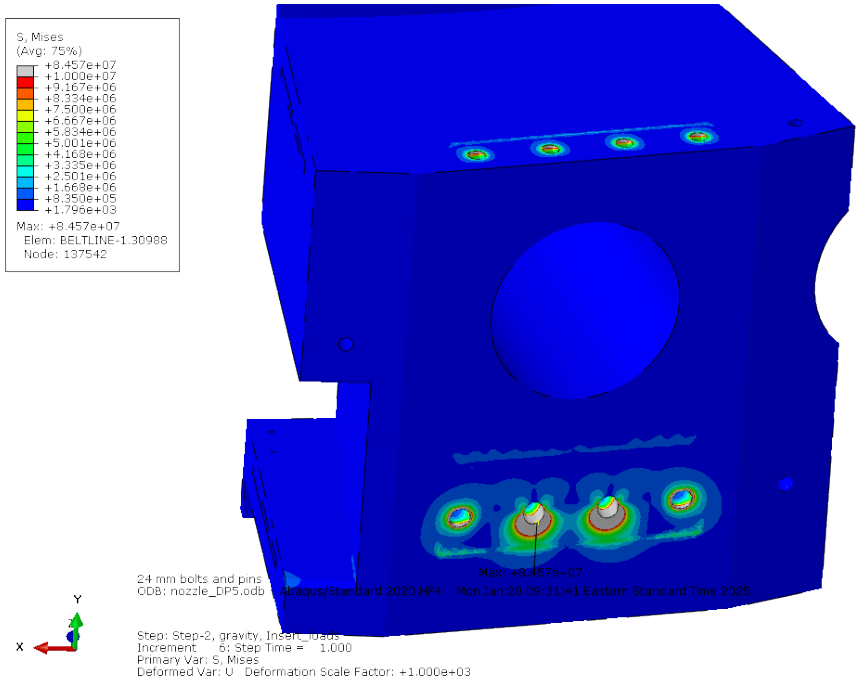


Step 2 Results

Lower Bracket bolt peak 430 MPa

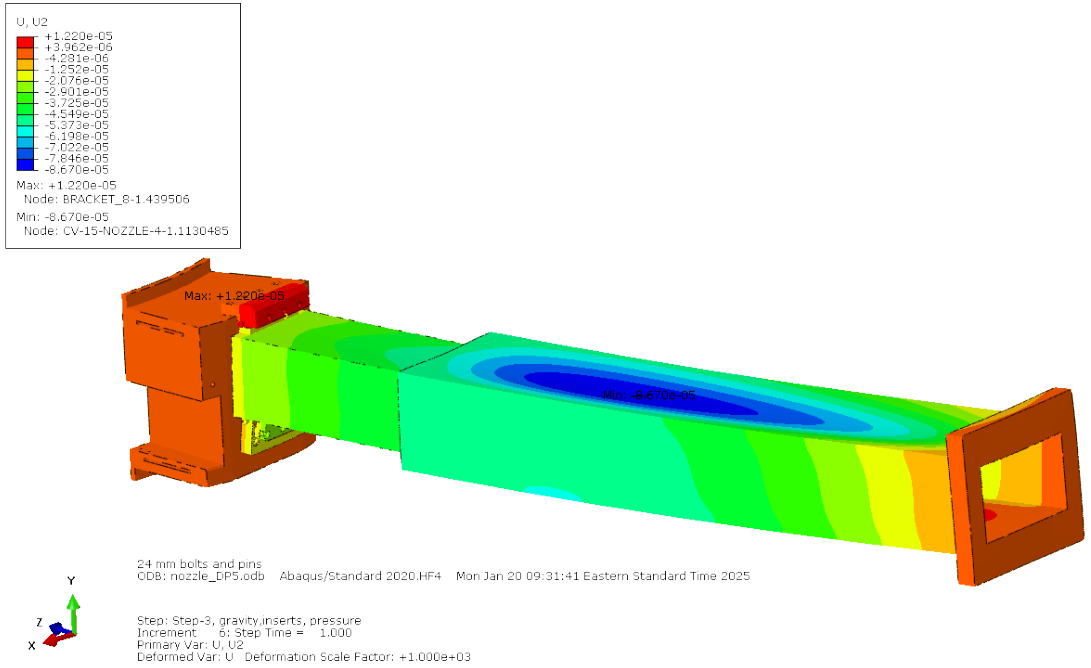


Beltline peak 85 MPa

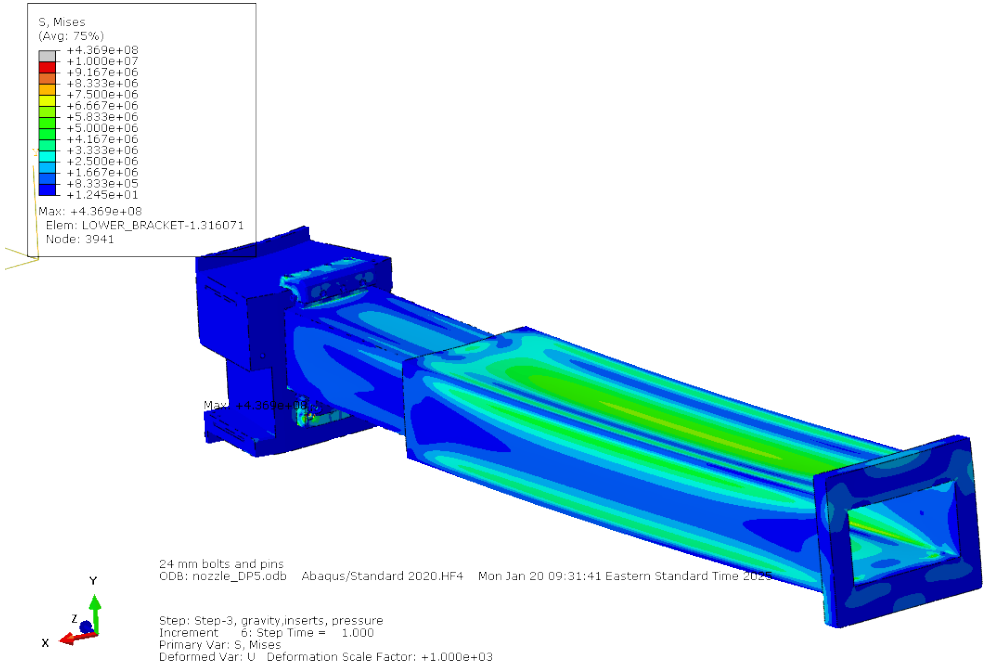


Step 3 Gravity, Insert mass and vacuum loads

U2 min .087 mm down

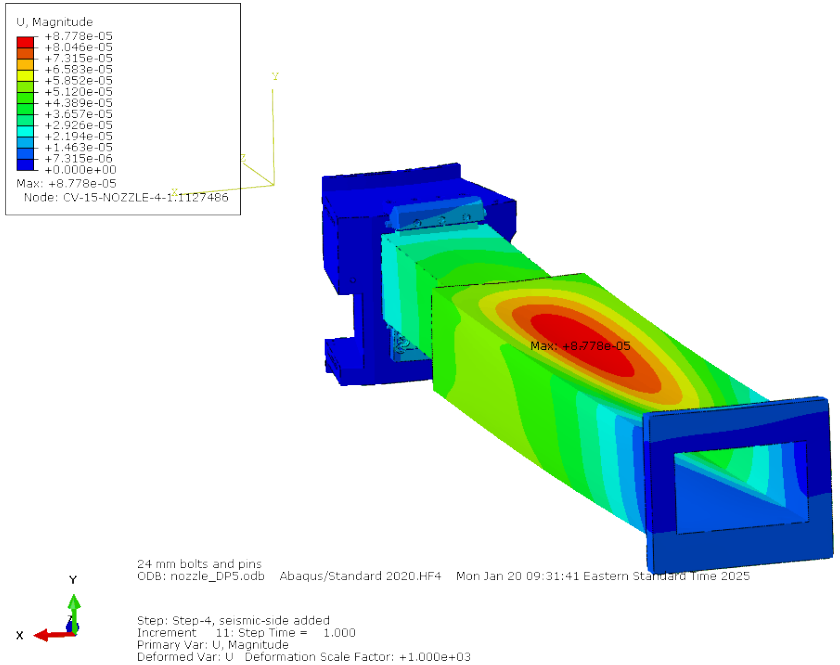


S 436 MPa on lower bolt – 10 MPa scale

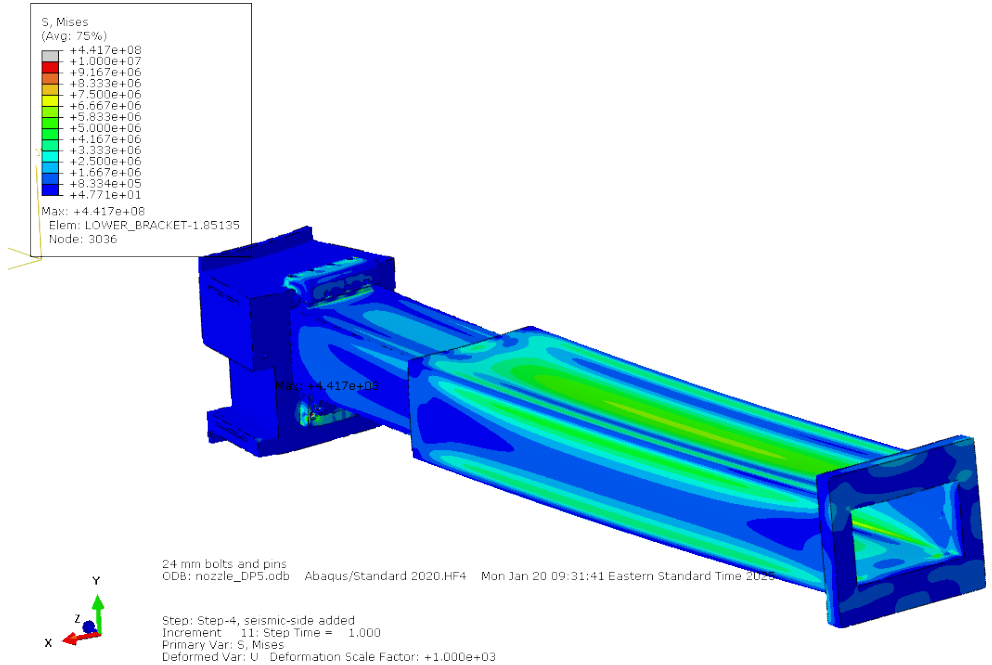


Step 4 Results with seismic side load added

Displacement

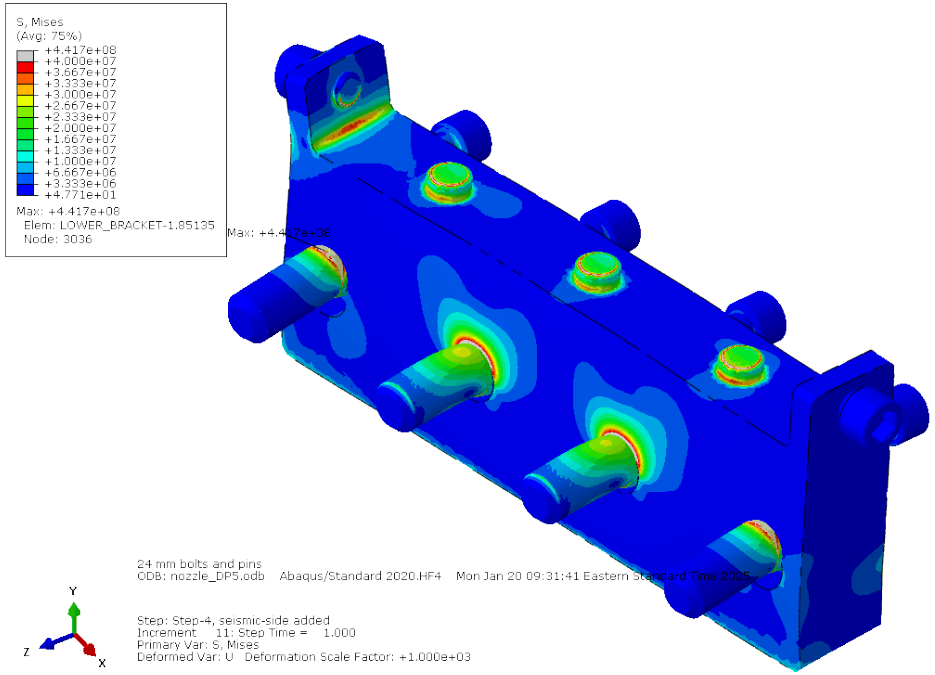


S peak 442 MPa

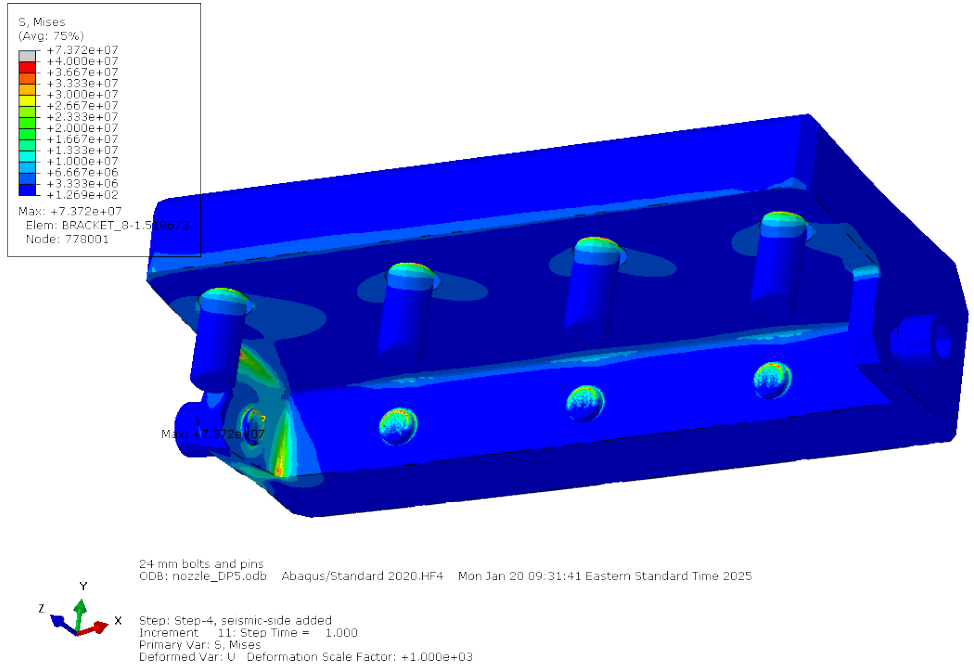


Step 4 Results with seismic side load added

Lower Bracket S peak 442 MPa

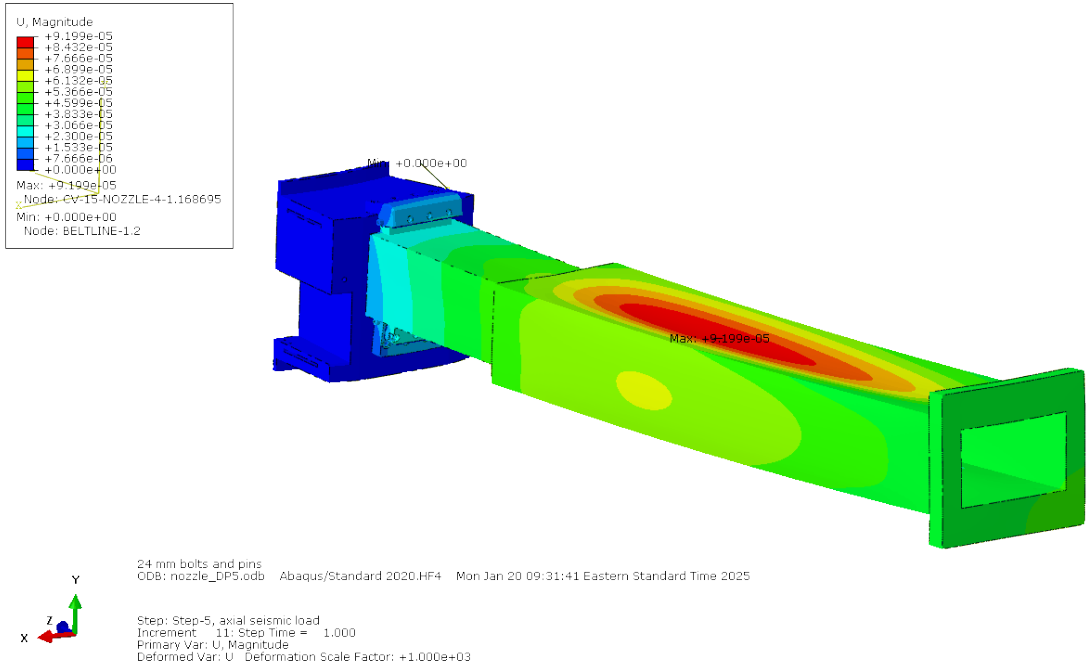


Bracket 8 S peak 74 MPa

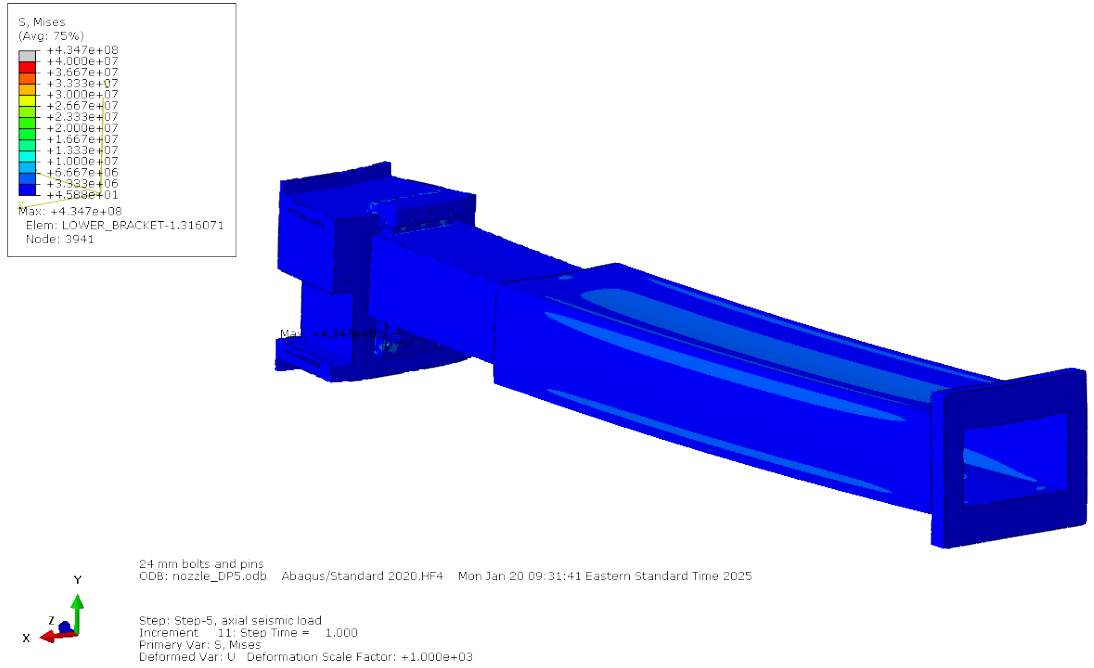


Step 5 Axial seismic .068G load

Displacement U

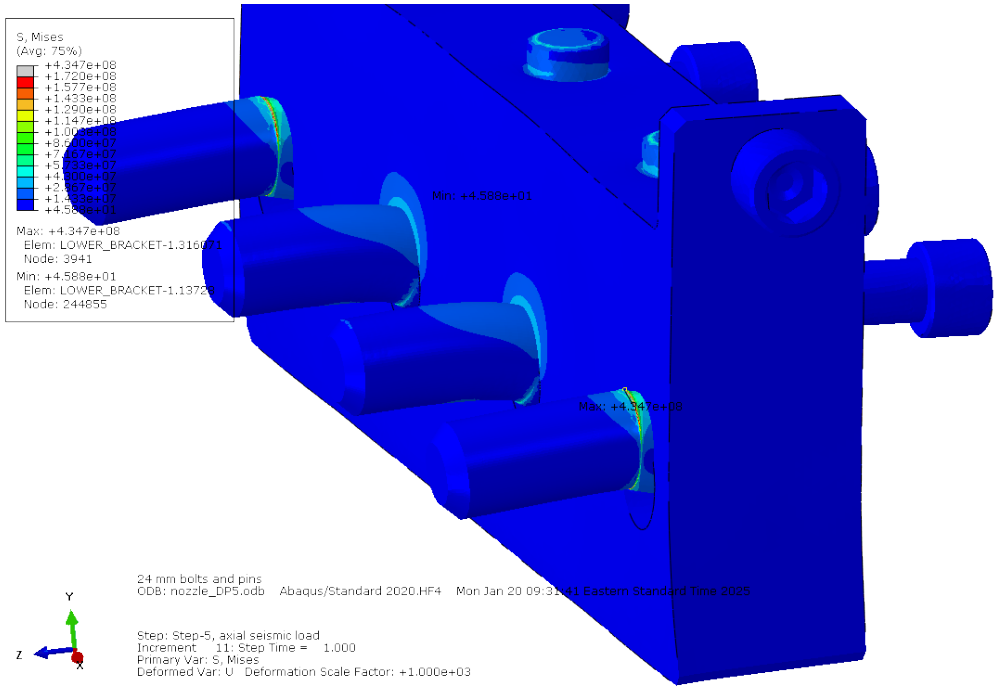


Assembly S peak 435 MPa

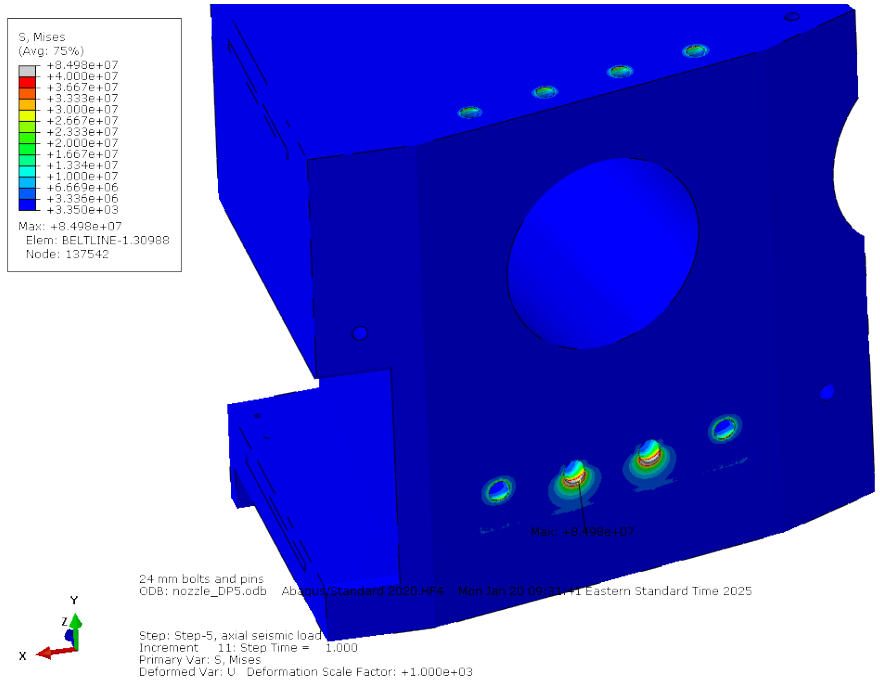


Step 5 Results Axial seismic .068G load

Lower Bracket peak 435 MPa

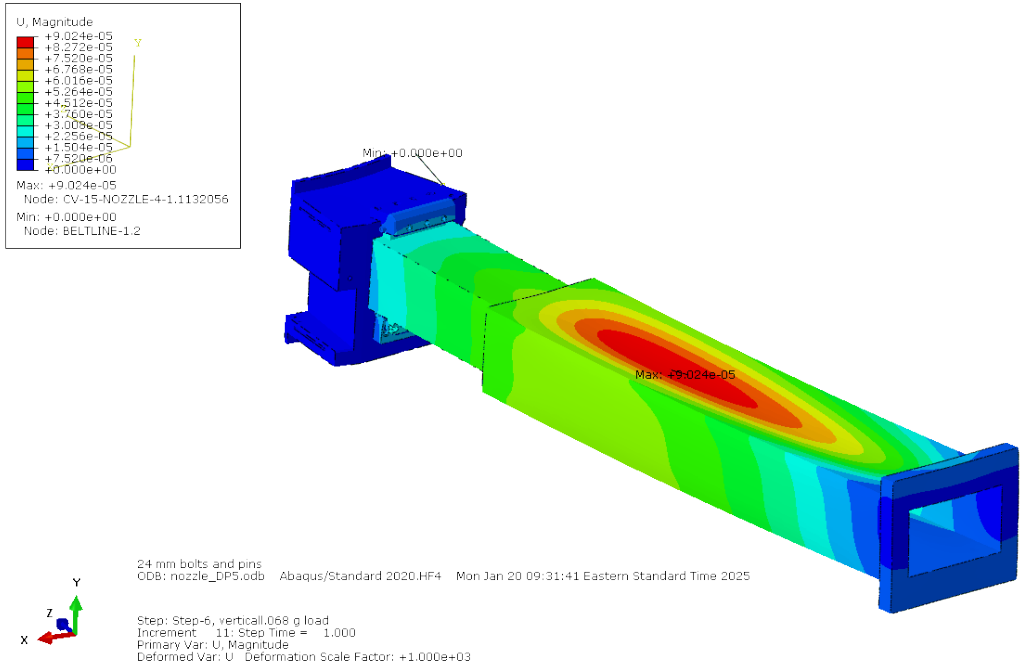


Beltline S peak 85 MPa

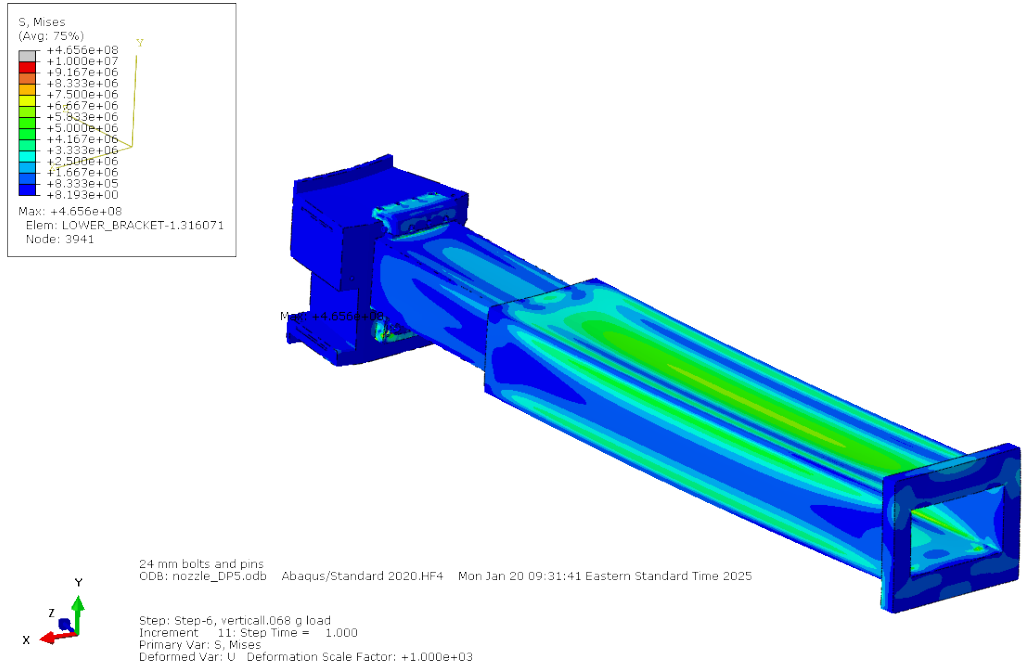


Step 6 Results with vertical seismic load

Displacement

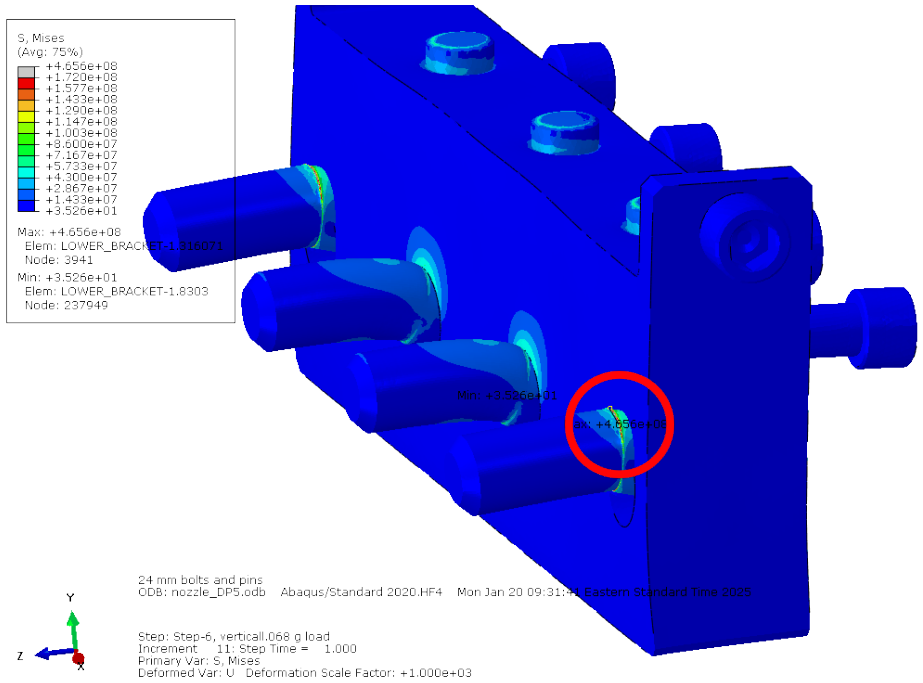


S peak 466 MPa in lower bracket bolt

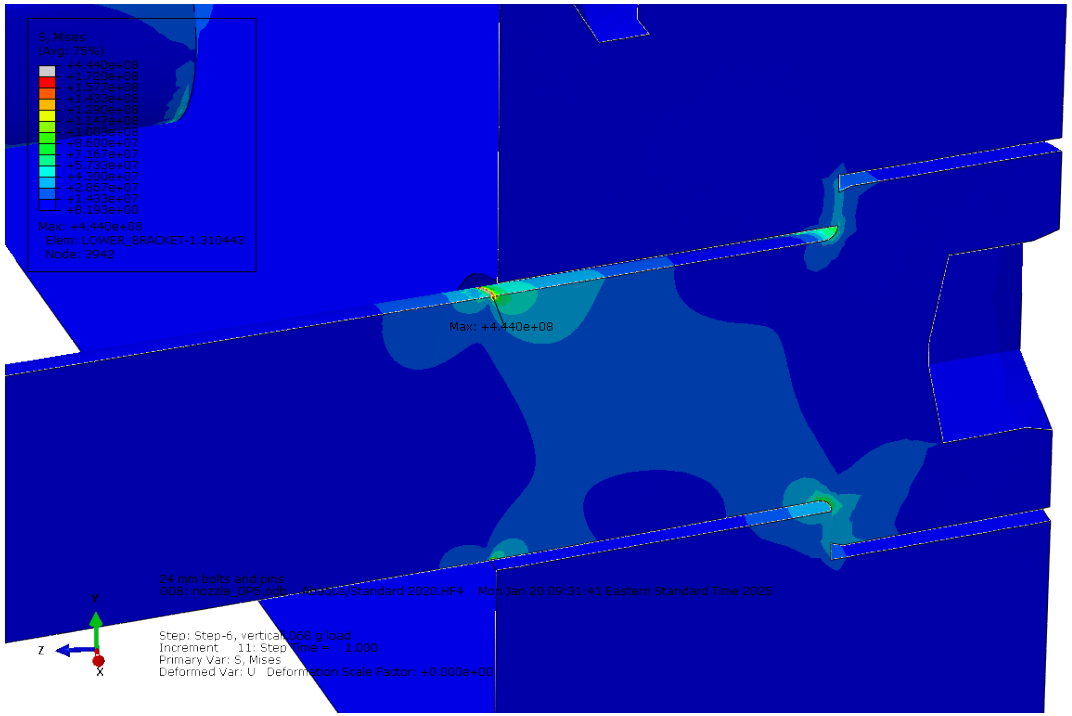


Step 6 Results with vertical seismic load

Lower Bracket S peak 466 MPa

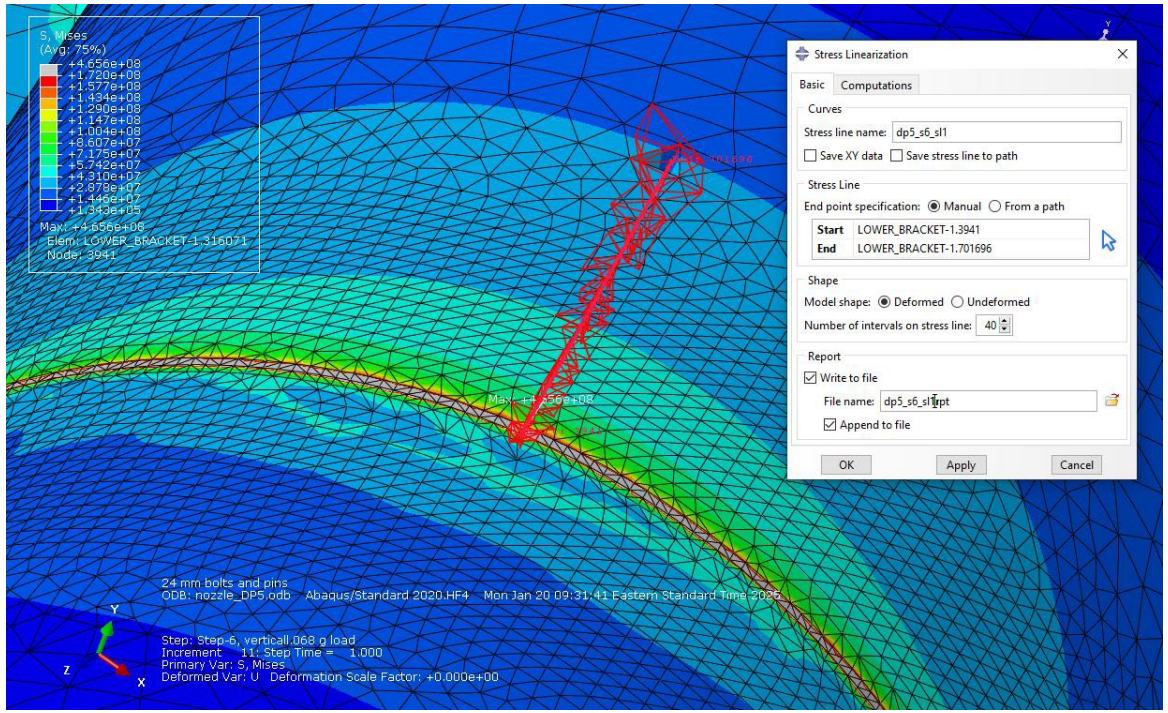


Bolt vertical cut around peak



Step 6 Results with vertical seismic load - linearization

Stress linearization path for bolt peak near top surface (sl1)



Peak Mises bending + Membrane 77 MPa at point 1

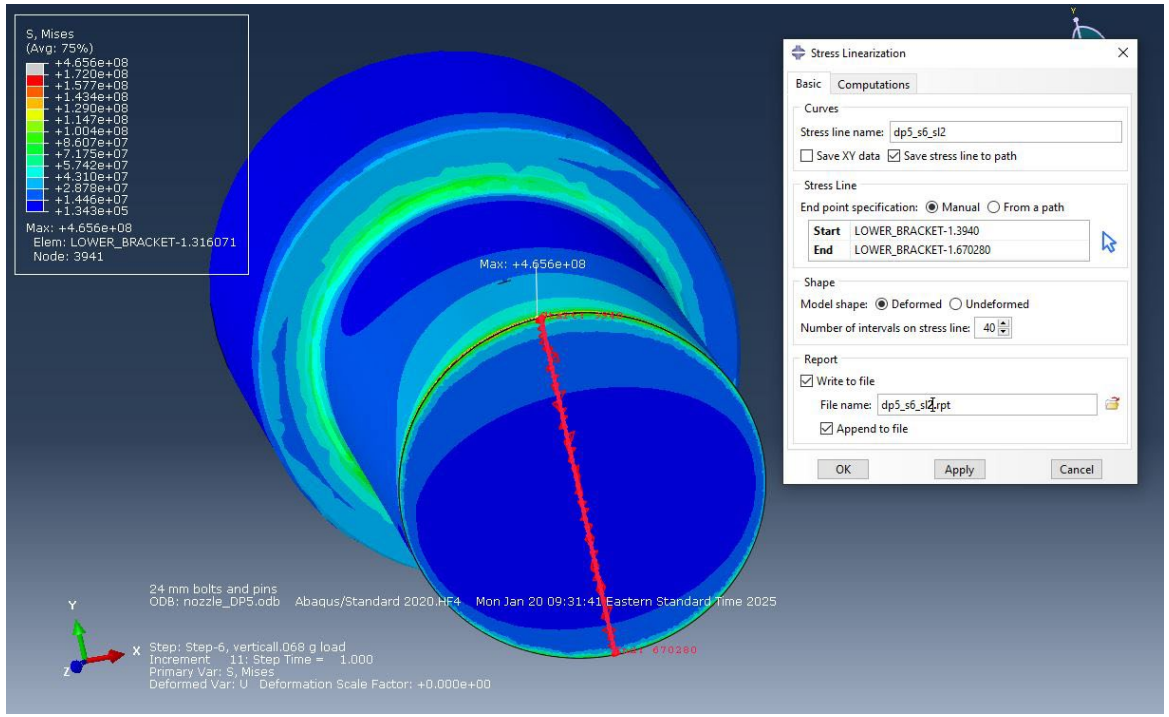
---------- INVARIANT RESULTS ----------

Bending components in equation for computing membrane plus bending stress invariants are: S11, S22, S33, S12, S13, S23

	Max. Prin.	Mid. Prin.	Min. Prin.	Tresca Stress	Mises Stress
Membrane (Average) Stress	4.9588e+07	7.03284e+06	2.19294e+06	4.73951e+07	4.517e+07
Membrane plus Bending, Point 1	9.11205e+07	2.16051e+07	8.50179e+06	8.26187e+07	7.69089e+07
Membrane plus Bending, Point 2	9.99376e+06	-6.0522e+06	-7.54135e+06	1.75351e+07	1.684e+07
Peak Stress, Point 1	3.68698e+08	1.26717e+08	7.63148e+07	2.92384e+08	2.70725e+08
Peak Stress, Point 2	1.85583e+07	7.90255e+06	3.06074e+06	1.54976e+07	1.37325e+07

Step 6 Results with vertical seismic load - linearization

Vertical path sl2 172 MPa scale



Peak Mises membrane + bending 30 MPa

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------------------------------------ INVARIANT RESULTS ------------------------------------

Bending components in equation for computing
membrane plus bending stress invariants are:   S11, S22, S33, S12, S13, S23

                        Max.        Mid.        Min.       Tresca       Mises
                        Prin.       Prin.       Prin.      Stress      Stress
    Membrane
(Average) Stress  1.32668e+07  3.03408e+06  -1.11539e+06  1.43822e+07  1.28214e+07

  Membrane plus
Bending, Point 1  5.55536e+07  3.21043e+07  2.25867e+07  3.29669e+07  2.93876e+07

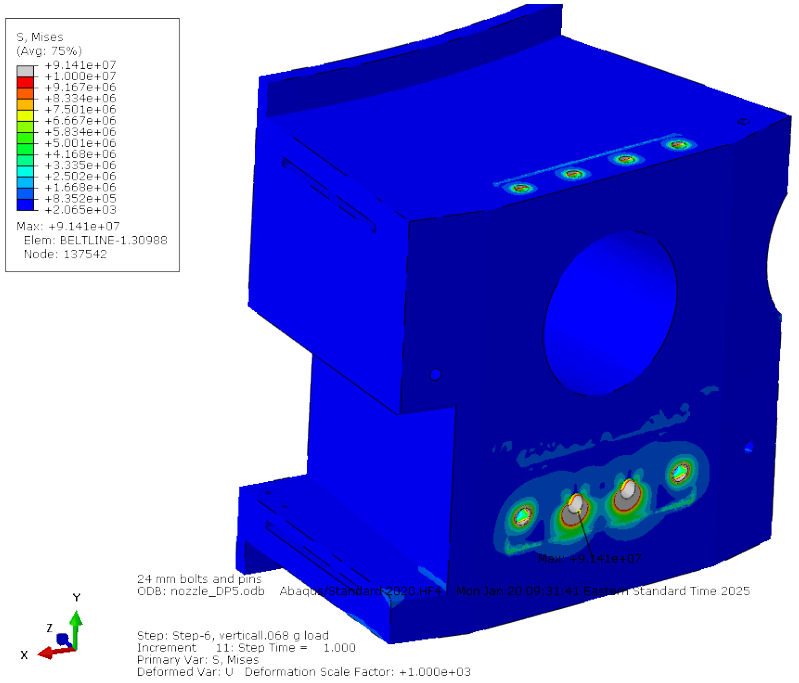
  Membrane plus
Bending, Point 2  -1.65183e+07  -2.85179e+07  -3.48373e+07  1.8319e+07  1.6117e+07

   Peak Stress,
     Point 1       1.97556e+08  6.87966e+07  4.89608e+07  1.48595e+08  1.39737e+08

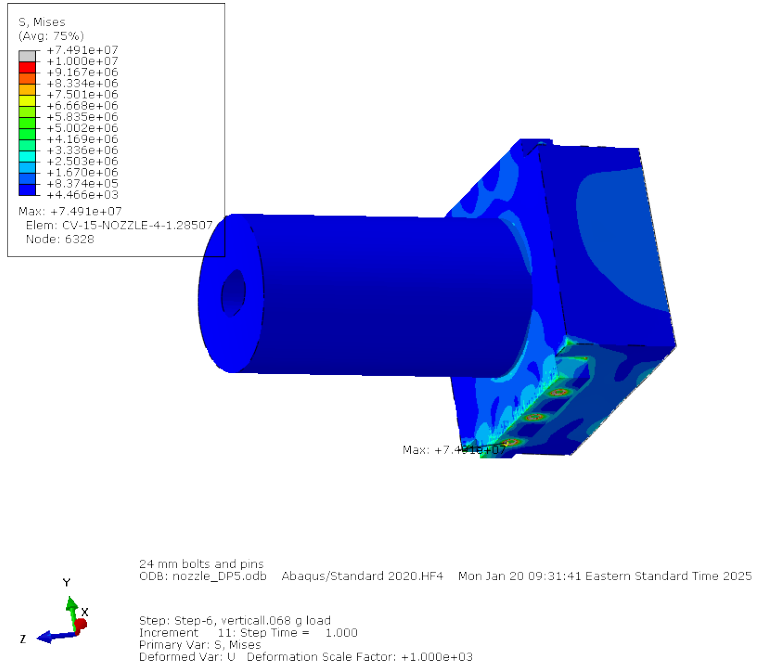
   Peak Stress,
     Point 2       -1.99517e+07  -3.20104e+07  -9.33546e+07  7.34029e+07  6.81781e+07
```

Step 6 Results with vertical seismic load

Beltline peak S 91 MPa 10 MPa scale

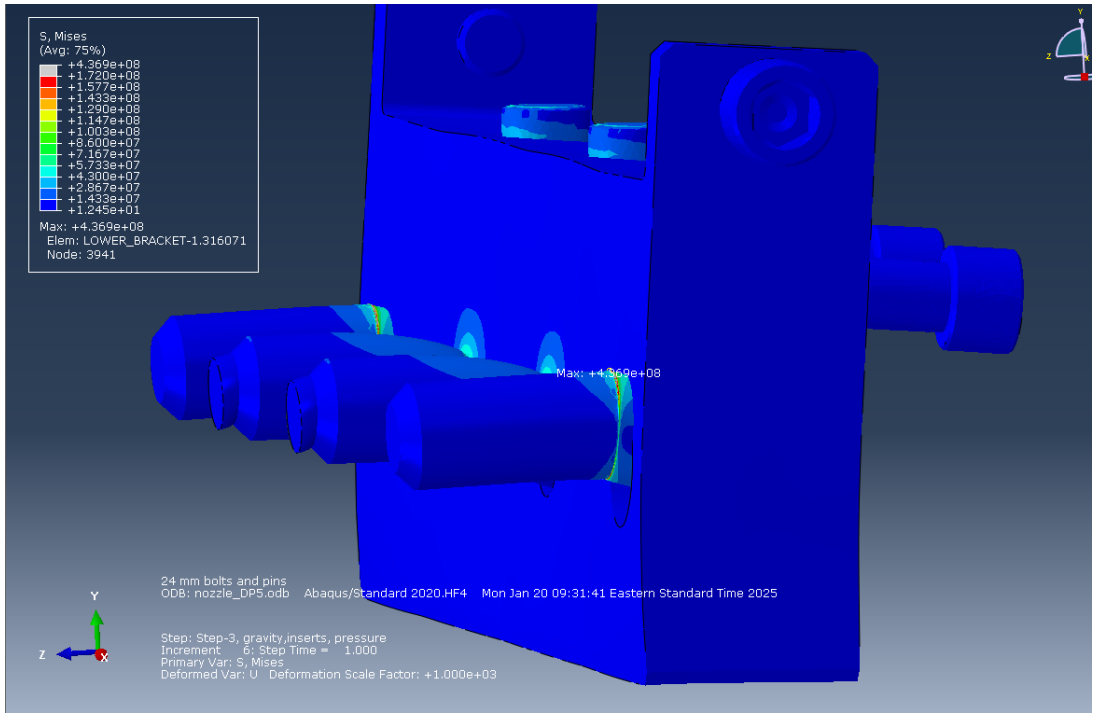


Nozzle peak S 75 MPa 10 MPa scale

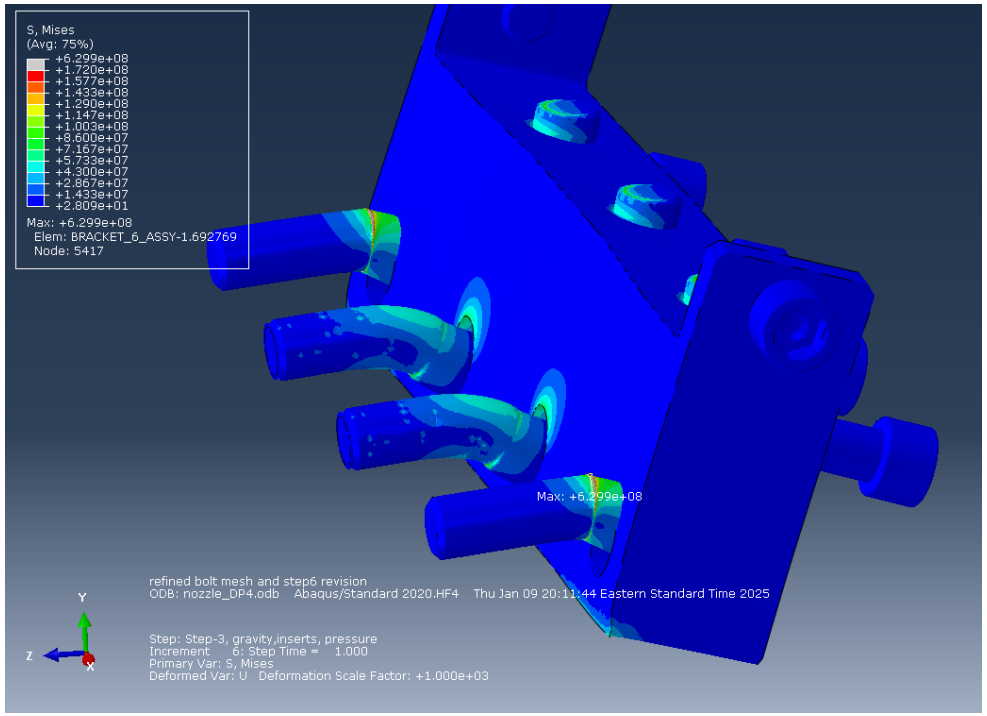


DP4 and DP5 Lower Bracket and pins comparison @ step3 with common Stress scale max of 172 MPa and displacement scale factor of 1000

DP5

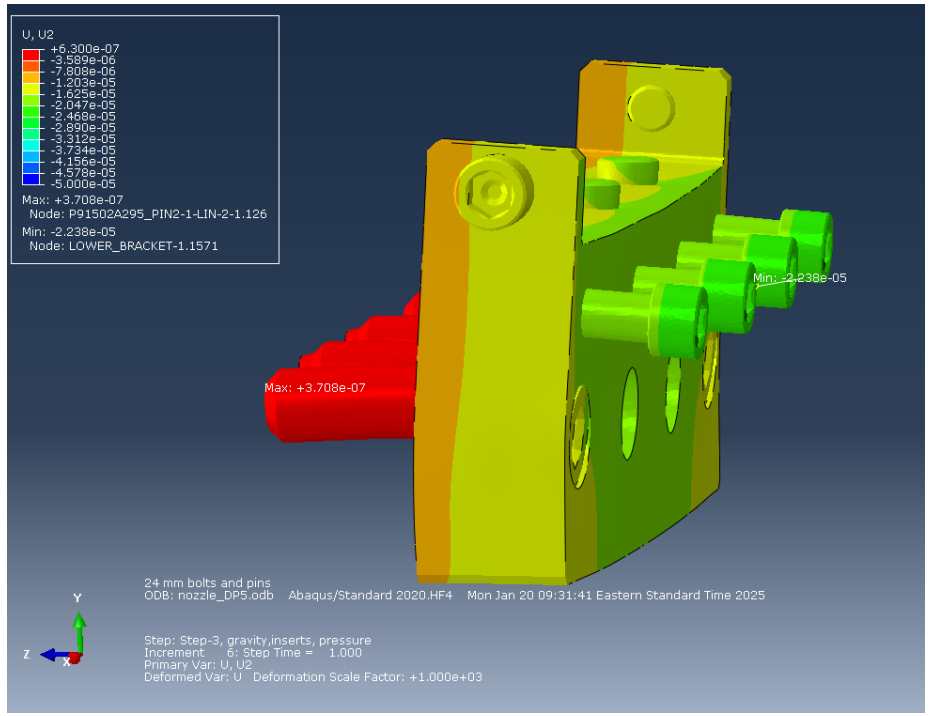


DP4

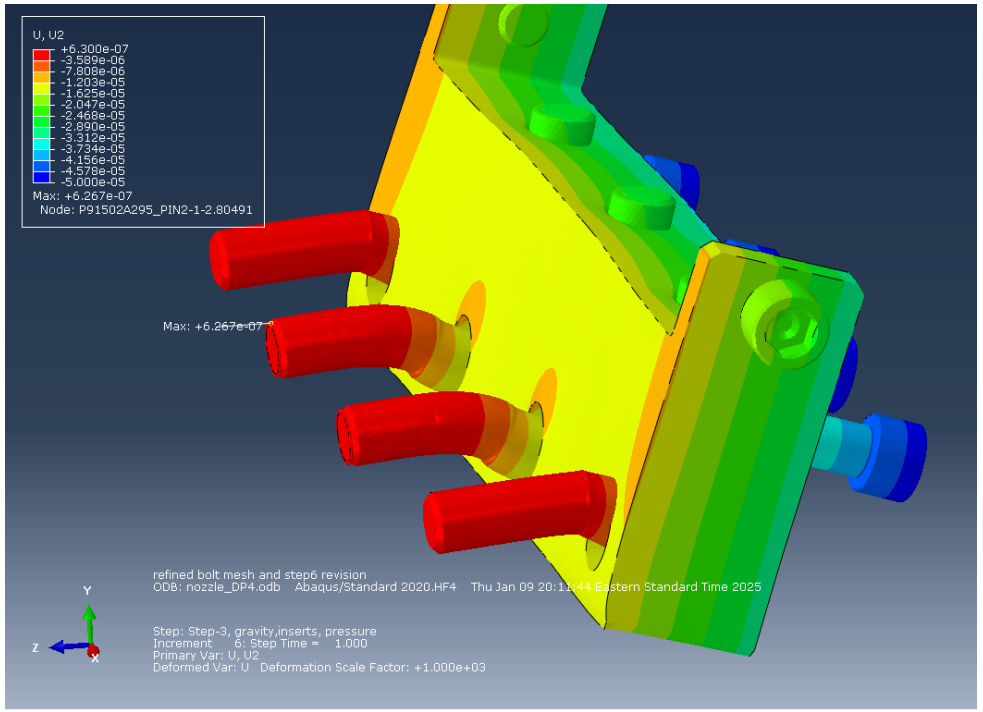


DP4 and DP5 Lower Bracket and pins vertical displacement comparison for step3 with common displacement scale factor of 1000

DP5 24 mm bolts/ pins and 25 mm extended bracket



DP4 20 mm bolts/pins



Summary

- Model DP5 with 24 mm bolts and pins and with the bracket extended 25 mm down showed lower peak stresses and significantly reduced displacements
- Stress linearization for DP5 had a peak Mises membrane plus bending of 77 MPa versus 165 MPa for DP4
- Models do not account for actual stress distribution around threads and displacements with threads, but the axial bolt loads are low (~ 3.52e3 N for one bolt in step 6)
- All other locations besides the bolts had stresses will below 1.5 Sm limit of 172 MPa