Calculation No: NSTXU-CALC-11-16-00 **Revision No:** 0

Title: Calculation of Thermal and Structural FEA: Outboard Divertor Row 5 Tiles and Variants Styles 1 and 2

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

Qualify Outboard Divertor Row 5 Tile and Attachments

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

ANSYS 19.0, 19.1, 19.2

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

1. NSTX-U-RQMT-GRD-001-02, GENERAL REQUIREMENTS DOCUMENT, Stefan, Gerhardt, 2018.
2. NSTX-U-RQMT-RD-003-01, NSTX-U Disruption Analysis Requirements, Stefan, Gerhardt, 2018.
3. NSTXU-CALC-55-03-00, PFCs Fields and dBdts, Art Brooks, October 13, 2017.
4. NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc, I. Zatz, 2016.
5. NSTX-U-RQMT-SRD-003-02, System Requirements Document on Plasma Facing Component, Stefan, Gerhardt, July 2018.
6. PFCR-MEMO-005-00, Impact of faceting on heat flux to the outboard divertor PFCS, M. Reinke, June 2017.

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

Assume that all the OBD345 tiles without cooling underneath should have the repetition period of 40 minutes.

Calculation (Calculation is either documented here or attached)

The transient thermal and structural models with halo and eddy loads have been analyzed to check the design qualification of OBD5 tiles. See the attached report for details.

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

All tiles meet their design requirements.

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

Preparer's printed name, signature and date

Brian C Linn
9/27/18

Brian C Linn

Digitally signed by Brian C Linn
Date: 2018.09.28 13:51:12 -04'00'

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

Checker's printed name, signature, and date

Claire R. Luttrell

Digitally signed by Claire R. Luttrell
Date: 2018.09.28 14:05:10 -04'00'




National Spherical Torus eXperiment - Upgrade

NSTX-U

Calculation of Thermal and Structural FEA: Outboard Divertor Row 5 Tiles and Variants Styles 1 and 2

NSTXU-CALC-11-16-00

September 27, 2018

Brian C Linn
Digitally signed by Brian C Linn
Date: 2018.09.28 13:51:34 -04'00'

Prepared By
Brian C. Linn, Engineering Analyst

Claire R. Luttrell
Digitally signed by Claire R. Luttrell
Date: 2018.09.28 14:05:36 -04'00'

Reviewed By
Claire Luttrell, Title

Michael Jaworski
Digitally signed by Michael Jaworski
Date: 2018.09.28 23:27:04 -04'00'

Approved By – Responsible Engineer
Michael A. Jaworski, Research Physicist

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	9/17/18	Initial Release	

Overview

The purpose of the analysis is to verify the adequacy of the design to meet the minimum heat flux requirements in combination with EM forces from eddy and halo currents without exceeding the T953 graphite stress limits. The allowable stress limits for T953 graphite are half of the ultimate tensile and compressive strength, consistent with the brittle material requirements specified in the NSTX-U Structural Design Criteria (NSTX_CRIT-0001-02B). Vendor provided data gives an ultimate compressive strength of 110MPa for T953. Published values of the UTS of T953 were not available and material testing was performed to establish UTS of 40MPa for T953. Four row 5 tiles will be made from FMI3D, a grade of Carbon-Fiber-Composite (CFC). The material is anisotropic and vendor provided data stated that the ultimate tensile strength and ultimate compressive strength through the material's weakest direction are 139 MPa and 129 MPa, respectively.

The heat flux requirement for OBD tiles is defined in requirements in NSTX-U-RQMT-SRD-003-02 tables 4.4-2 (row 3) and 4.4-3 (rows 4 and 5). Thermal analysis presented here was performed based on the worst-case thermal transient required. Electromagnetic forces analyzed in these analyses were calculated from the NSTX-U Disruption Requirements document, NSTX-U-RQMT-RD-003-00. Halo current forces were implemented as either (1) a force applied to the tile plasma facing surface(s) corresponding to the component-average nodal forces determined by eddy current analysis or (2) as a body-distributed force applied at mesh nodes. The type of EM load defined in each analysis is indicated in each variant subreport.

Similar to previous designs, the OBD3-5 tiles use T-bar supports held by bolts with Belleville washers and with compliant Grafoil underneath. The new design OBD mounting structure incorporates several minor modifications aimed at allowing the tile to more freely expand when thermally loaded and thus minimize internal stresses induced in the tile. All analyses assumed hold-down bolts preloaded to 500lbs (2670N); this reduced preload was specified to permit thermal deformation while still preventing movement of the assembly under disruption electromagnetic loads.

This analysis covers the design qualification of the standard OBD row 5 tiles and mounting shown below. This includes the thermal and structural response from plasma heating during normal operation combined with disruption loading. Variants of each standard cutout accommodating embedded diagnostic sensors were also analyzed. Tables 1 and 2 provide a summary of the peak stresses determined for all variants analyzed in this report. The detailed results for each variant are given in the applicable section of this report.

PPPL Dwg. No.	Description	Max Temp	Max S1 MPa	Min S3 MPa	Comments
E-ED1406-1	R5 style 1 base tile	549C [1]	6.9	-23.4 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1406-2	Mirnov	555C [1]	6.3	-24.6 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1406-3	Thermocouple	544C [1]	7.5	-24.4 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1406-8	Langmuir Probe (2x)	532C [1]	11.4	-23.2 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1406-9	X-Ray Spectrometer	457C [1]	6.2	-21.1	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. HF Scaling not applied to S3 reported, as the peak S3 occurred in the tbar slot and is not heat flux driven.
E-ED1406-10	PCHERS Lower Bay Ramped Tile	442C [1]	9.2	-25.3	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. HF Scaling not applied to S3 reported, as the peak S3 occurred in the tbar slot and is not heat flux driven.
E-ED1406-11	PCHERS Lower Bay Chamfered Tile	455C [1]	9.6	-48	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. HF Scaling not applied to S3 reported, as the peak S3 occurred in the tbar slot and is not heat flux driven.

Table 1 – Summary of analysis results for OBD Row 5 Style 1 tiles. The allowables for tiles made from T953 Graphite are S1=20MPa, S3=-55MPa:

PPPL Dwg. No.	Description	Max Temp	Max S1 MPa	Min S3 MPa	Comments
E-ED1407-1	R5 style 2 base tile	515C [1]	7.4	-23.7 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1407-3	Thermocouple	N/A	N/A	N/A	This variant need not be analyzed because the cutout for this diagnostic can be considered qualified by the analysis of its implementation in the Row 3 Style 1 and Row 5 Style 1 tiles. See calculation report NSTXU-11-14-00 and the section in this calculation for tile E-ED1406-3
E-ED1407-5	Langmuir Probe (2x)	531C [1]	13.3	-21.4 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1407-6	Diagnostic Gap - Ramp	697C [1]	8.1	-37.2 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1407-8	X-Ray Spectrometer	505C [1]	10.6	-23.2 [1,2]	[1]Acceptable at SRD Rev1 heating; result scaled down for SRD Rev 2 heating. [2]Heat flux driven surface stress
E-ED1407-9	Diagnostic Gap - Chamfer	1194C	20	-56.9	*This tile will be made from FMI3D (CFC). Temperature reported here is a scaled value based on a T953 tile analysis performed. For justification of scaling factors used, see the subreport given for R4 tile variant E-ED1405-10 of Calculation Report NSTXU-CALC-11-15-00. A structural analysis was not performed; this tile is considered qualified by analysis of E-ED-1405-11.
E-ED1407-10	PCHERS Upper Bay Chamfer Tile	842C	20.8	-29.5	*This tile will be made from FMI3D (CFC). Results shown here are scaled values based on the T953 tile analysis performed. For justification of scaling factors used, see the subreport given for R4 tile variant E-ED1405-10 of Calculation Report NSTXU-CALC-11-15-00.
E-ED1407-11	Island Tiles, Lower Bay B/C and F/G	1159C	61.8	-56.5	*This tile will be made from FMI3D (CFC). Results shown here are scaled values based on the T953 tile analysis performed. For justification of scaling factors used, see the subreport given for R4 tile variant E-ED1405-10 of Calculation Report NSTXU-CALC-11-15-00.

Table 2 – Summary of analysis results for OBD Row 5 Style 2 tiles. All tiles made from T953 graphite unless otherwise indicated. T953 graphite allowables are S1=20MPa, S3=-55MPa. Tiles indicated as being made from CFC (FMI3D) have allowables S1=69.5 MPa, S3=-64.5 MPa.

Contents

1 Subreport E-ED1406-1, R5 Style 1 Base Tile

OBD345 R5, S1 Round 1
Base Tile / Teebar Analysis

PPPL NSTX-U PFCs

Eliott Fountain
May 17, 2018

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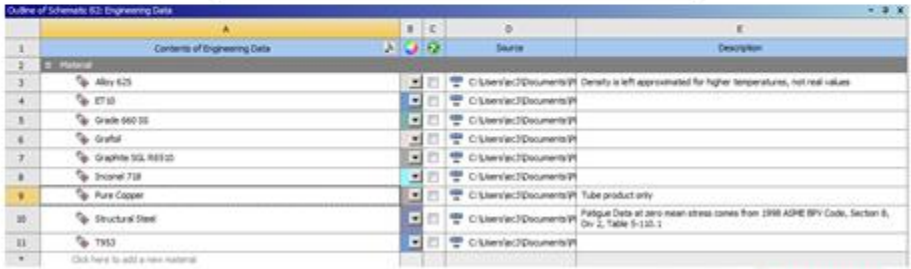
Project Schematic / Engineering Data



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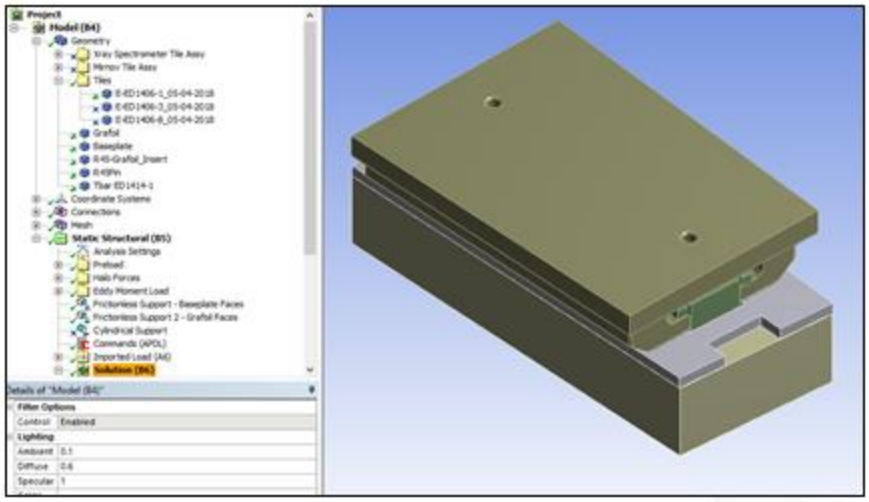

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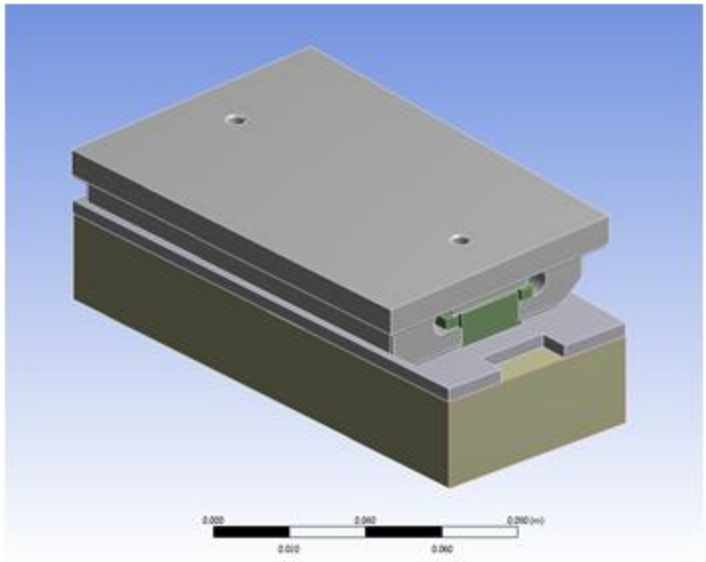
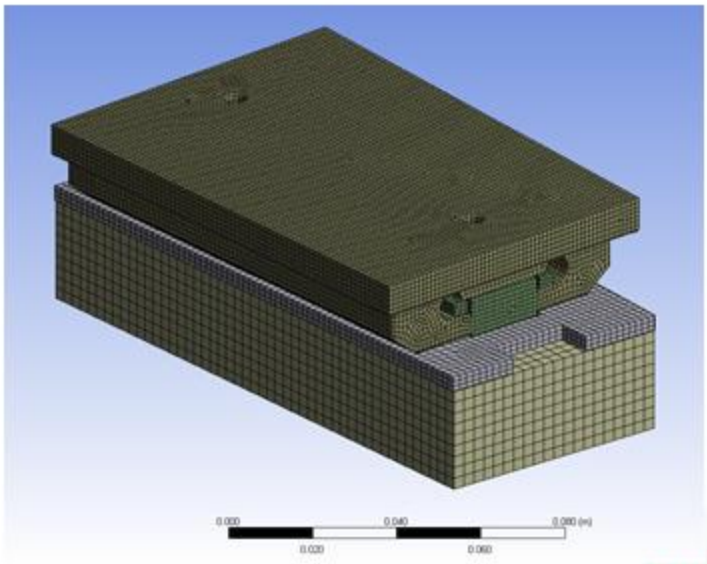


Mesh 556k Nodes, Hex Dominant



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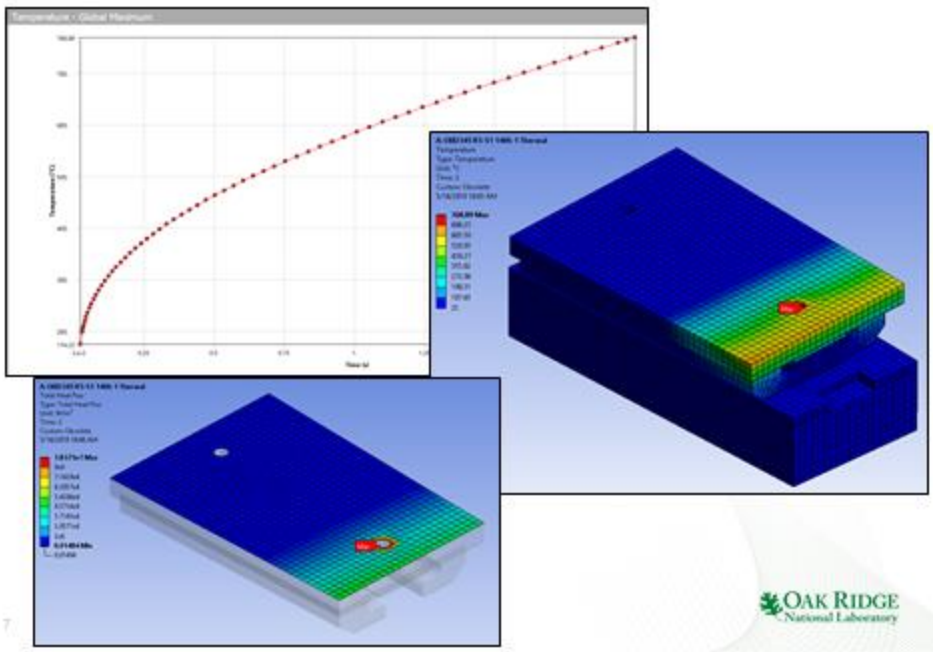
Thermal Results



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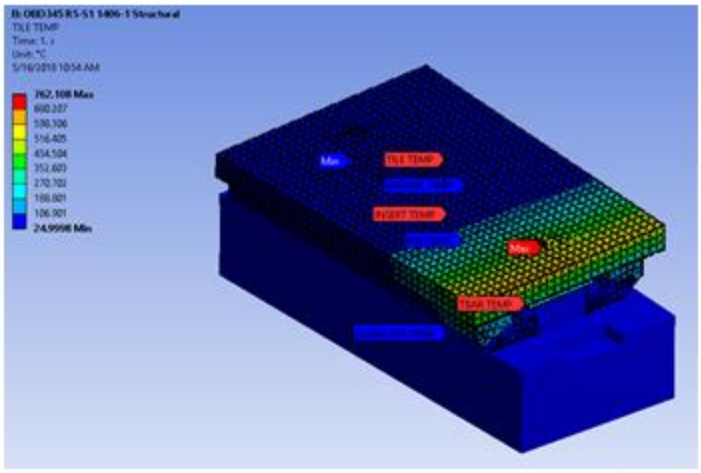
Mapped Temperature Loads



Max. Temperature: 762.1 °C

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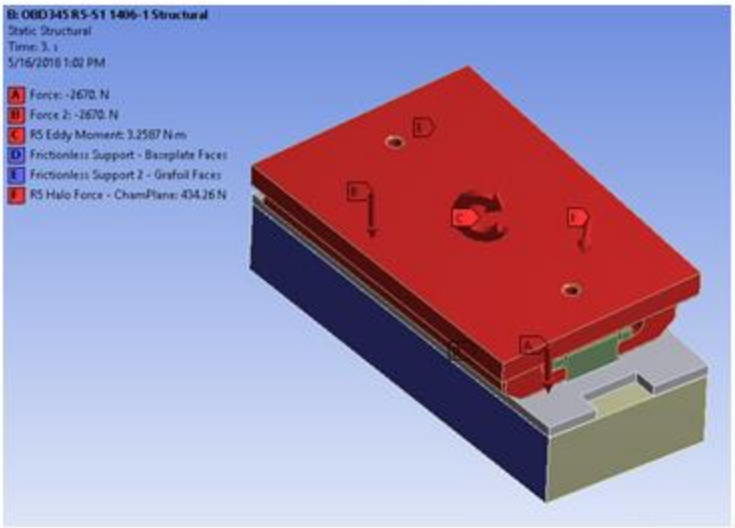
Mechanical Loads, step 3, t=3.0s



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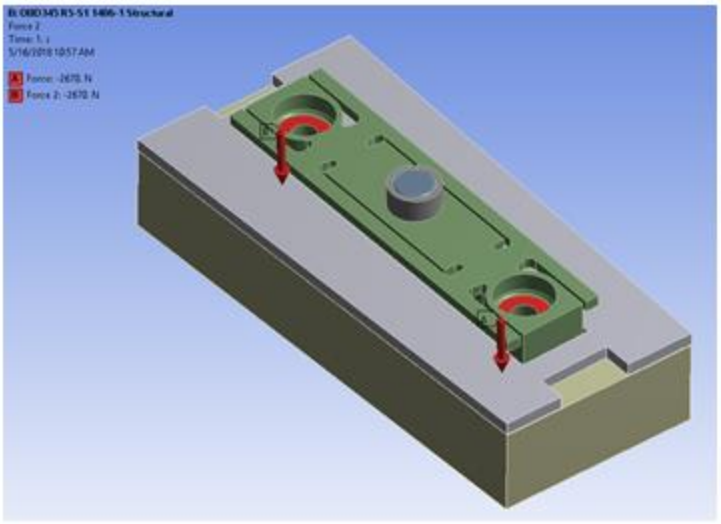
Preload Forces



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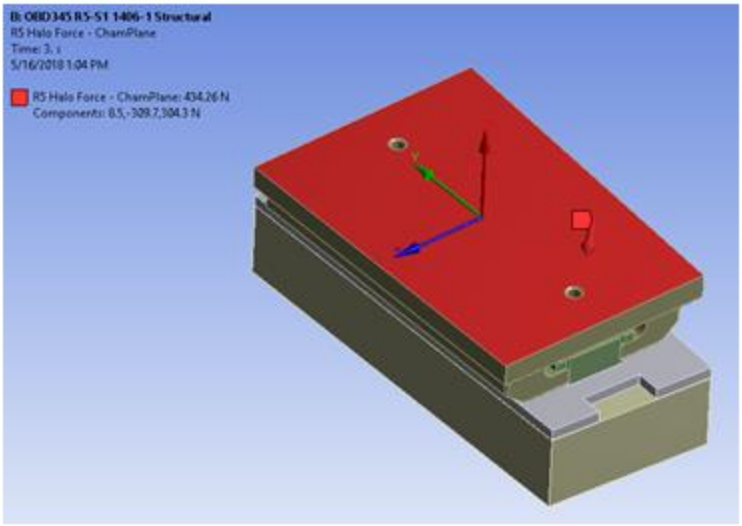

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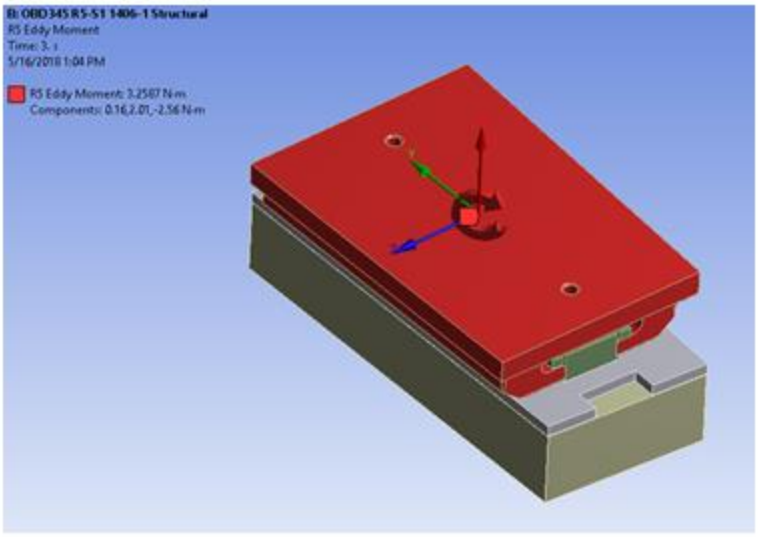

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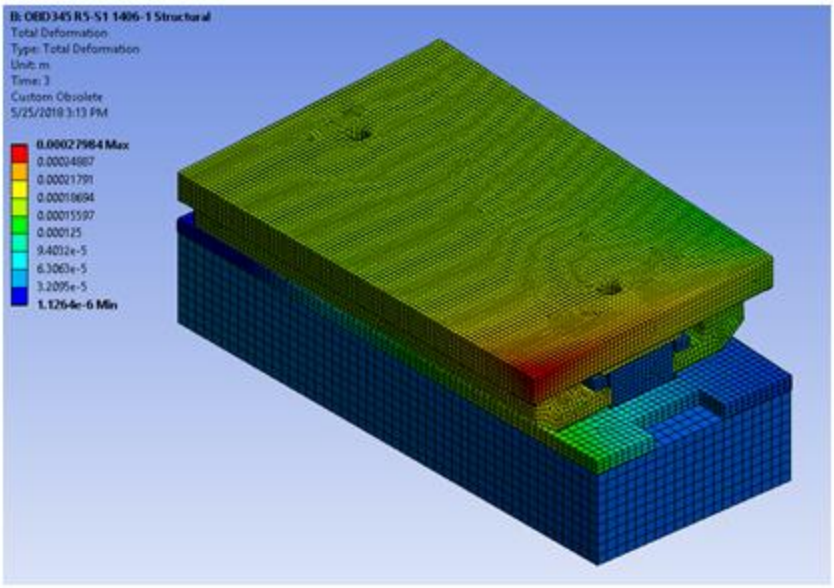
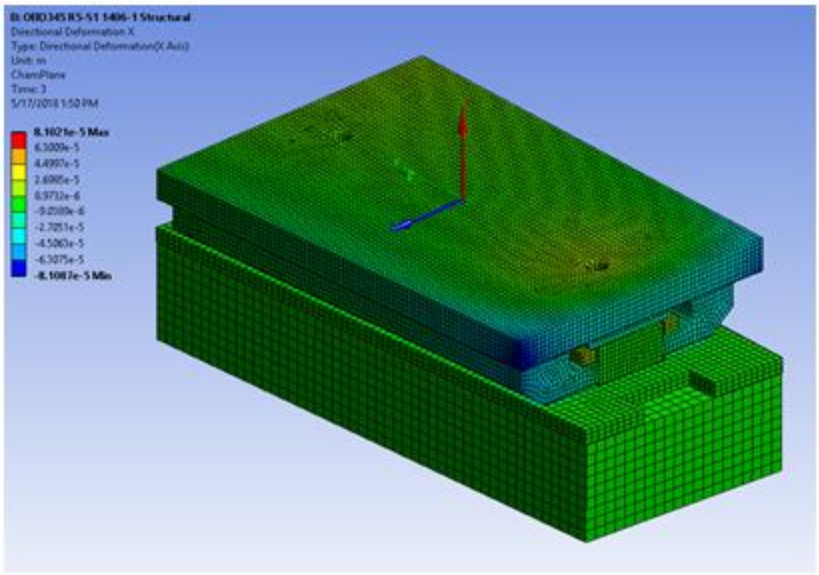
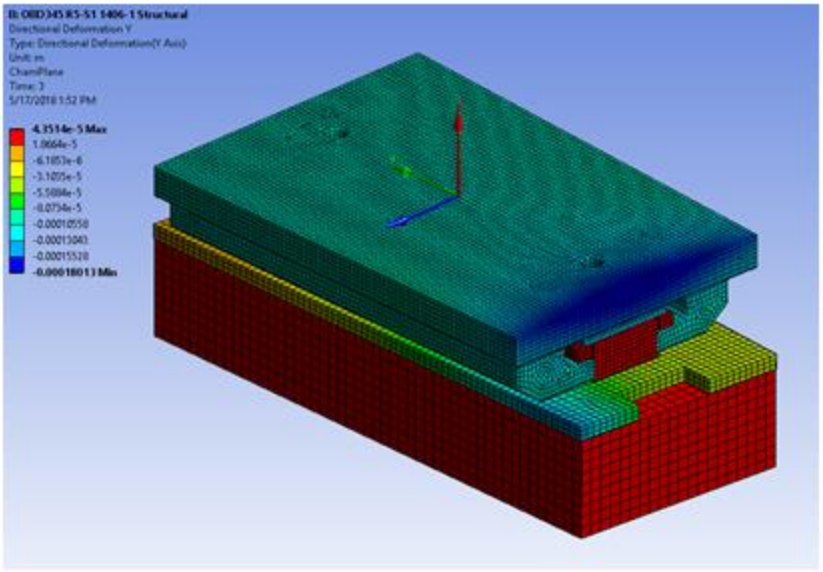


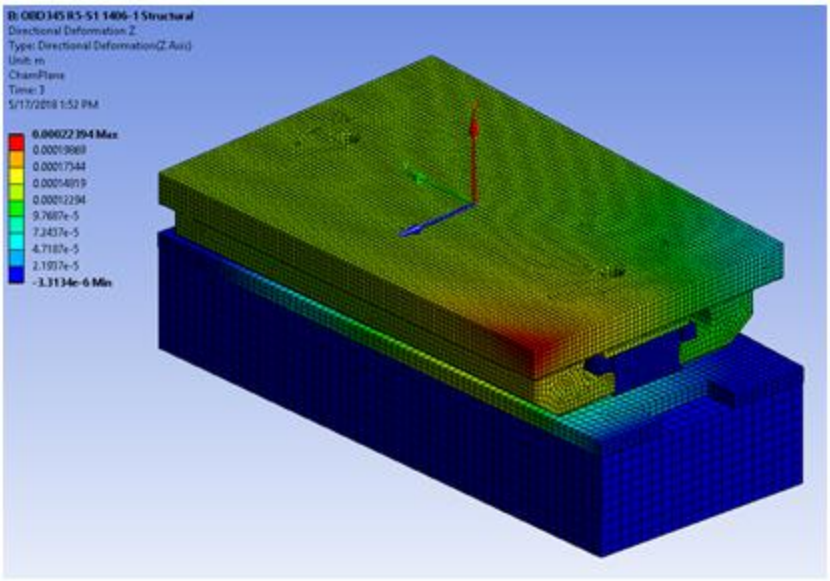
X-deformation from ChamPlane Origin



Y-deformation from ChamPlane Origin



Z-deformation from ChamPlane Origin



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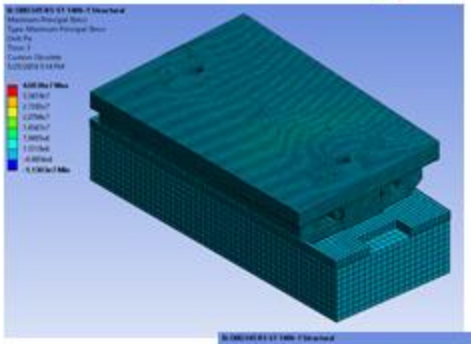

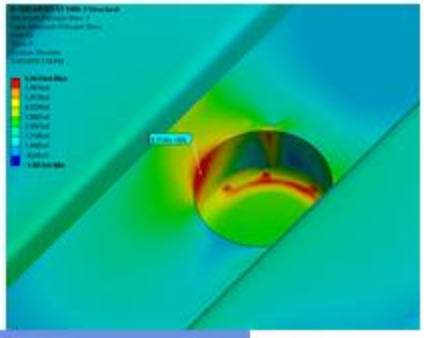

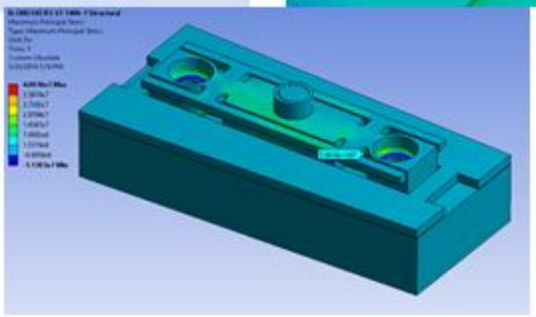

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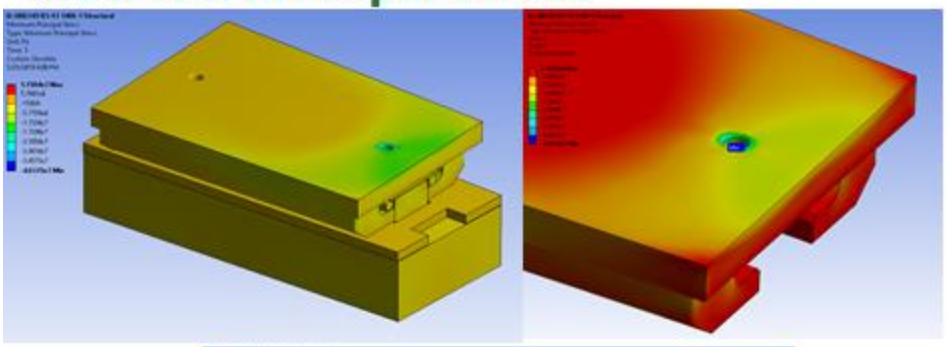
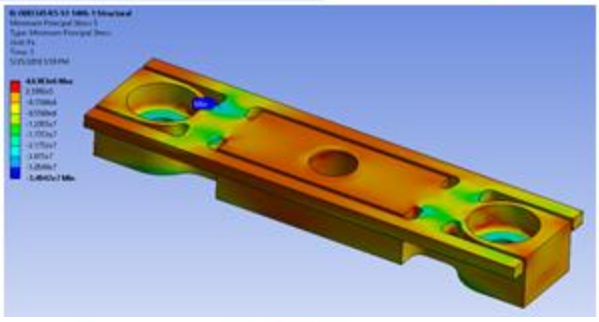
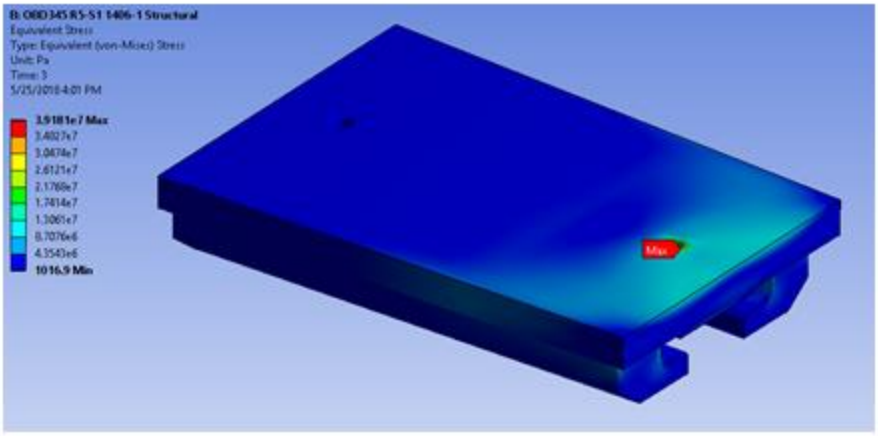
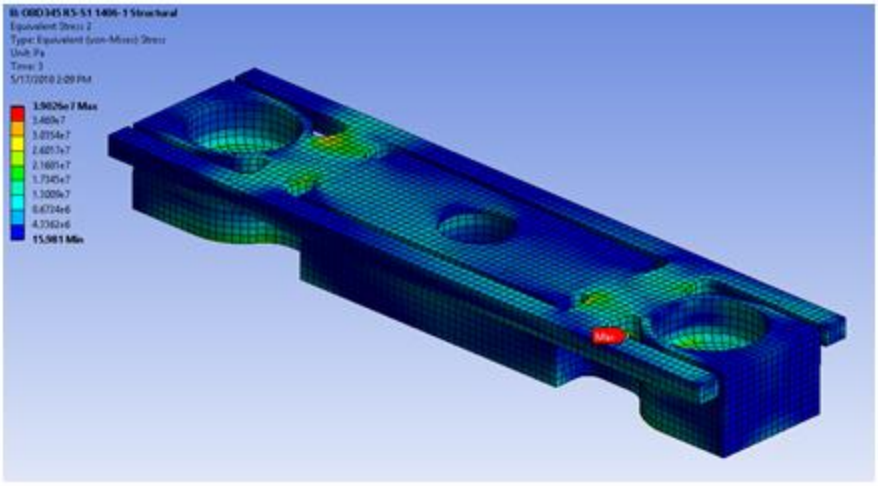




Von Mises Stress in Tile



Von Mises Stress in TeeBar



Summary

- Tile

  S1 Allowable: 20 MPa
  S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 MPa

  Maximum Principal Stress: 6.96 MPa
  Minimum Principal Stress: -40.3 MPa

  Therefore, **SF ~ 1.36**

- Teebar

  $1/3\sigma_{UTS}$ In625 = 261 MPa

  Maximum von Mises Stress: 39.0 MPa

  Therefore, **SF ~ 6.7**

2 Subreport E-ED1406-2 R5 Style 1 Mirnov Variant

OBD345 R5, S1 Round 1
E-ED1406-2 Tile Analysis

PPPL NSTX-U PFCs

Eliott Fountain
June 6, 2018

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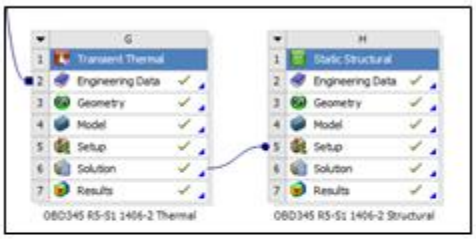
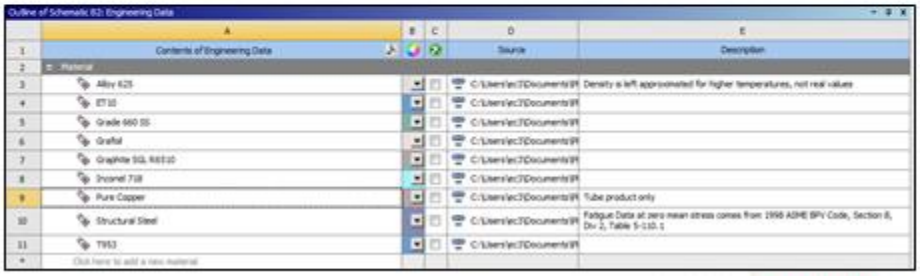
Project Schematic / Engineering Data





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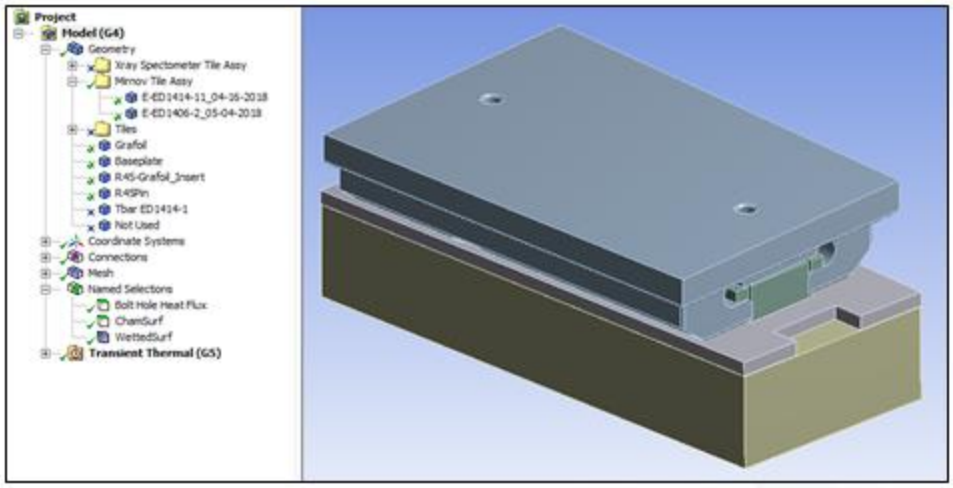
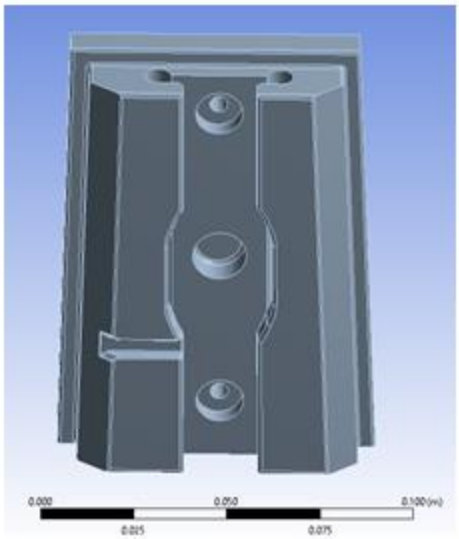
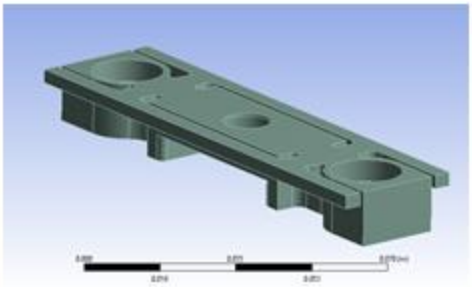
Components

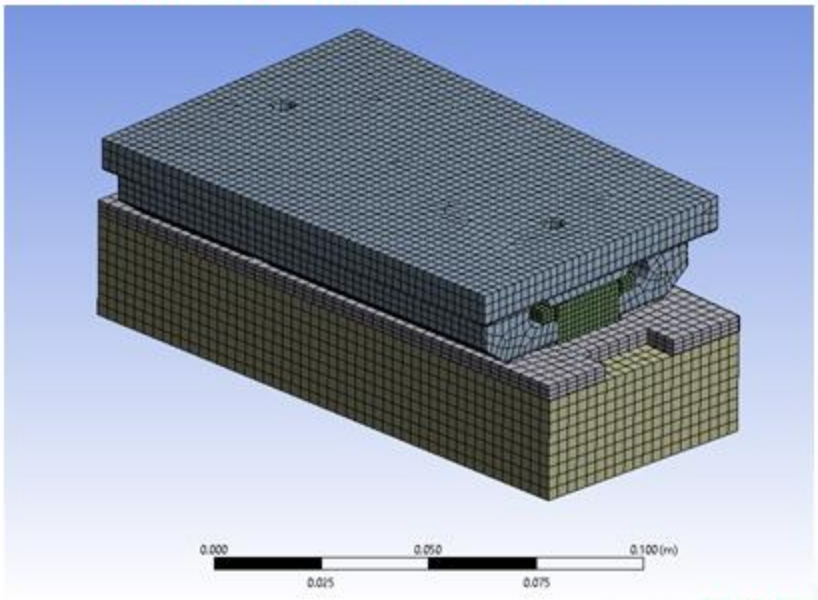


Base Tile / Teebar Geometry





Mesh 233k Nodes, Hex Dominant



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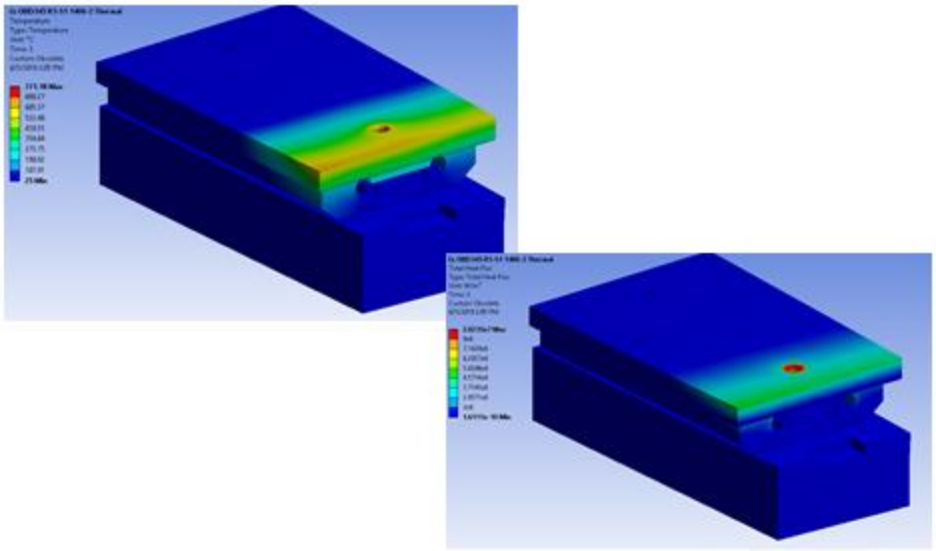
Thermal Results



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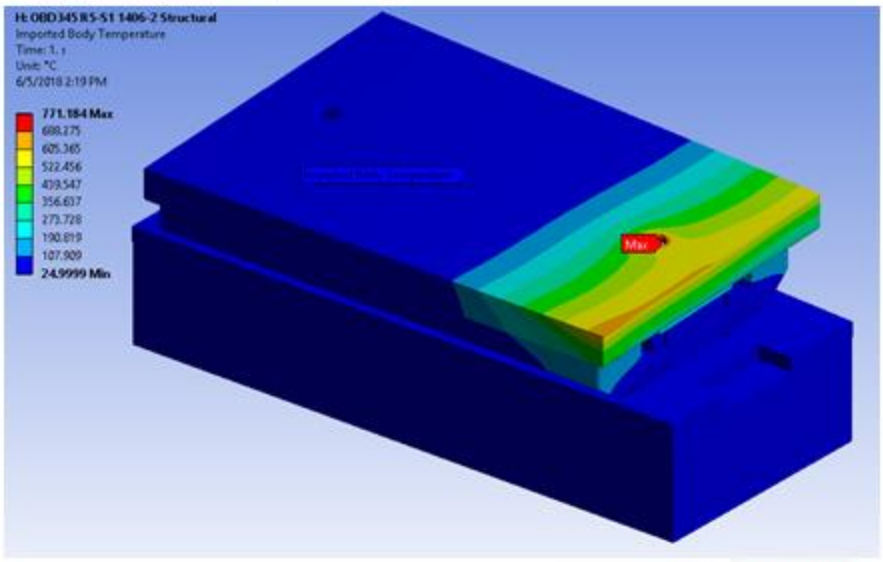
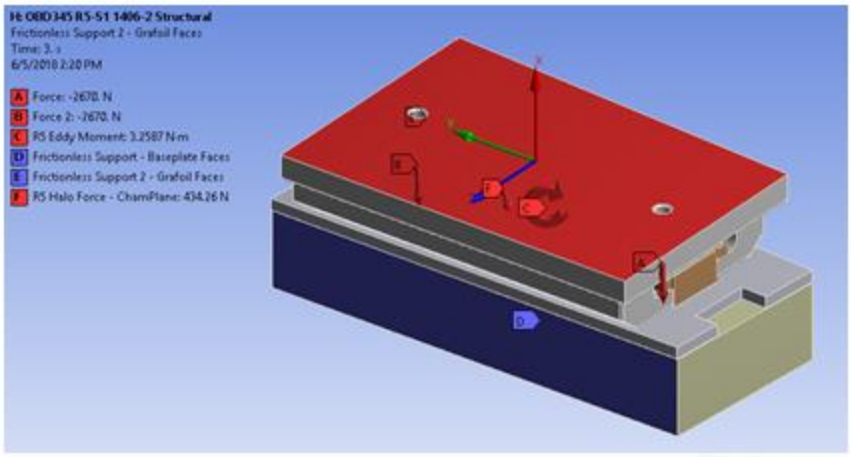
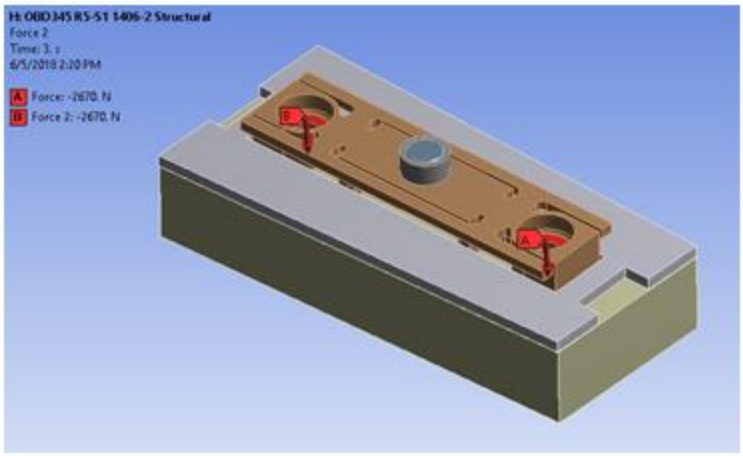
Mapped Temperature Loads



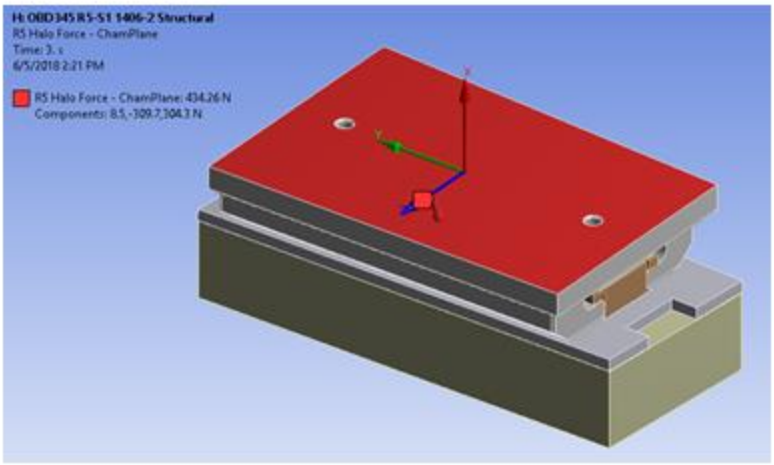
Mechanical Loads, step 3, t=3.0s



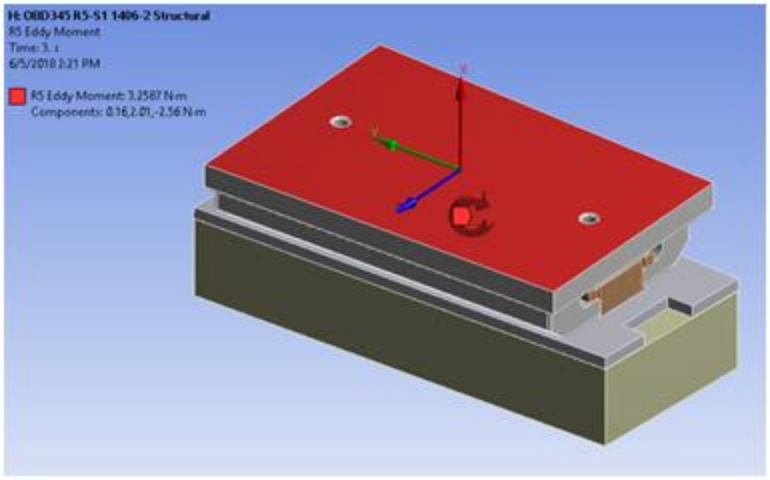
Preload Forces



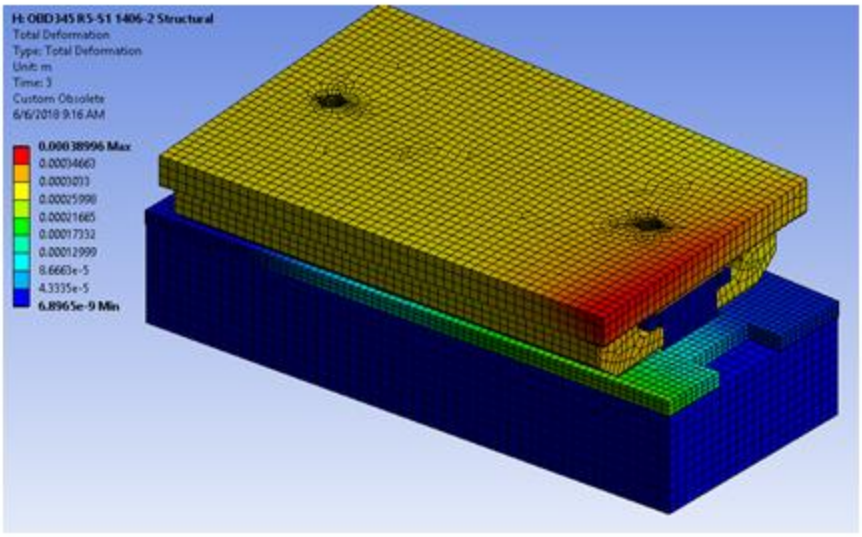
Halo Forces



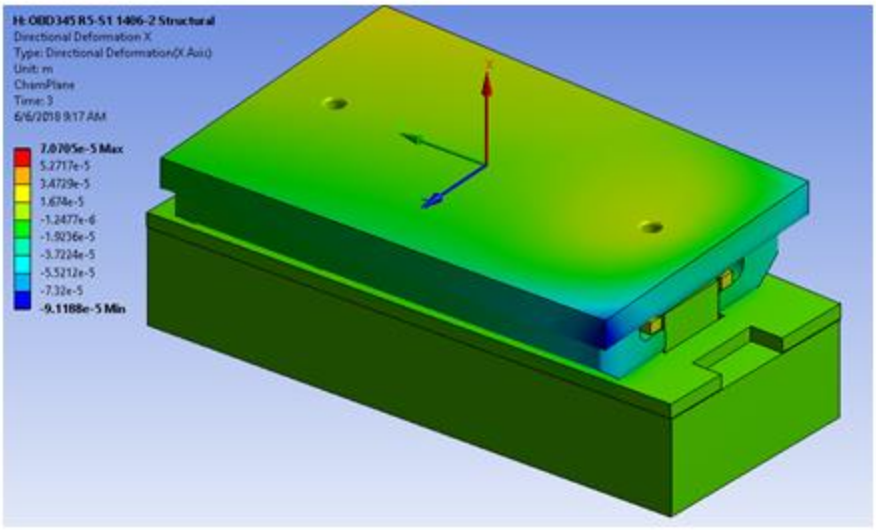
Eddy Moment



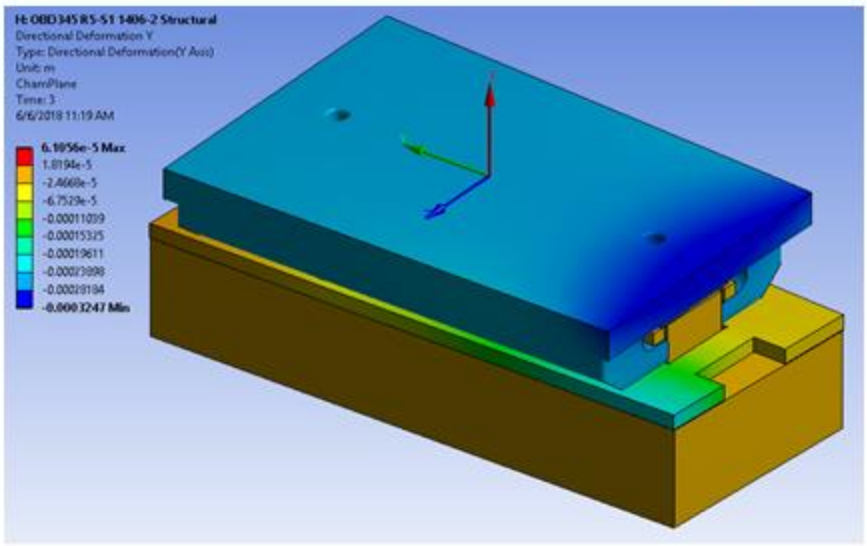
Total Deformation



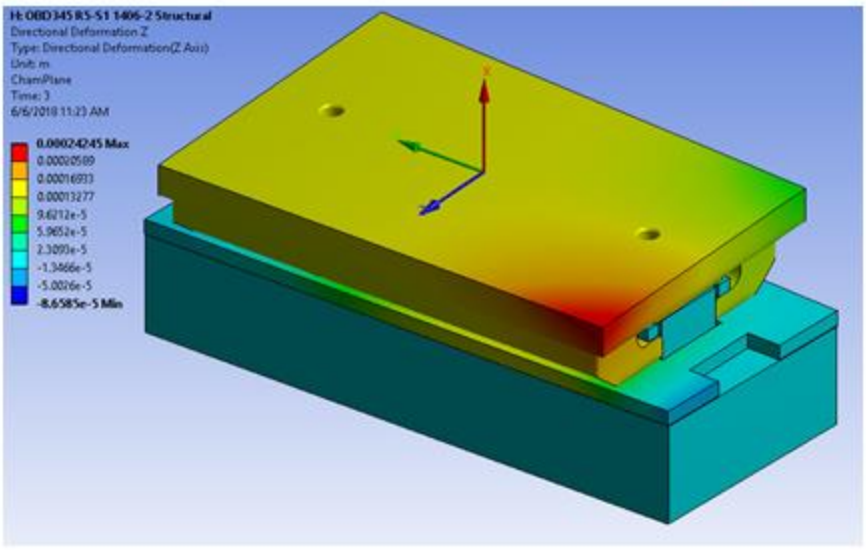
X-deformation from ChamPlane Origin



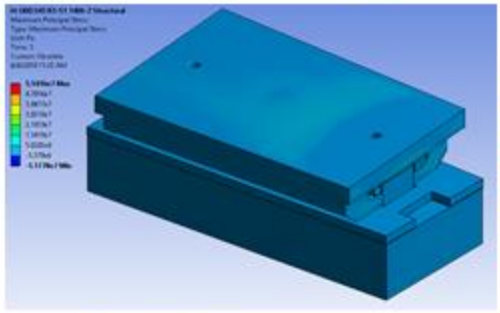
Y-deformation from ChamPlane Origin

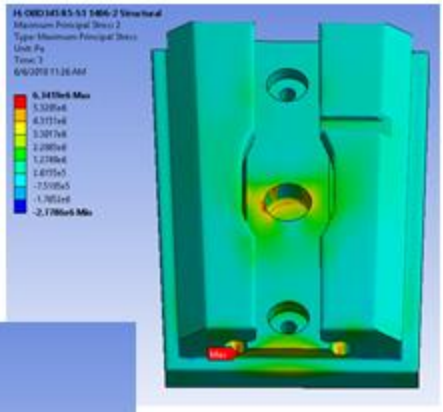


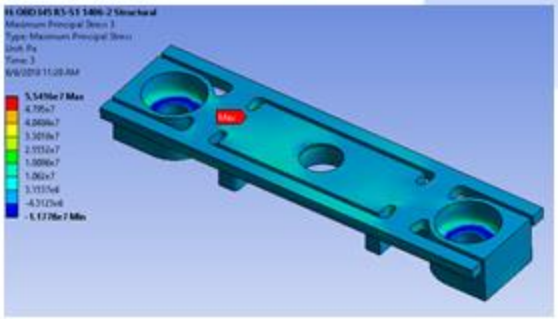
Z-deformation from ChamPlane Origin



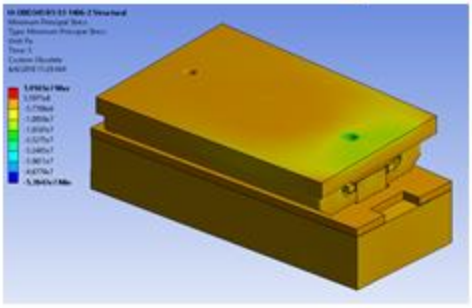
Maximum Principal Stress

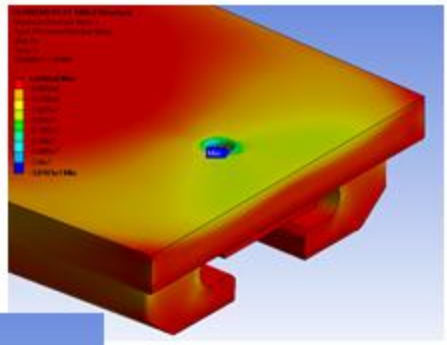


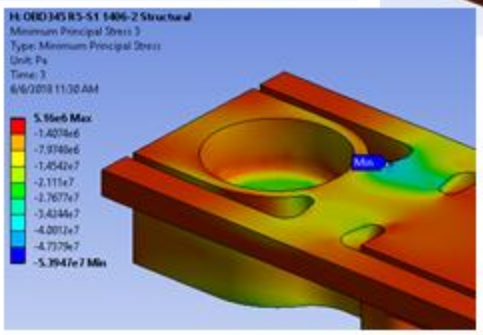




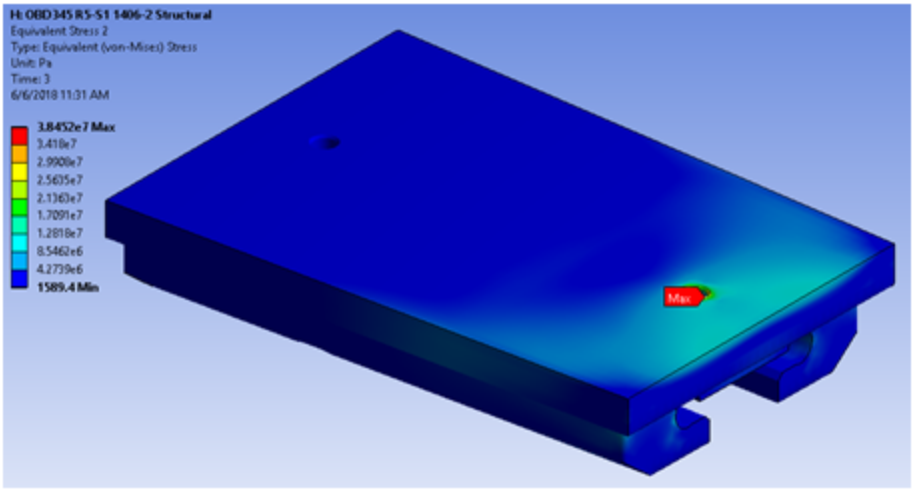
Minimum Principal Stress



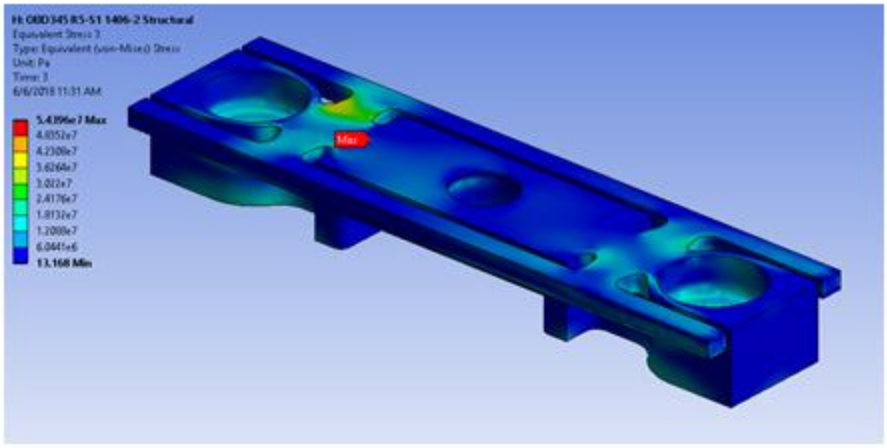




Von Mises Stress in Tile



Von Mises Stress in TBar



Summary

- Mirnov Tile E-ED1406-2

  S1 Allowable: 20 MPa
  S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 MPa

  Maximum Principal Stress: 6.34 MPa
  Minimum Principal Stress: -39.1 MPa

  Therefore, **SF ~ 1.4**

- Tbar

  $1/3\sigma_{UTS}$ In625 = 261 MPa

  Maximum von Mises Stress: 54.4 MPa

  Therefore, **SF ~ 4.8**

3 Subreport E-ED1406-3 R5 Style 1 Thermocouple Variant

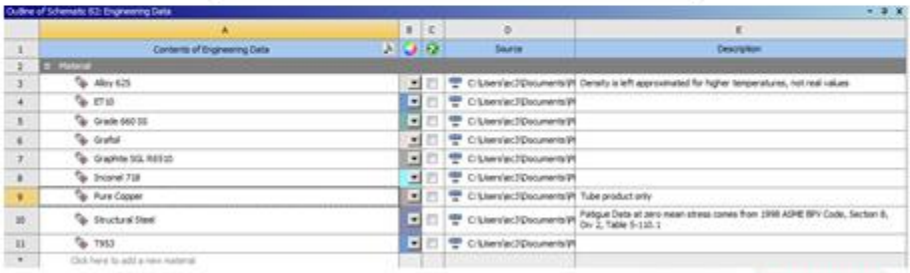
OBD345 R5, S1 Round 1
E-ED1406-3 Tile Analysis

PPPL NSTX-U PFCs

Eliott Fountain
May 25, 2018

OAK RIDGE National Laboratory

Project Schematic / Engineering Data



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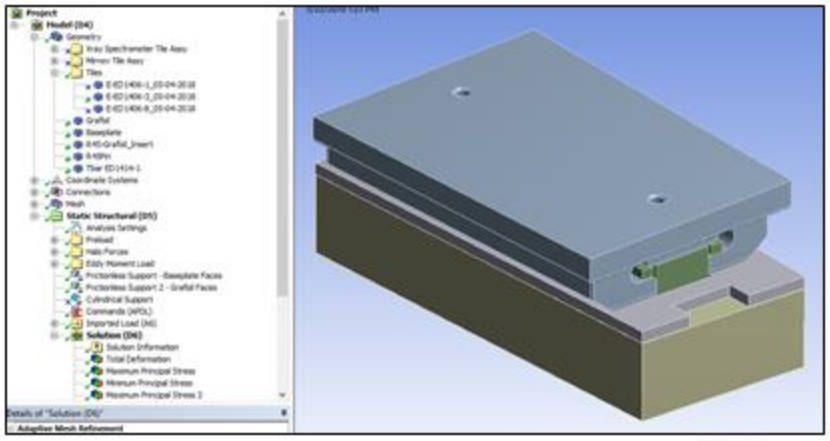
Components



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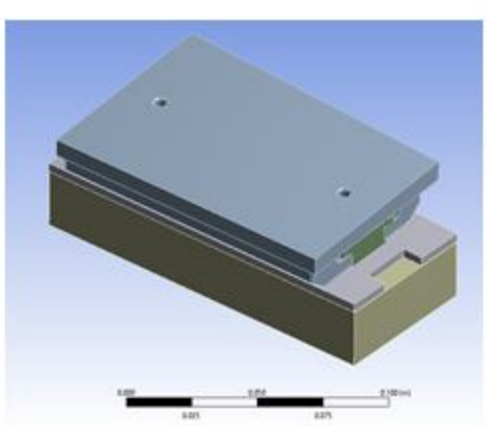
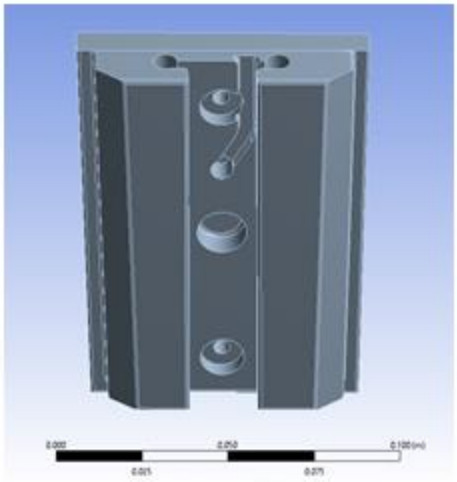
Base Tile Geometry





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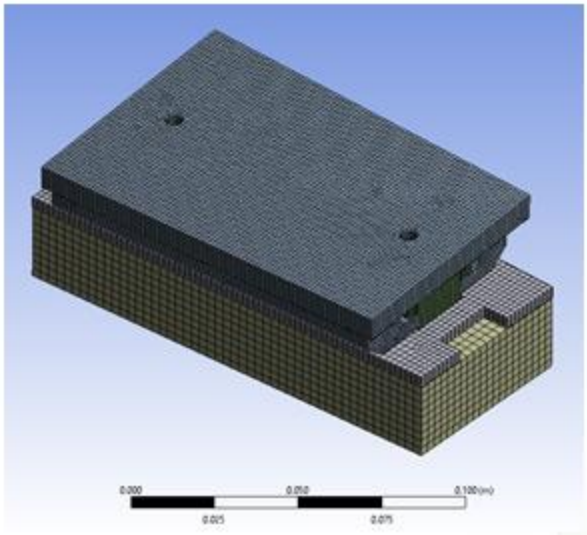
Mesh 596k Nodes, Hex Dominant



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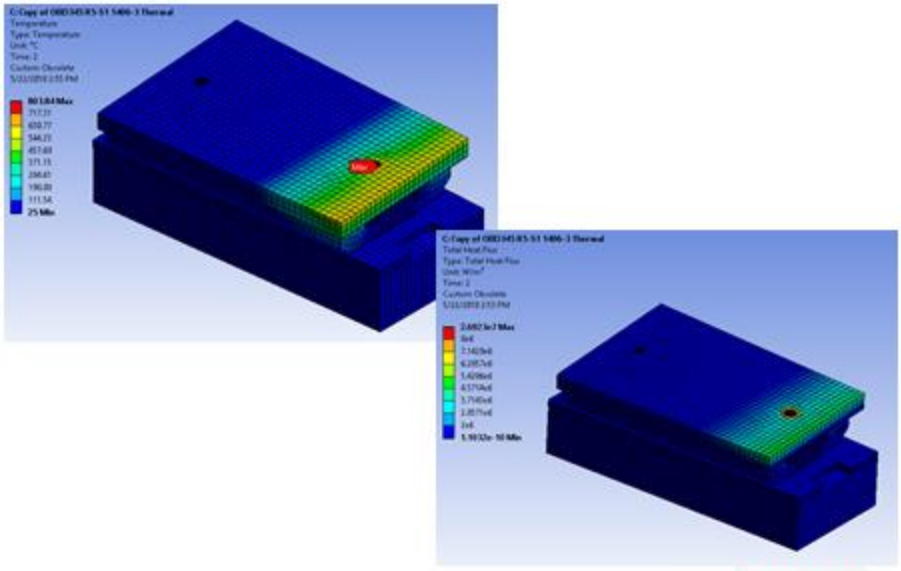
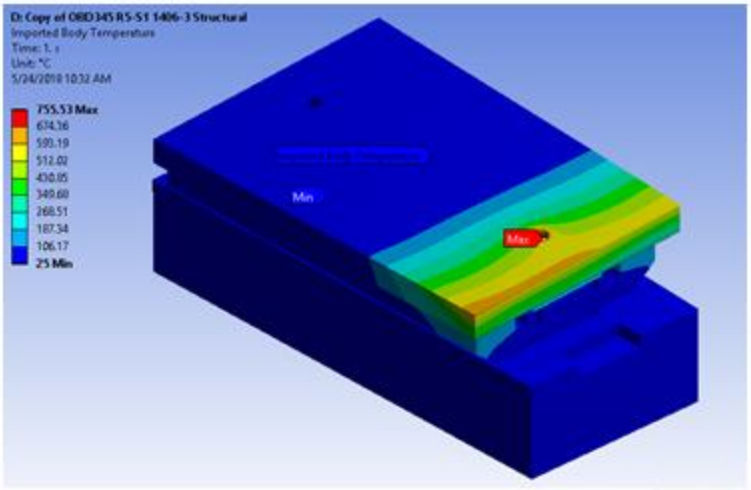
Thermal Results



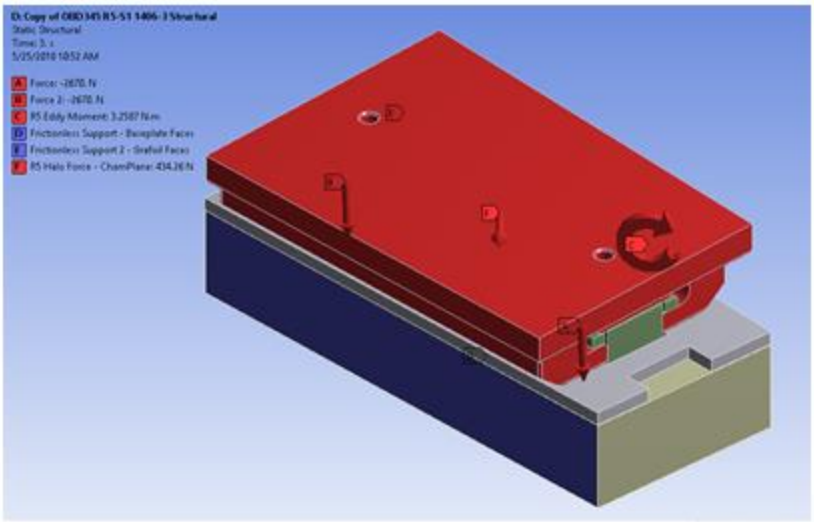
OAK RIDGE National Laboratory

Mapped Temperature Loads



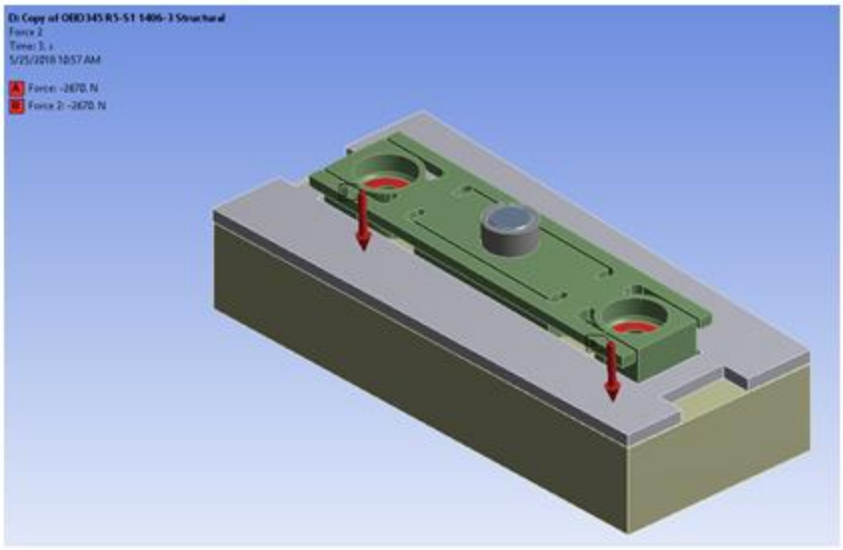
OAK RIDGE National Laboratory

Mechanical Loads, step 3, t=3.0s

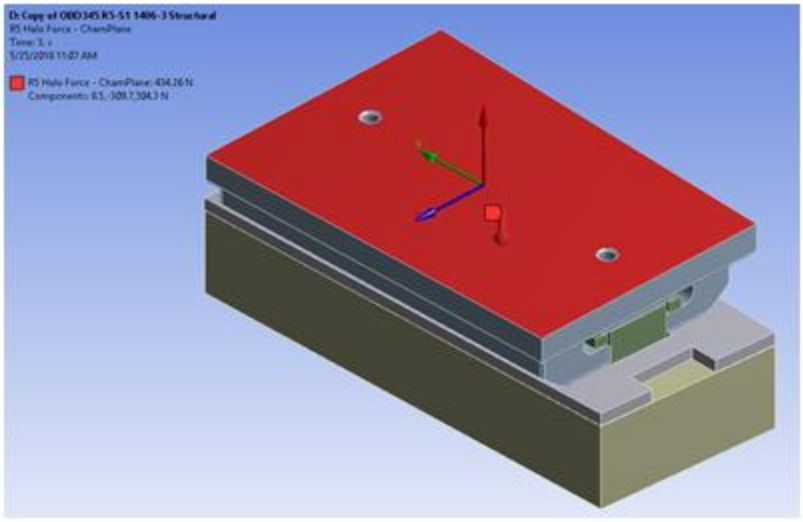


OAK RIDGE National Laboratory

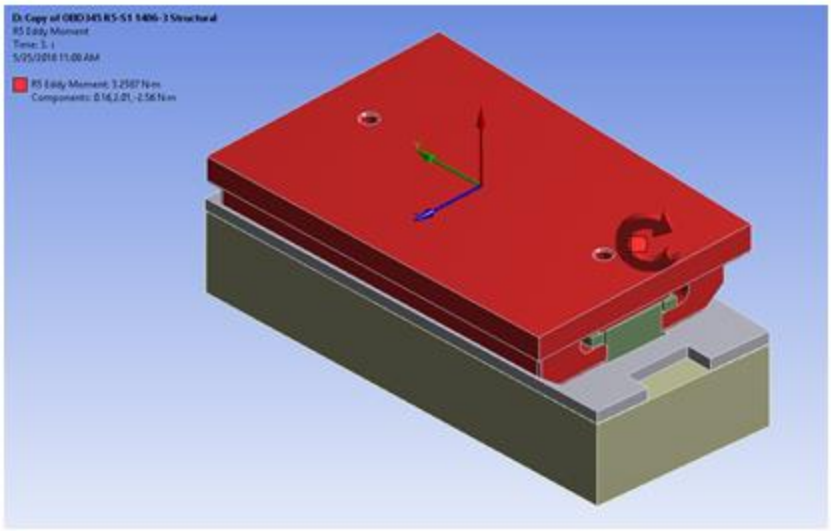
Preload Forces



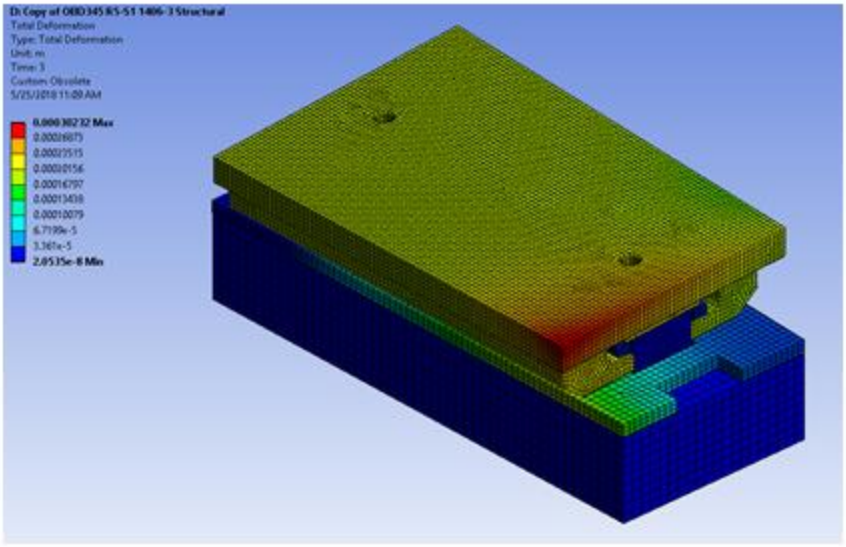
Halo Forces



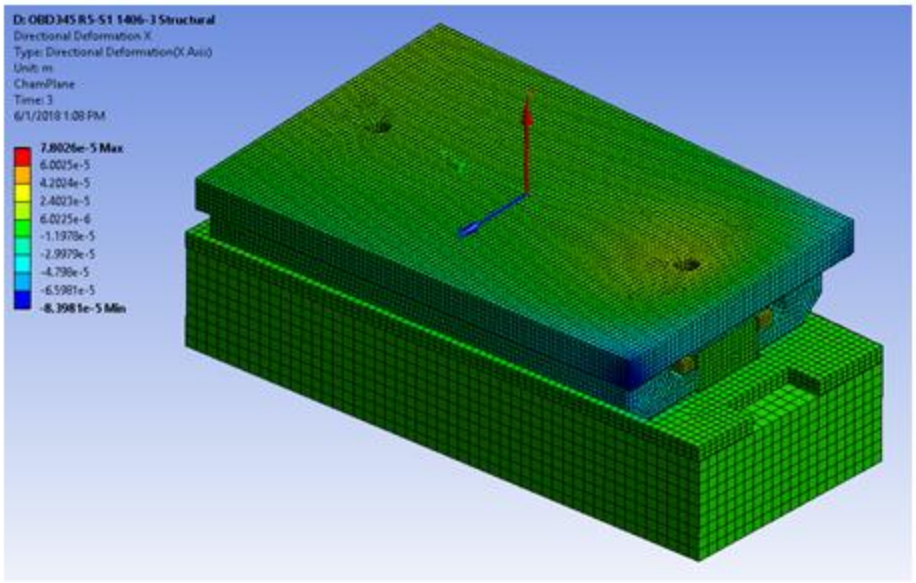
Eddy Moment



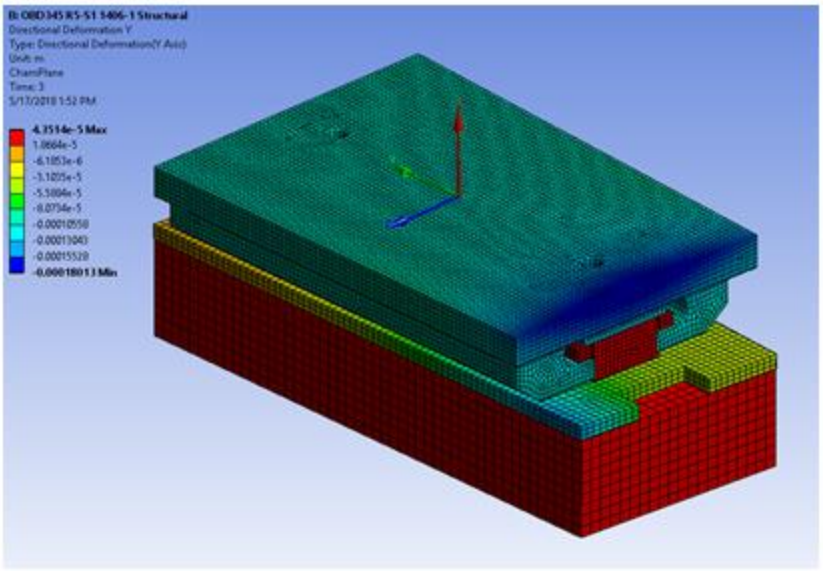
Total Deformation



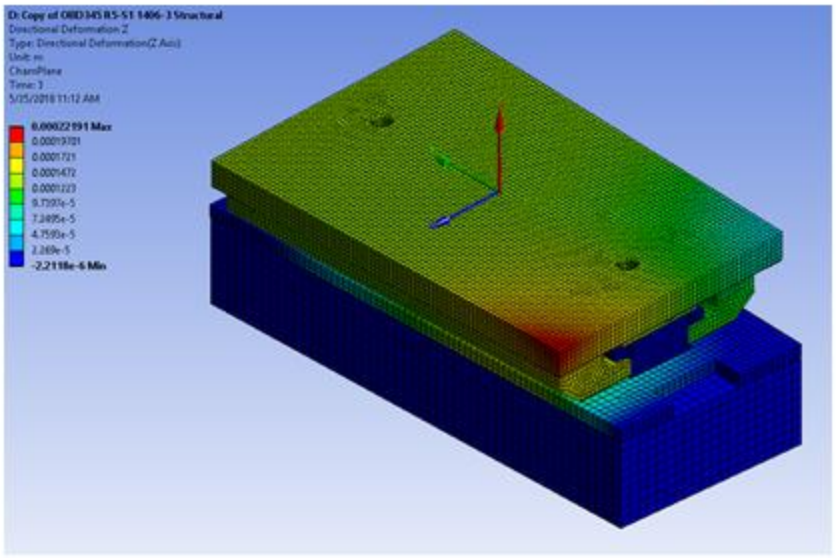
X-deformation from ChamPlane Origin



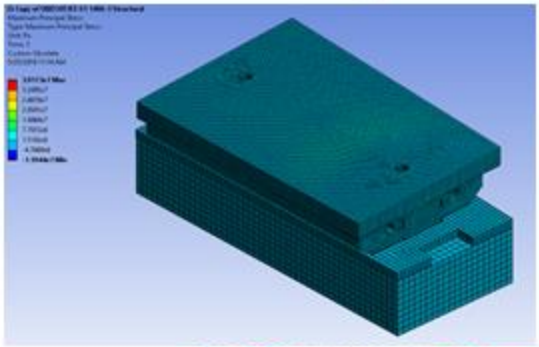
Y-deformation from ChamPlane Origin

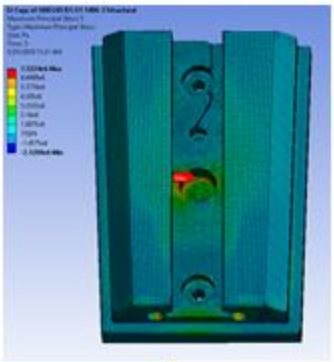


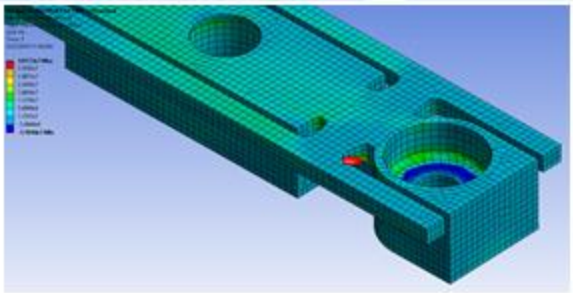
Z-deformation from ChamPlane Origin



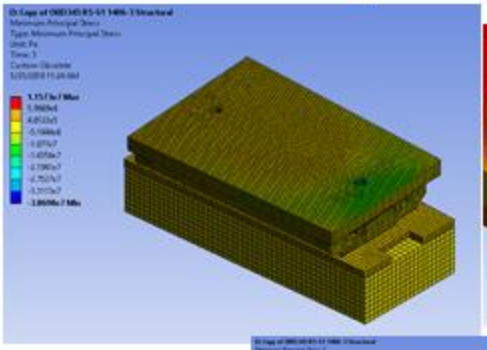
Maximum Principal Stress

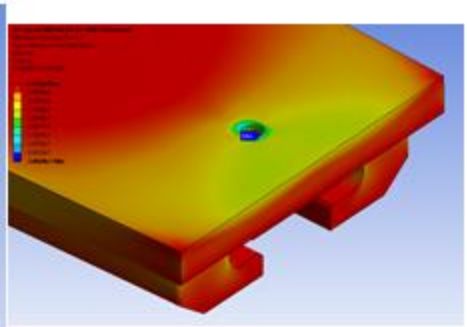


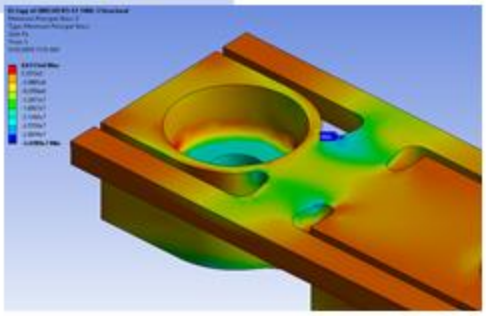




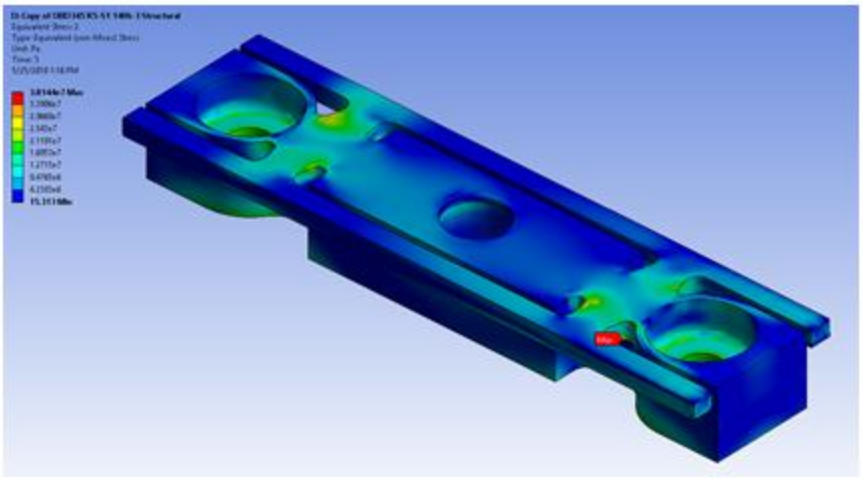
Minimum Principal Stress







Von Mises Stress in TBar



Summary

- Tile

  S1 Allowable: 20 MPa
  S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 MPa

  Maximum Principal Stress: 7.52 MPa
  Minimum Principal Stress: -38.7 MPa

  Therefore, **SF ~ 1.4**

- Tbar

  $1/3\sigma_{UTS}$ In625 = 261 MPa

  Maximum von Mises Stress: 38.1 MPa

  Therefore, **SF ~ 6.8**

4 Subreport E-ED1406-8 R5 Style 1 Langmuir Probe Variant

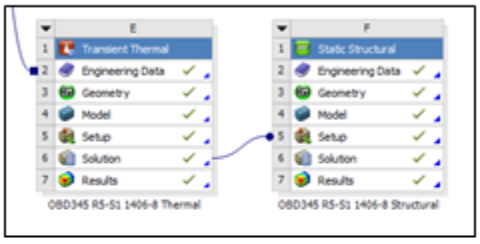
OBD345 R5, S1 Round 1 E-ED1406-8 Analysis

PPPL NSTX-U PFCs

Eliott Fountain
June 1, 2018

OAK RIDGE National Laboratory

Project Schematic / Engineering Data



Outline of Schematic B2: Engineering Data

	A: Contents of Engineering Data	B	C	D: Source	E: Description
2	Material				
3	Alloy 625			C:\Users\ec3\Documents\PI	Density is left approximated for higher temperatures, not real values
4	ET10			C:\Users\ec3\Documents\PI	
5	Grade 660 SS			C:\Users\ec3\Documents\PI	
6	Grafoil			C:\Users\ec3\Documents\PI	
7	Graphite SGL R6510			C:\Users\ec3\Documents\PI	
8	Inconel 718			C:\Users\ec3\Documents\PI	
9	Pure Copper			C:\Users\ec3\Documents\PI	Tube product only
10	Structural Steel			C:\Users\ec3\Documents\PI	Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
11	T953			C:\Users\ec3\Documents\PI	
*	Click here to add a new material				

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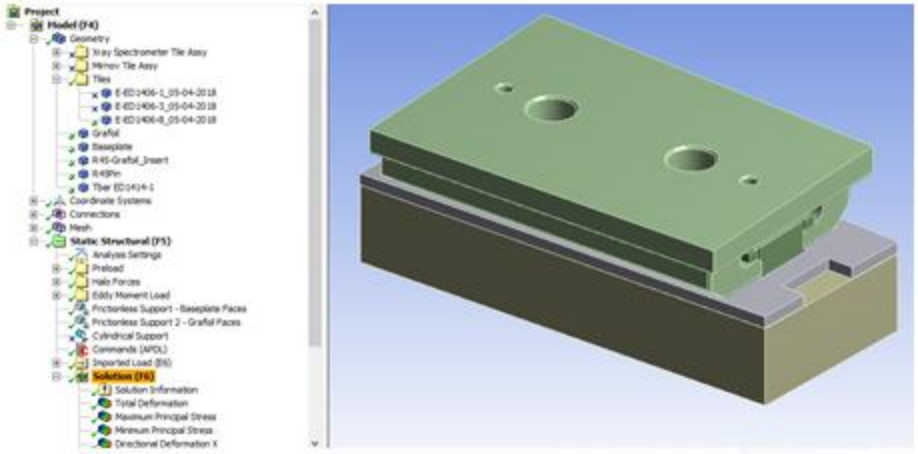
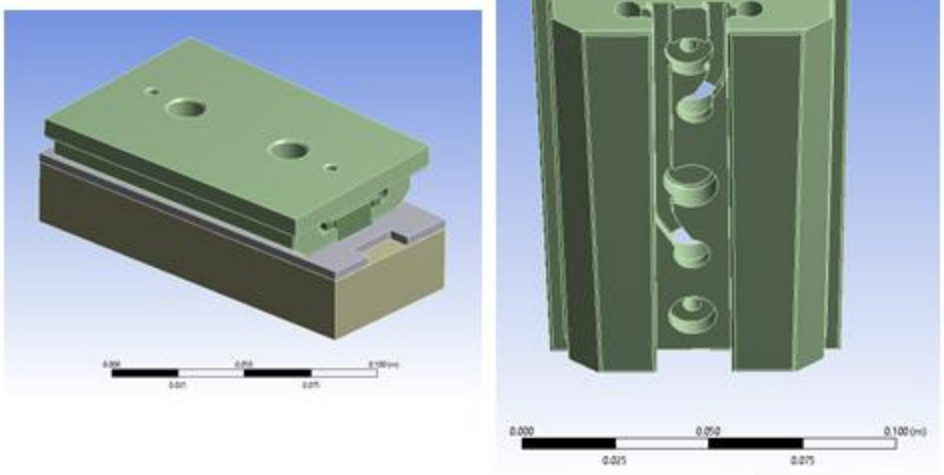
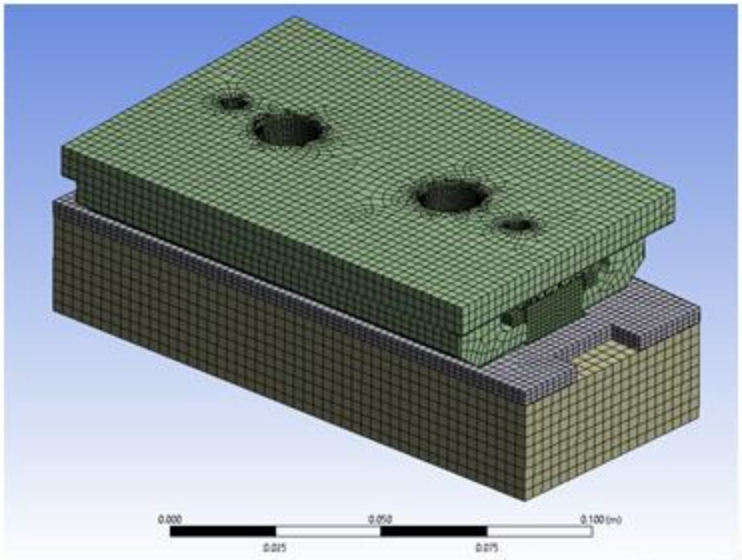
Components



Base Tile Geometry

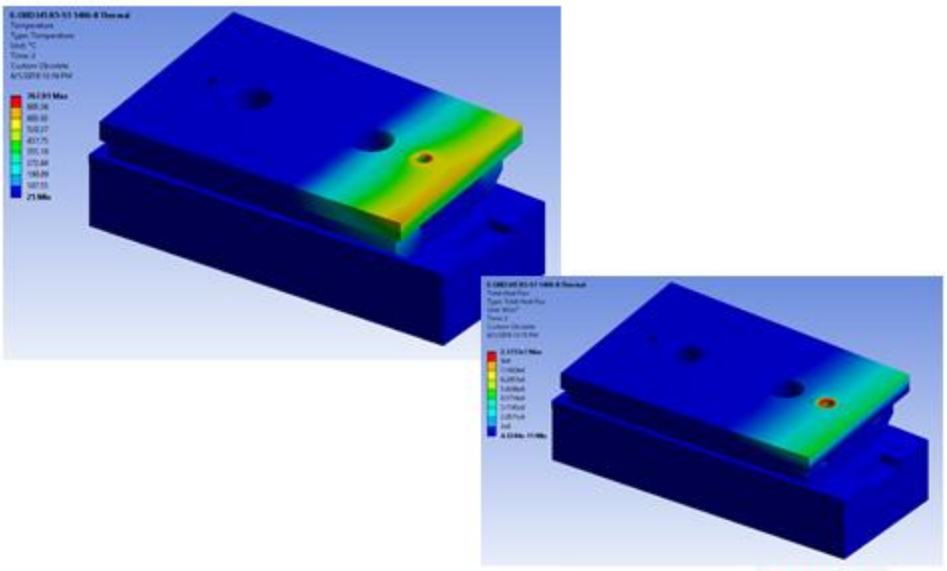


Mesh 596k Nodes, Hex Dominant



OAK RIDGE National Laboratory

Thermal Results



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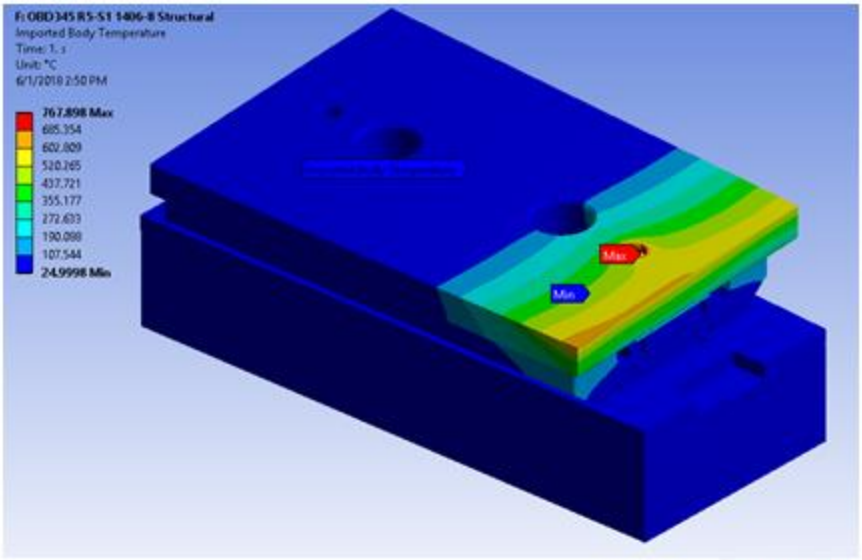
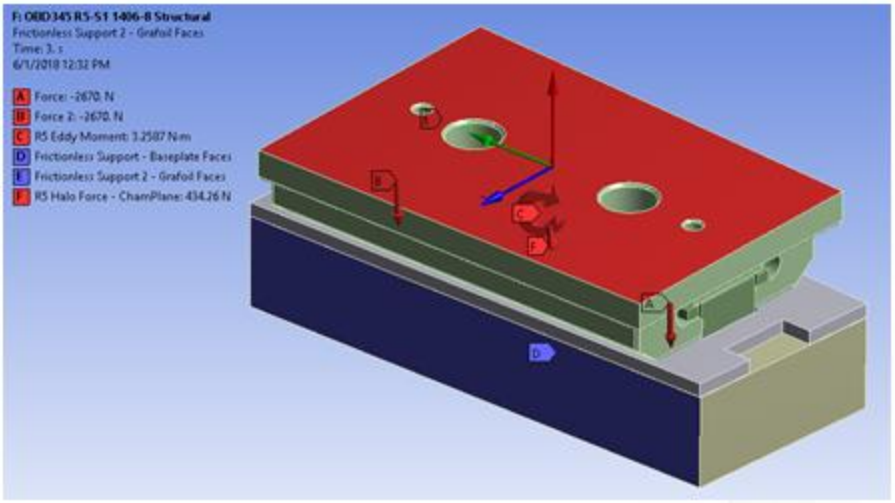
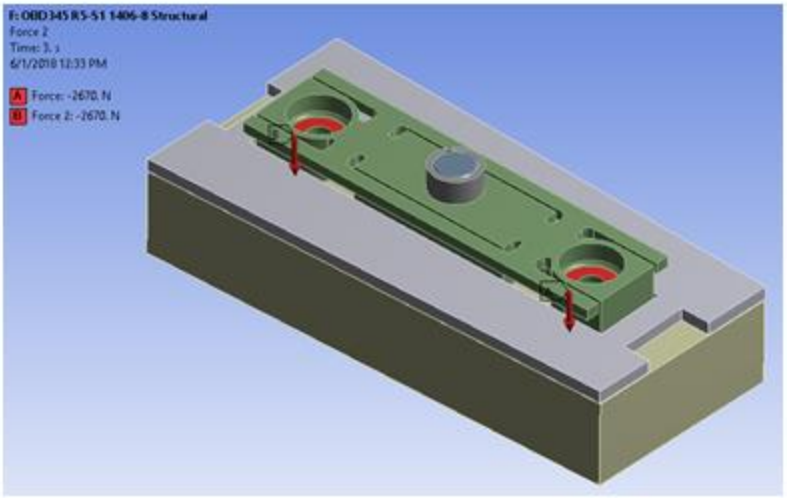
Mapped Temperature Loads



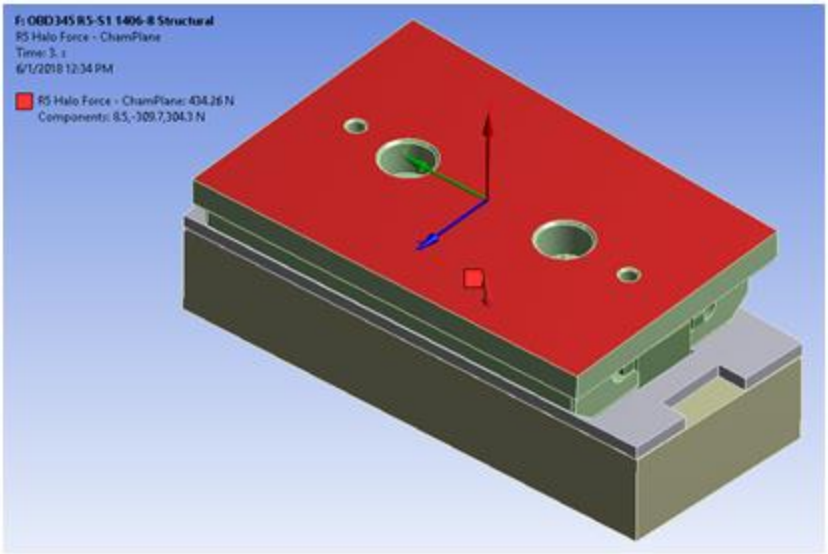
Mechanical Loads, step 3, t=3.0s



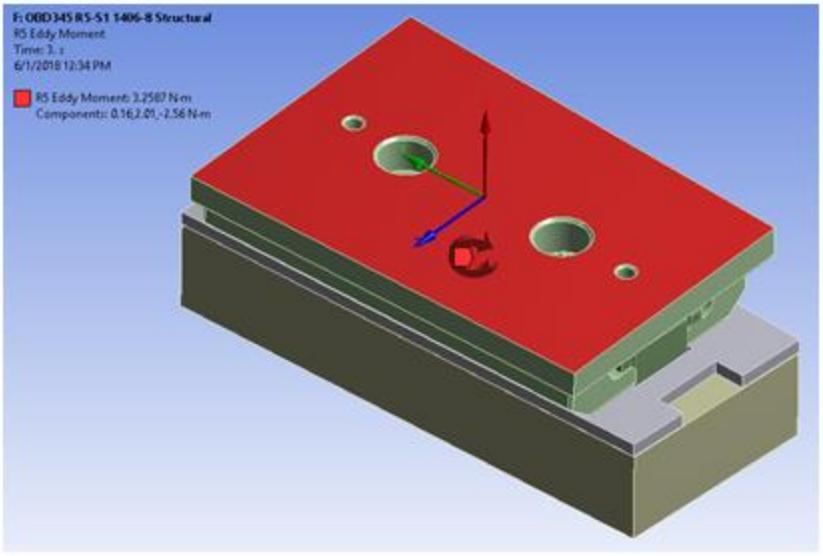
Preload Forces



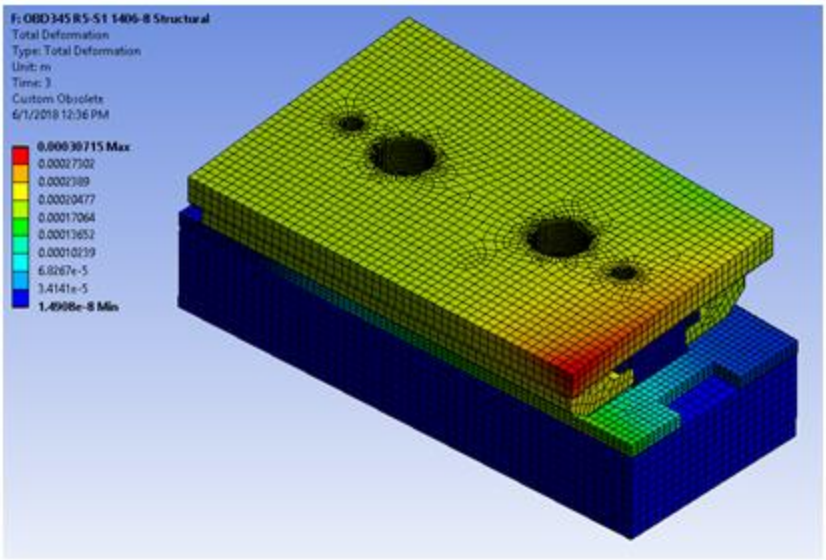
Halo Forces



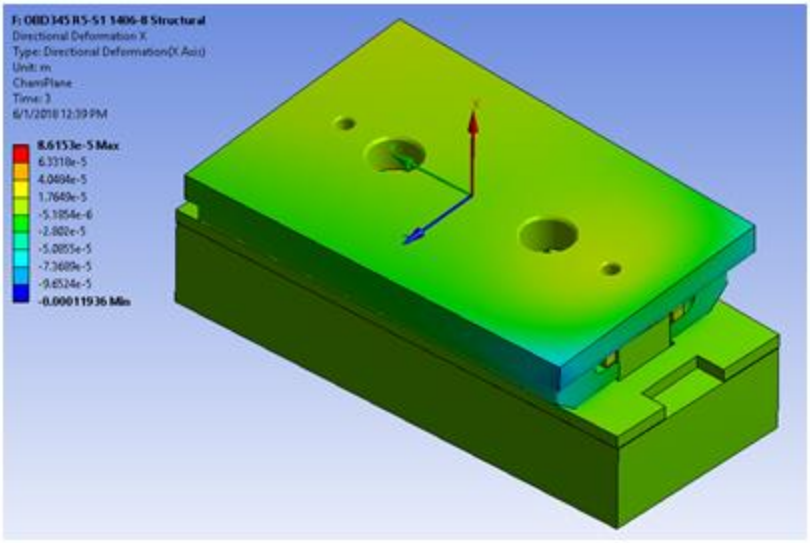
Eddy Moment



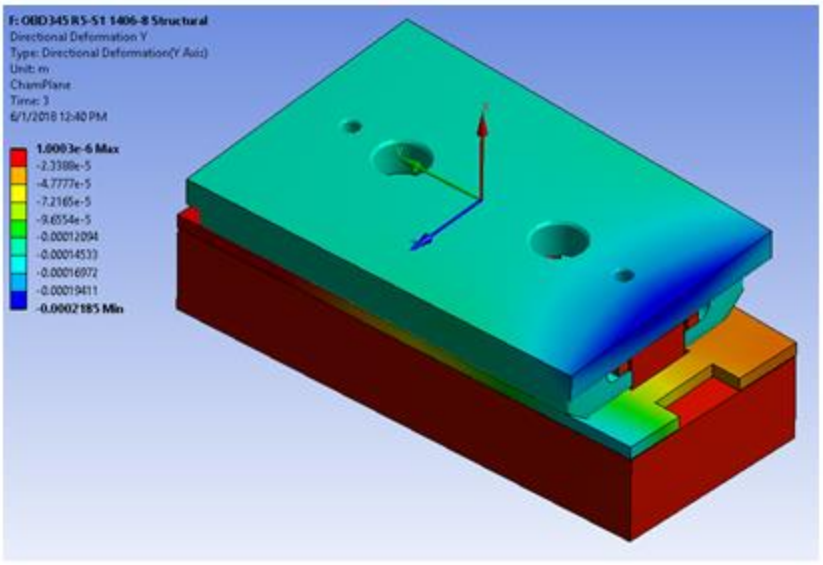
Total Deformation



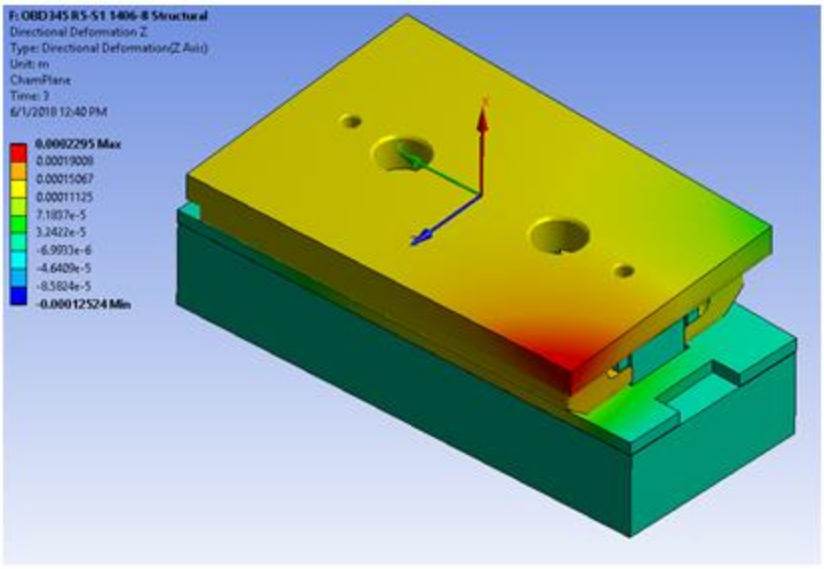
X-deformation from ChamPlane Origin



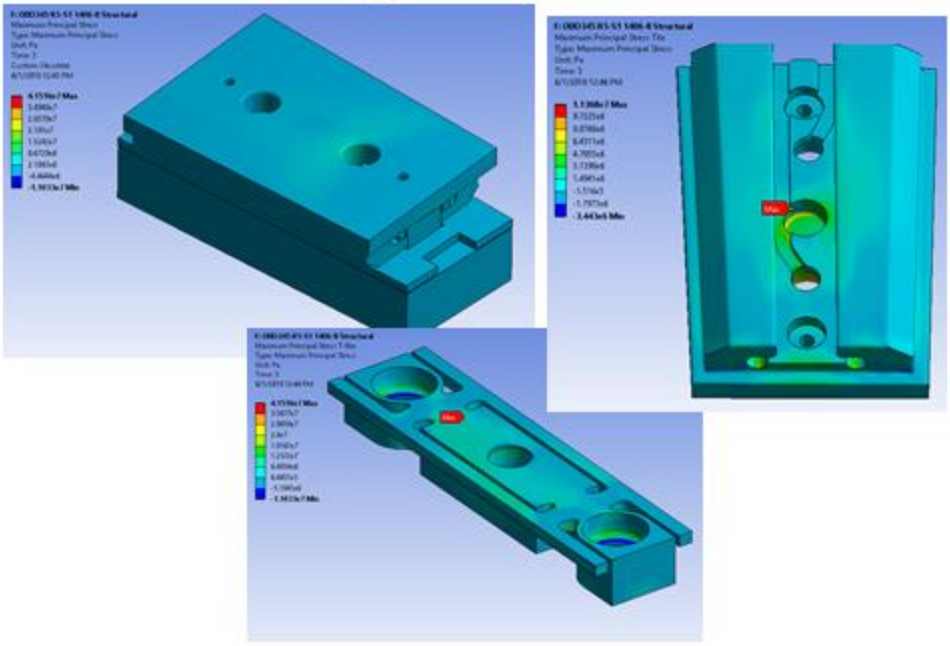
Y-deformation from ChamPlane Origin



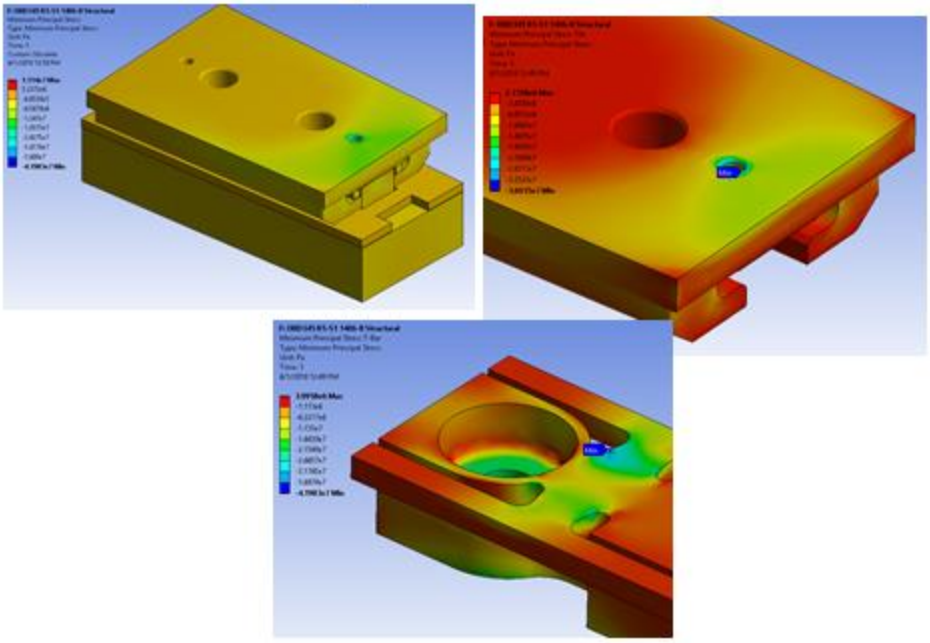
Z-deformation from ChamPlane Origin



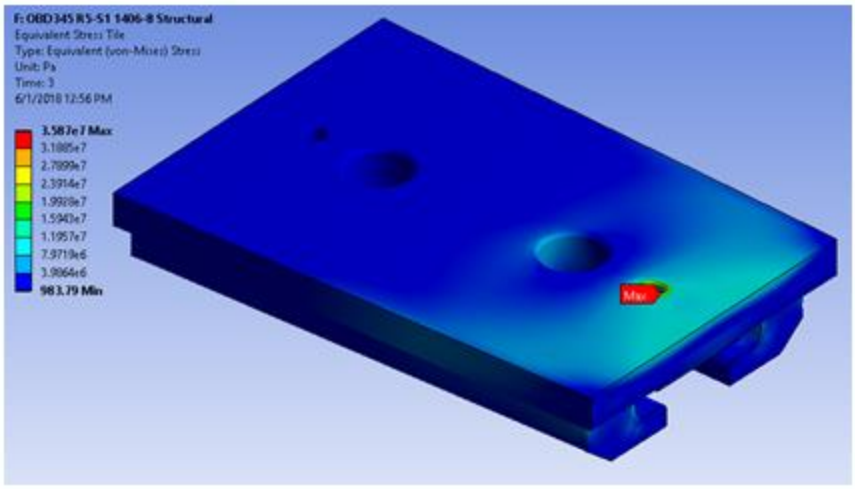
Maximum Principal Stress



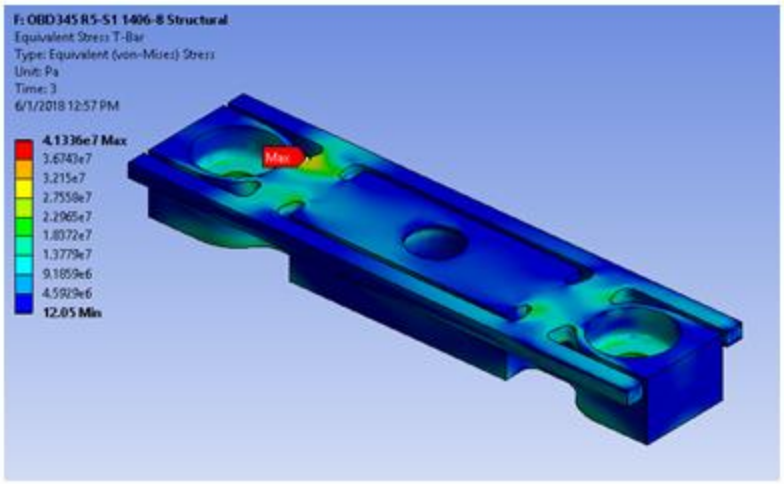
Minimum Principal Stress



Von Mises Stress in Tile



Von Mises Stress in TBar



Summary

- Tile

  S1 Allowable: 20 MPa
  S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 MPa

  Maximum Principal Stress: 11.4 MPa
  Minimum Principal Stress: -36.9 MPa

  Therefore, **SF ~ 1.5**

- Tbar

  $1/3\sigma_{UTS}$ In625 = 261 MPa

  Maximum von Mises Stress: 41.3 MPa

  Therefore, **SF ~ 6.3**

5 Subreport E-ED1406-9 R5 Style 1 X-Ray Spectrometer Variant

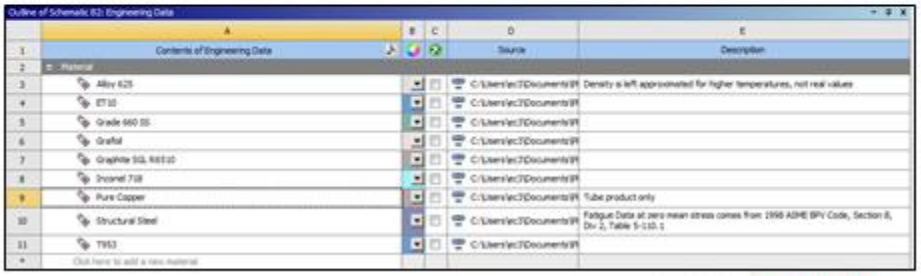
OBD345 R5, S1 Round 1
E-ED1406-9 Analysis

PPPL NSTX-U PFCs

Eliott Fountain
June 12, 2018

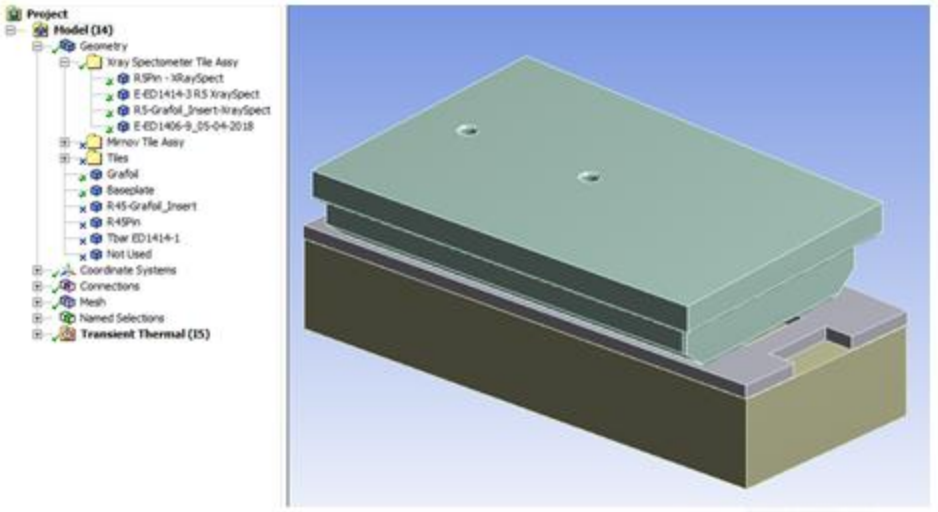
OAK RIDGE National Laboratory

Project Schematic / Engineering Data

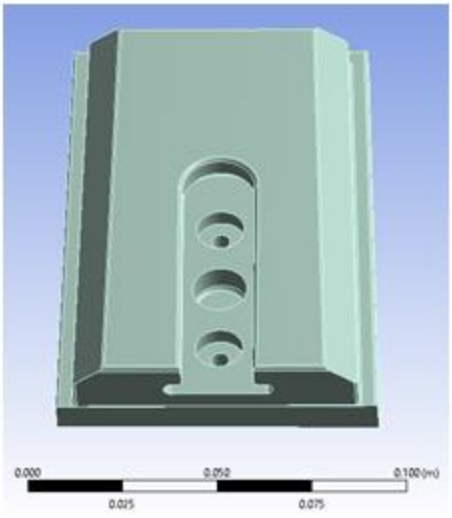


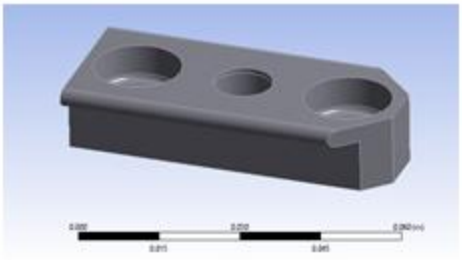
OAK RIDGE National Laboratory

Components

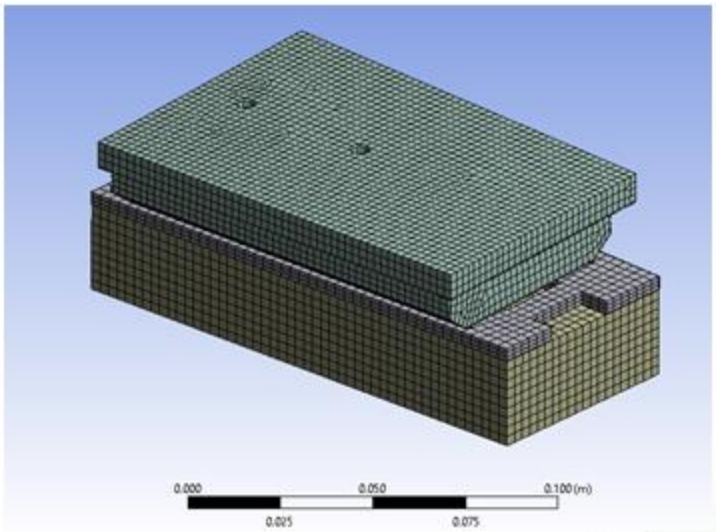


Base Tile / Tbar Geometry



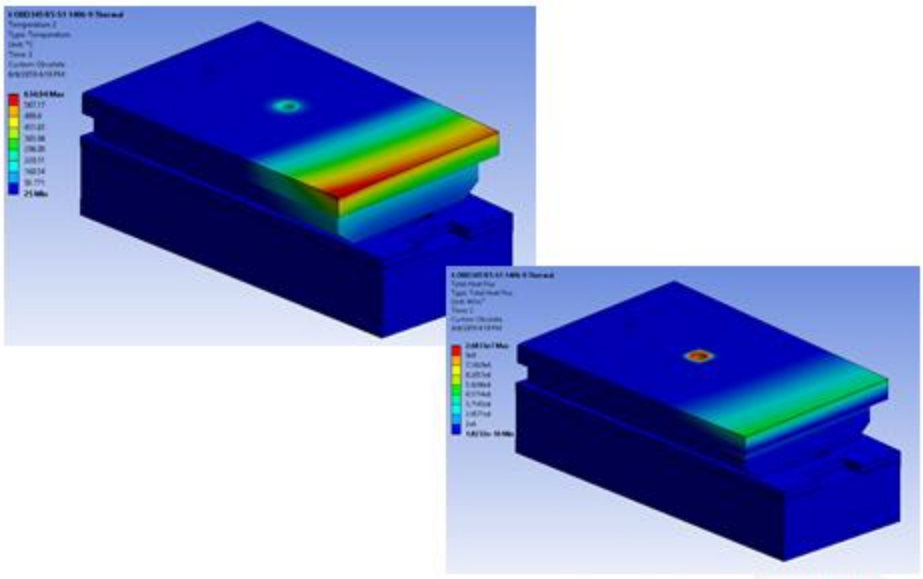


Mesh 233k Nodes, Hex Dominant



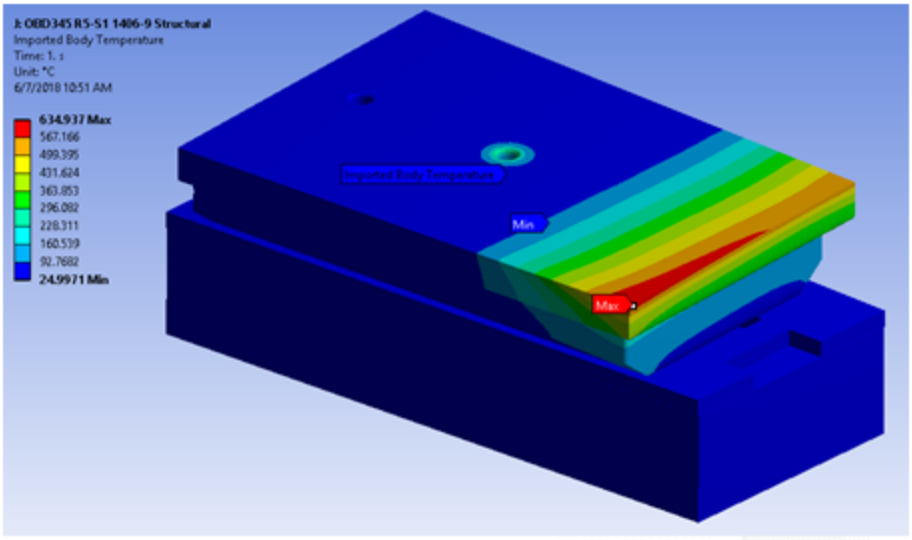
OAK RIDGE National Laboratory

Thermal Results

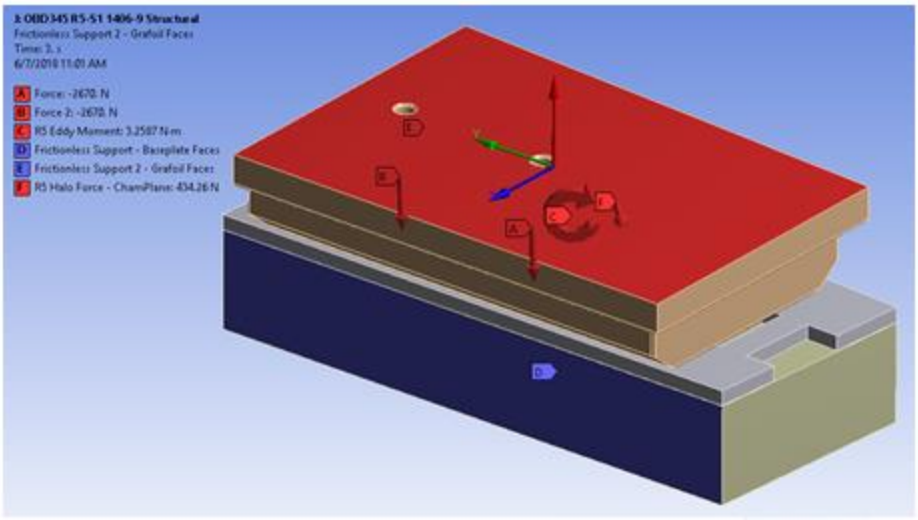


OAK RIDGE National Laboratory

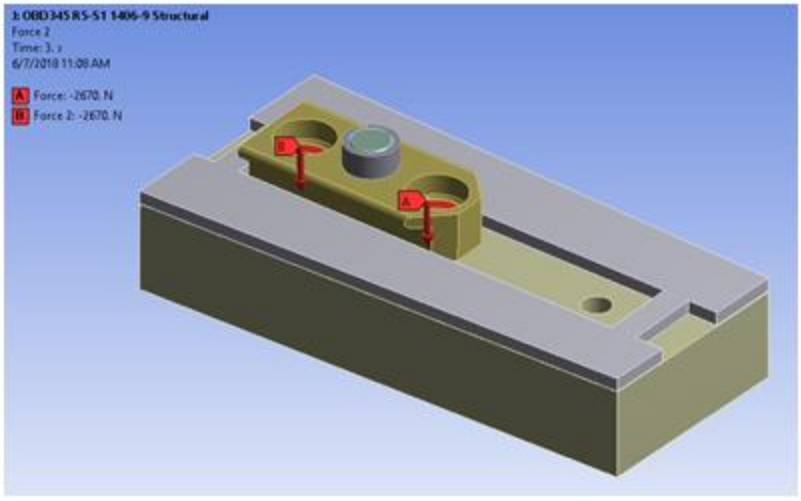
Mapped Temperature Loads



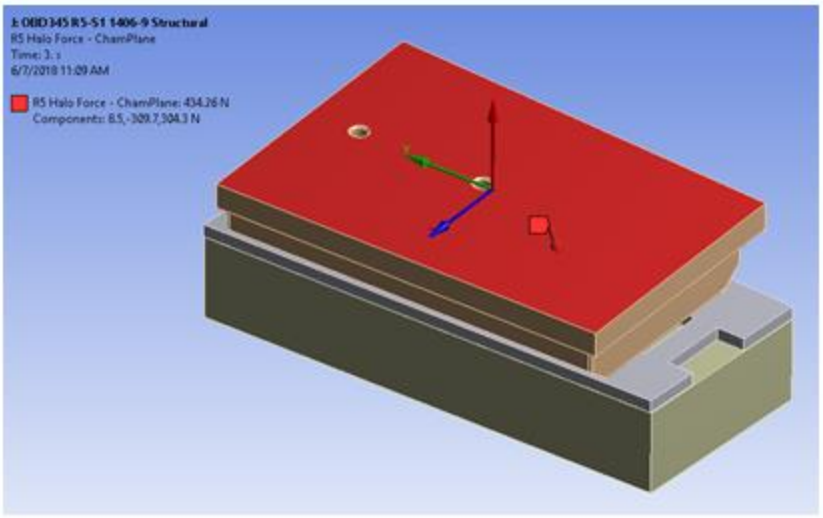
Mechanical Loads, step 3, t=3.0s



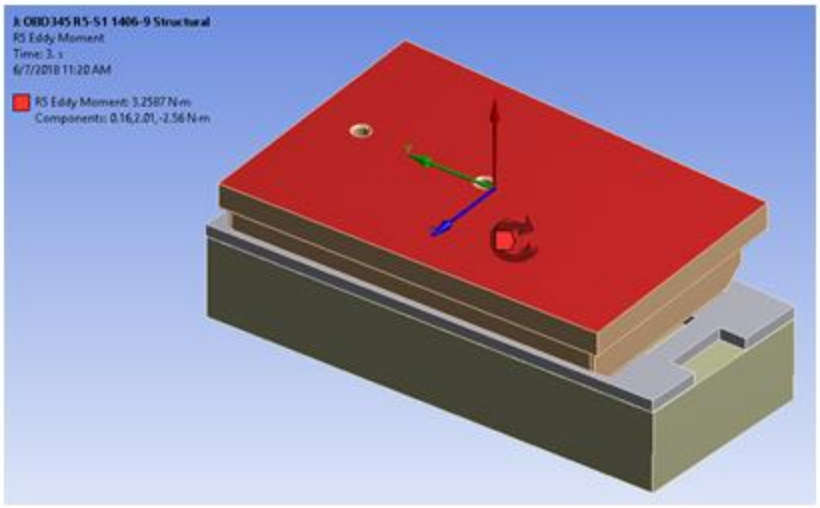
Preload Forces



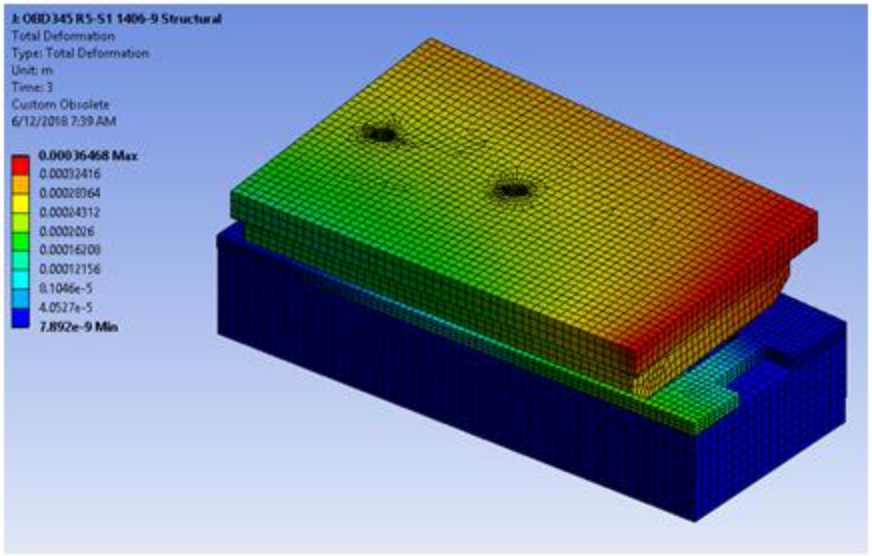
Halo Forces



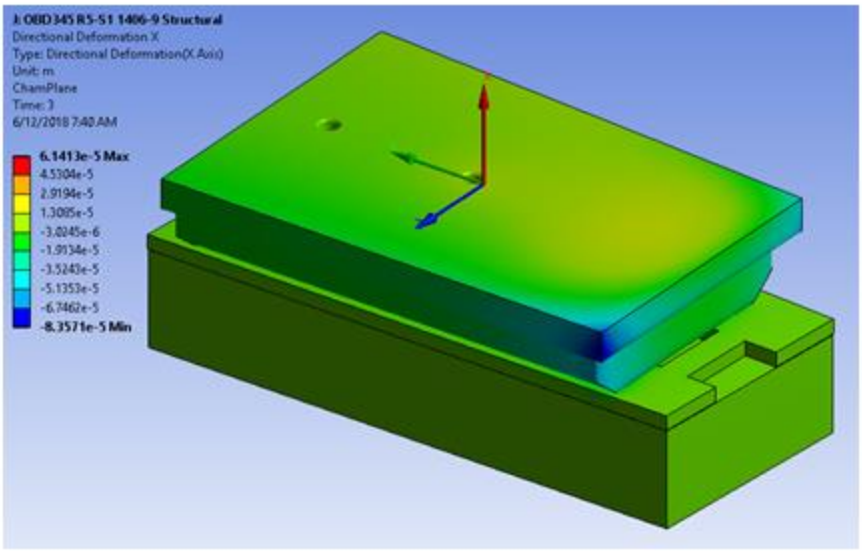
Eddy Moment



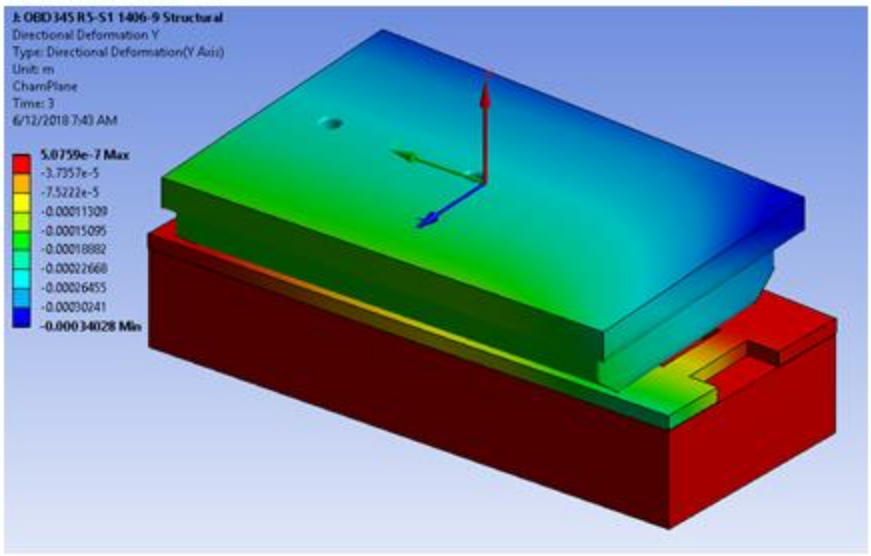
Total Deformation



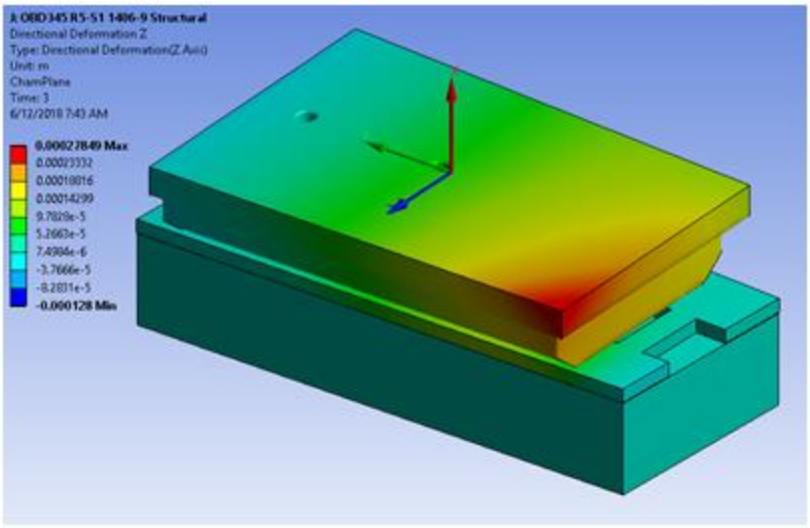
X-deformation from ChamPlane Origin



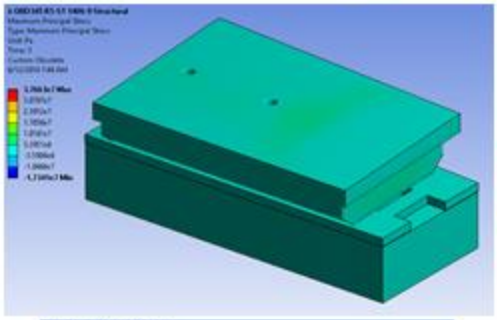
Y-deformation from ChamPlane Origin

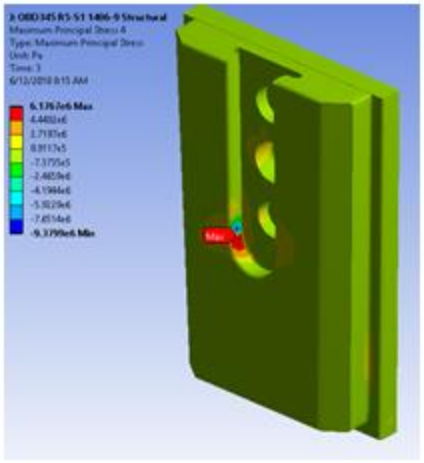


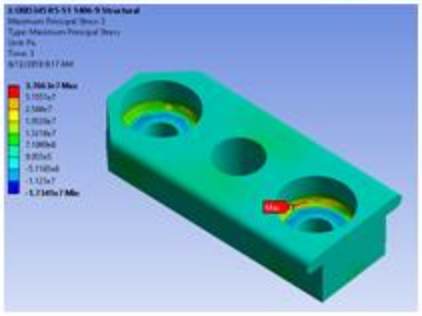
Z-deformation from ChamPlane Origin



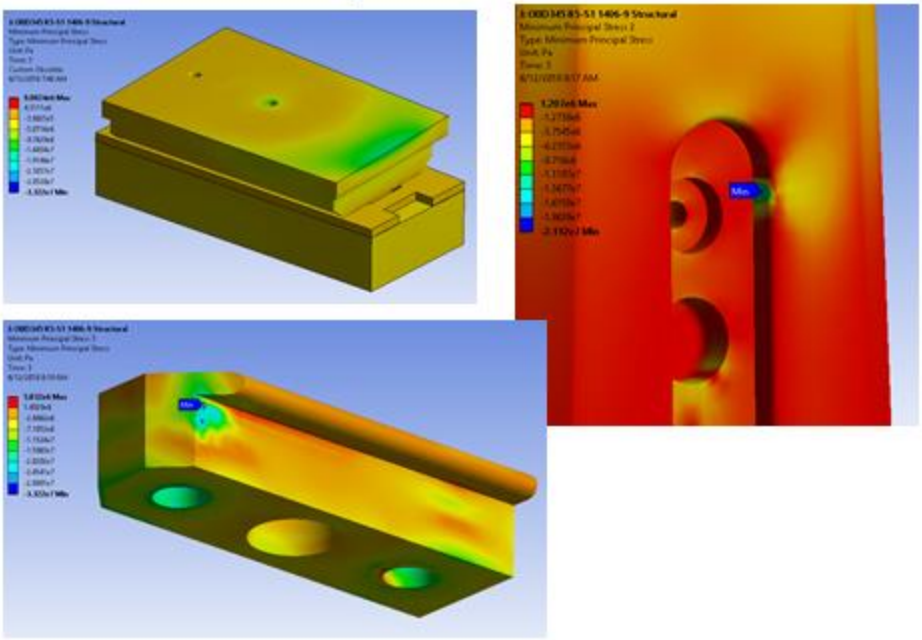
Maximum Principal Stress



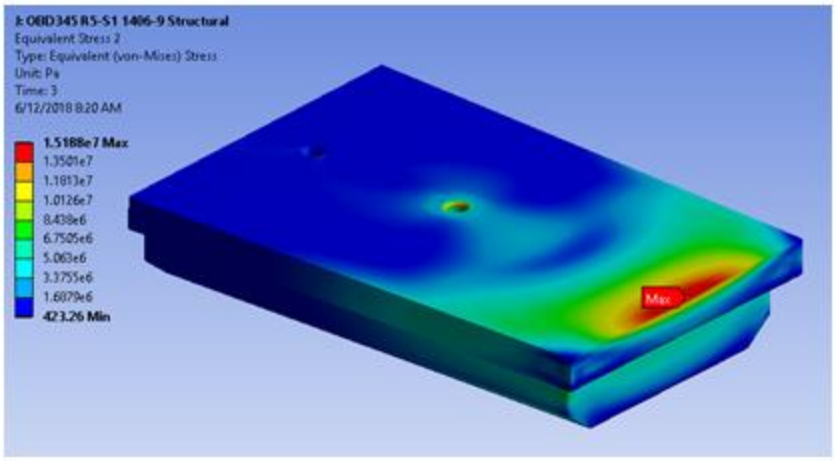




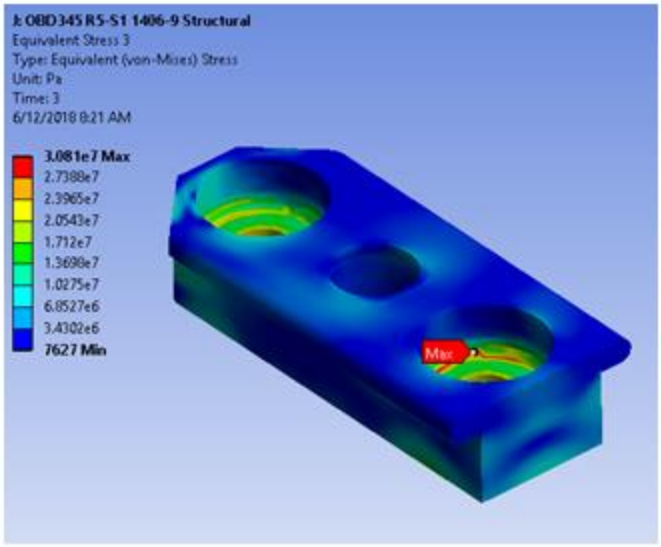
Minimum Principal Stress



Von Mises Stress in Tile



Von Mises Stress in TBar



Summary

- Tile

  S1 Allowable: 20 MPa
  S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 MPa

  Maximum Principal Stress: 6.2 MPa
  Minimum Principal Stress: -21.1 MPa

  Therefore, **SF ~ 2.6**

- Tbar

  $1/3\sigma_{UTS}$ In625 = 261 MPa

  Maximum von Mises Stress: 30.8 MPa

  Therefore, **SF ~ 8.5**

6 Subreport E-ED1406-10 R5 Style 1 PCHERS Lower Bay Ramped Tile

Analysis Completed by ORNL

Summary

Principle stresses in the T953 tile meet their allowables. Peak stresses in all components are lists in Table 13, Table 14, and Table 15.

The components considered in the analysis are listed below in Figure 43 and Figure 44.

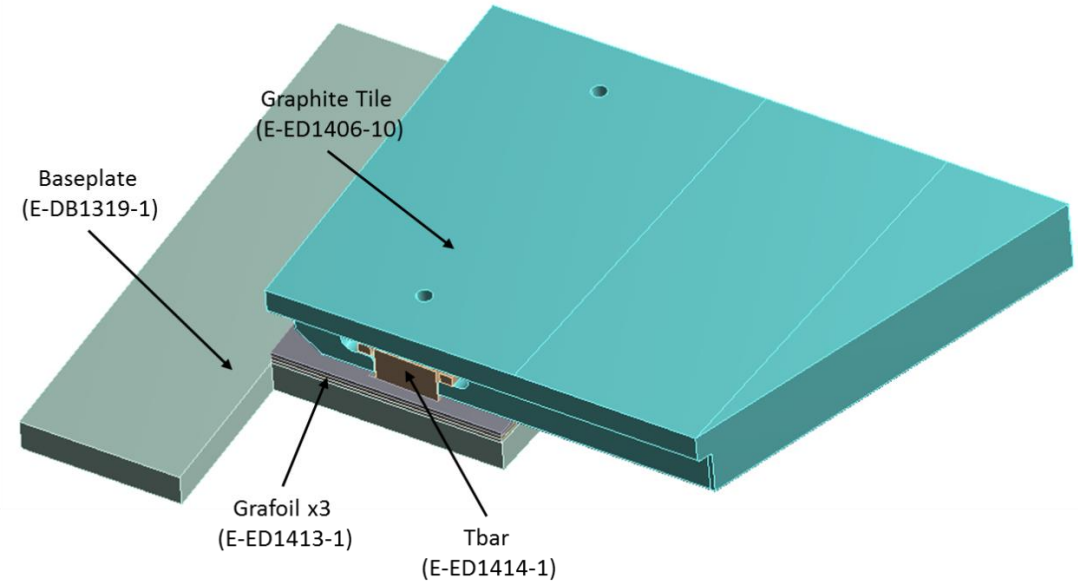


Figure 1: Outboard Diverter Row 5 style 1 variant (1406-10) Re

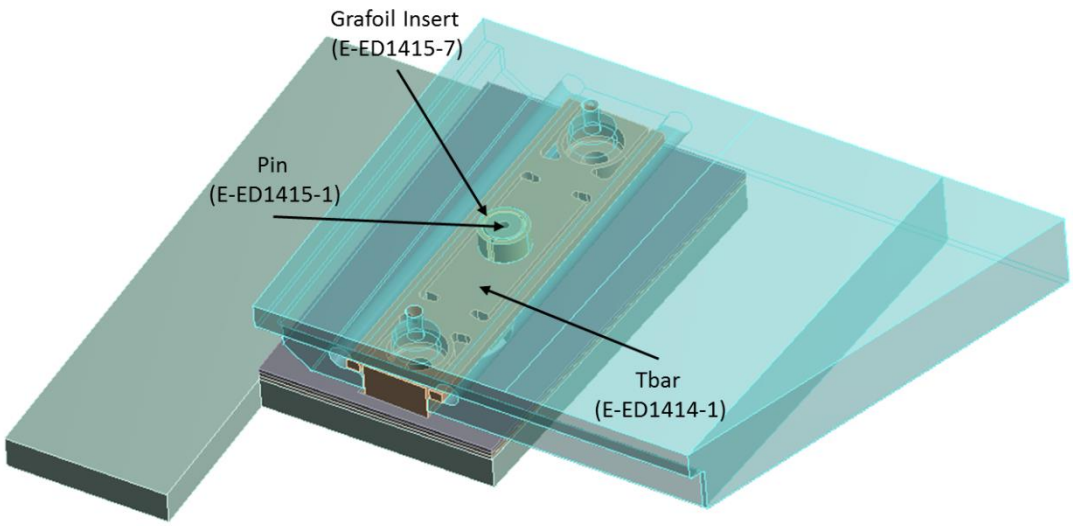


Figure 2: Outboard Diverter Row 5 style 1 variant (1406-10) components considered in analysis.

The total number of elements and nodes for the whole assembly is 1,644,029 and 2,363,053 respectively. Figure 45 shows the mesh used in the analysis with and without the graphite tile. Figure 46 shows the mesh of the mounting side of the graphite tile.

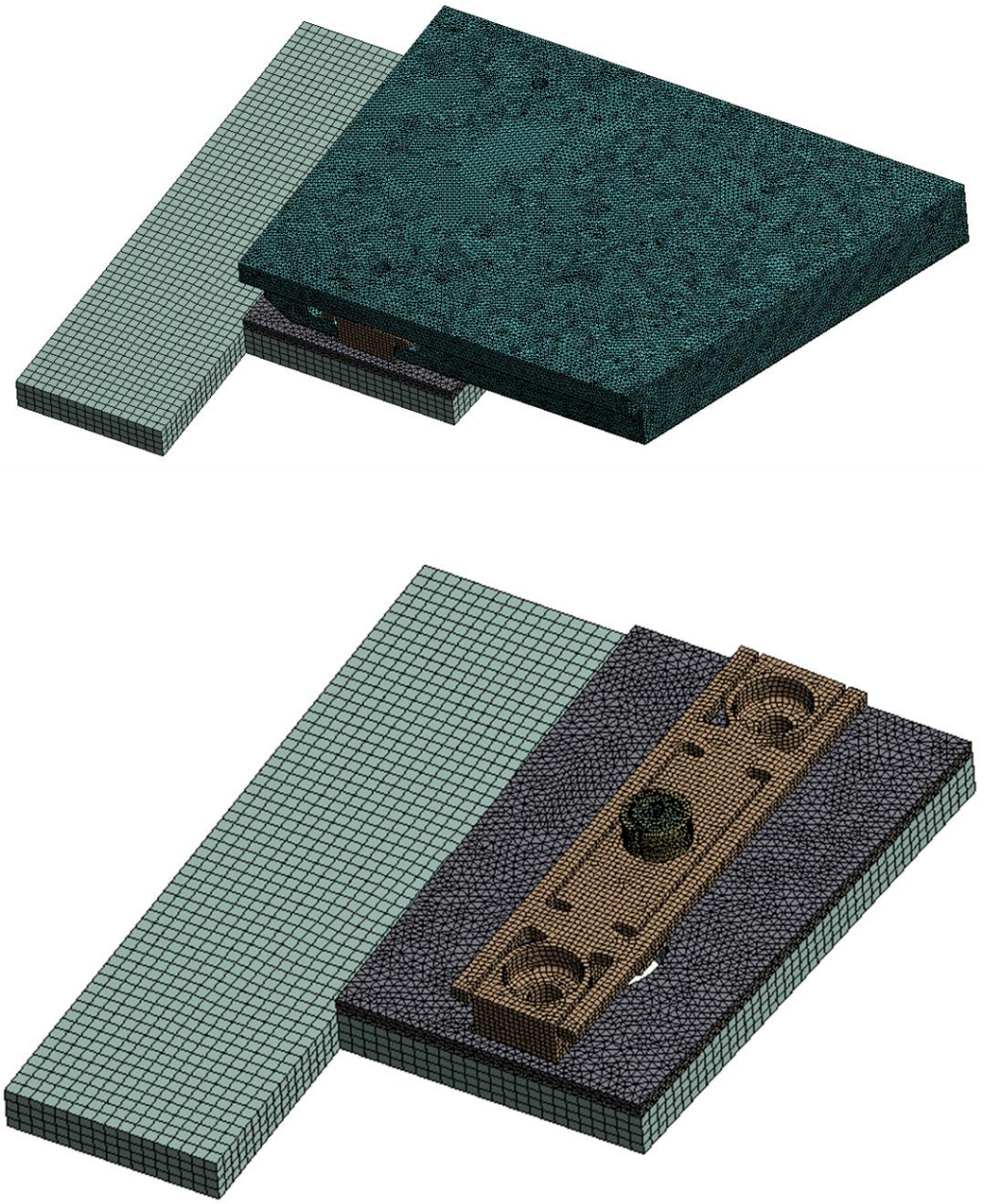


Figure 3: Mesh of the Outboard Diverter Row 5 style 1 variant (1406-10)

Figure 4: Mounting side of the graphite tile.

Table 11 lists each component of the assembly and its material.

Table 1: Components and their materials.

Component	Material
Graphite Tile (E-ED1406-10)	T953
Grafoil (E-ED1413-1)	Grafoil
Baseplate (E-DB1319-1)	Pure Copper
Grafoil Insert (E-ED1415-7)	Grafoil
Pin (E-ED1415-1)	Inconel 718
Tbar (E-ED1414-1)	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

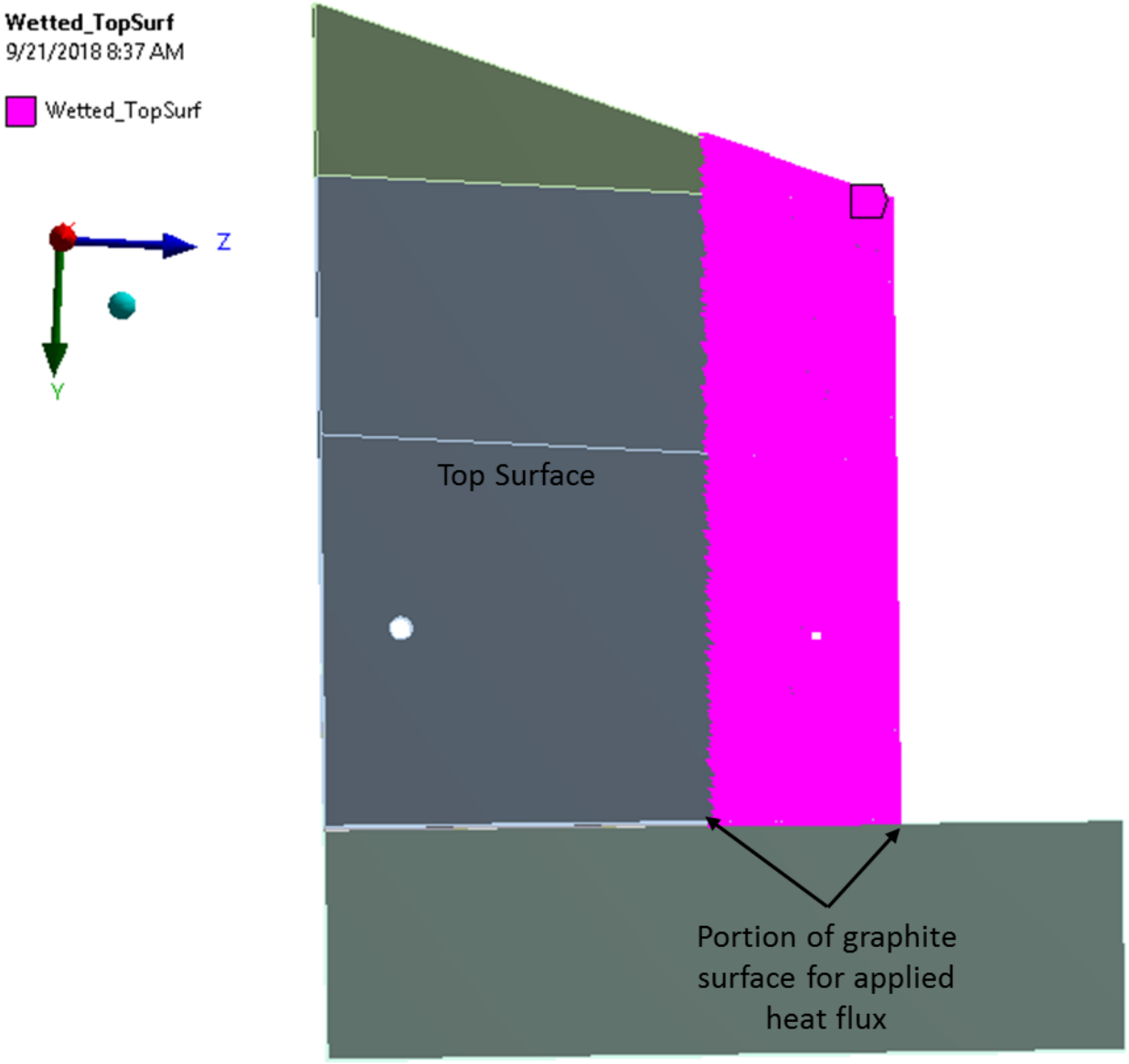


Figure 5: Thermal boundary conditions

Top Surface heat flux = 4,536,144 W/m^2 with a gradient heat flux along the y-direction of –41,237,672 W/m^2/° with the extent being 0.04 m.

The peak temperature in the assembly was 614 °C in the graphite tile. Figure 48 and Figure 49 shows the temperature contour because of the applied heat fluxes. Table 12 lists the peak temperature for each component.

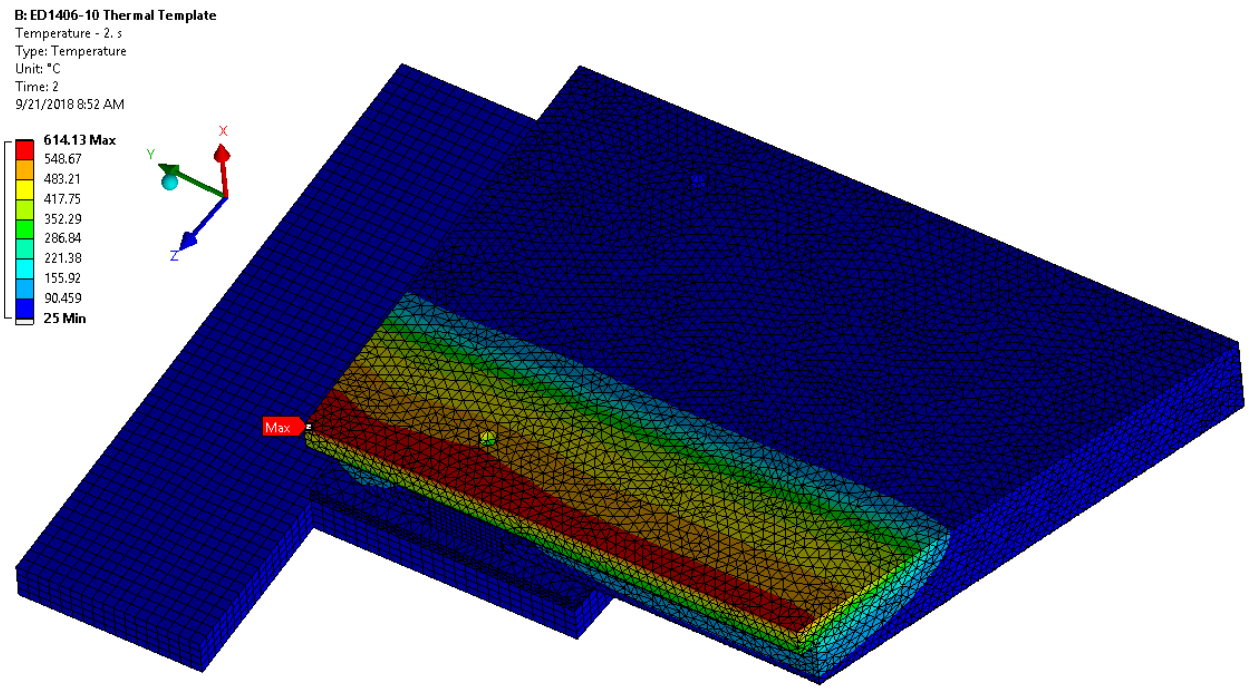


Figure 6: Temperature contour plot of the Outboard Diverter Row 5 style 1 variant (1406-10)

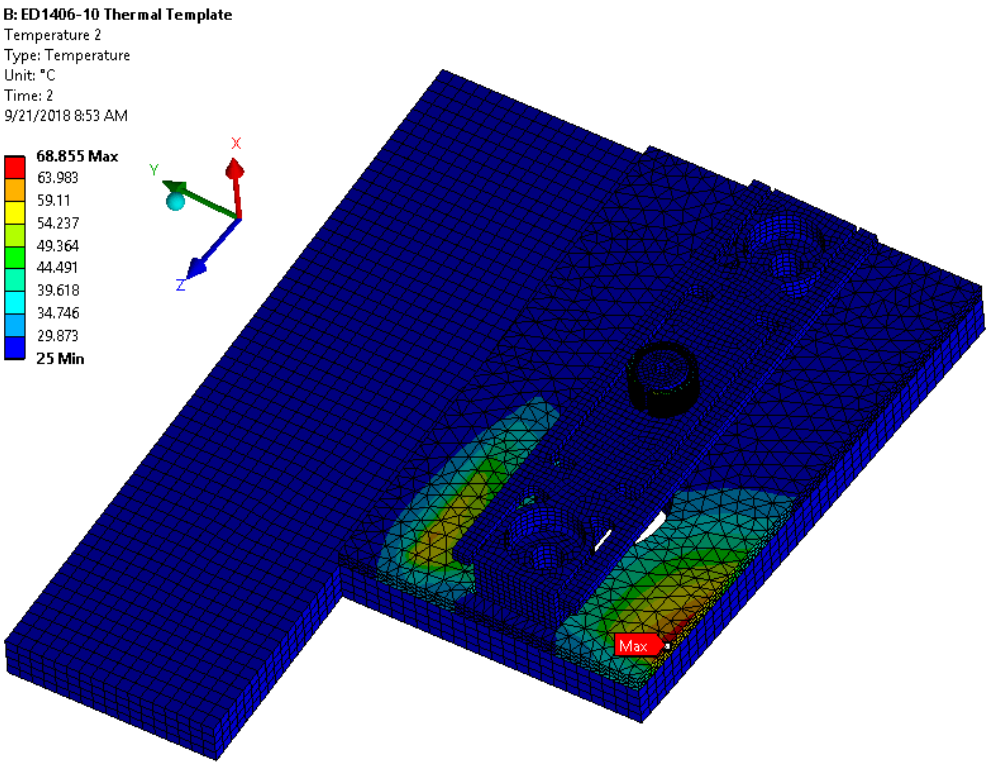


Figure 7: Temperature contour plot of the Outboard Diverter Row 5 style 1 variant (1406-10) without graphite tile

Table 2: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1406-10)	614
Grafoil (E-ED1413-1)	69
Baseplate (E-DB1319-1)	25
Grafoil Insert (E-ED1415-7)	53
Pin (E-ED1415-1)	25
Tbar (E-ED1414-1)	25

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar (ED1414-1) as shown in Figure 50. Figure 51 and Figure 10 shows the halo force and eddy current loading applied to the graphite tile respectively.

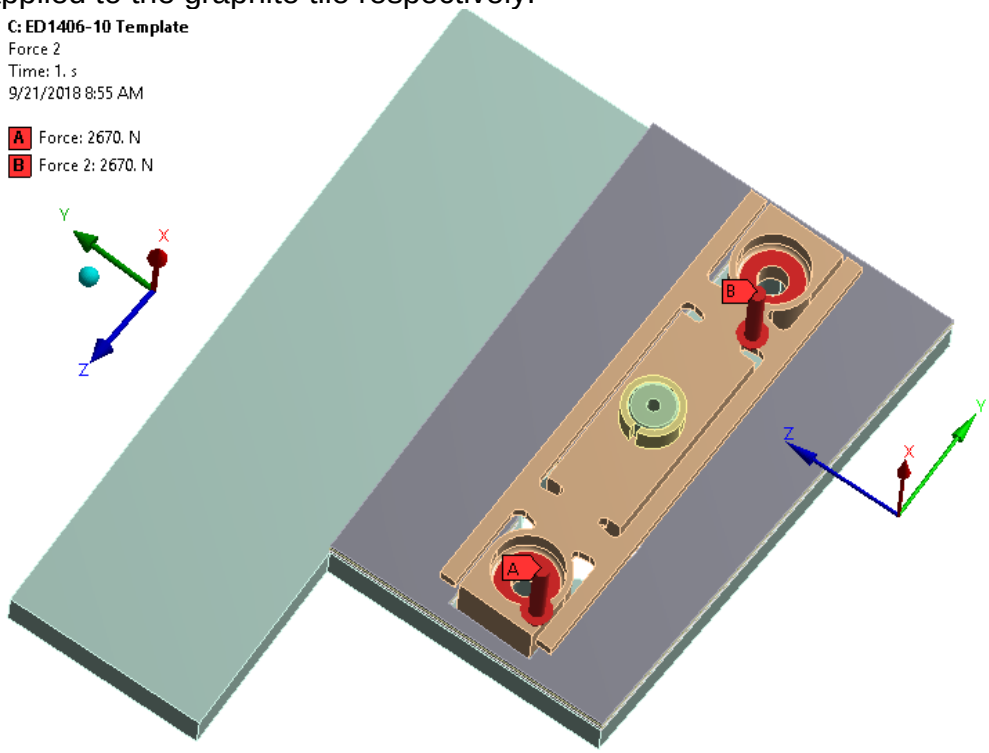


Figure 8: Bolt preload force applied to the Tbar.

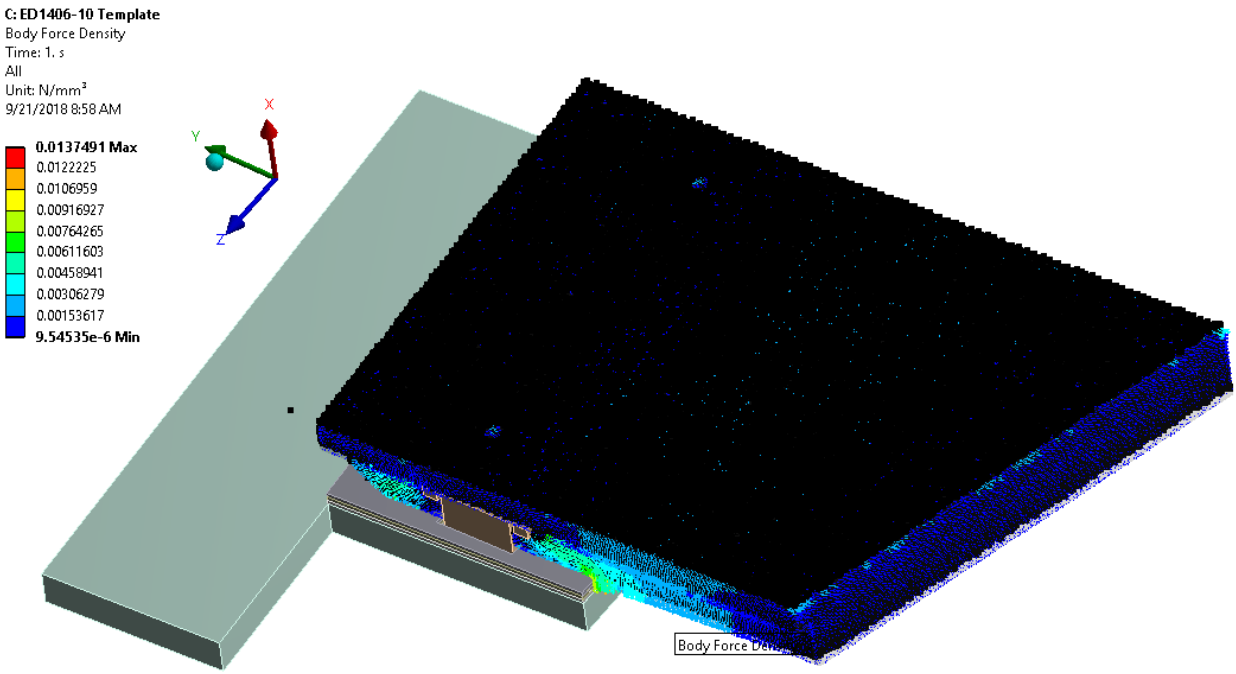


Figure 9: Halo force applied as a body force density to the graphite tile.

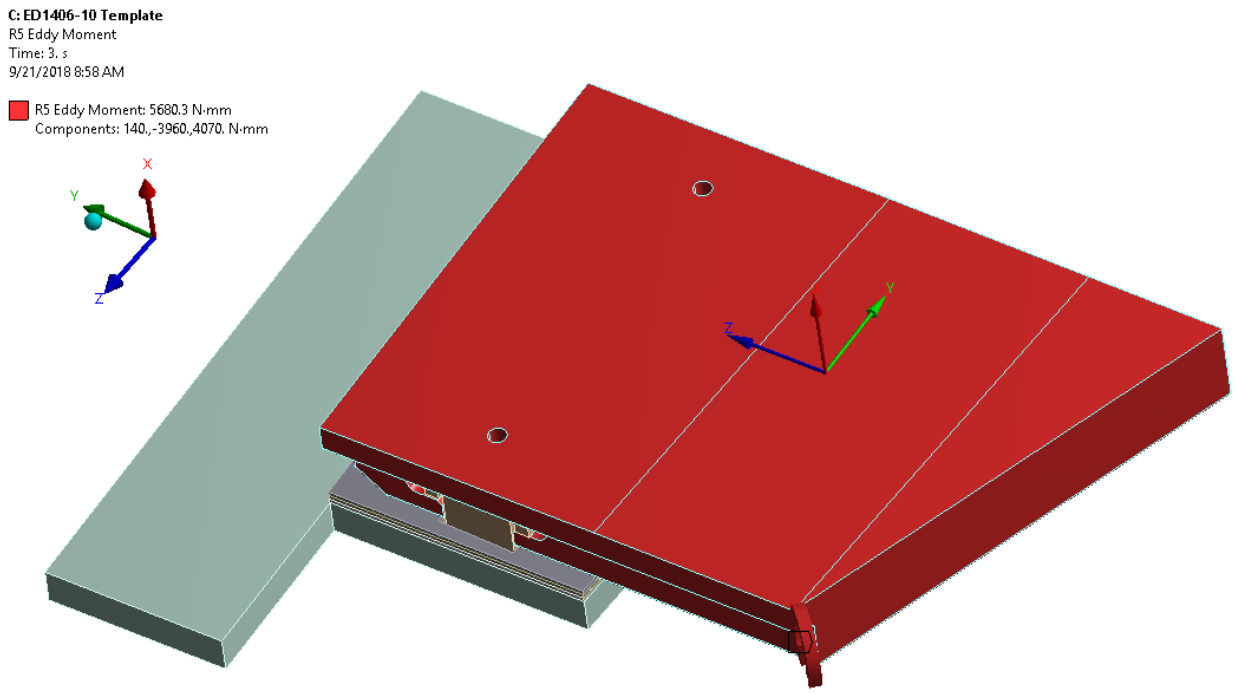


Figure 10: Eddy current load on graphite tile.

Frictionless constraints were applied to one side of the baseplate and two sides of the grafoil. Figure 52 shows the location of these constraints highlighted in blue.

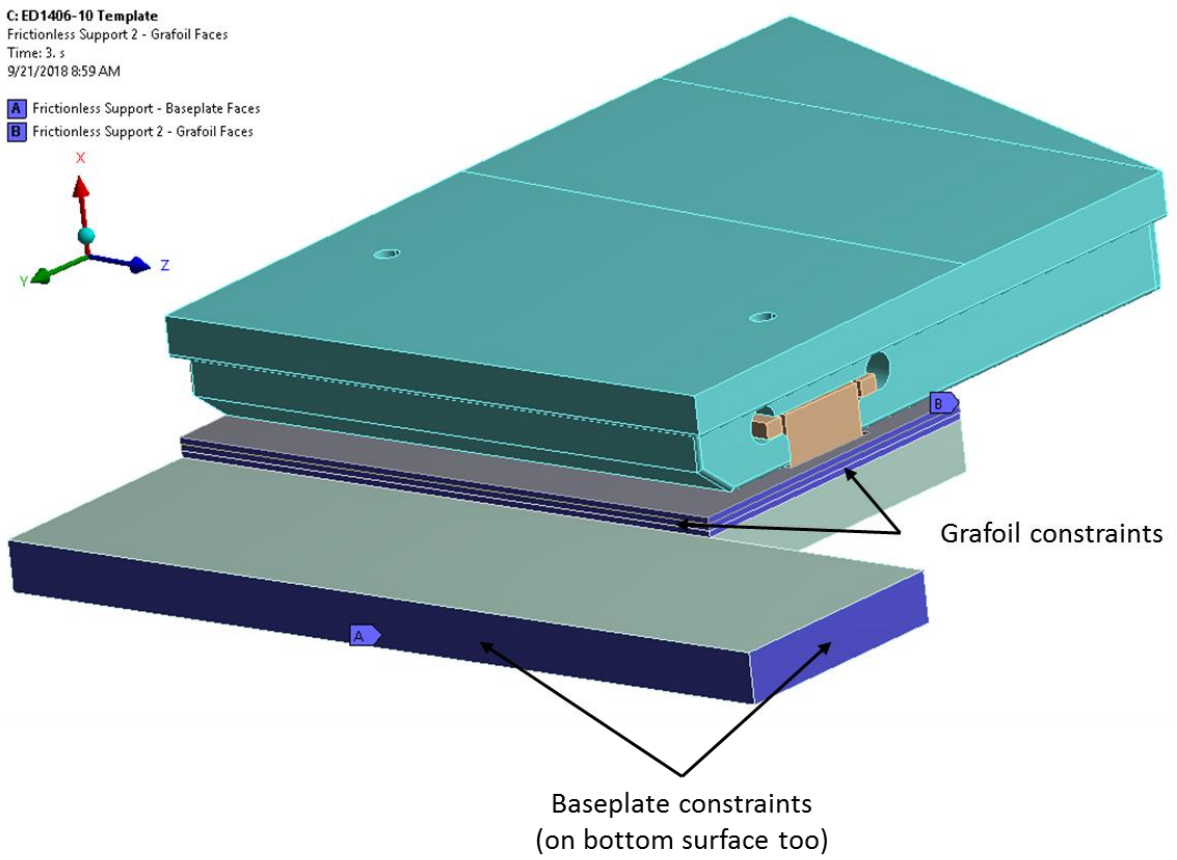


Figure 11: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R45-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1. Figure 53 shows the surfaces in contact with each other labeled A through E.

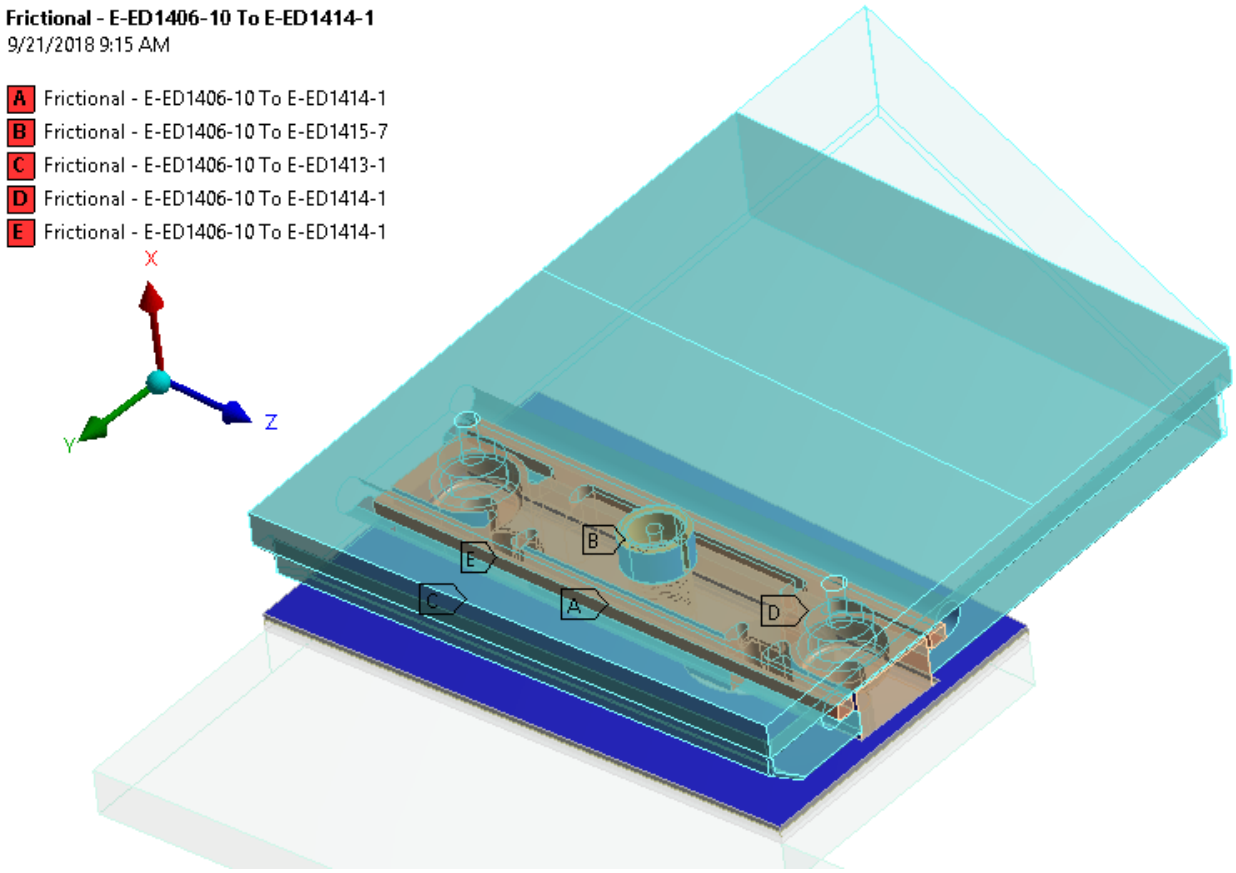


Figure 12: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition. Figure 54 shows the surfaces in contact with each other labeled A through D.

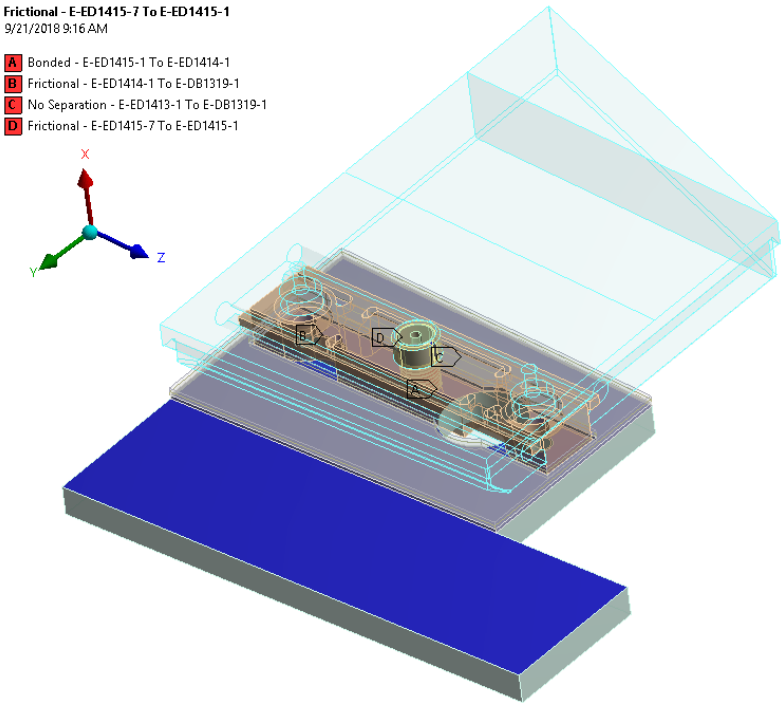


Figure 13: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 55. X, Y, Z deformation contour in the assembly is shown Figure 56, Figure 57, and Figure 58.

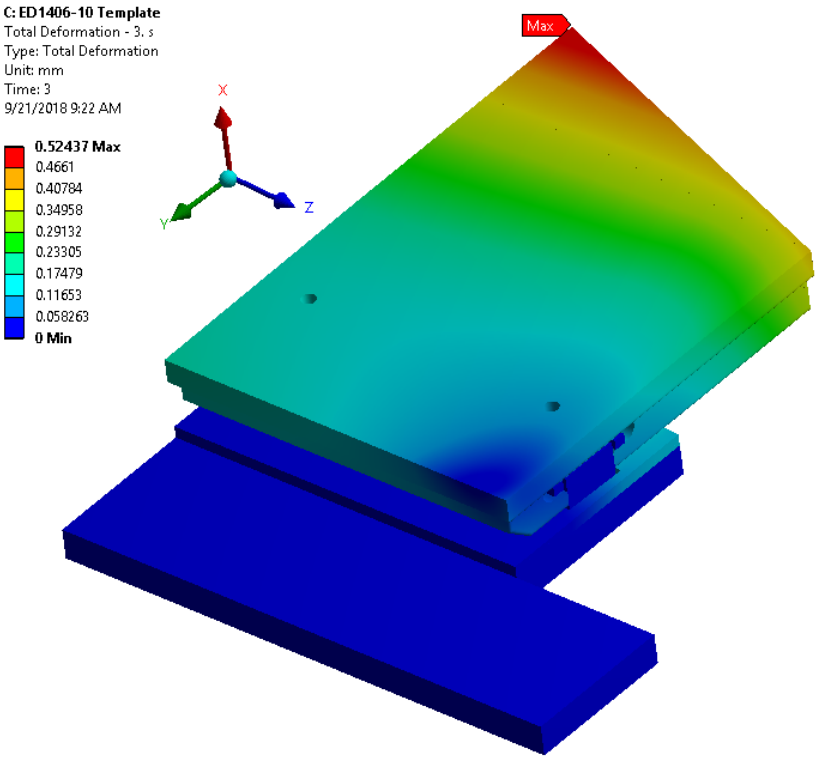


Figure 14: Total deformation of the assembly

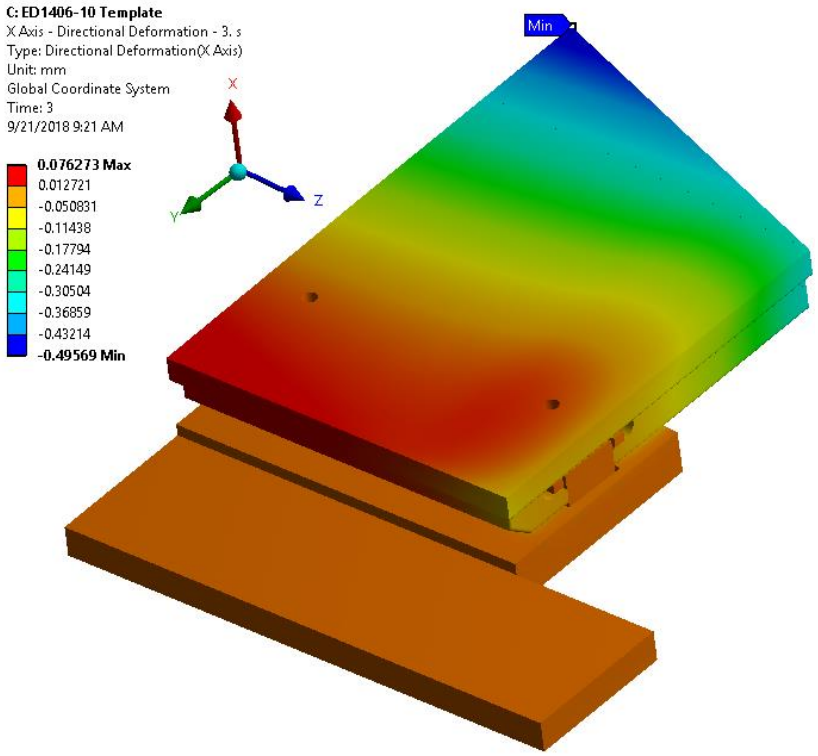


Figure 15: X-direction displacement

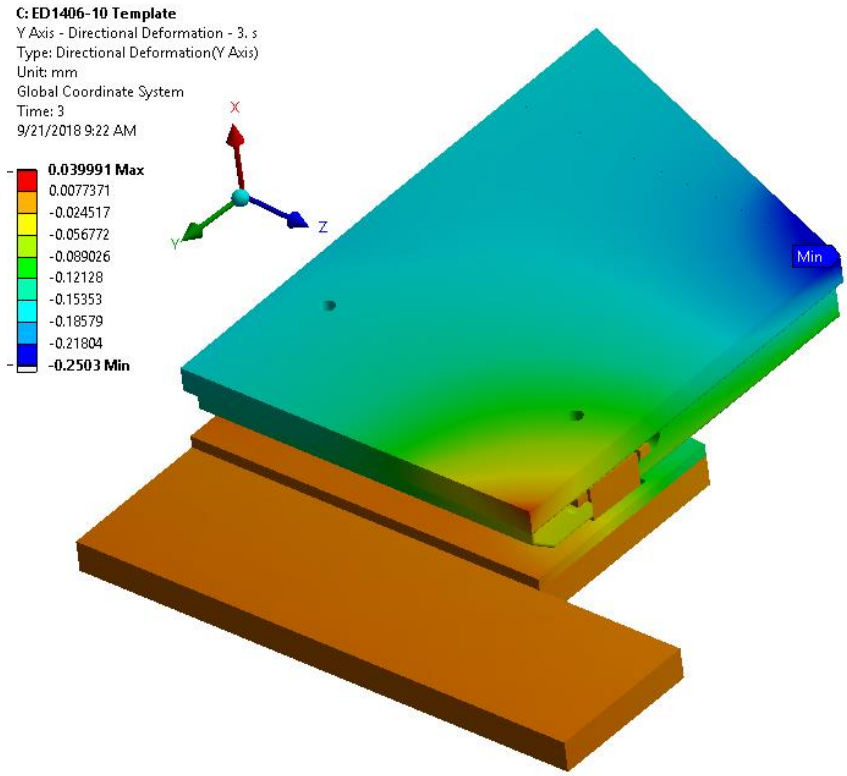


Figure 16: Y-direction displacement

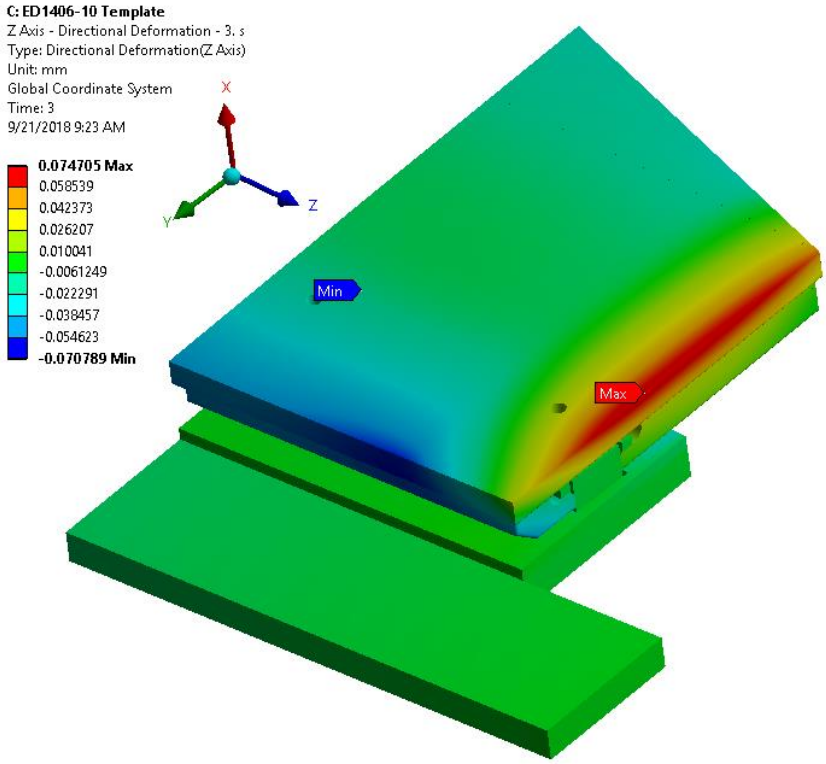


Figure 17: Z-direction displacement

Table 13 and Table 14 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 15 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 3: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1406-10)	9.90	20	BPL+Halo
Graphite Tile – Tbar Slot	9.00	20	BPL+Halo
Graphite Tile – Shear Pin Hole	8.77	20	BPL+Halo
Grafoil (E-ED1413-1)	0.41	20	BPL+Halo+Eddy
Grafoil Insert (E-ED1415-7)	0.55	20	BPL+Halo

Table 4: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1406-10)	-25.27	-55	BPL+Halo+Eddy
Graphite Tile – Tbar Slot	-20.63	-55	BPL
Graphite Tile – Shear Pin Hole	-3.09	-55	BPL+Halo
Grafoil (E-ED1413-1)	-1.23	-55	BPL+Halo
Grafoil Insert (E-ED1415-7)	-3.86	-55	BPL+Halo

Table 5: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate (E-DB1319-1)	13.70	??	BPL
Pin (E-ED1415-1)	20.57	276	BPL+Halo
Tbar (E-ED1414-1)	189.60	261	BPL+Halo

All stresses resulted in values below their respective allowables. Figure 59 shows the location of the peak minimum principal stress with bolt preload and the halo load. The location of maximum principal stress with bolt preload and the halo load is shown in Figure 60.

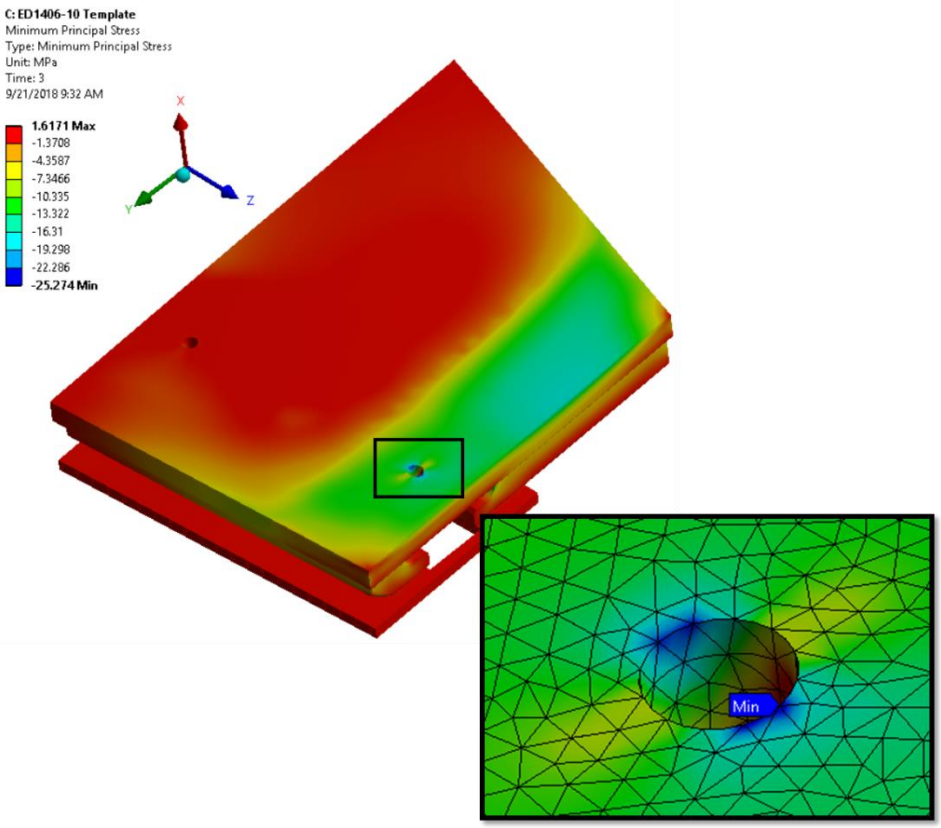


Figure 18: Location of peak minimum stress in OBD Row 5 style 1 -10

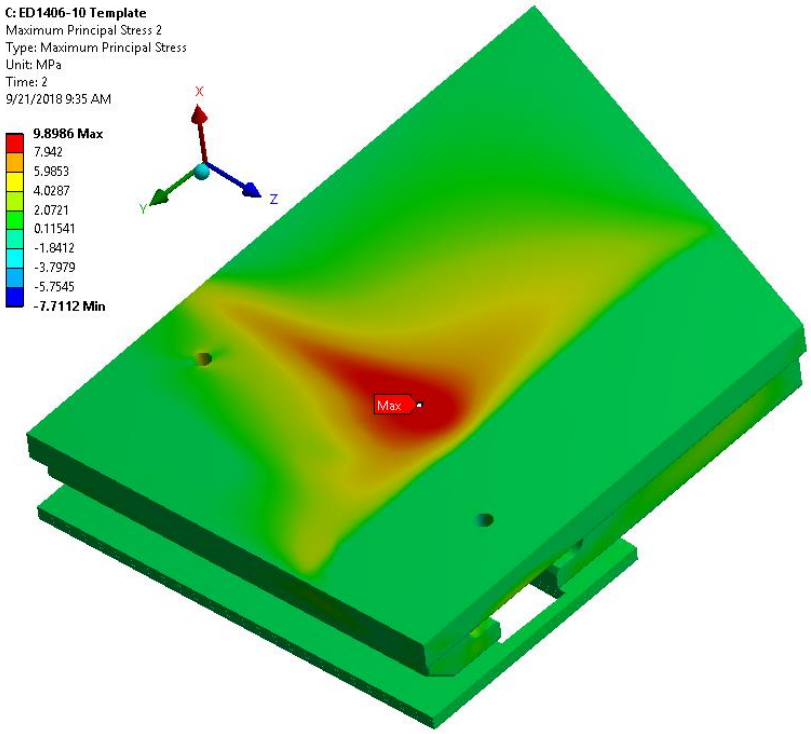


Figure 19: Location of peak maximum principal stress.

The location of peak equivalent stress with bolt preload and the halo load is shown in Figure 61.

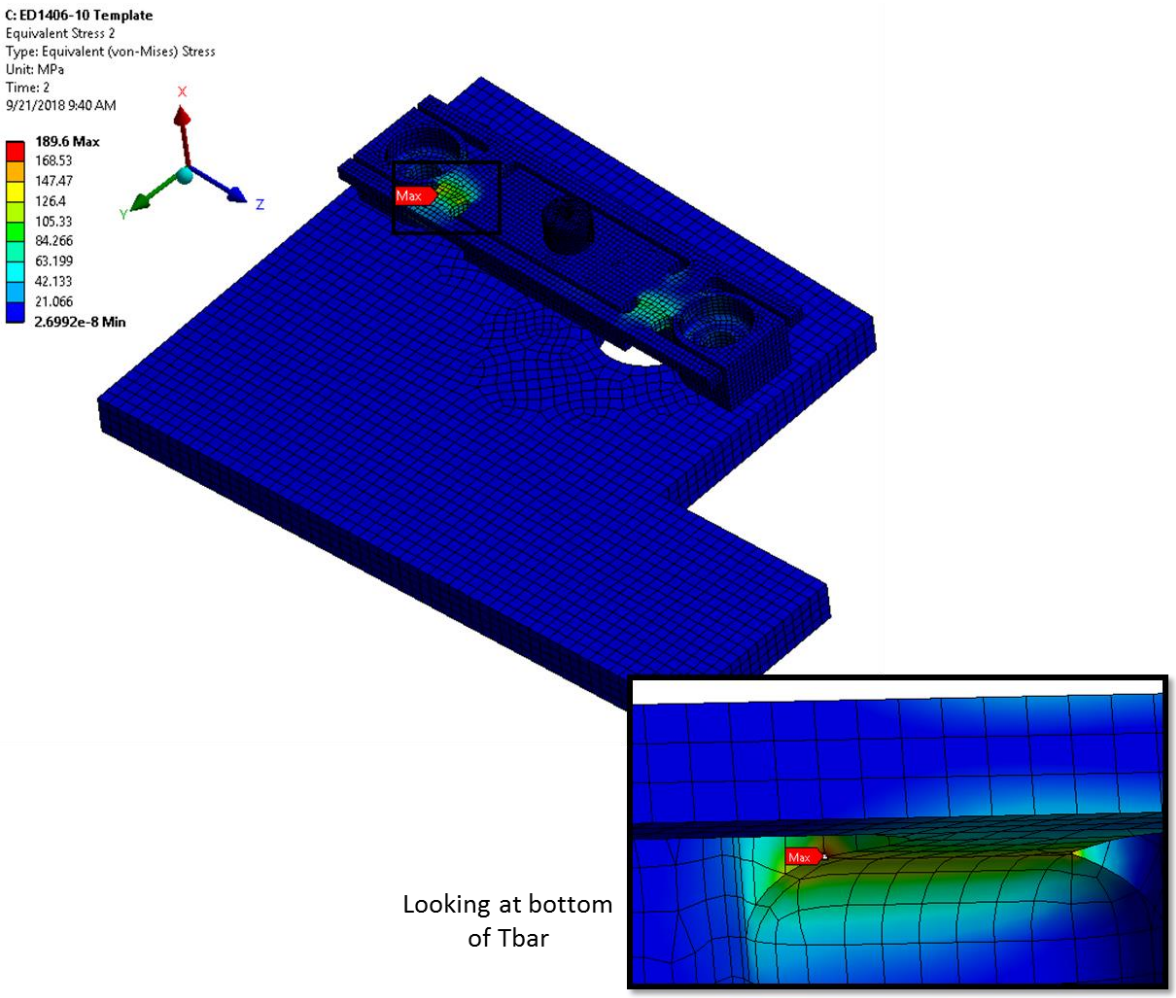


Figure 20: Location of peak equivalent stress for combined loading.

7 Subreport E-ED1406-11 R5 Style 1 PCHERS Lower Bay Chamfered Tile

ORNL Analyst: Dennis Youchison

Summary:

The minimum principal stress and von Mises stress in the Tbar exceeds its allowable. See Figure 59. Consideration should be given to Inconel 718 for this Tbar. Peak stresses in all components are lists in Table 13, Table 14, and Table 15.

The components considered in the analysis are listed below in Figure 43 and Figure 44.

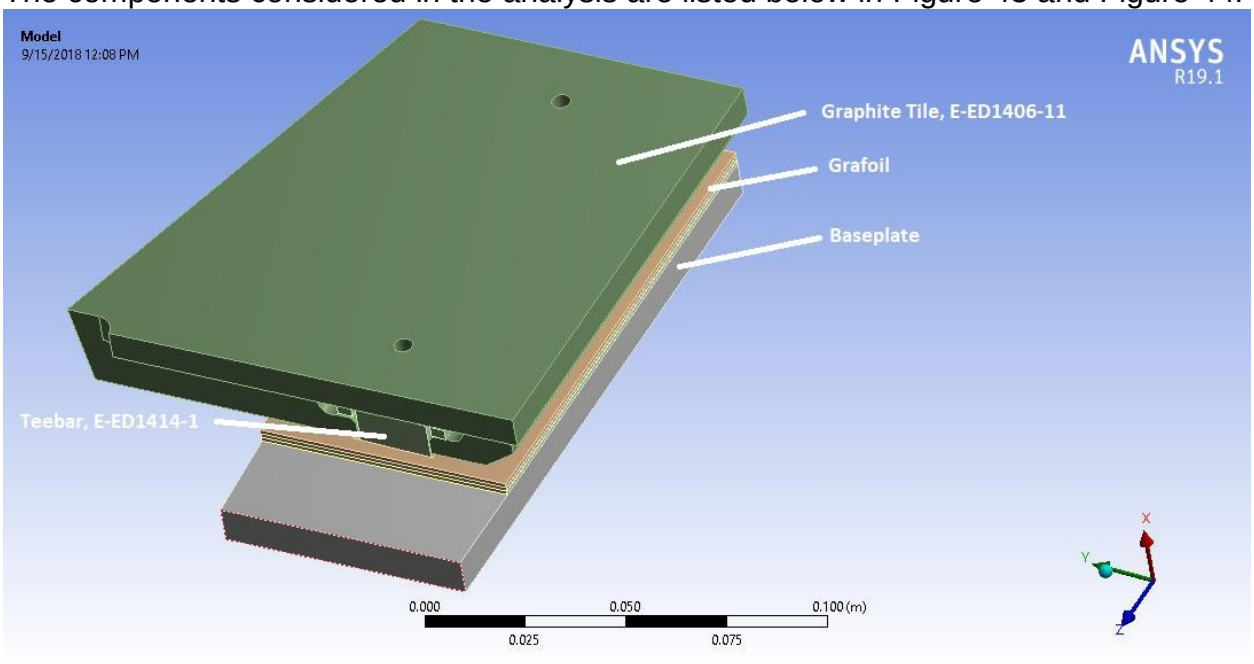


Figure 21: Outboard Diverter Row 5 style 1 variant (1406-11).

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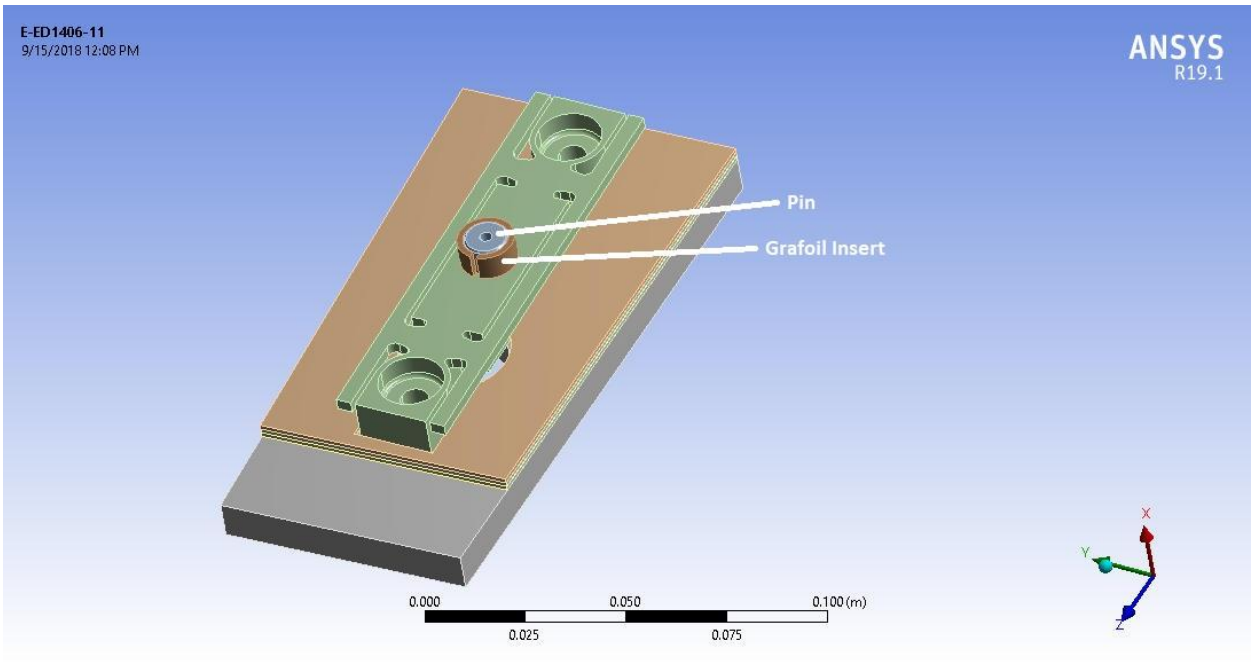


Figure 22: Outboard Diverter Row 5 style 1 variant (1406-11) hardware components considered in analysis.

The total number of elements and nodes for the whole assembly is 204,050 and 398,010 respectively. Figure 45 shows the mesh used in the analysis with and without the graphite tile. Figure 46 shows the mesh of the mounting side of the graphite tile.

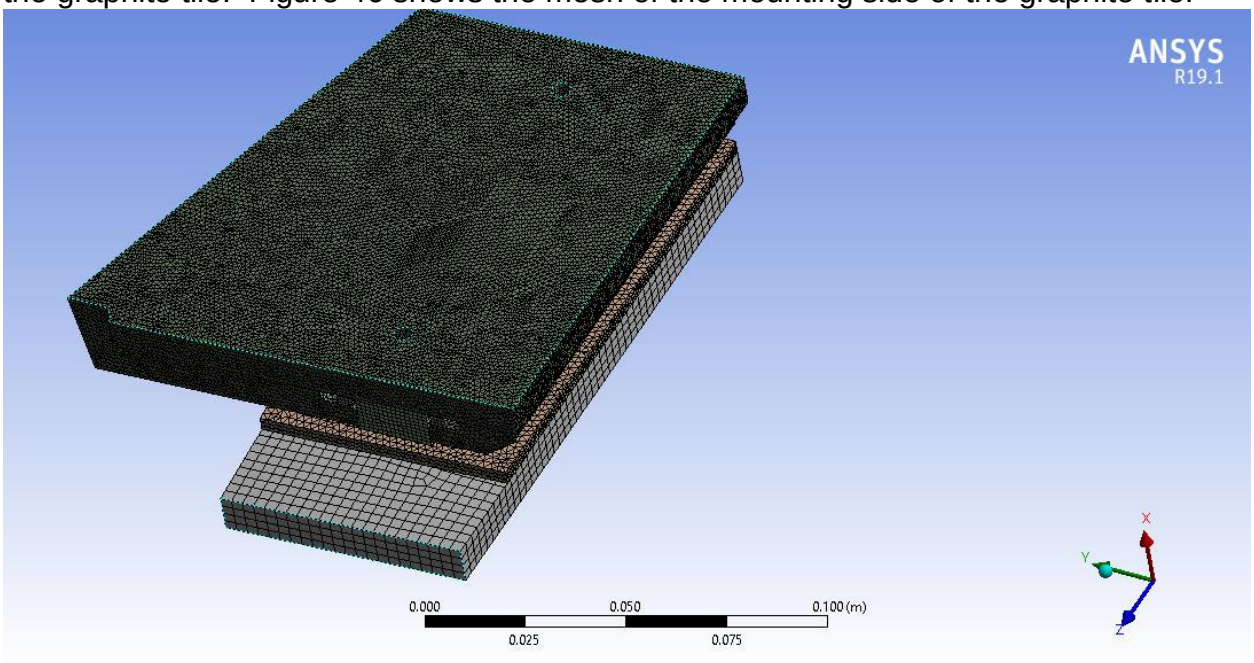


Figure 23: Mesh of the Outboard Diverter Row 5 style 1 variant (1406-11)

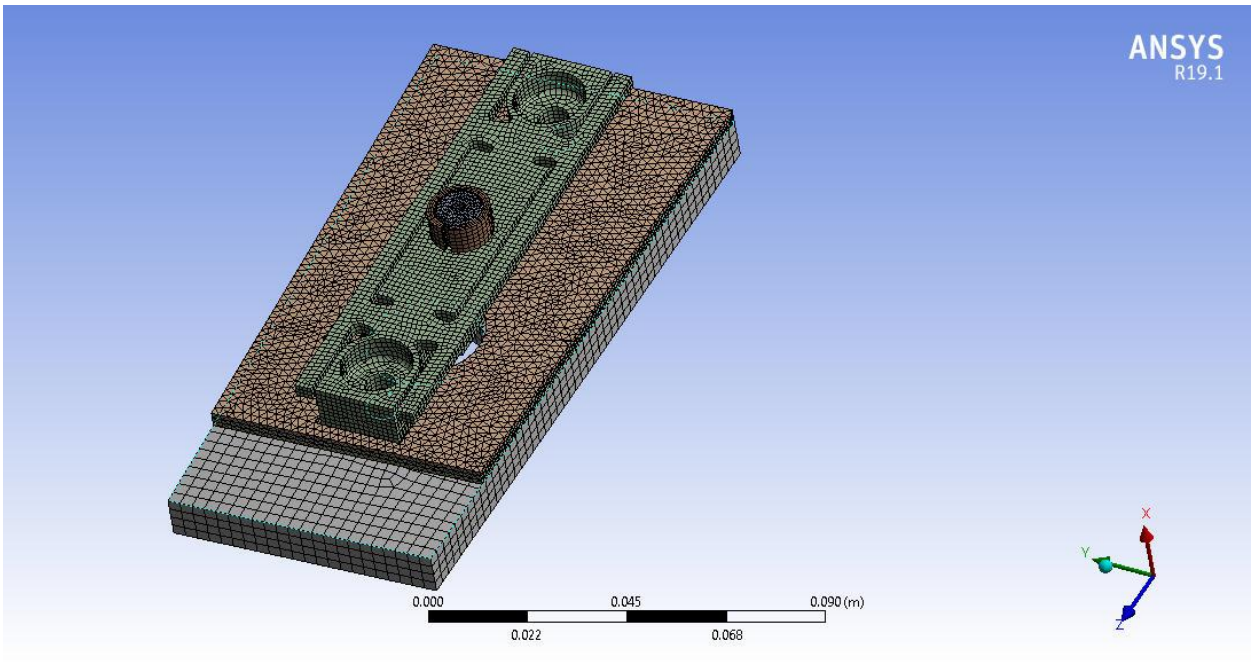


Figure 24: Mesh in hardware.

Table 11 lists each component of the assembly and its material.

Table 6: Components and their materials.

Component	Material
Graphite Tile (E-ED1405-12)	T953
Grafoil	Grafoil
Baseplate	Pure Copper
R45-Grafoil Insert	Grafoil
R45 Pin	Inconel 718
Tbar (ED1414-1)	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis. Figure 25 shows the heat flux distribution across the tile face.

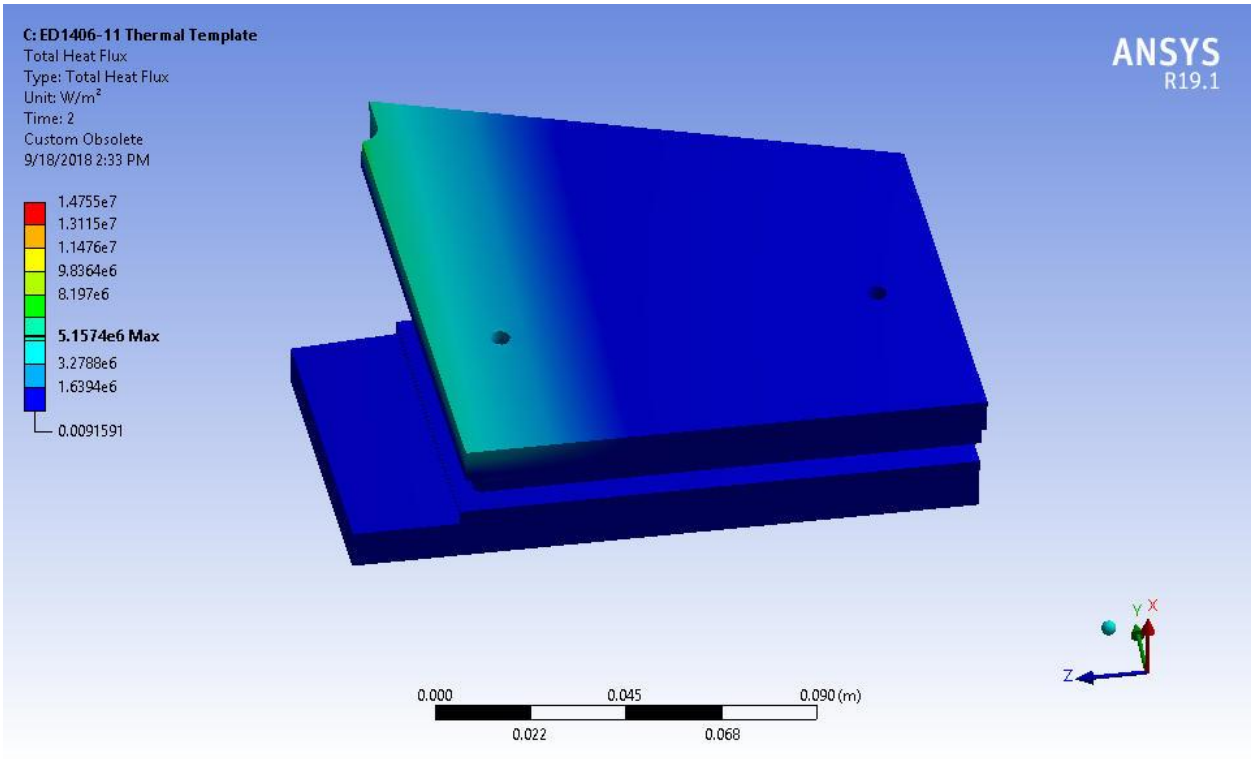


Figure 25. Applied heat flux distribution

Graphite heat flux = 4457468 W/m^2 with a gradient heat flux along the y-direction of –111436707 W/m.

The peak temperature in the assembly was 632 ^{o}C in the graphite tile. Figure 48 and Figure 49 shows the temperature contour as a result of the applied heat fluxes. Table 12 lists the peak temperature for each component.

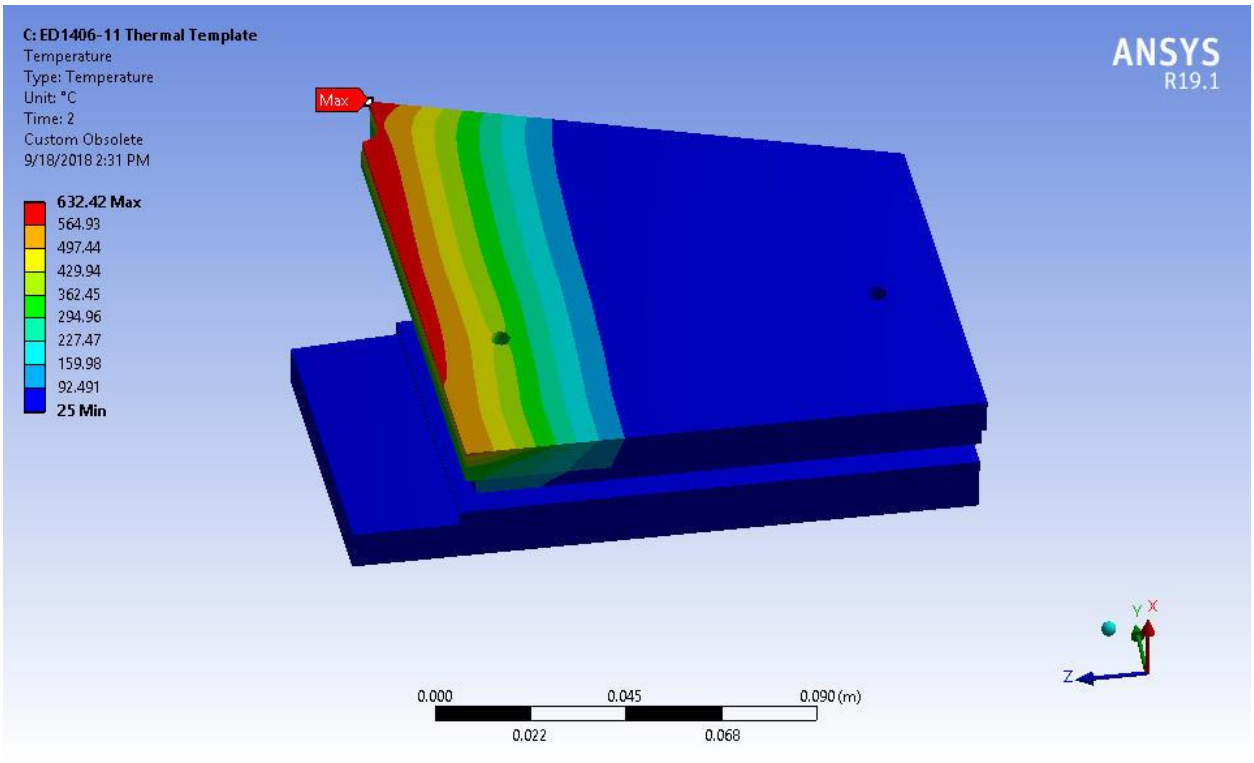


Figure 26: Temperature contour plot of the Outboard Diverter Row 5 style 1 variant (1406-11)

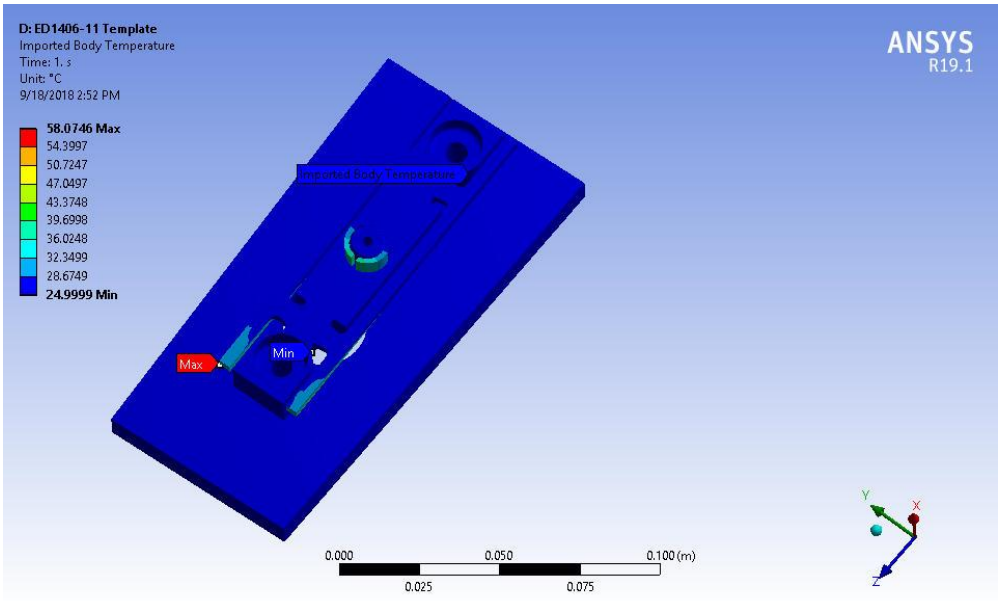


Figure 27: Temperature contour plot of the Outboard Diverter Row 5 style 1 variant (1406-11) without graphite tile

Table 7: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1405-12)	632
Grafoil	25
Baseplate	25
R45-Grafoil Insert	38
R45 Pin	25
Tbar (ED1414-1)	58

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar (ED1414-1) as shown in Figure 50. Figure 51 shows the eddy moment and Figure 30 shows the halo force density loading applied to the graphite tile.

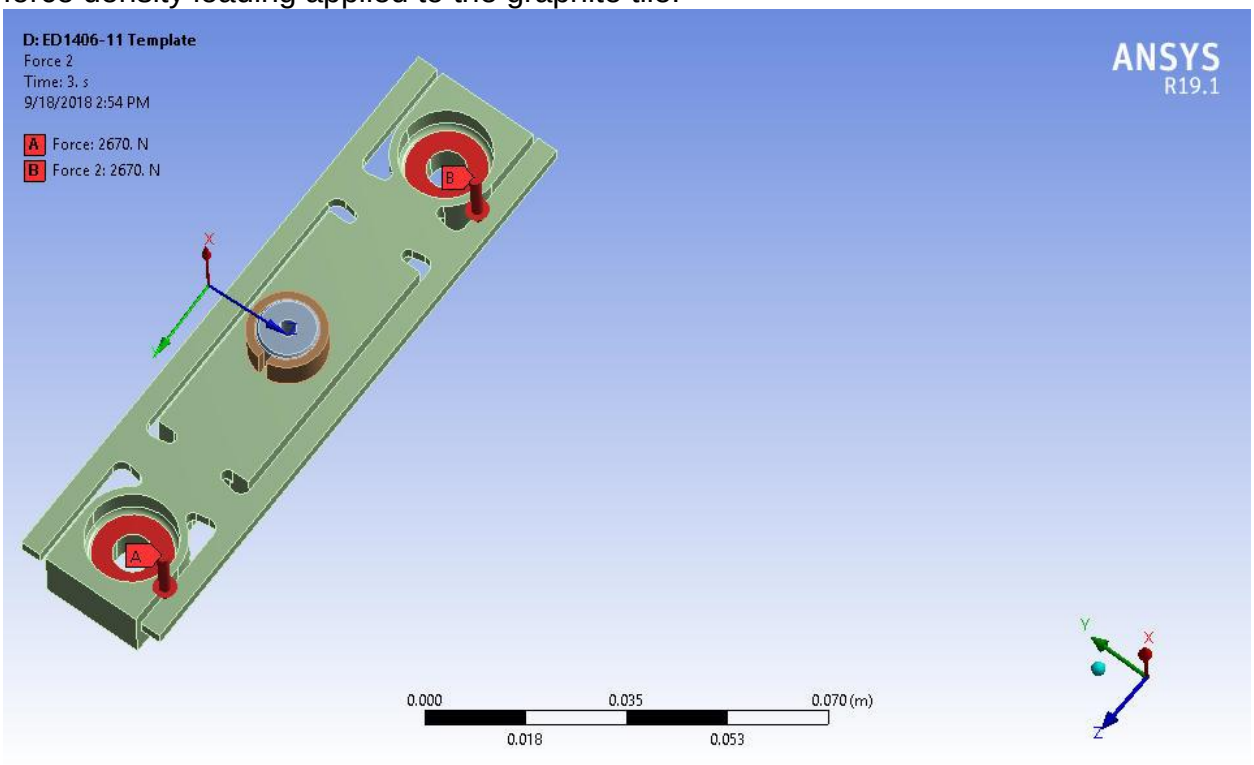


Figure 28: Bolt preload force applied to the Tbar.

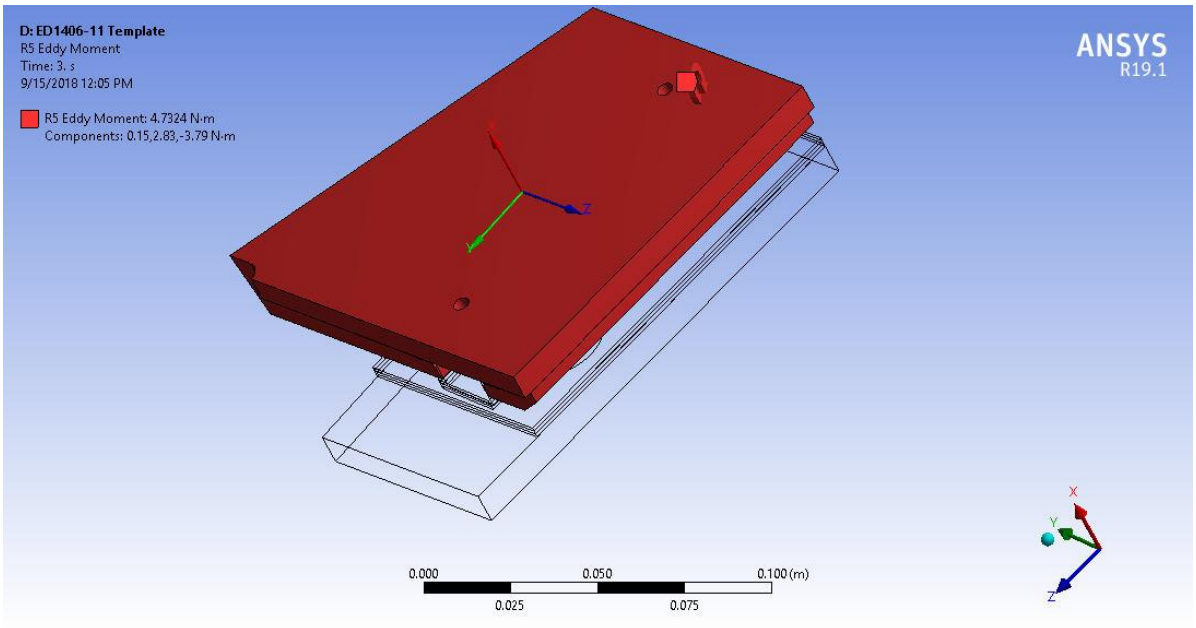


Figure 29: Eddy moment applied to the graphite tile.

Frictionless constraints were applied to three sides of the baseplate and two sides of the grafoil. Figure 52 shows the location of these constraints highlighted in blue.

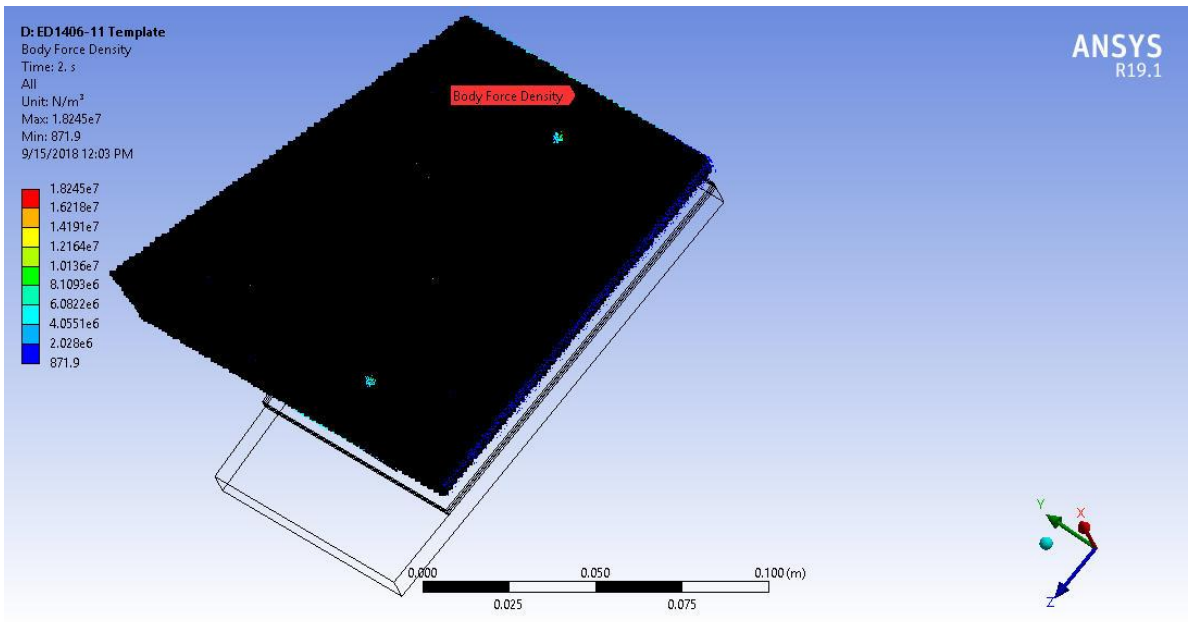


Figure 30. Applied halo force density

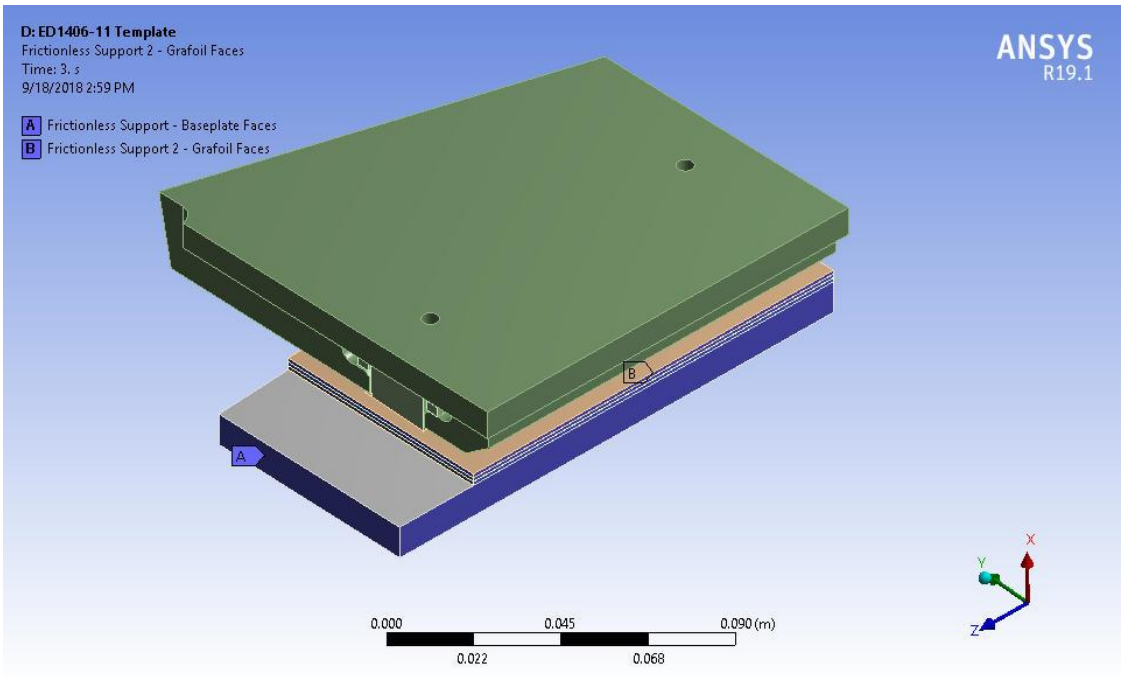


Figure 31: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R45-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1. Figure 53 shows the surfaces in contact with each other labeled A through E.

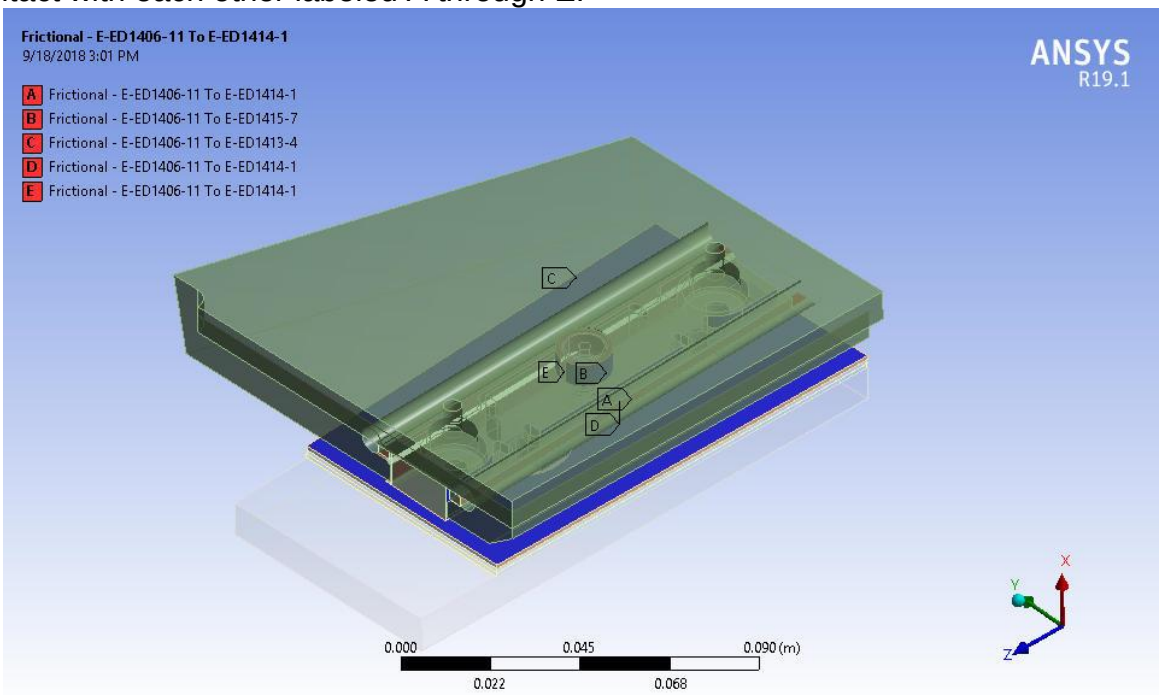


Figure 32: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition. Figure 54 shows the surfaces in contact with each other labeled A through D.

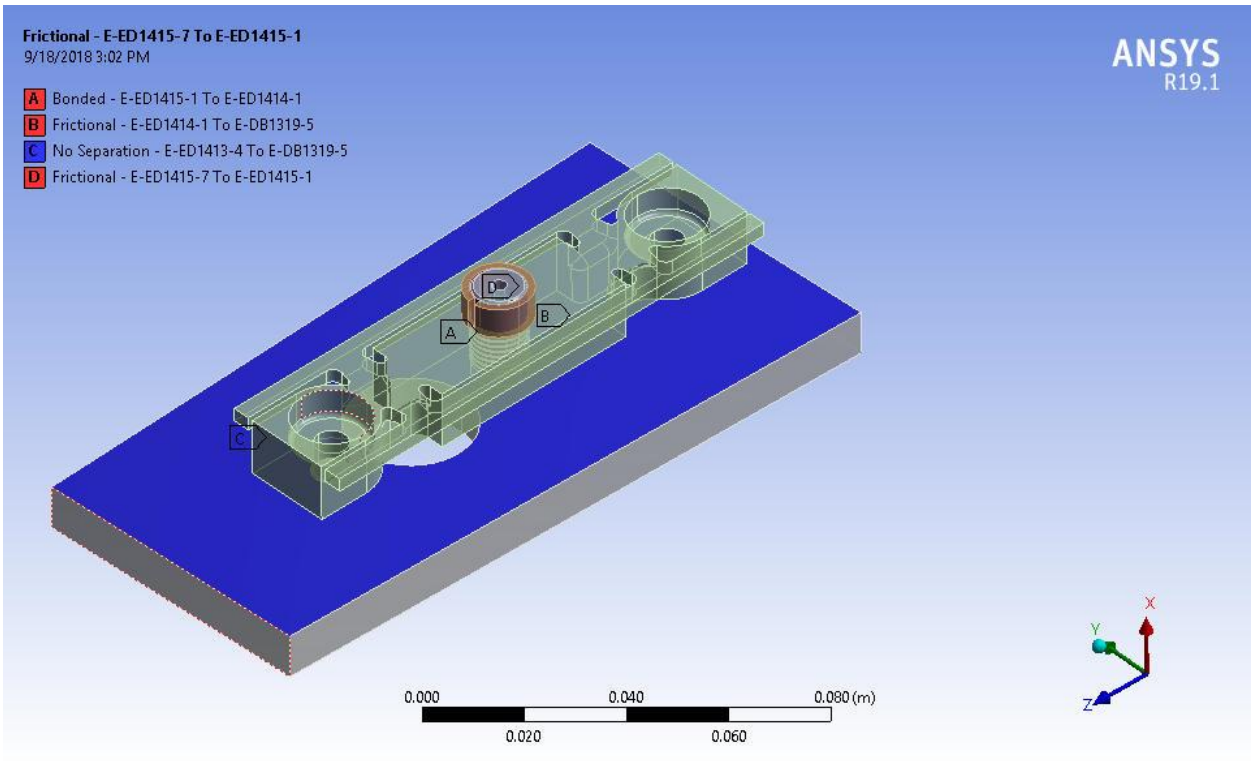


Figure 33: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 55. X, Y, Z deformation contour in the assembly is shown Figure 56, Figure 57, and Figure 58. The minimum principal stresses appear in **Figure 38** while the maximum principal stresses appear in Figure 39.

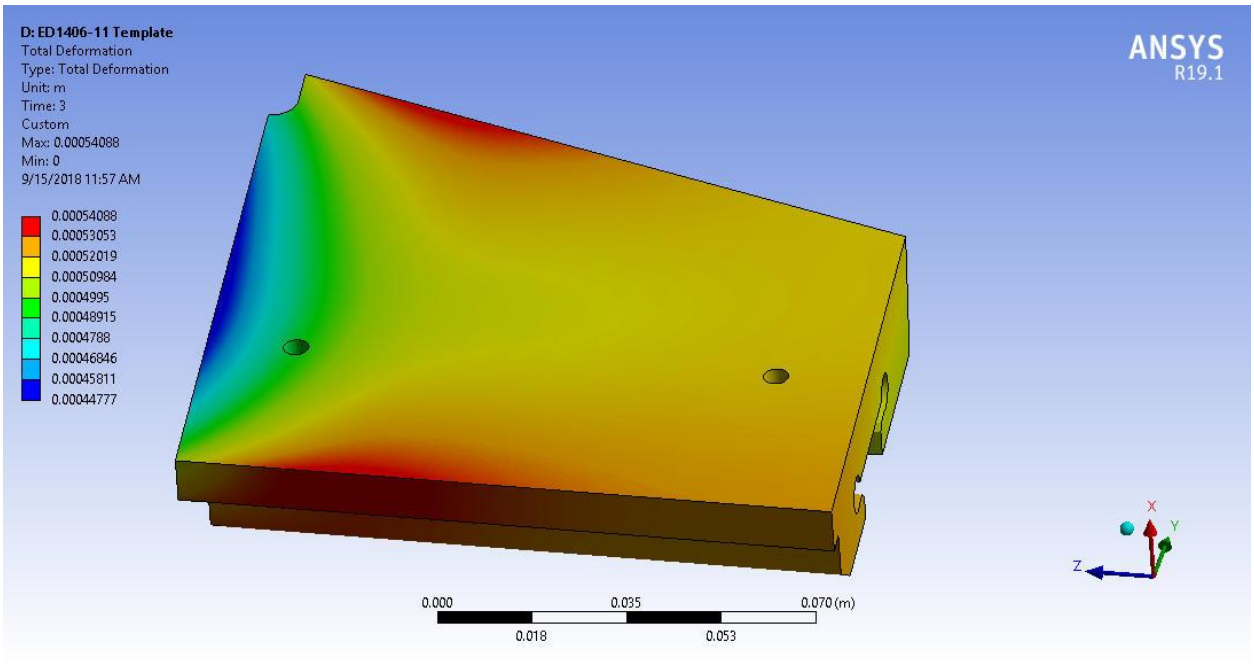


Figure 34: Total deformation of the assembly

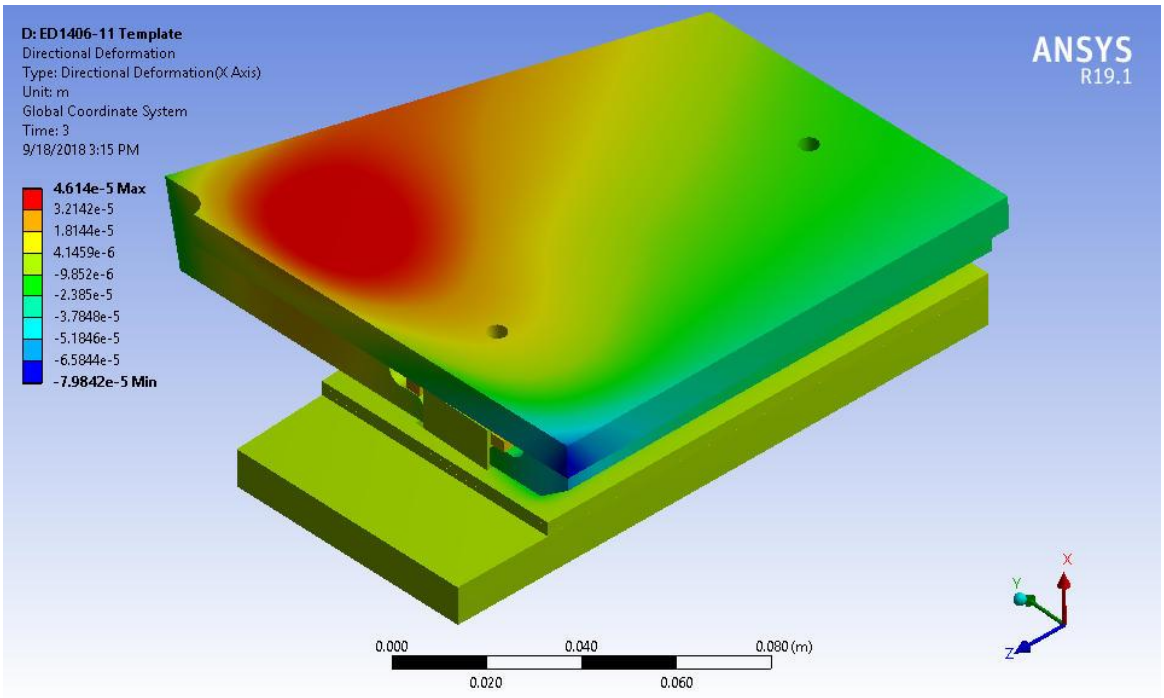


Figure 35: X-direction displacement

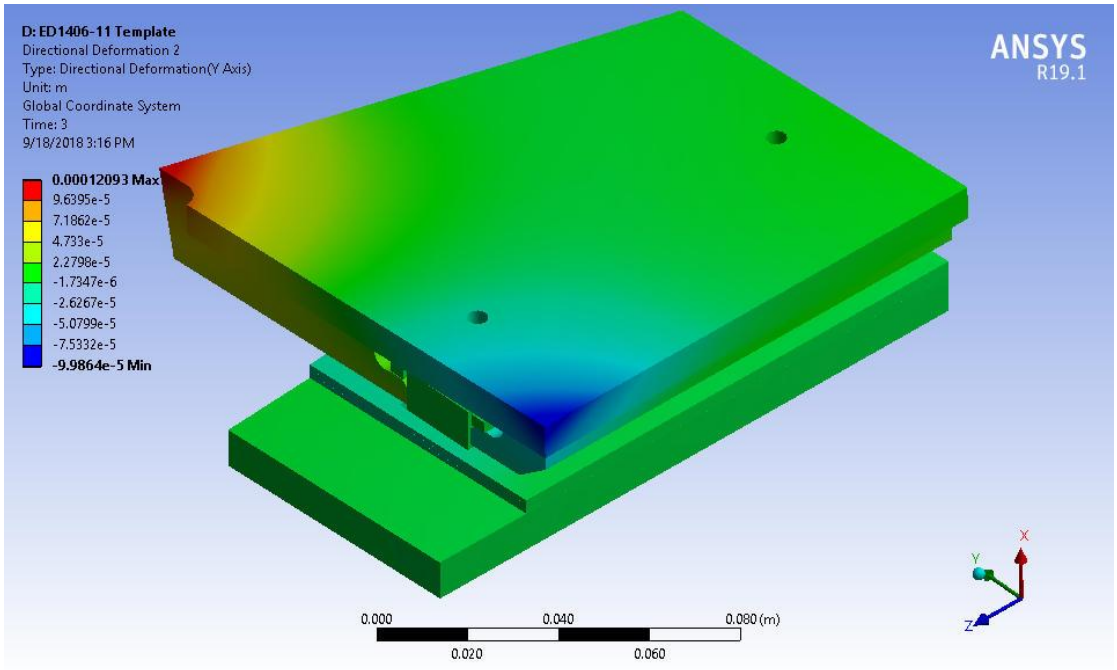


Figure 36: Y-direction displacement

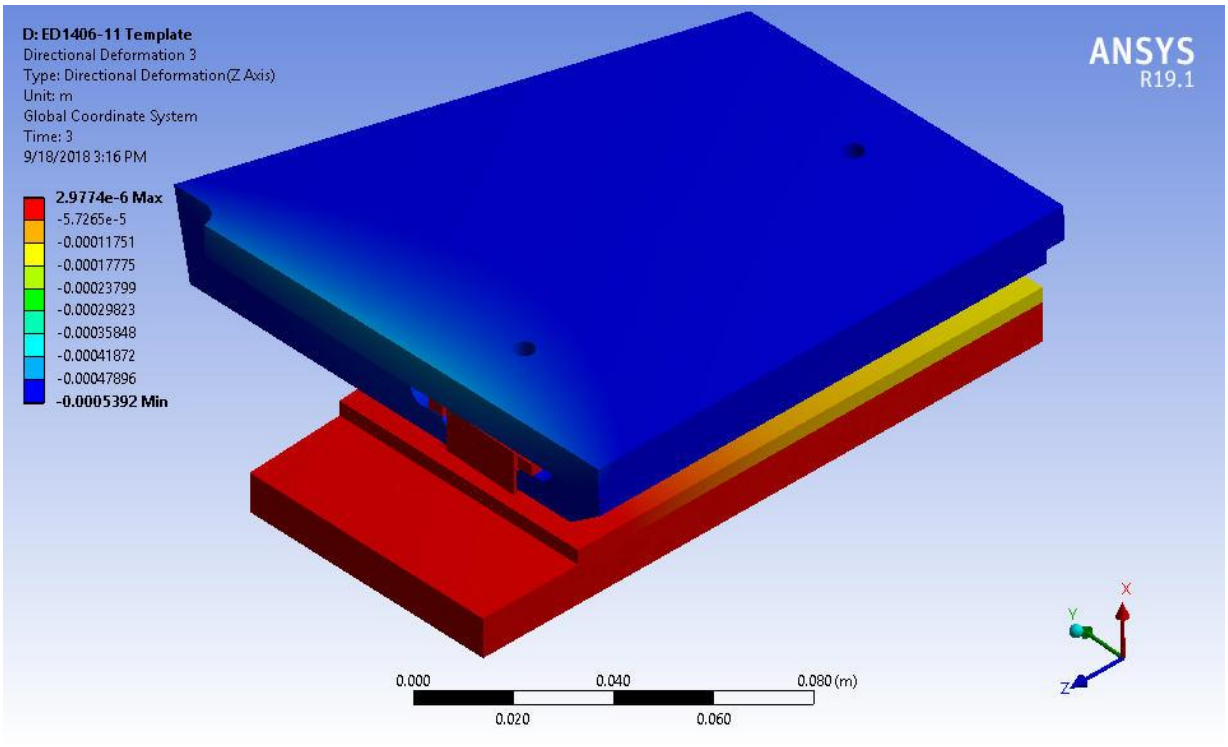


Figure 37: Z-direction displacement

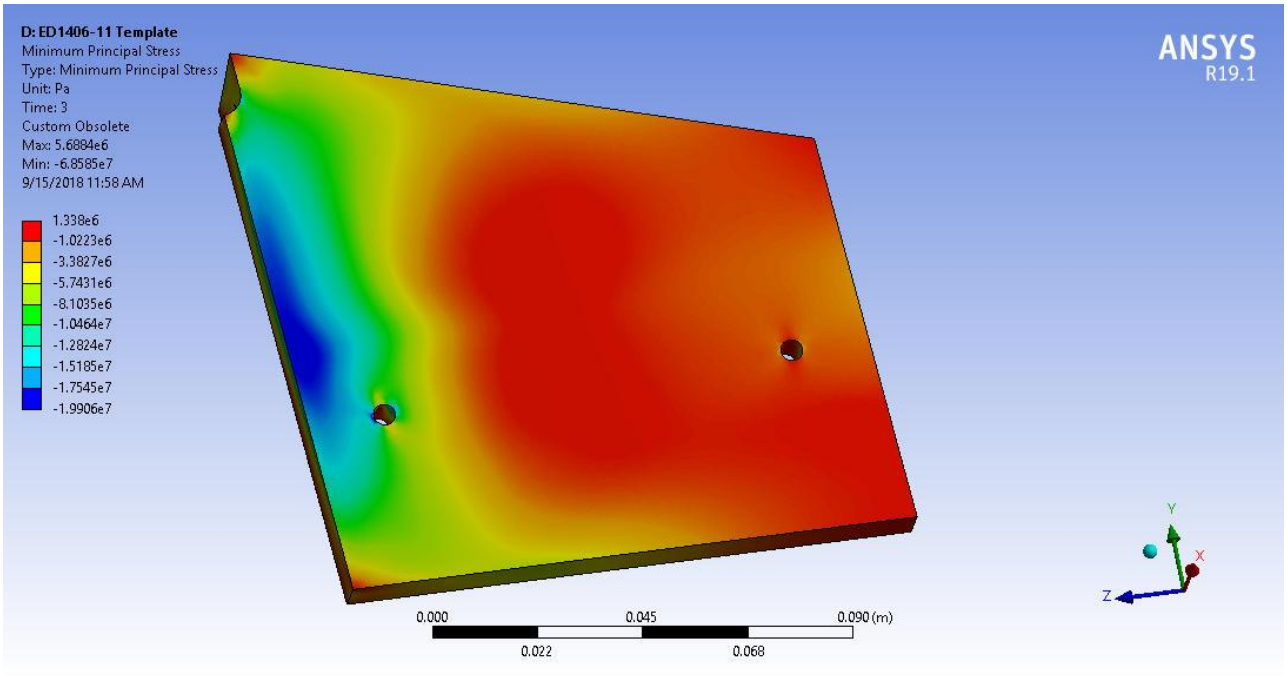


Figure 38. Minimum Principal stress

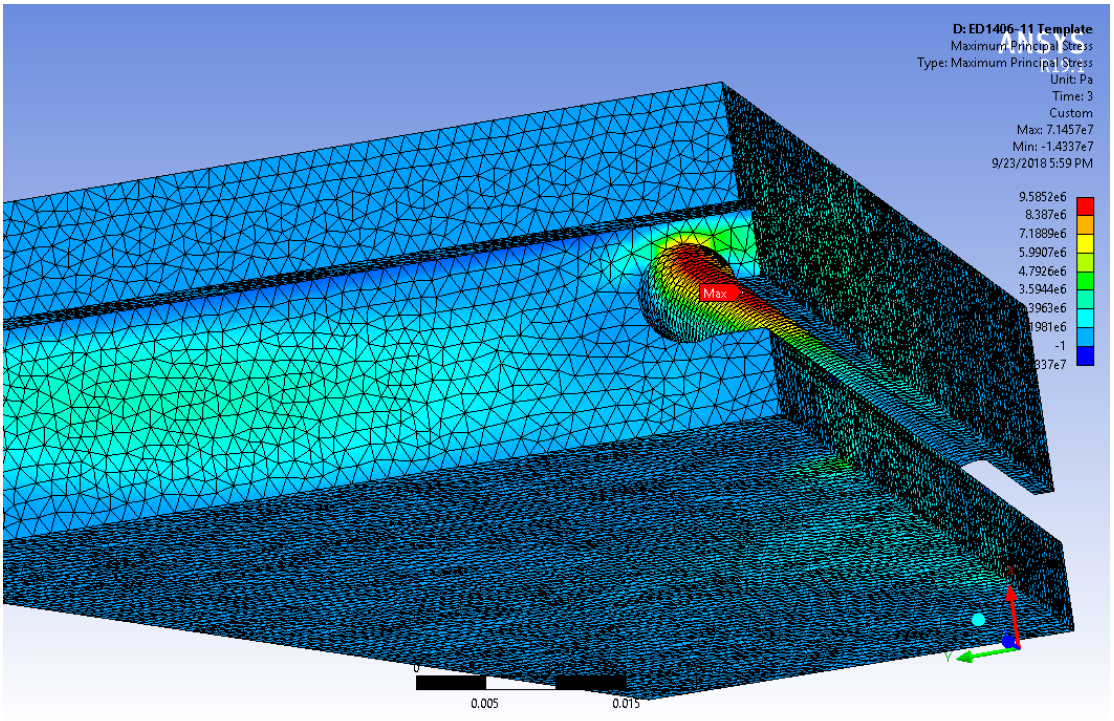


Figure 39. Maximum principal stress

Table 13 and Table 14 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 15 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 8: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1406-11)	9.6	20	BPL+Halo+Eddy
Graphite Tile – Tbar Slot	9.6	20	BPL+Halo+Eddy
Graphite Tile – Shear Pin Hole	4.95	20	BPL+Halo+Eddy
Grafoil	0.3	20	BPL+Halo+Eddy
R45-Grafoil Insert	3.2	20	BPL+Halo+Eddy

Table 9: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1406-11)	-19	-55	BPL+Halo+Eddy
Graphite Tile – Tbar Slot	-48	-55	BPL+Halo+Eddy
Graphite Tile – Shear Pin Hole	-3.5	-55	BPL+Halo+Eddy
Grafoil	-0.6	-55	BPL+Halo+Eddy
R45-Grafoil Insert	-12.5	-55	BPL+Halo+Eddy

Table 10: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	15.4	33.5	BPL+Halo+Eddy
R45 Pin	15.3	720	BPL+Halo+Eddy
Tbar (ED1414-1)	71.7	261	BPL+Halo+Eddy

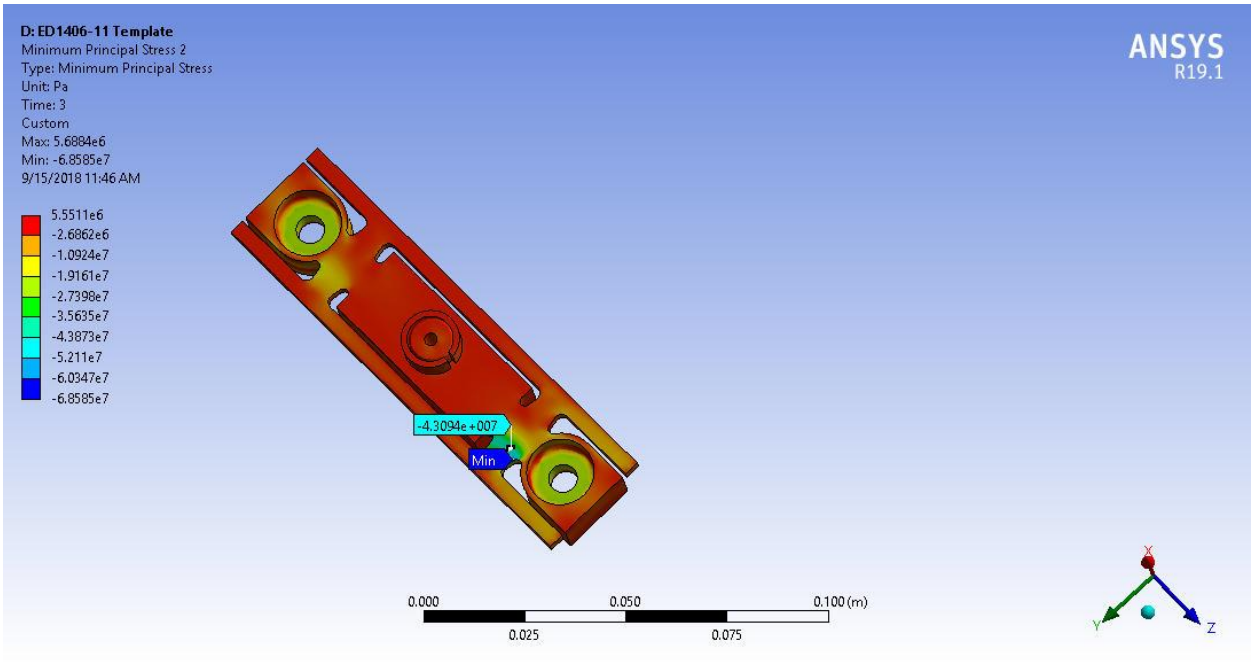


Figure 40: Location of peak minimum stress in Tbar

The maximum principal stress occurred in the Tbar as shown in Figure 60.

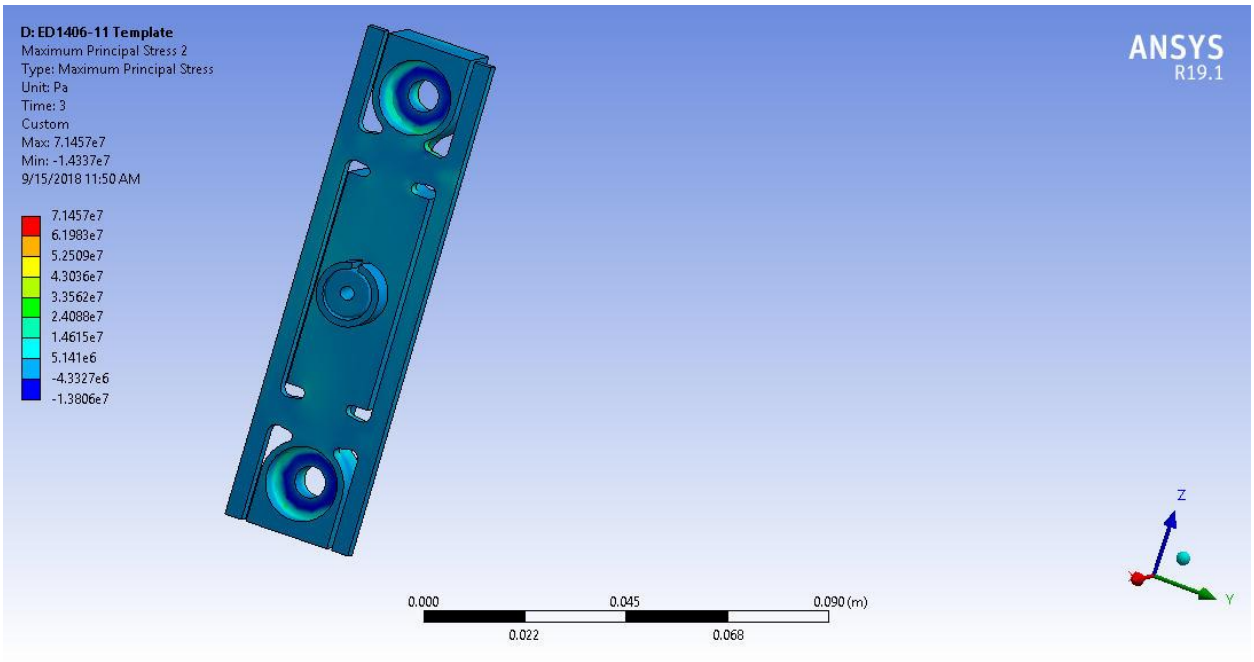


Figure 41: Location of peak maximum principal stress.

The peak equivalent stress for combined loading is shown in Figure 61.

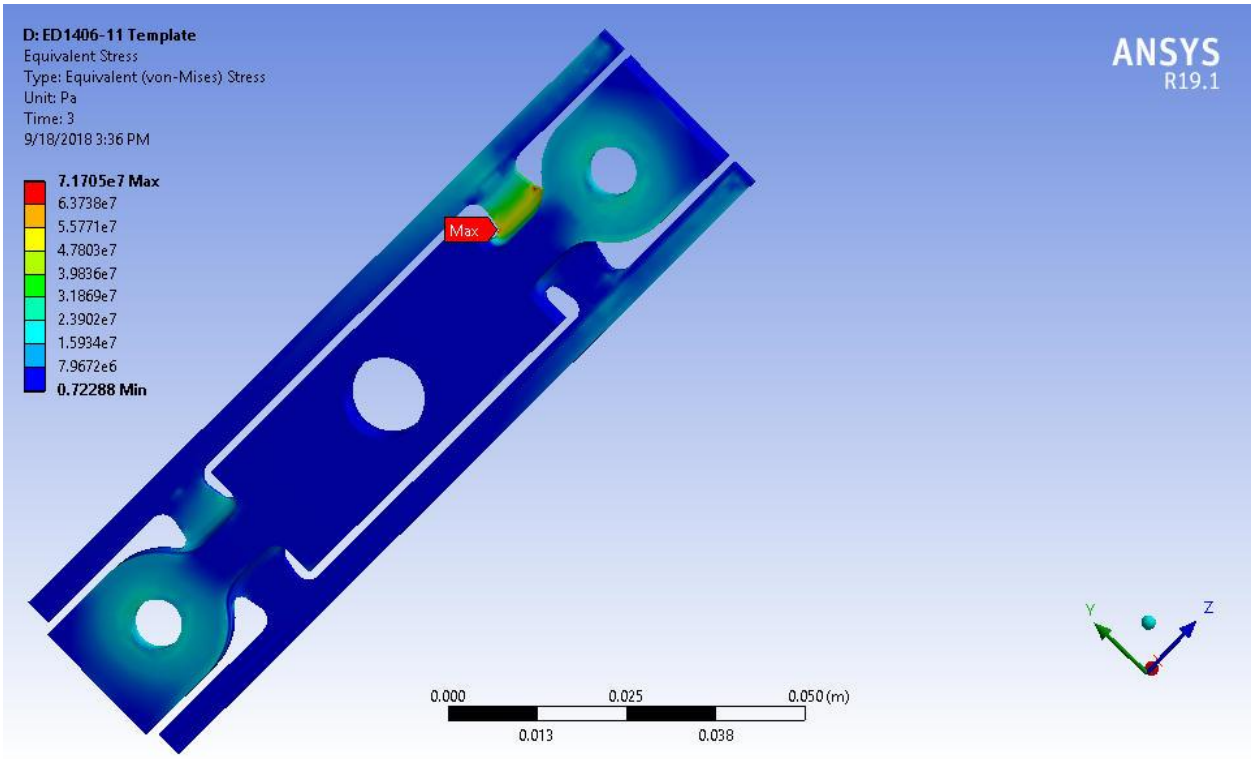


Figure 42: Location of peak equivalent stress for combined loading.

8 Subreport E-ED1407-1 R5 Style 2 Base Tile

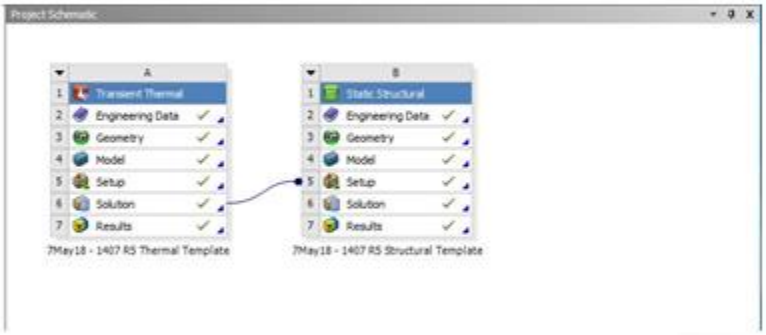
OBD345 R5, S2 round 1
E-ED1407-1
Base Tile update

PPPL NSTX-U PFCs

Dennis Youchison
May 10, 2018

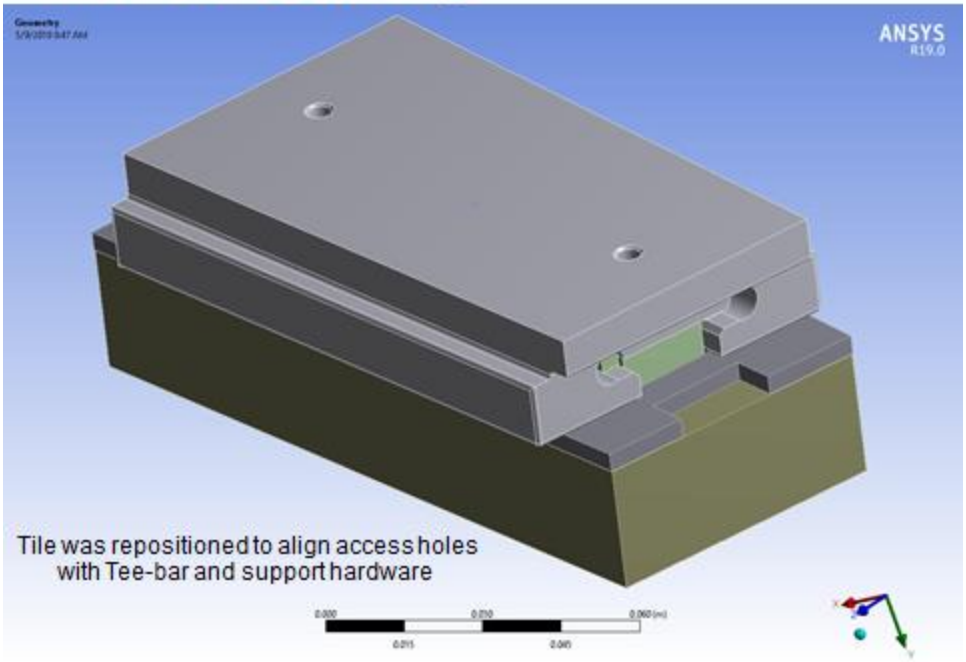
OAK RIDGE National Laboratory

OBD345 R5, S2 round 1
Base Tile, E-ED1407-1,
Material T953

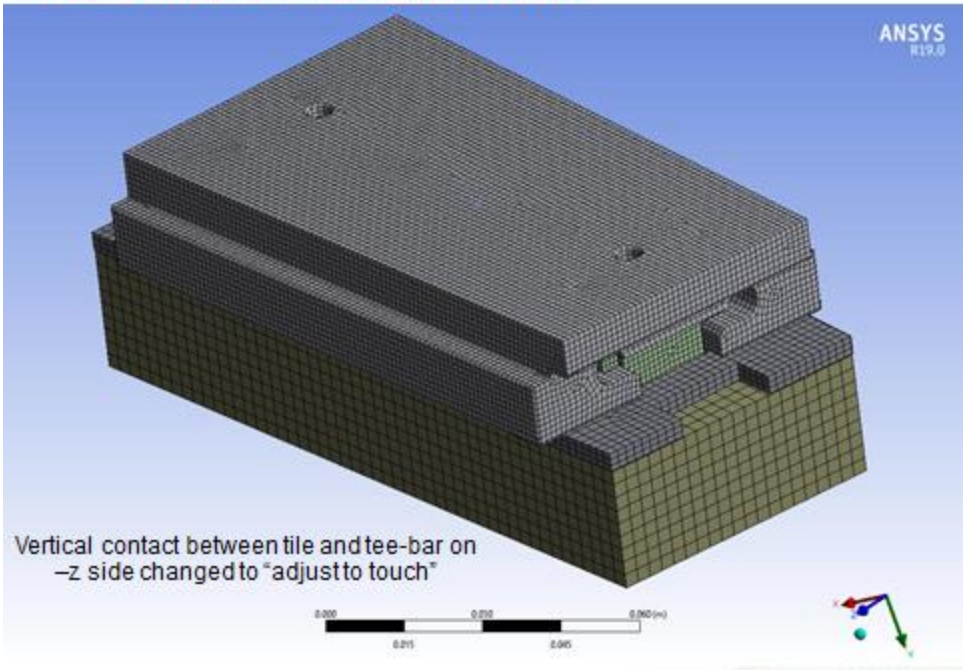


OAK RIDGE National Laboratory

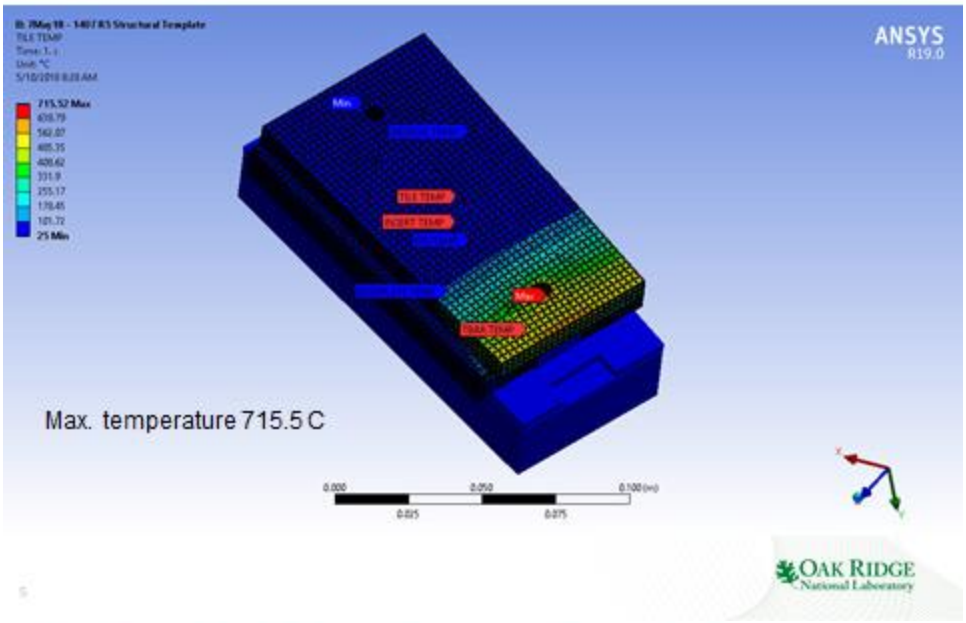
Base Tile Geometry



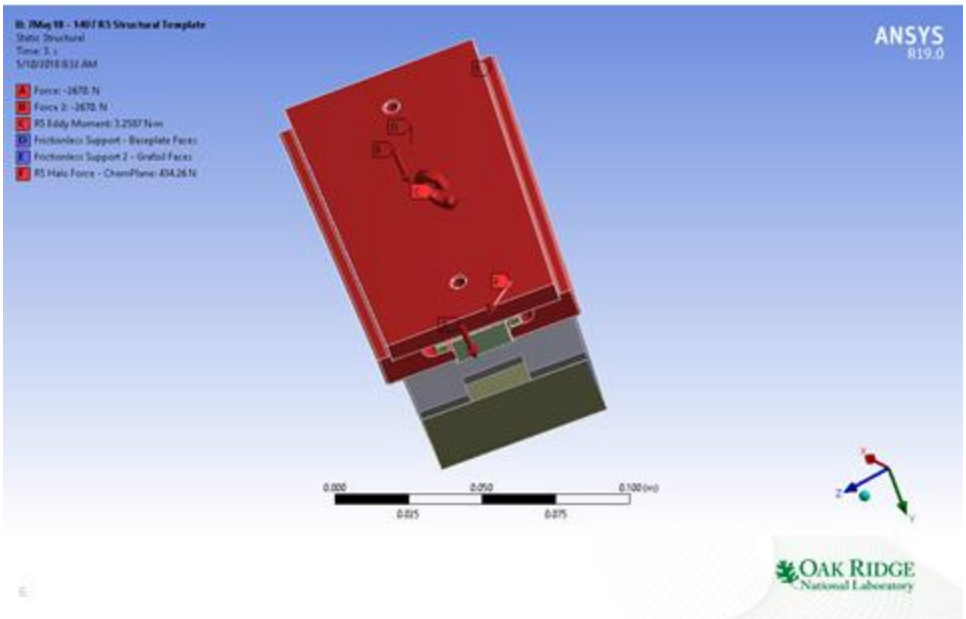
Mesh 132k Hex Dominant



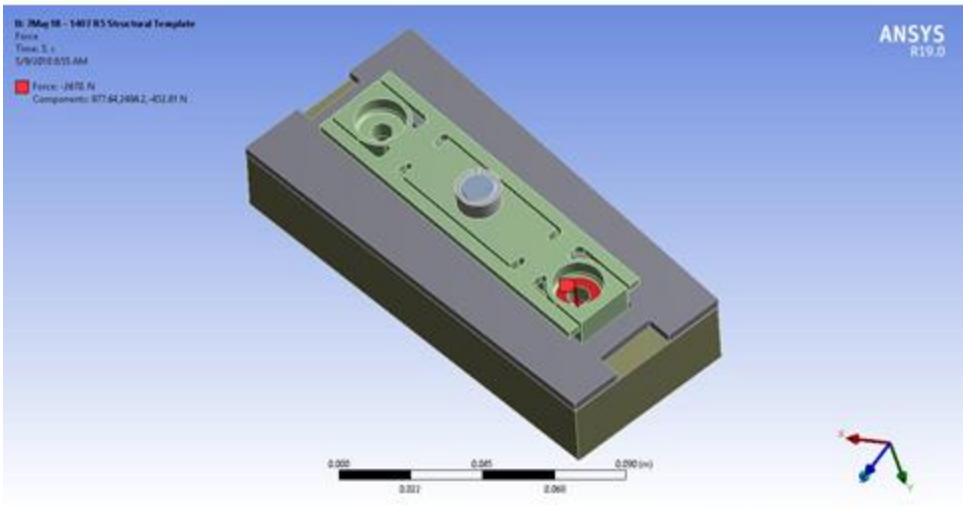
Mapped SS Temperature Loads



Mechanical Loads, step 3, t=3.0s



Force 1 defined



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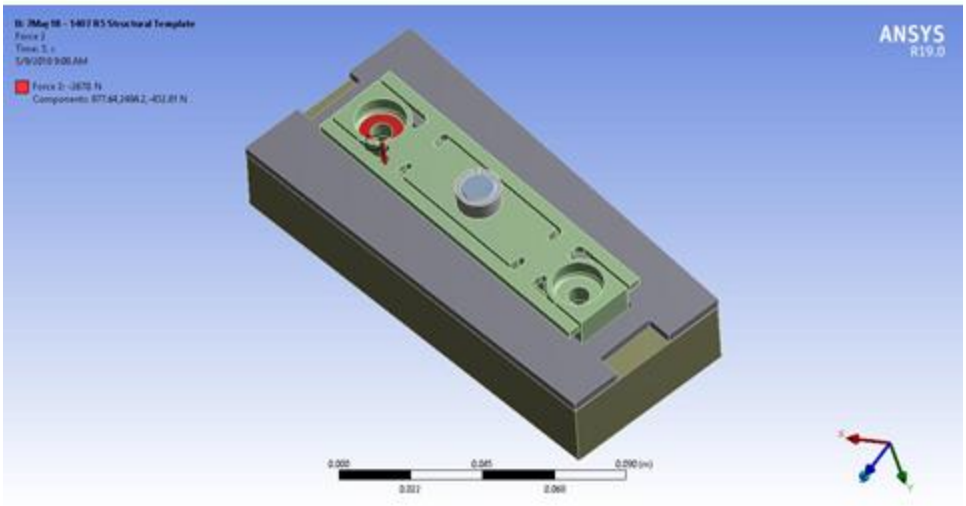
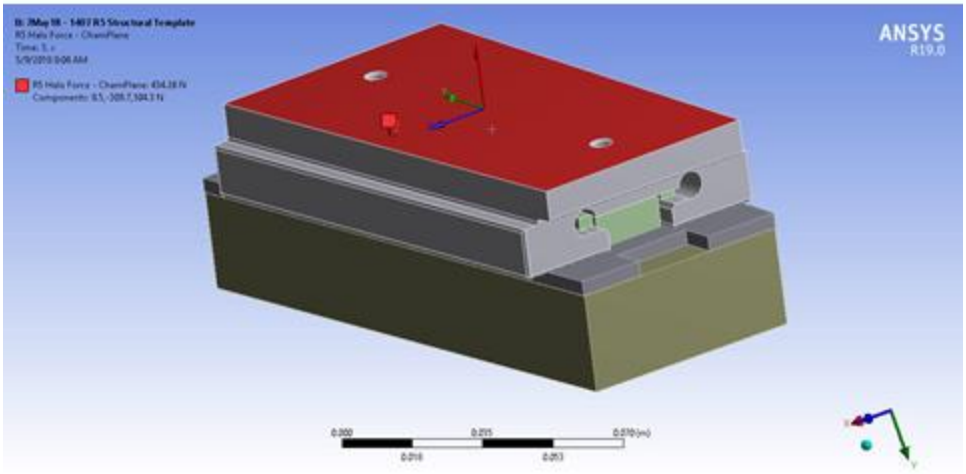
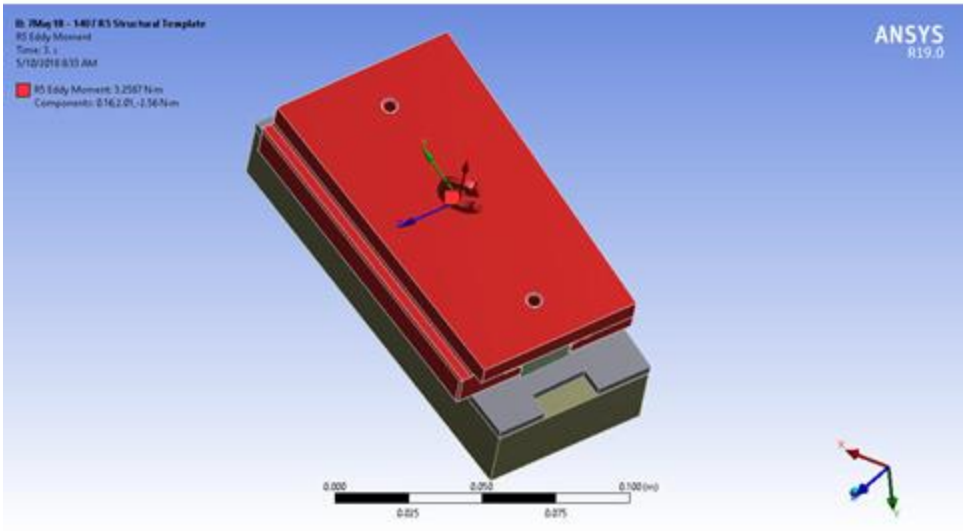
Force 2 defined



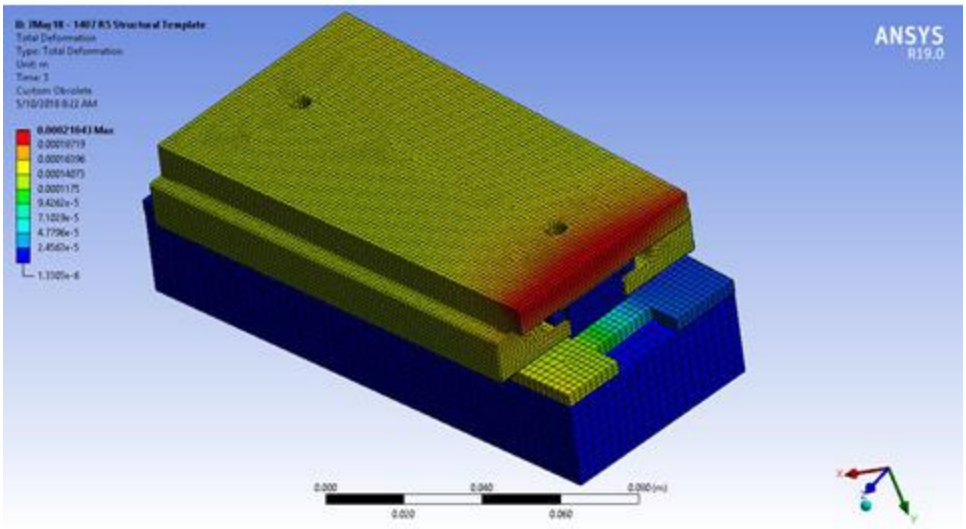
Halo Forces



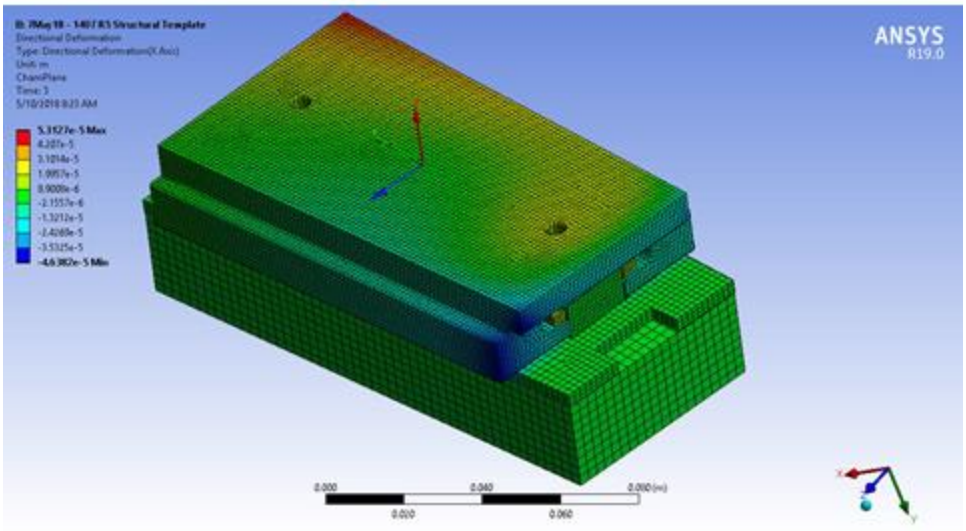
Eddy Moment



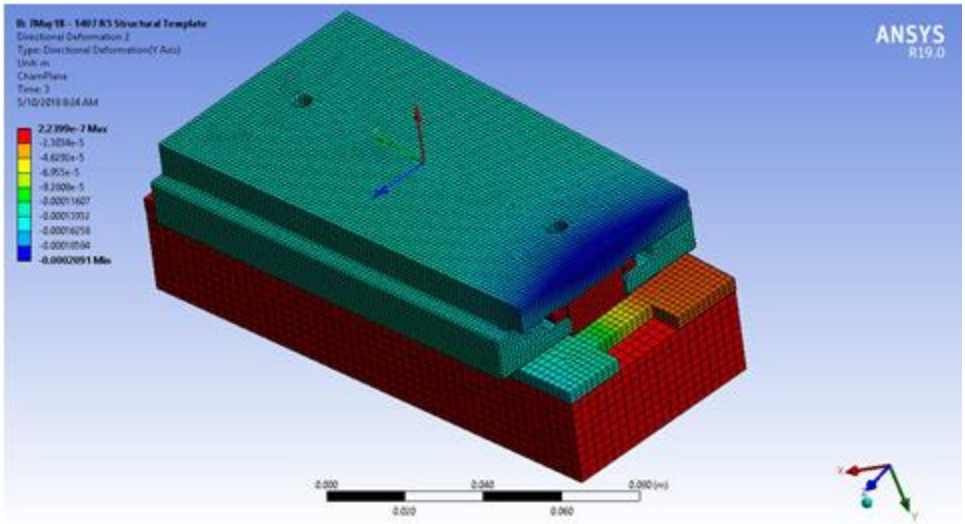
Total Deformation



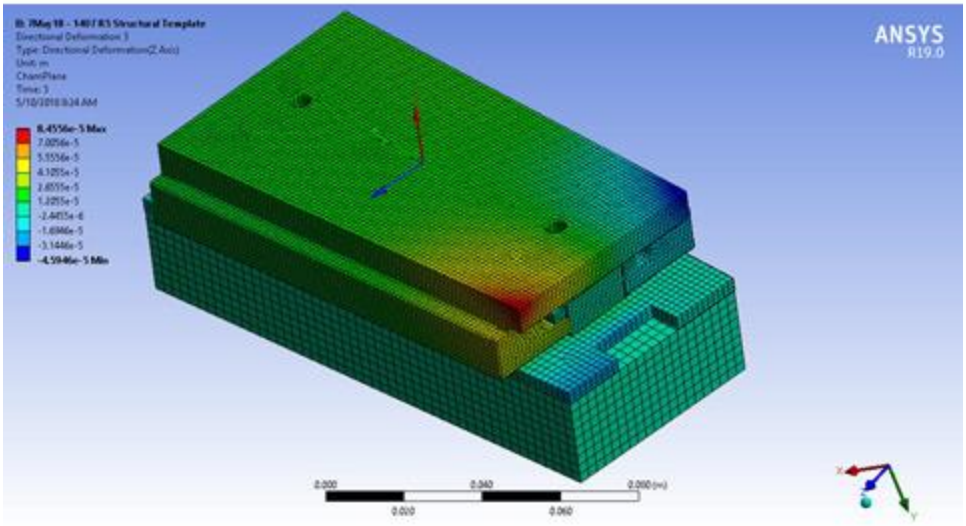
X-deformation from ChamPlane Origin



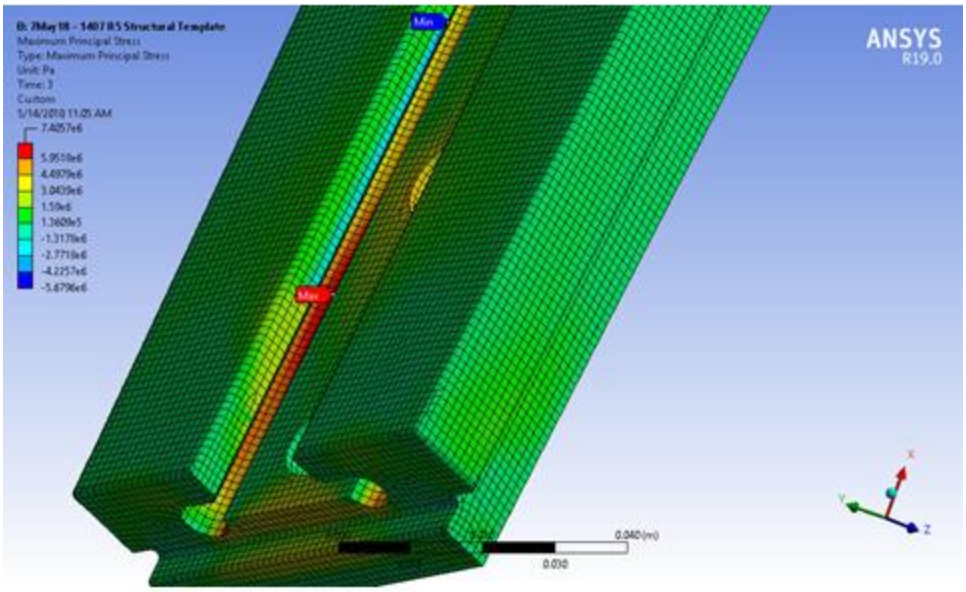
Y-deformation from ChamPlane Origin



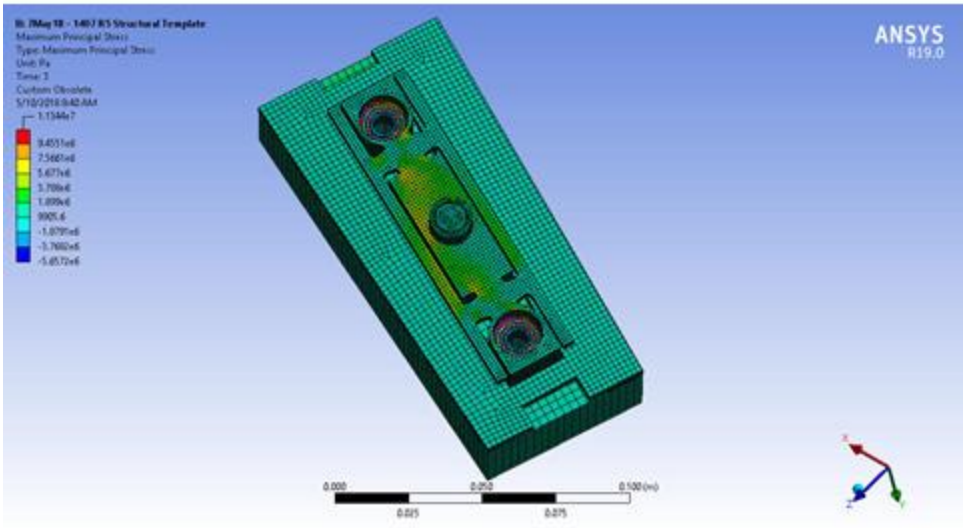
Z-deformation from ChamPlane Origin



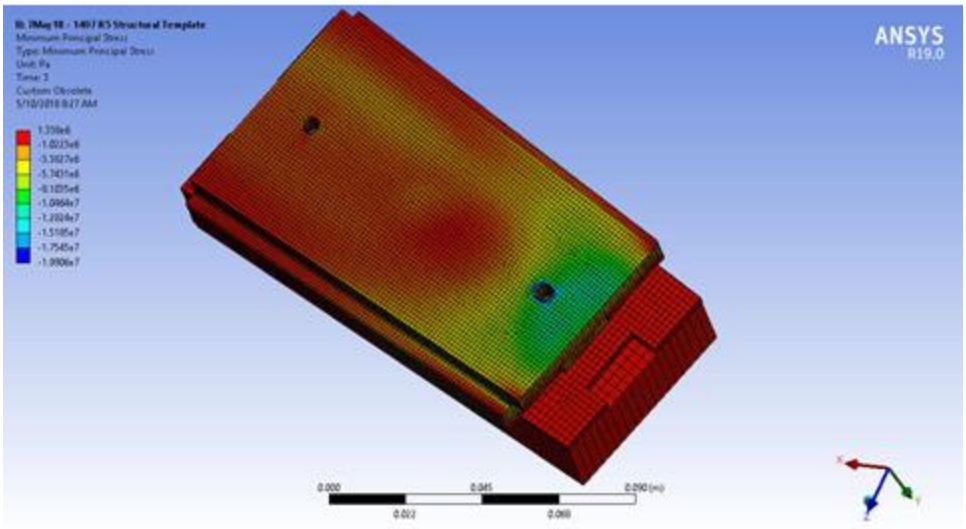
Maximum Principal Stress



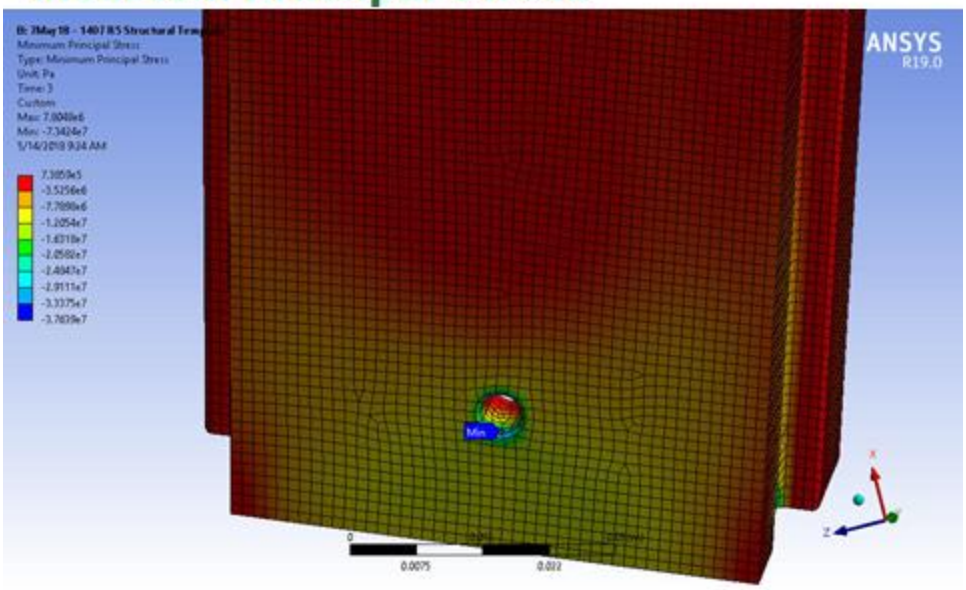
Maximum Principal Stress



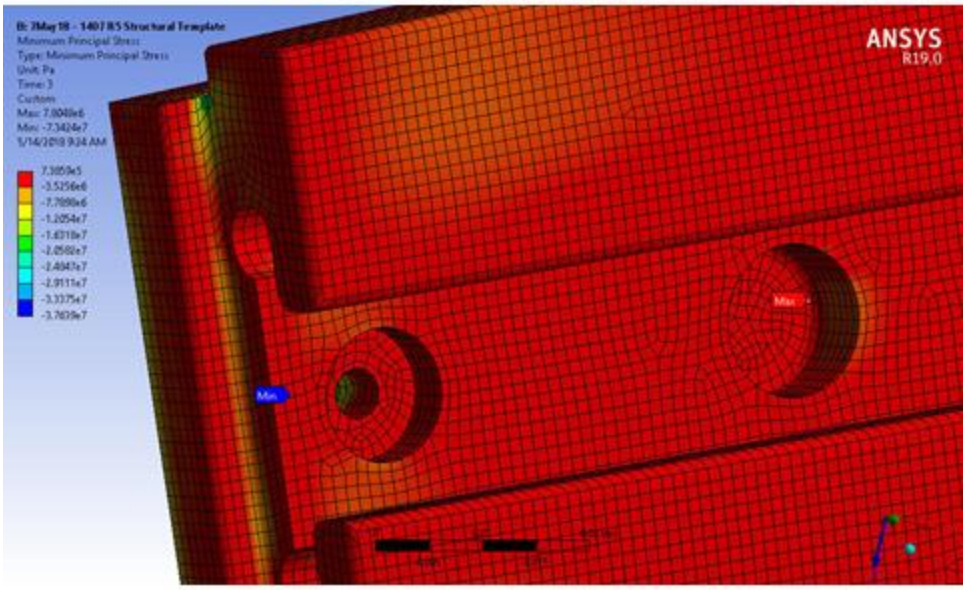
Minimum Principal Stress



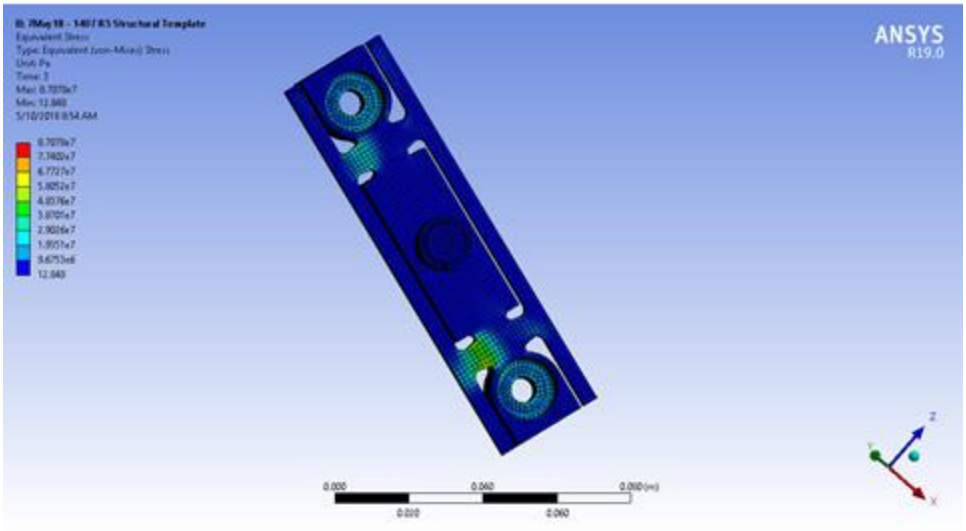
Minimum Principal Stress



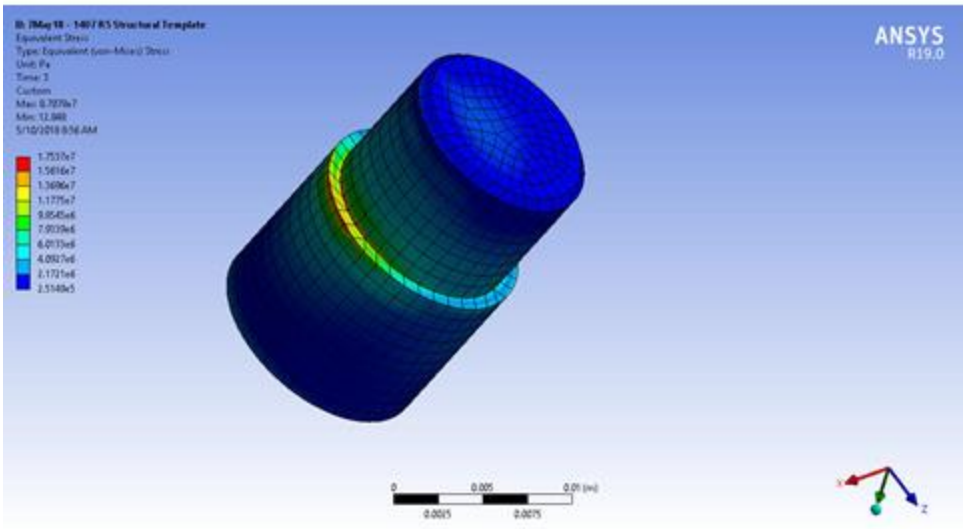
Minimum Principal Stress in Shear Pin Hole



Von Mises Stress in Tbar



Von Mises Stress in Pin



Summary

<u>Tile</u>
S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 Mpa
S1 allowable = 20 MPa

Max. principal stress was 7.4 MPa and the Min. principal stress was 37.6 MPa
SF>1.5

<u>Teebar</u>
UTS of In625 is 782 MPa
$1/3\sigma_{UTS}$ In625 = 261 MPa
$2/3\sigma_{YS}$ In625 = 266 MPa

Max. von Mises stress was 87.1 MPa: SF~3

9 Subreport E-ED1407-5 R5 Style 2 Langmuir Probe Variant

ORNL Analyst: Jason Cook

Summary:

The minimum principal stress in the chamfer of one of the bolt holes exceeds its allowable. See Figure 59. I do not have allowable stress values for pure copper or Inconel 718. Peak stresses in all components are lists in Table 13, Table 14, and Table 15.

The components considered in the analysis are listed below in Figure 43 and Figure 44.

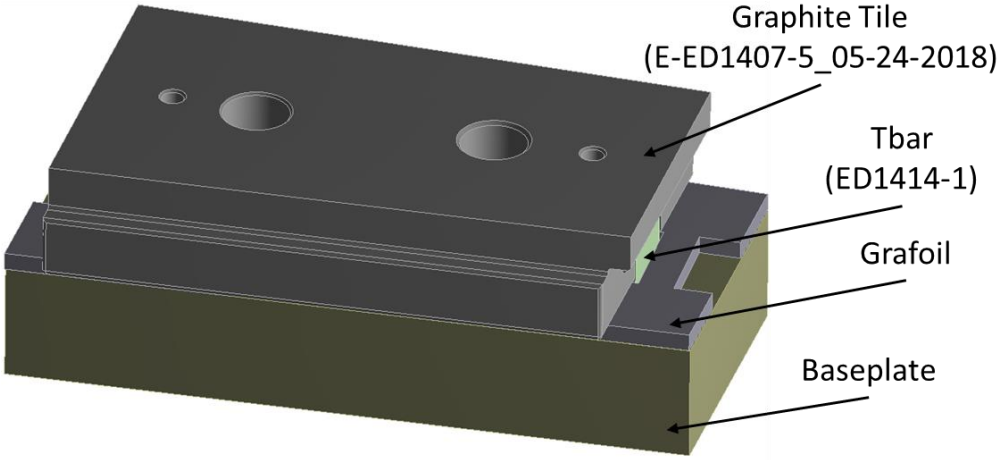


Figure 43: Outboard Diverter Row 5 style 2 variant (1407-5) Outboard Diverter Row 5 style 2 variant (1407-5).

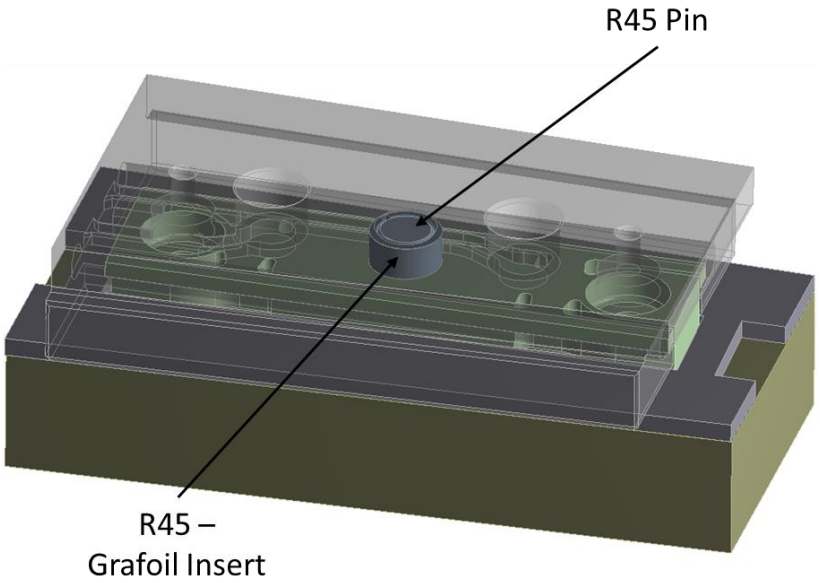
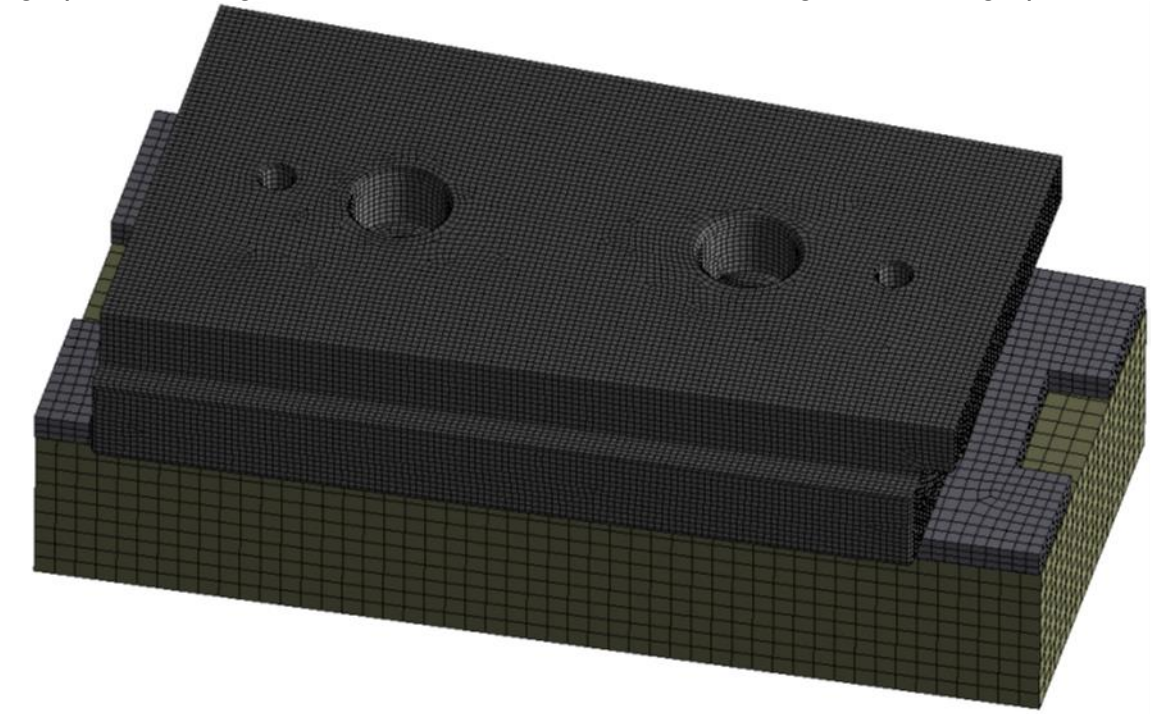


Figure 44: Outboard Diverter Row 5 style 2 variant (1407-5) components considered in analysis.

The total number of elements and nodes for the whole assembly is 243,641 and 919,025 respectively. Figure 45 shows the mesh used in the analysis with and without the graphite tile. Figure 46 shows the mesh of the mounting side of the graphite tile.



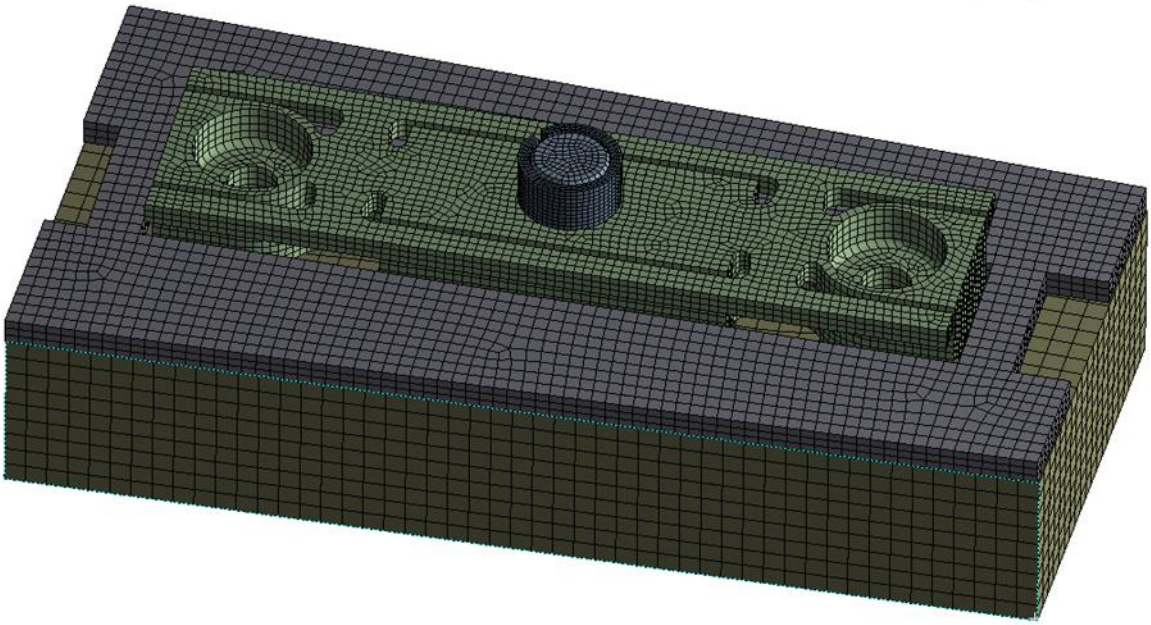


Figure 45: Mesh of the Outboard Diverter Row 5 style 2 variant (1407-5)

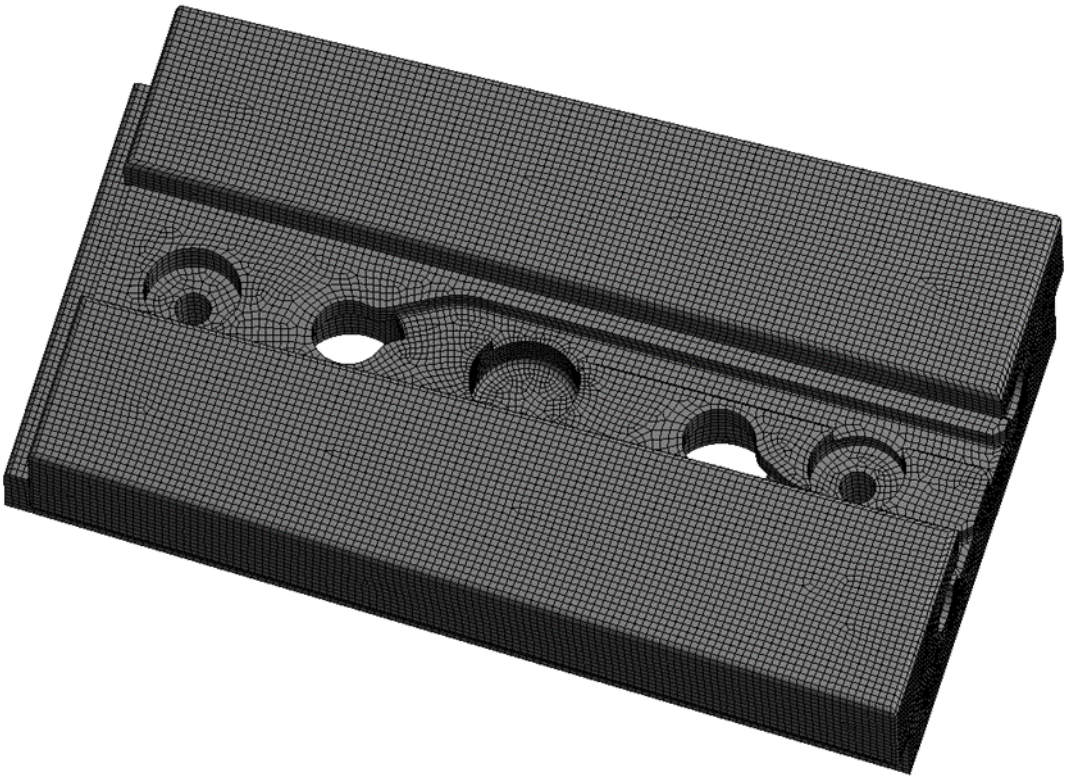


Figure 46: Mounting side of the graphite tile.

Table 11 lists each component of the assembly and its material.

Table 11: Components and their materials.

Component	Material
Graphite Tile (E-ED1407-5 05-04-2018)	T953
Grafoil	Grafoil
Baseplate	Pure Copper
R45-Grafoil Insert	Grafoil
R45 Pin	Inconel 718
Tbar (ED1414-1)	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

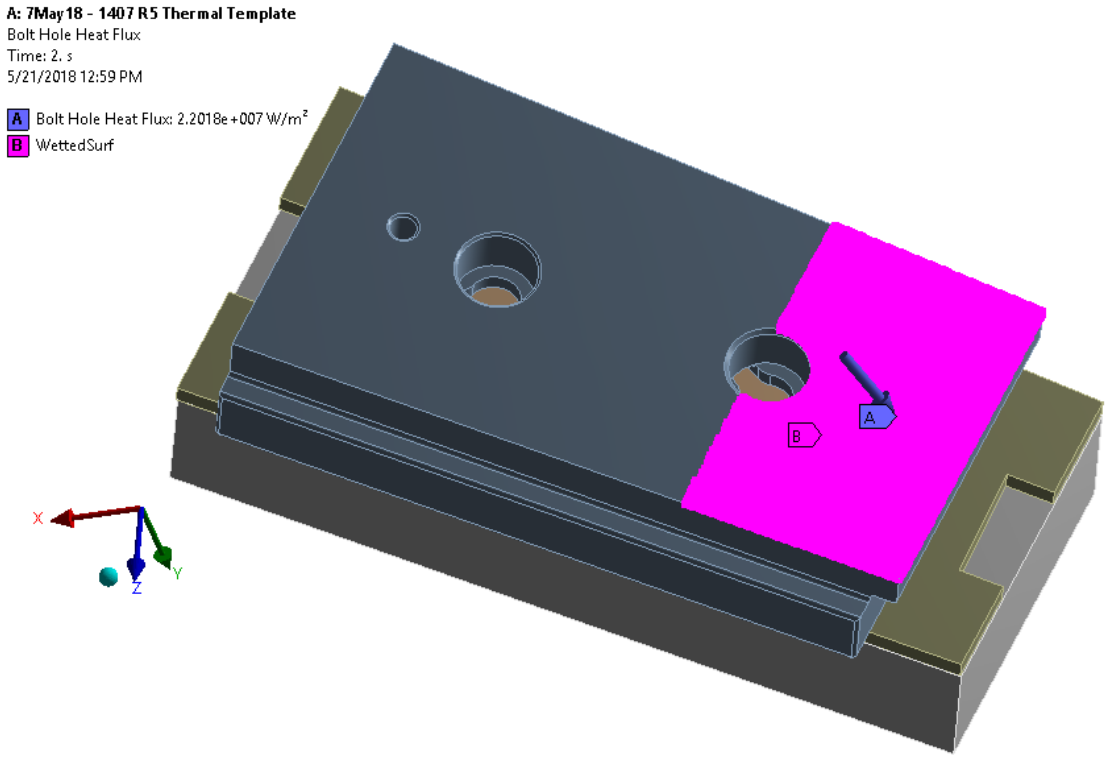


Figure 47: Thermal boundary conditions

Bolt hole heat flux = 2.2018×10^7 W/m^2
Graphite heat flux = 4,596,281 W/m^2 with a gradient heat flux along the y-direction of -114,907,019 W/m^2/°
The peak temperature in the assembly was 737 °C in the graphite tile. Figure 48 and Figure 49 shows the temperature contour as a result of the applied heat fluxes. Table 12 lists the peak temperature for each component.

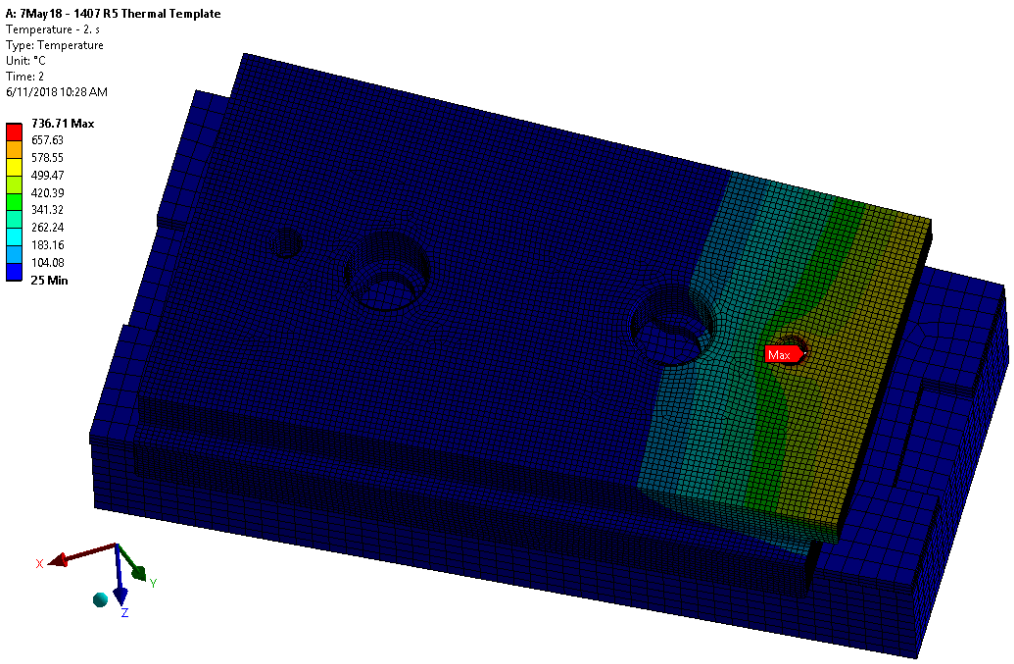


Figure 48: Temperature contour plot of the Outboard Diverter Row 5 style 2 variant (1407-5)

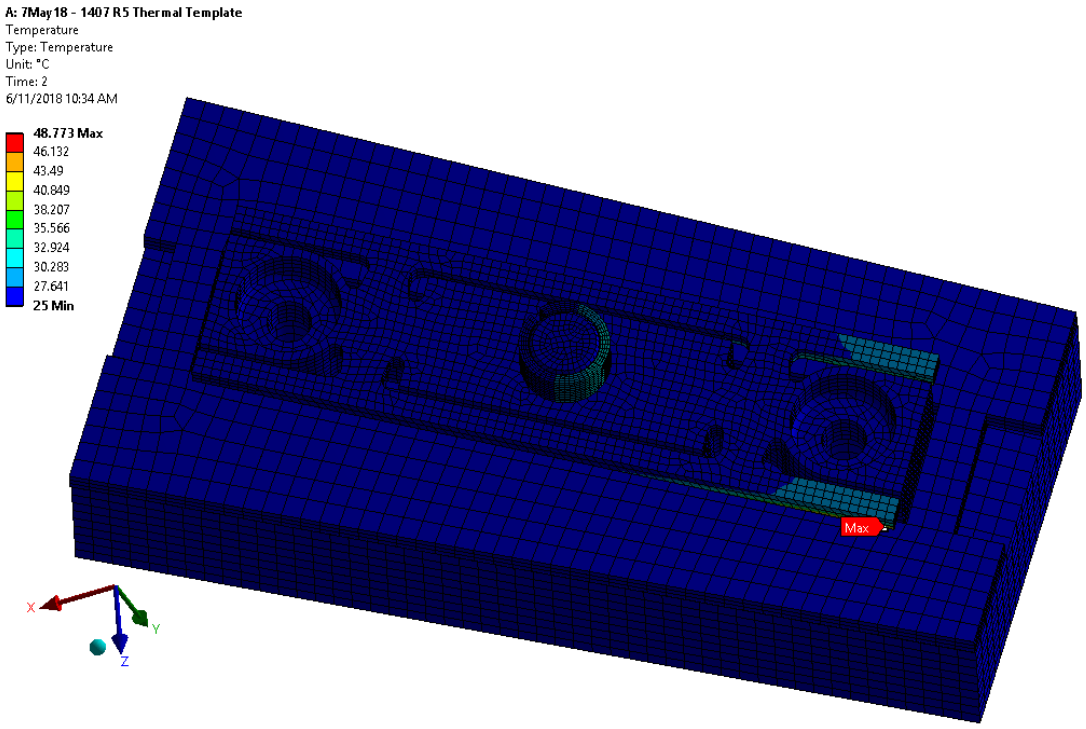


Figure 49: Temperature contour plot of the Outboard Diverter Row 5 style 2 variant (1407-5) without graphite tile

Table 12: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1407-5_05-04-2018)	737
Grafoil	25
Baseplate	25
R45-Grafoil Insert	32
R45 Pin	25
Tbar (ED1414-1)	49

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar (ED1414-1) as shown in Figure 50. Figure 51 shows the eddy moment and halo force loading applied to the graphite tile.

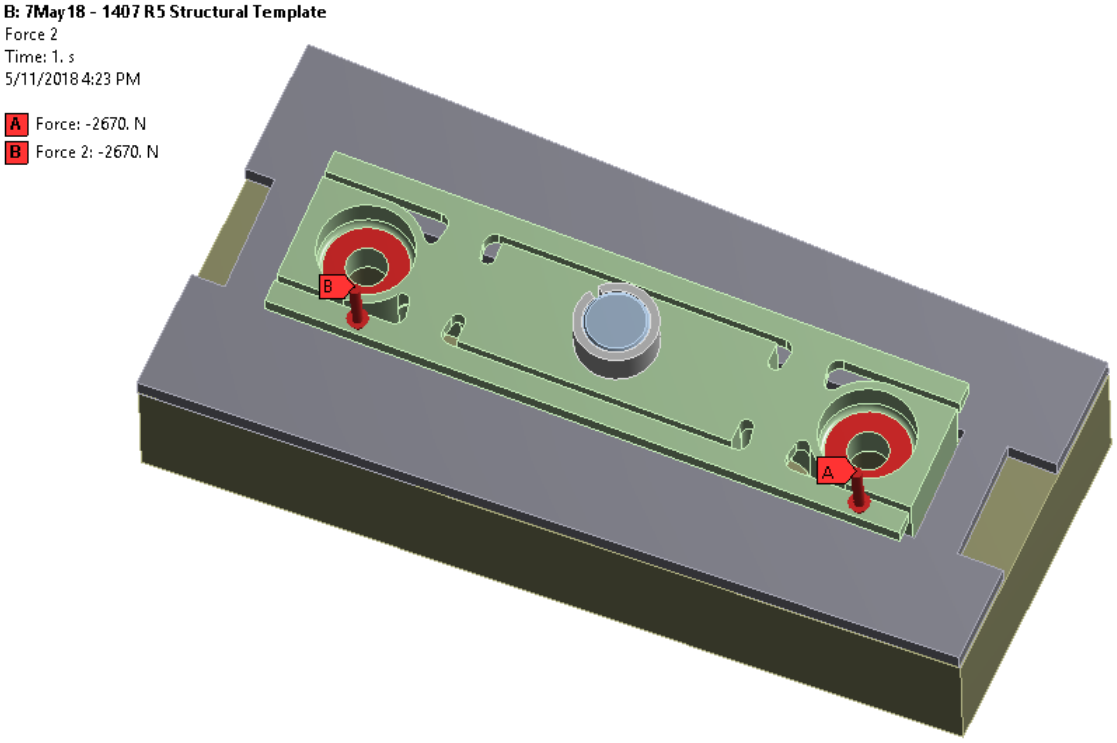


Figure 50: Bolt preload force applied to the Tbar.

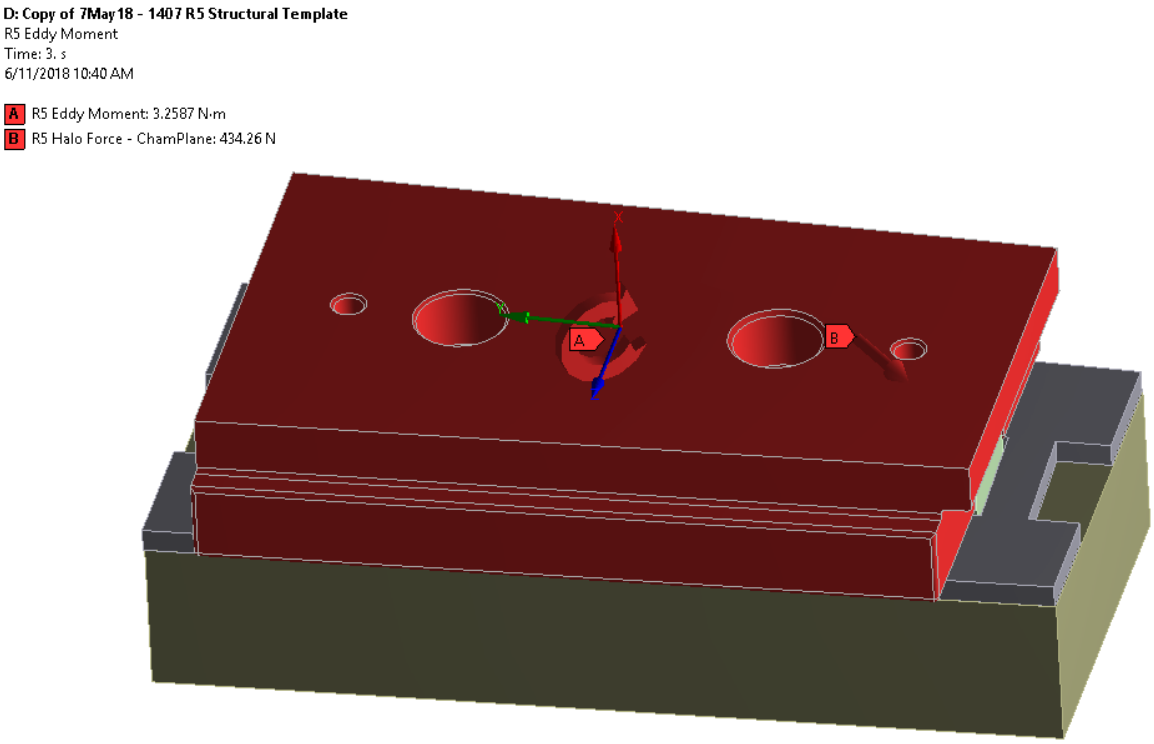


Figure 51: Eddy moment (A) and Halo force (B) applied to the graphite tile.

Frictionless constraints were applied to three sides of the baseplate and two sides of the grafoil. Figure 52 shows the location of these constraints highlighted in blue.

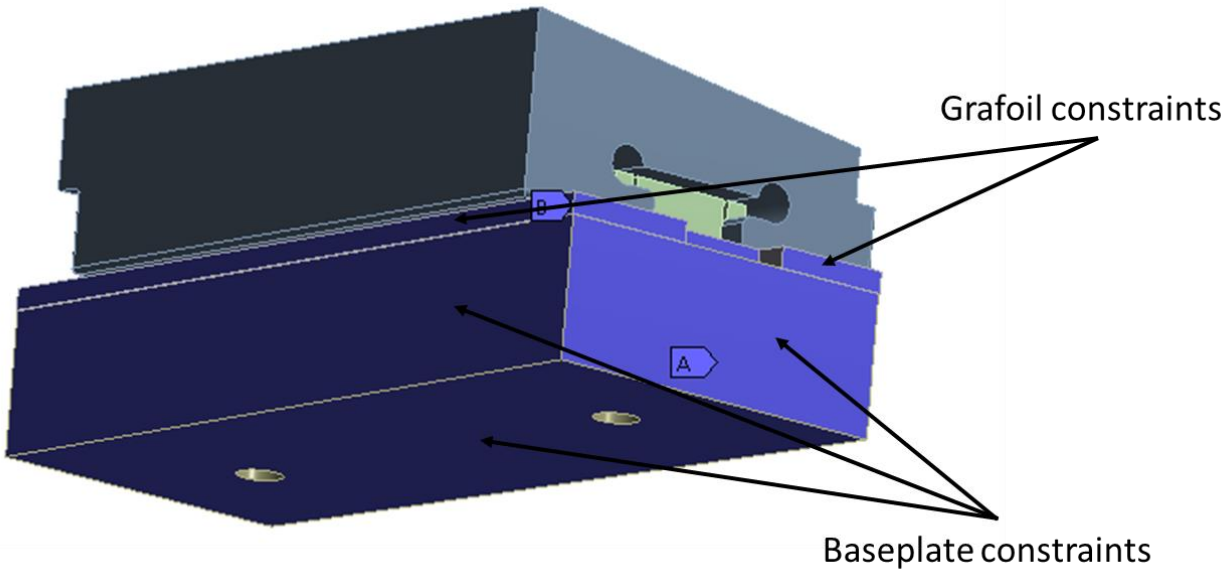


Figure 52: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R45-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1. Figure 53 shows the surfaces in contact with each other labeled A through E.

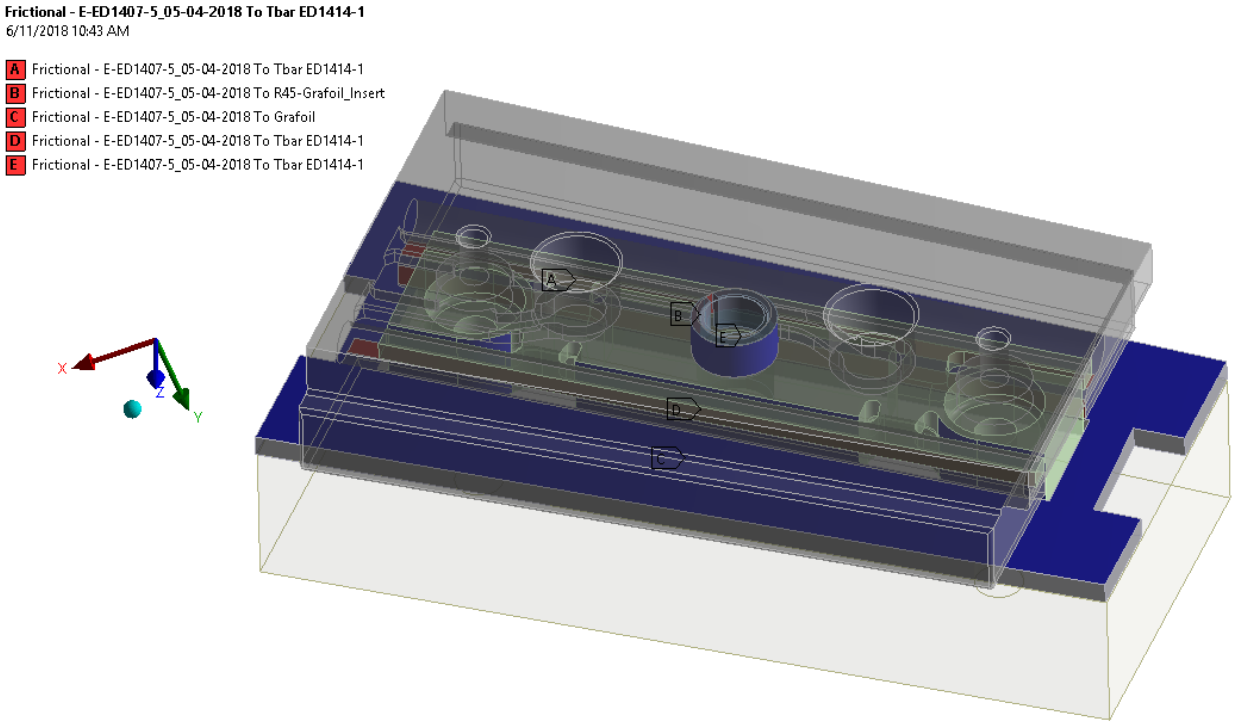


Figure 53: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition. Figure 54 shows the surfaces in contact with each other labeled A through D.

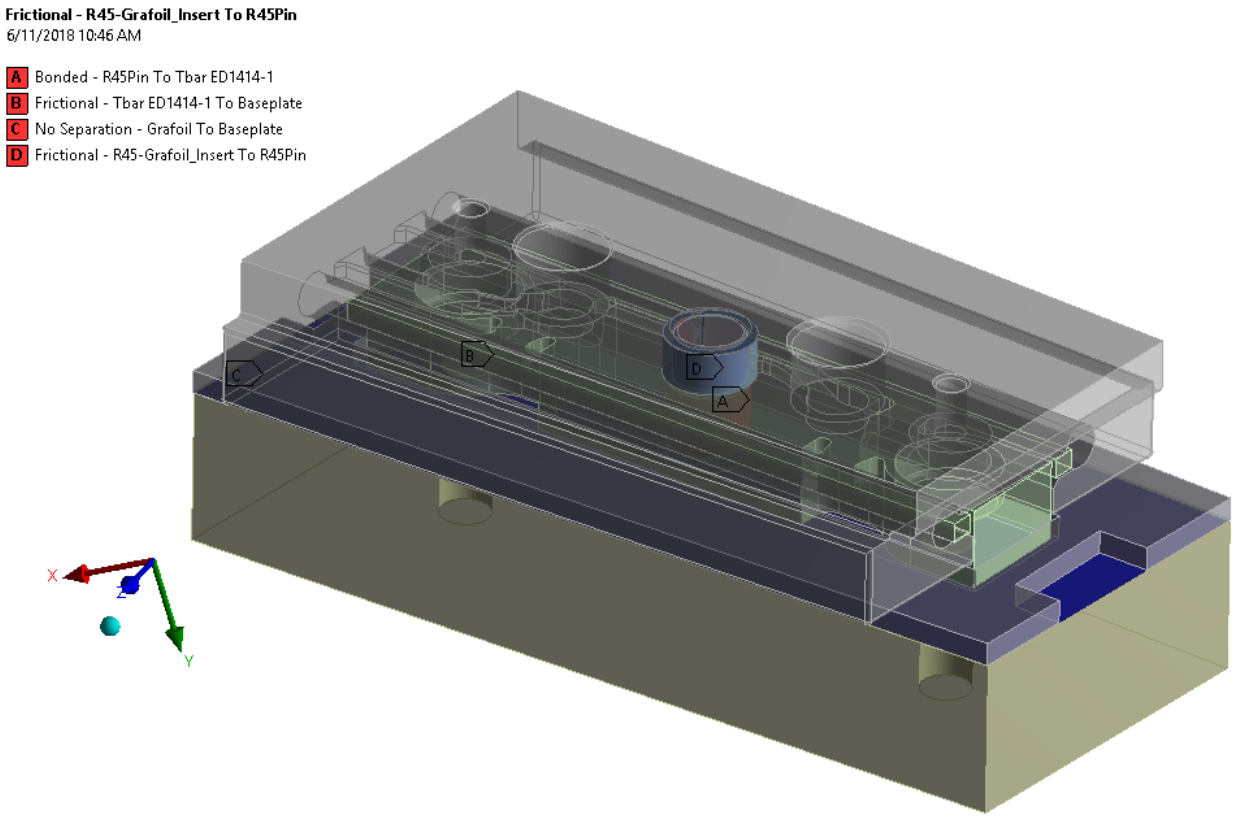


Figure 54: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 55. X, Y, Z deformation contour in the assembly is shown Figure 56, Figure 57, and Figure 58.

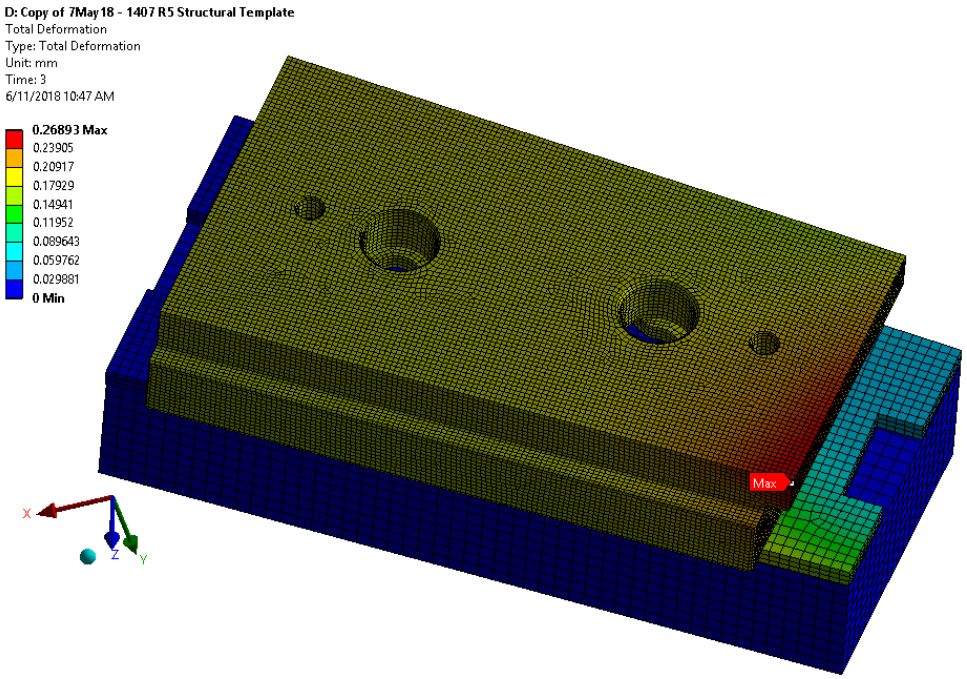


Figure 55: Total deformation of the assembly

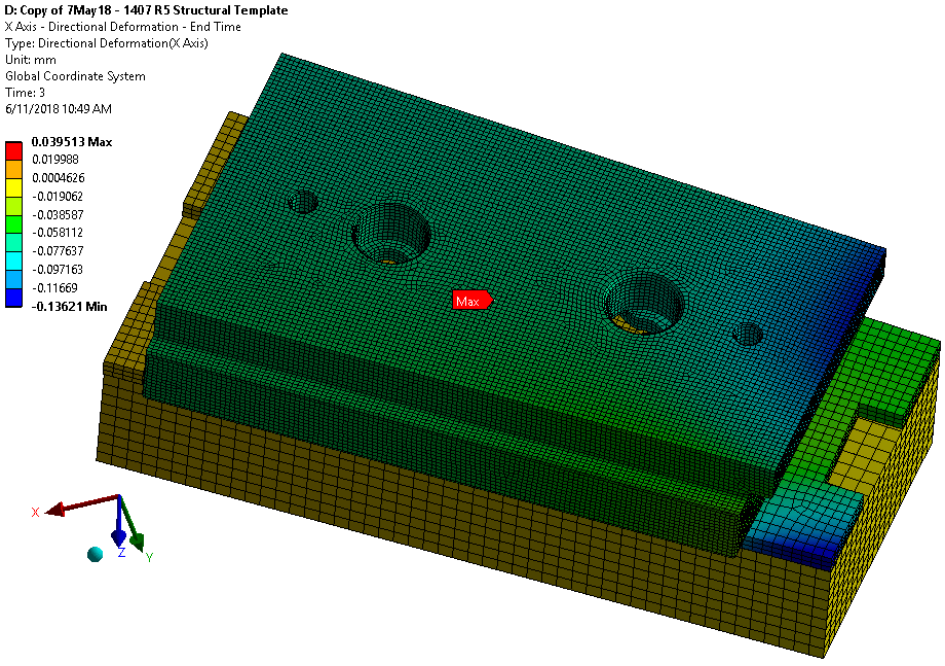


Figure 56: X-direction displacement

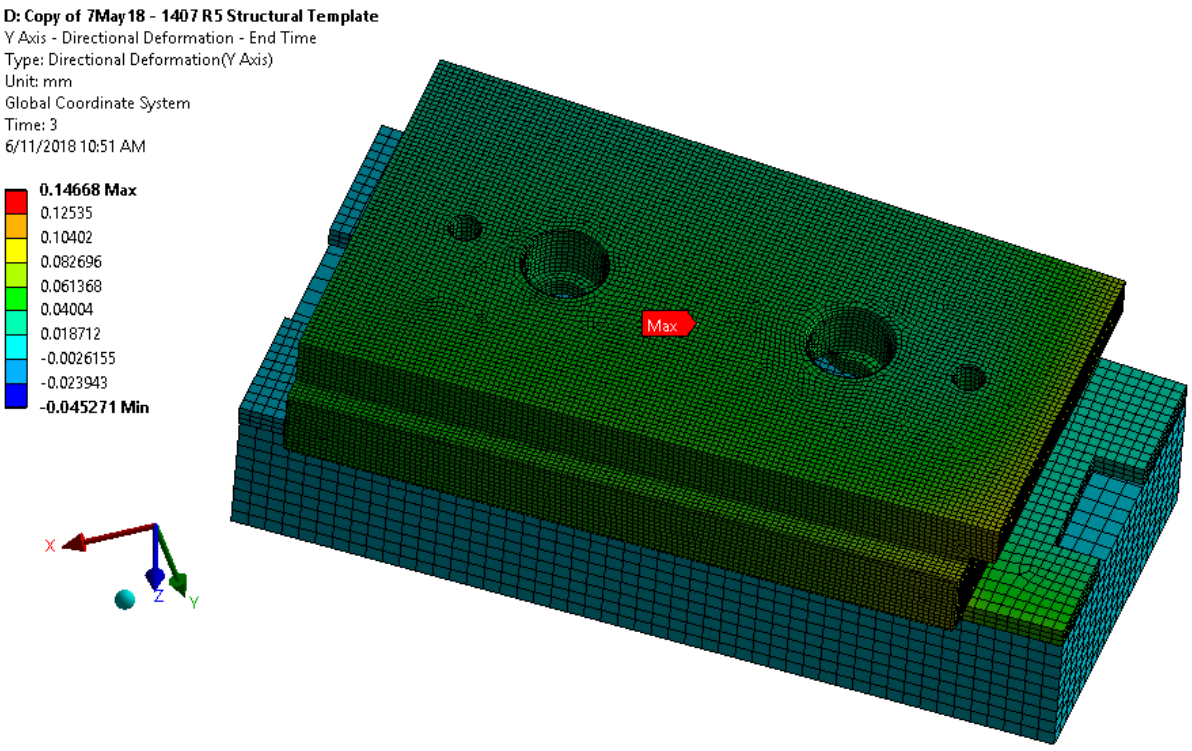


Figure 57: Y-direction displacement

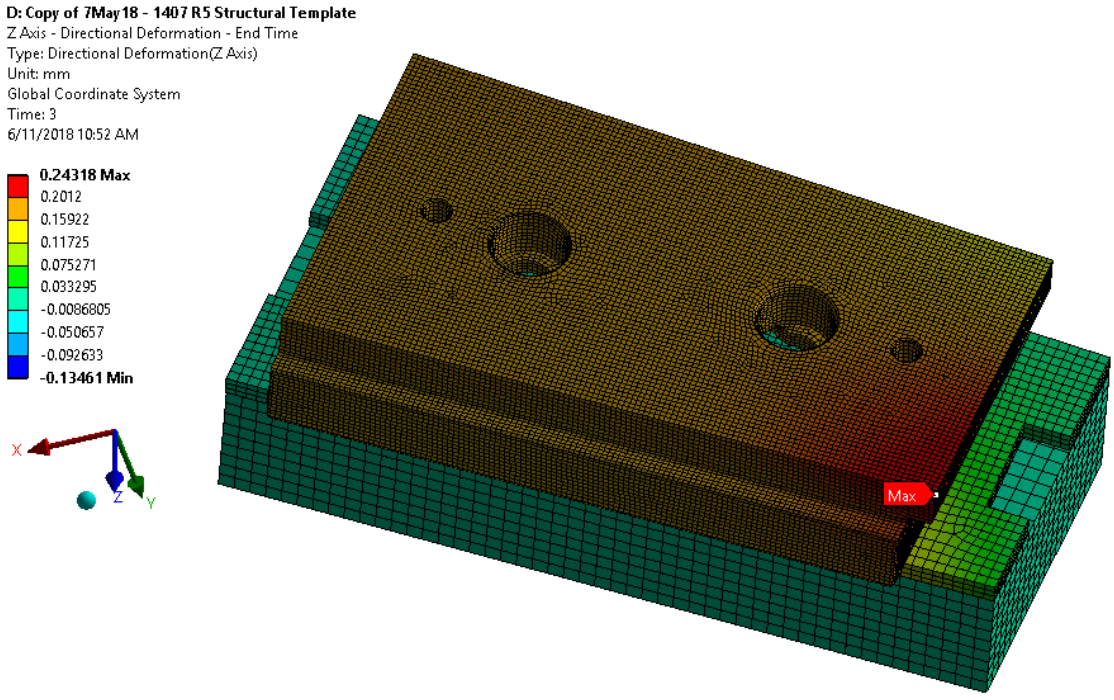


Figure 58: Z-direction displacement

Table 13 and Table 14 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 15 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 13: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-5 05-04-2018)	13.33	20	BPL+Halo
Graphite Tile – Tbar Slot	5.76	20	BPL+Halo
Graphite Tile – Shear Pin Hole	13.33	20	BPL+Halo
Grafoil	0.77	20	BPL+Halo+Eddy
R45-Grafoil Insert	5.03	20	BPL+Halo

Table 14: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-5 05-04-2018)	-33.91	-55	BPL+Halo
Graphite Tile – Tbar Slot	-9.98	-55	BPL+Halo+Eddy
Graphite Tile – Shear Pin Hole	-20.59	-55	BPL+Halo
Grafoil	-3.38	-55	BPL+Halo+Eddy
R45-Grafoil Insert	-15.21	-55	BPL+Halo

Table 15: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	15.10	??	BPL+Halo
R45 Pin	25.32	??	BPL+Halo
Tbar (ED1414-1)	86.18	261	BPL+Halo

All stresses resulted in values below their respective allowables. Figure 59 shows the location of the peak minimum principal stress with bolt preload and the halo load.

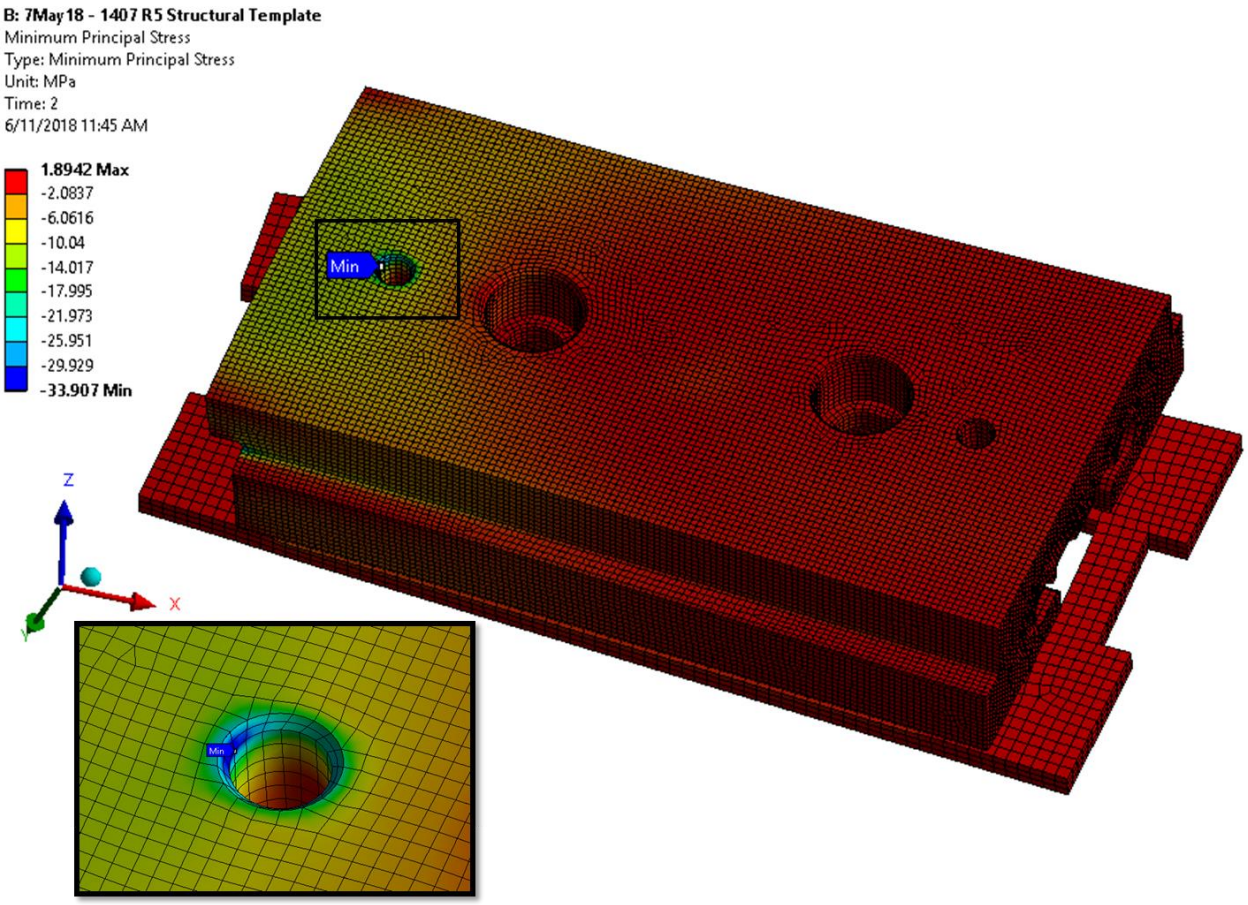


Figure 59: Location of peak minimum stress in OBD Row 5 style 2 -5

The location of maximum principal stress with bolt preload and the halo load is shown in Figure 60.

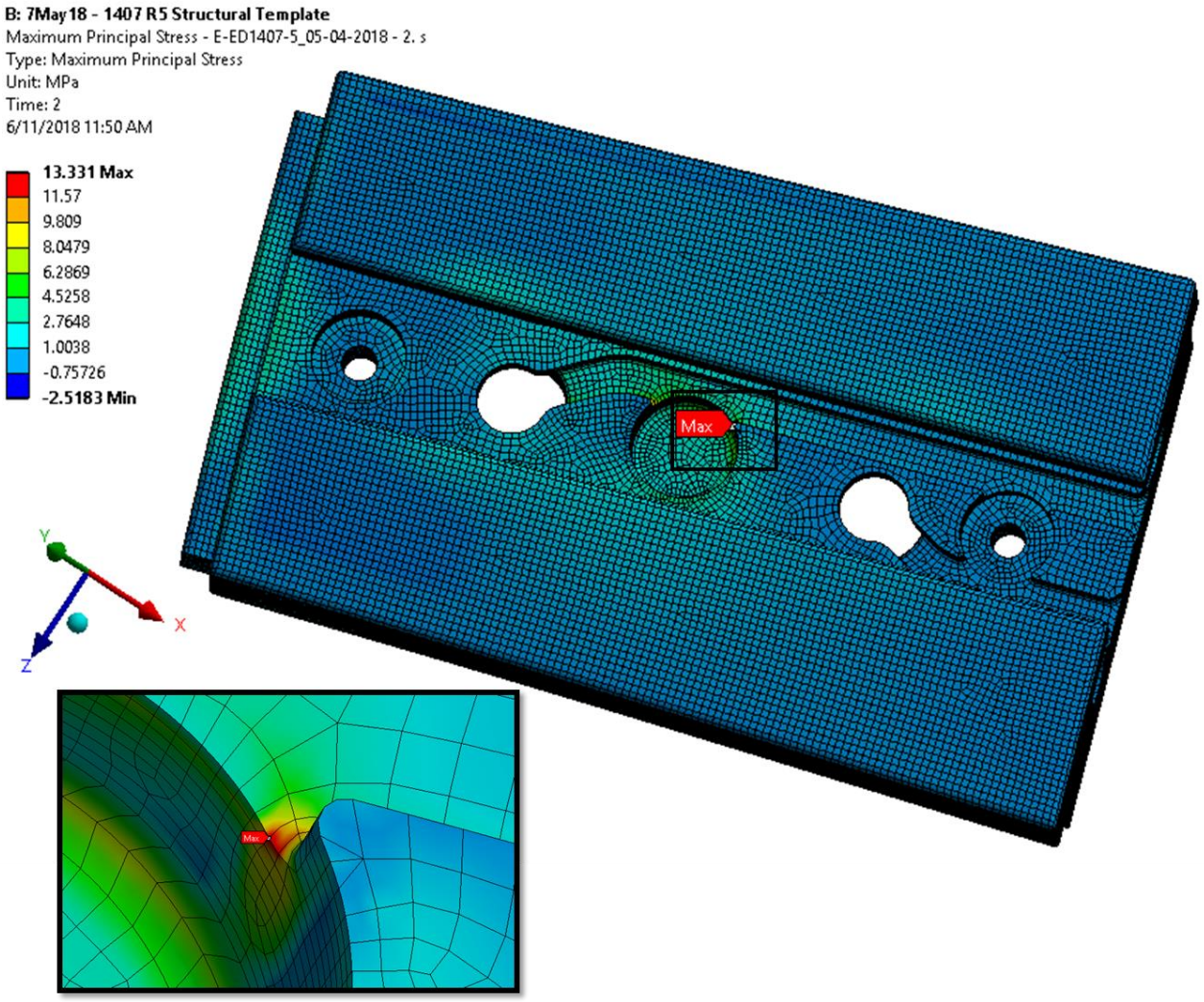


Figure 60: Location of peak maximum principal stress.

The location of peak equivalent stress with bolt preload and the halo load is shown in Figure 61.

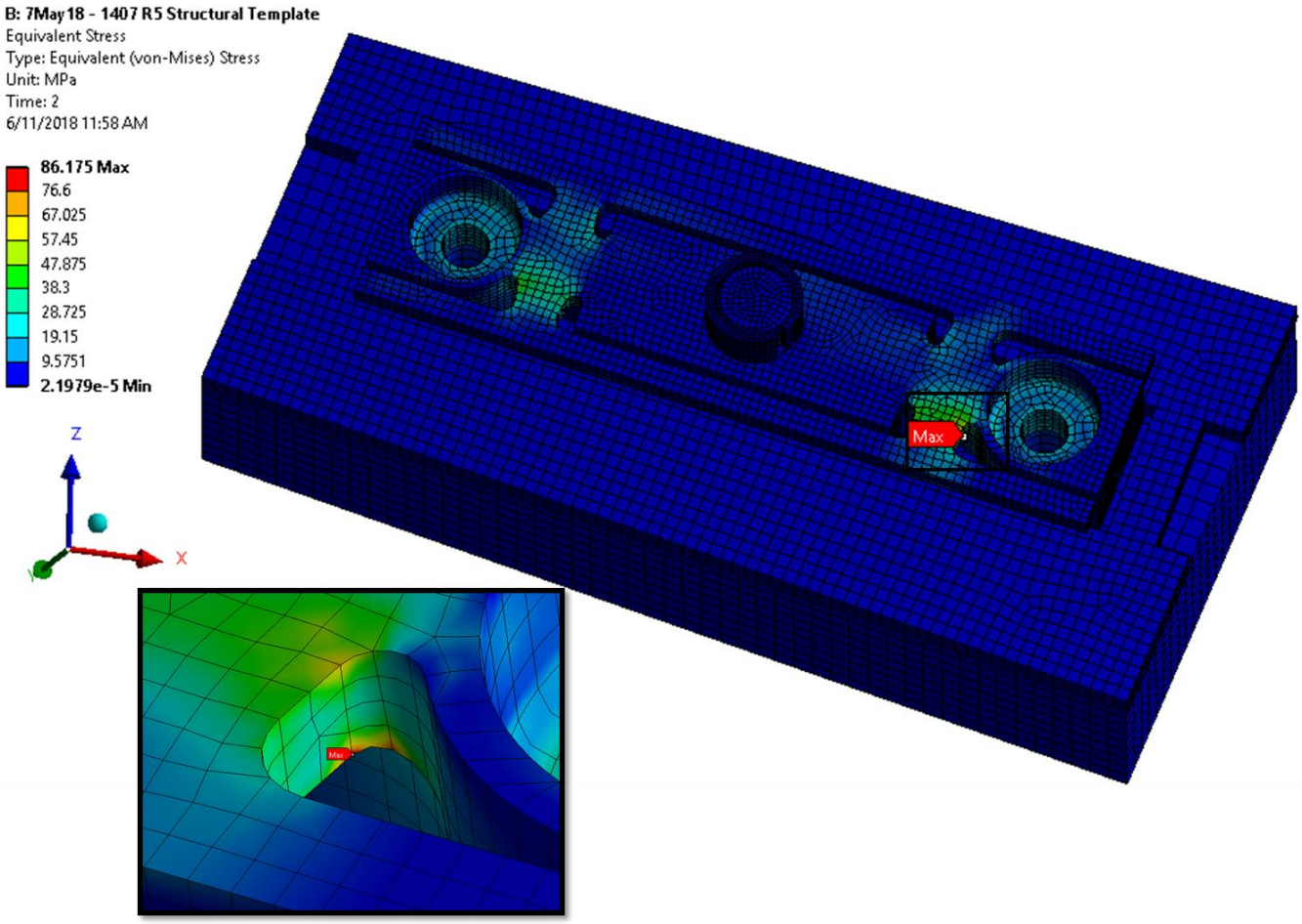


Figure 61: Location of peak equivalent stress for combined loading.

10 Subreport E-ED1407-6 R5 Style 2 Diagnostic Gap Ramp Variant

ORNL Analyst: Jason Cook

Summary:

The minimum principal stress in the chamfer of one of the bolt holes exceeds its allowable. See Figure 59. I do not have allowable stress values for pure copper or Inconel 718. Peak stresses in all components are lists in Table 13, Table 14, and Table 15.

The components considered in the analysis are listed below in Figure 43 and Figure 44.

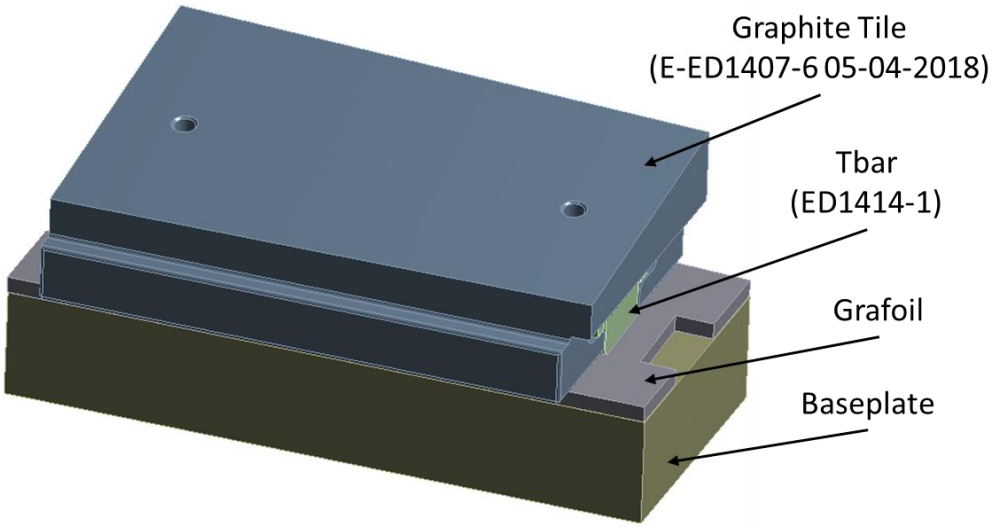


Figure 62: Outboard Diverter Row 5 style 2 variant (1407-6) Outboard Diverter Row 5 style 2 variant (1407-6).

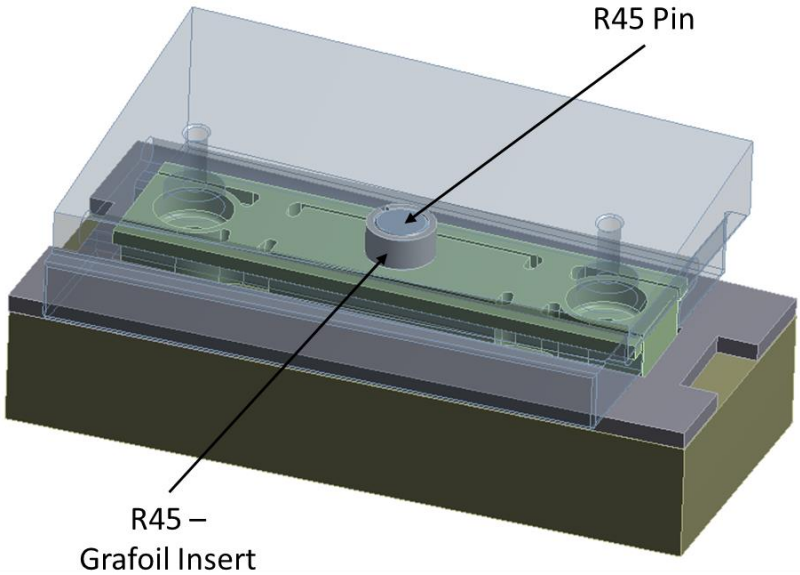


Figure 63: Outboard Diverter Row 5 style 2 variant (1407-6) components considered in analysis.

The total number of elements and nodes for the whole assembly is 155,865 and 604,943 respectively. Figure 45 shows the mesh used in the analysis with and without the graphite tile. Figure 46 shows the mesh of the mounting side of the graphite tile.

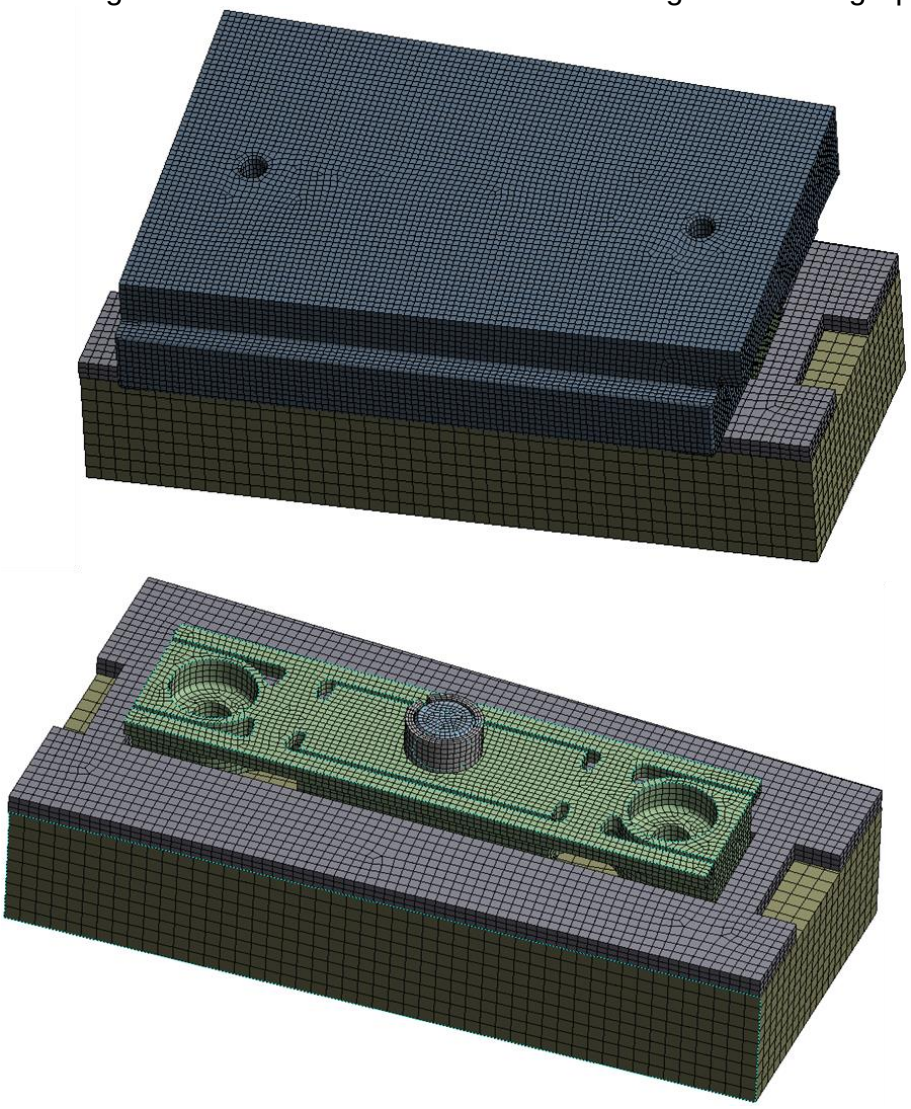


Figure 64: Mesh of the Outboard Diverter Row 5 style 2 variant (1407-6)

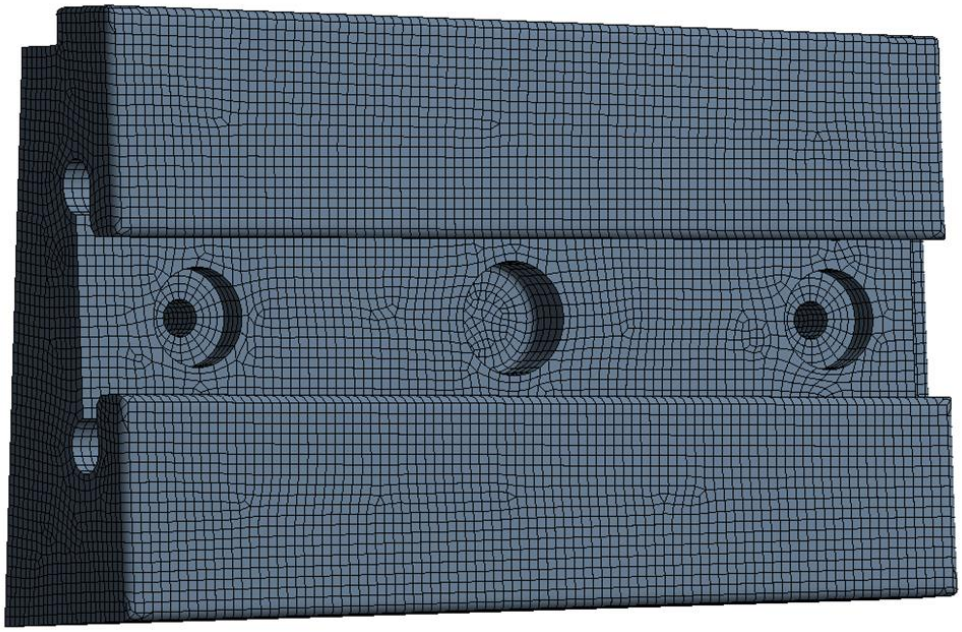


Figure 65: Mounting side of the graphite tile.

Table 11 lists each component of the assembly and its material.

Table 16: Components and their materials.

Component	Material
Graphite Tile (E-ED1407-6 05-04-2018)	T953
Grafoil	Grafoil
Baseplate	Pure Copper
R45-Grafoil Insert	Grafoil
R45 Pin	Inconel 718
Tbar (ED1414-1)	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

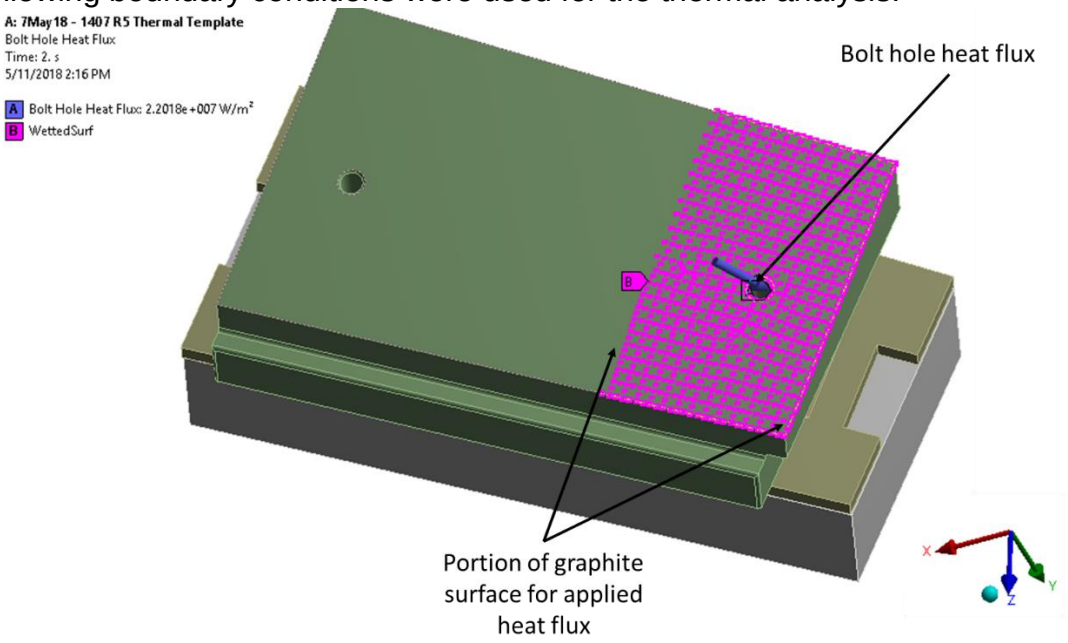


Figure 66: Thermal boundary conditions

Bolt hole heat flux = 2.2018×10^7 W/m^2

Graphite heat flux = 7,818,427 W/m^2 with a gradient heat flux along the y-direction of -195,460,681 W/m^2/°

The peak temperature in the assembly was 968.16 in the graphite tile. Figure 48 and Figure 49 shows the temperature contour as a result of the applied heat fluxes. Table 12
lists the peak temperature for each component.

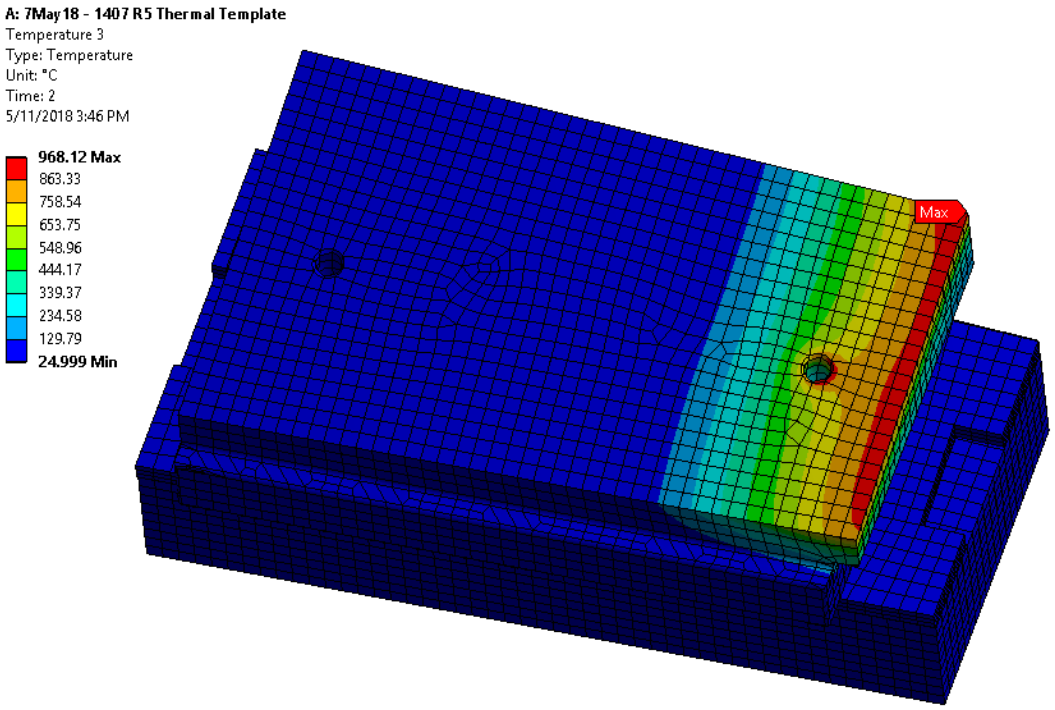


Figure 67: Temperature contour plot of the Outboard Diverter Row 5 style 2 variant (1407-6)

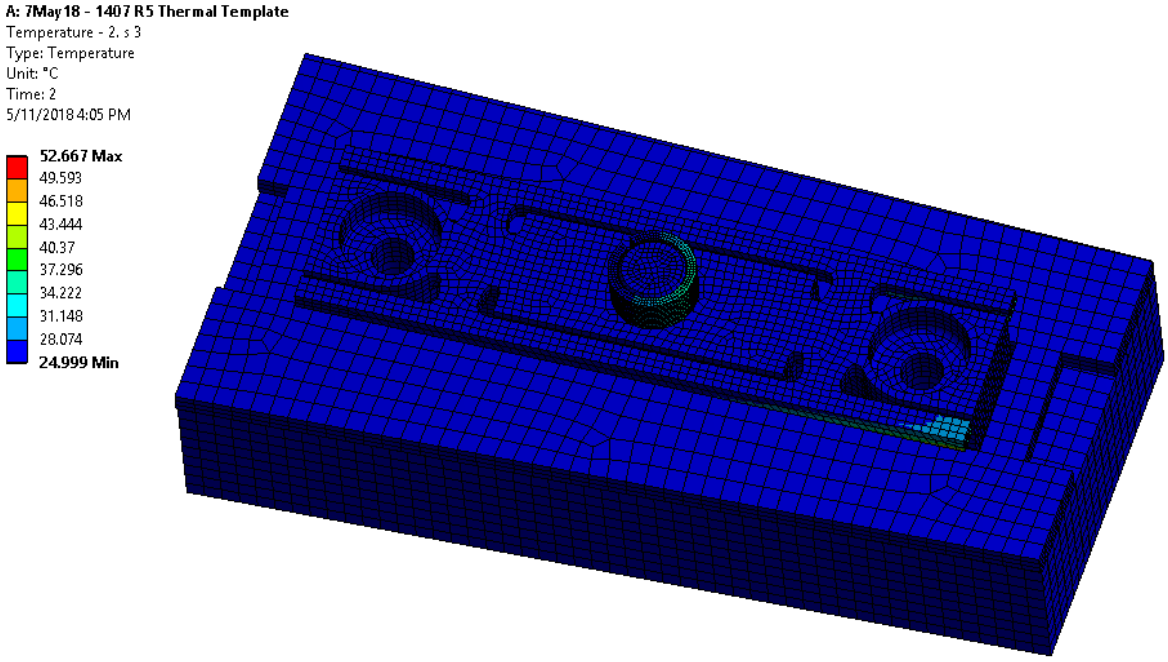


Figure 68: Temperature contour plot of the Outboard Diverter Row 5 style 2 variant (1407-6) without graphite tile

Table 17: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1407-6 05-04-2018)	968
Grafoil	25
Baseplate	25
R45-Grafoil Insert	36
R45 Pin	25
Tbar (ED1414-1)	53

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar (ED1414-1) as shown in Figure 50. Figure 51 shows the eddy moment and halo force loading applied to the graphite tile.

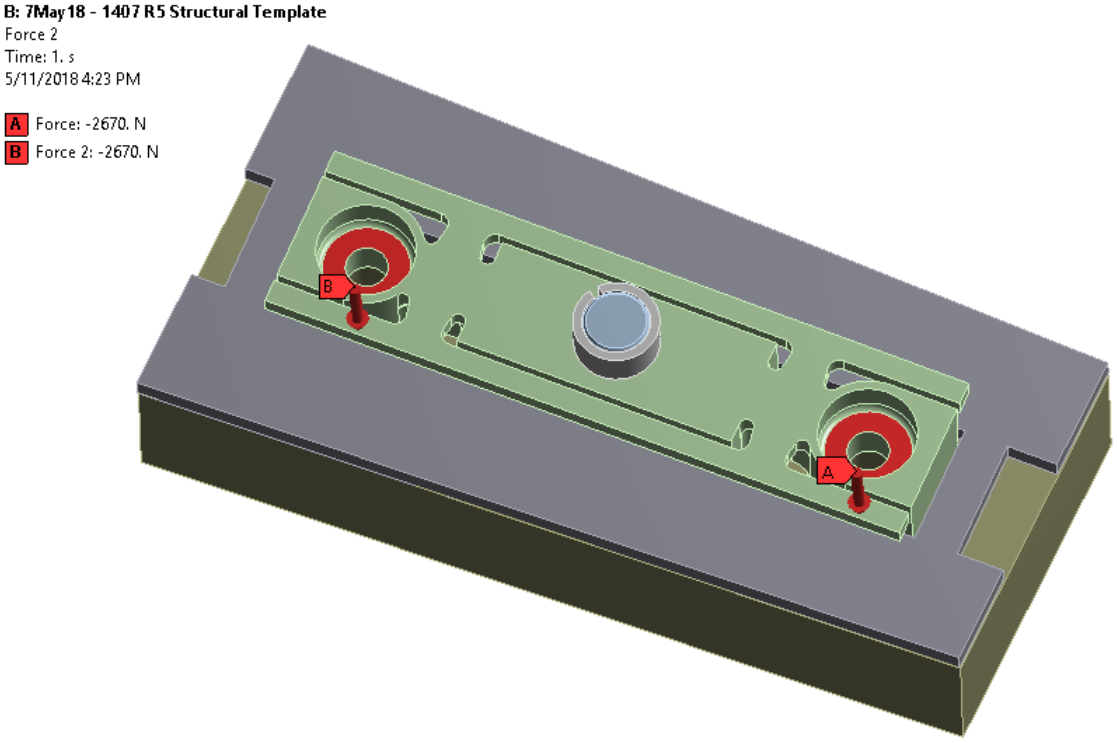


Figure 69: Bolt preload force applied to the Tbar.

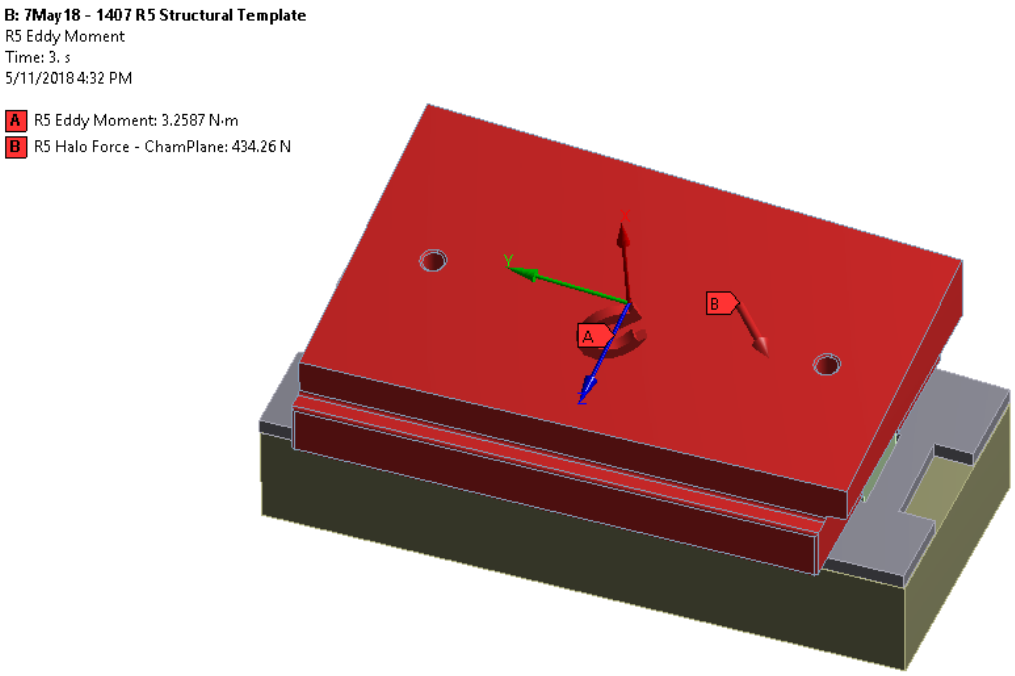


Figure 70: Eddy moment (A) and Halo force (B) applied to the graphite tile.

Frictionless constraints were applied to three sides of the baseplate and two sides of the grafoil. Figure 52 shows the location of these constraints highlighted in blue.

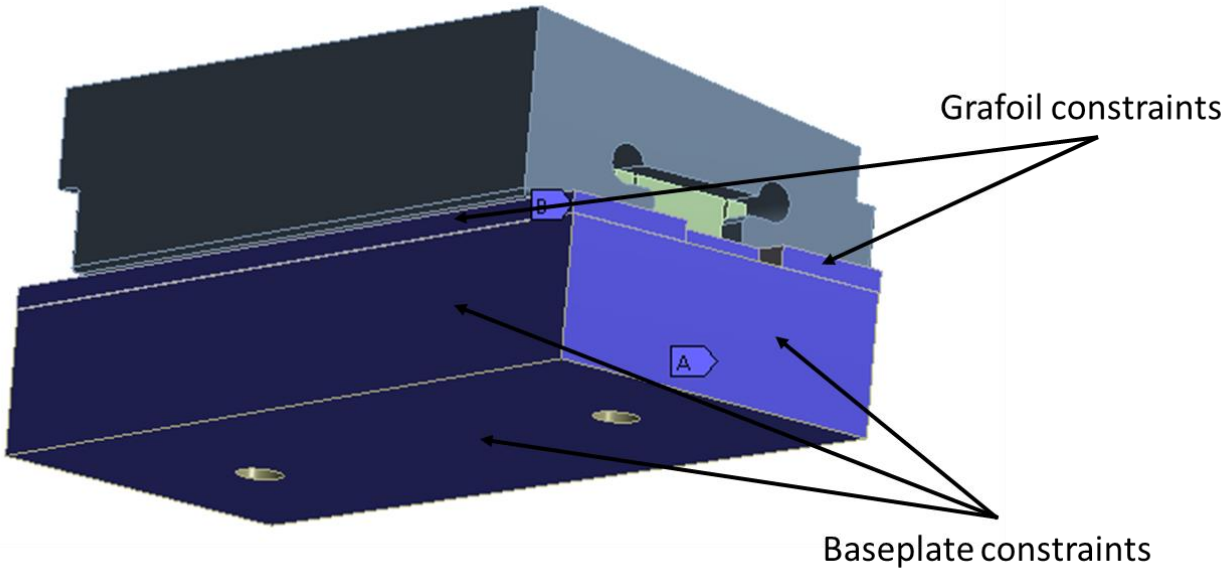


Figure 71: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R45-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1. Figure 53 shows the surfaces in contact with each other labeled A through E.

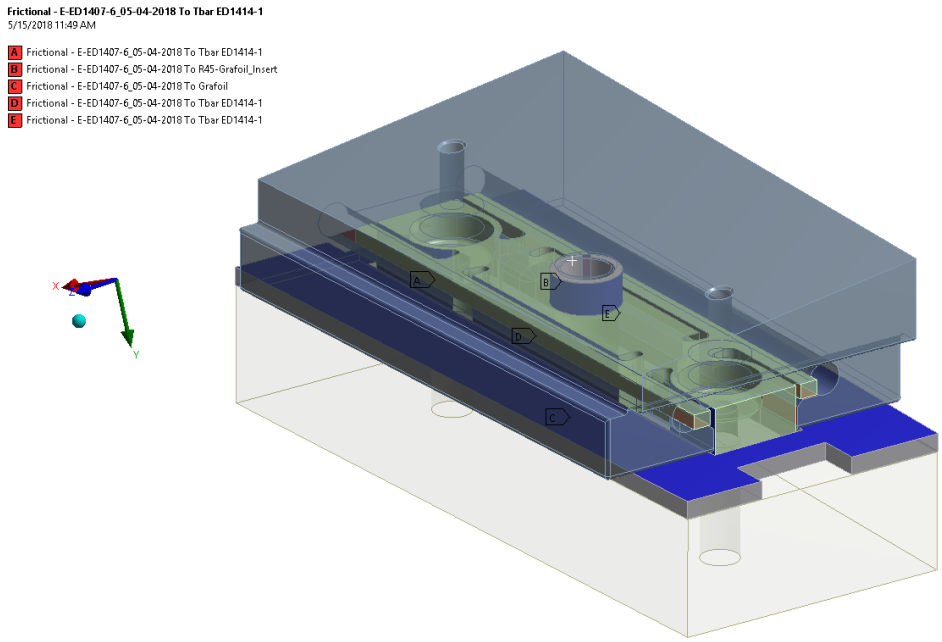


Figure 72: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition. Figure 54 shows the surfaces in contact with each other labeled A through D.

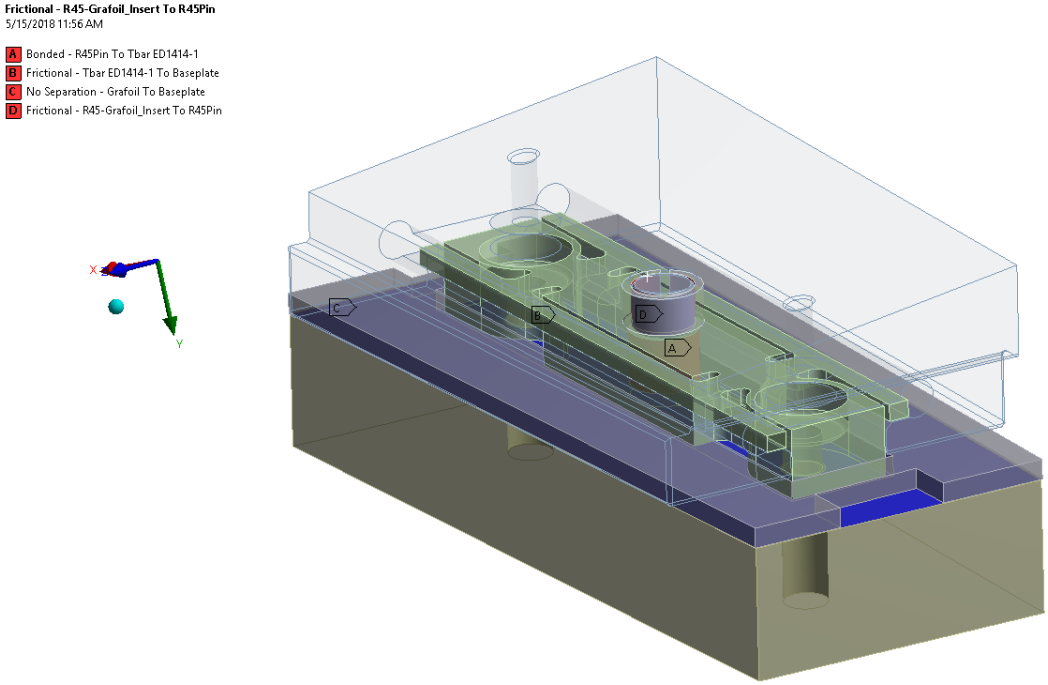


Figure 73: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 55. X, Y, Z deformation contour in the assembly is shown Figure 56, Figure 57, and Figure 58.

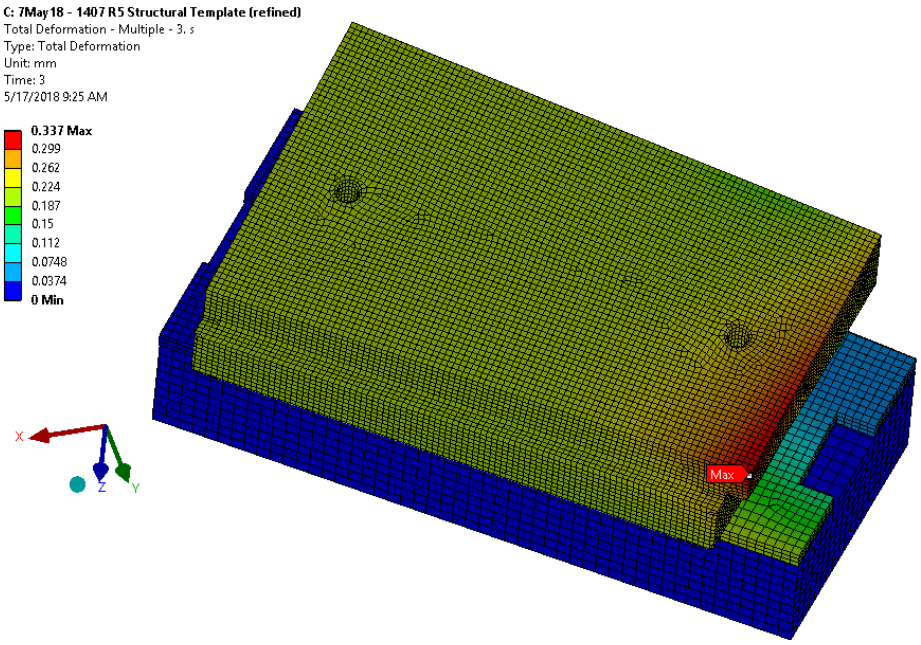


Figure 74: Total deformation of the assembly

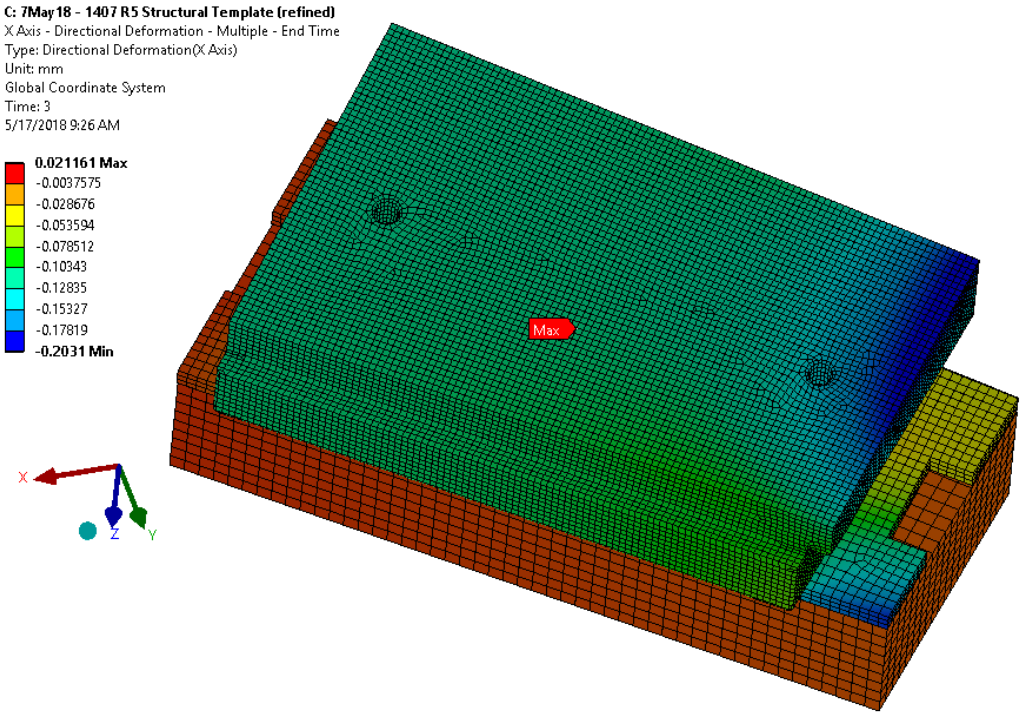


Figure 75: X-direction displacement

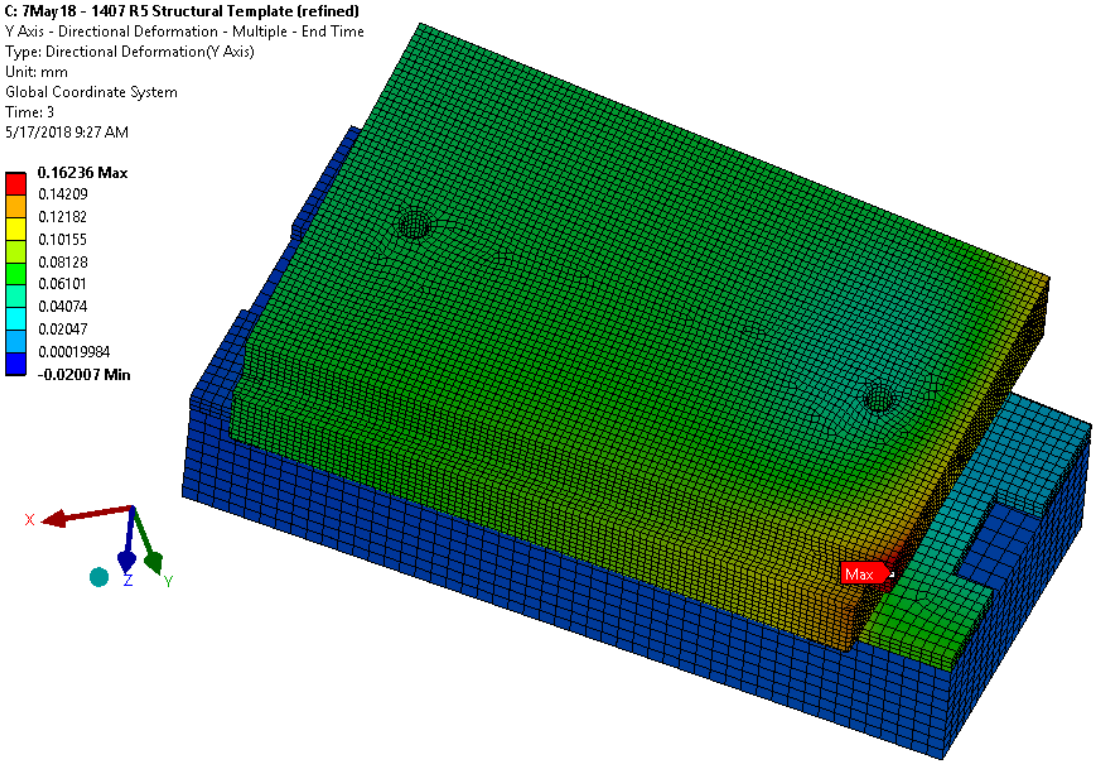


Figure 76: Y-direction displacement

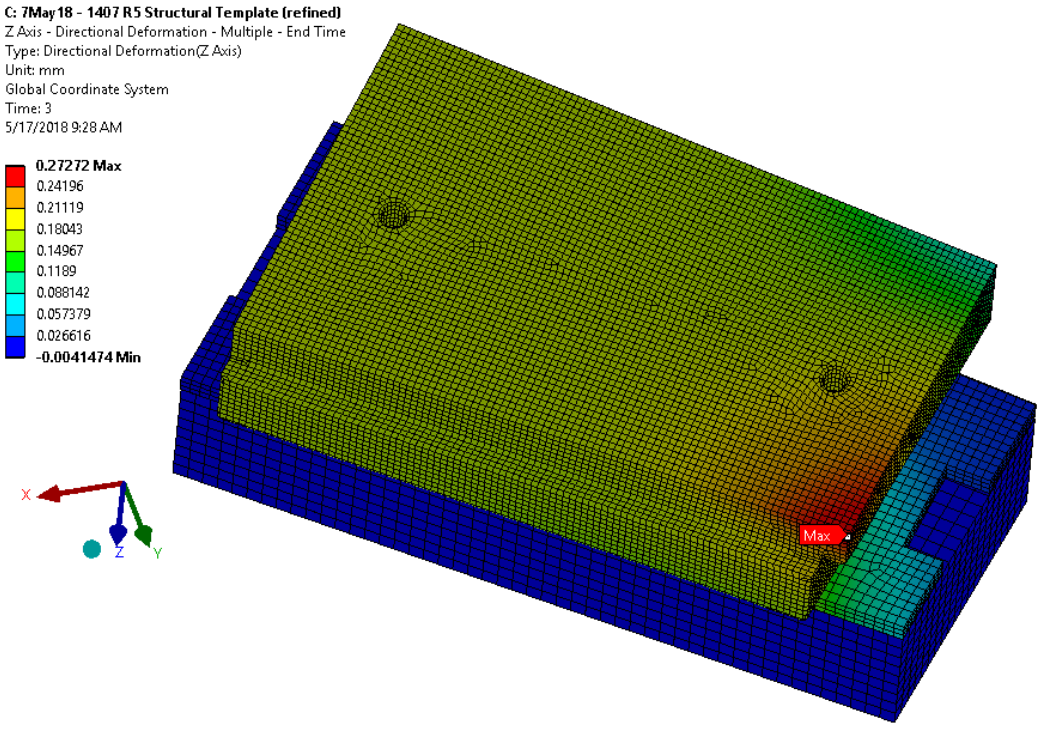


Figure 77: Z-direction displacement

Table 13 and Table 14 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 15 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 18: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-6 05-04-2018)	8.11	20	BPL+Halo+Eddy
Graphite Tile – Tbar Slot	7.80	20	BPL+Halo
Graphite Tile – Shear Pin Hole	7.43	20	BPL+Halo+Eddy
Grafoil	0.47	20	BPL+Halo
R45-Grafoil Insert	4.06	20	BPL+Halo+Eddy

Table 19: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-6 05-04-2018)	-59.15	-55	BPL+Halo
Graphite Tile – Tbar Slot	-10.24	-55	BPL
Graphite Tile – Shear Pin Hole	-5.61	-55	BPL+Halo+Eddy
Grafoil	-0.84	-55	BPL+Halo+Eddy
R45-Grafoil Insert	-13.31	-55	BPL+Halo+Eddy

Table 20: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	14.91	??	BPL+Halo
R45 Pin	22.02	??	BPL+Halo
Tbar (ED1414-1)	77.44	261	BPL

The minimum principal stress in the chamfer of the bolt hole, shown in Figure 59, exceeded its allowable.

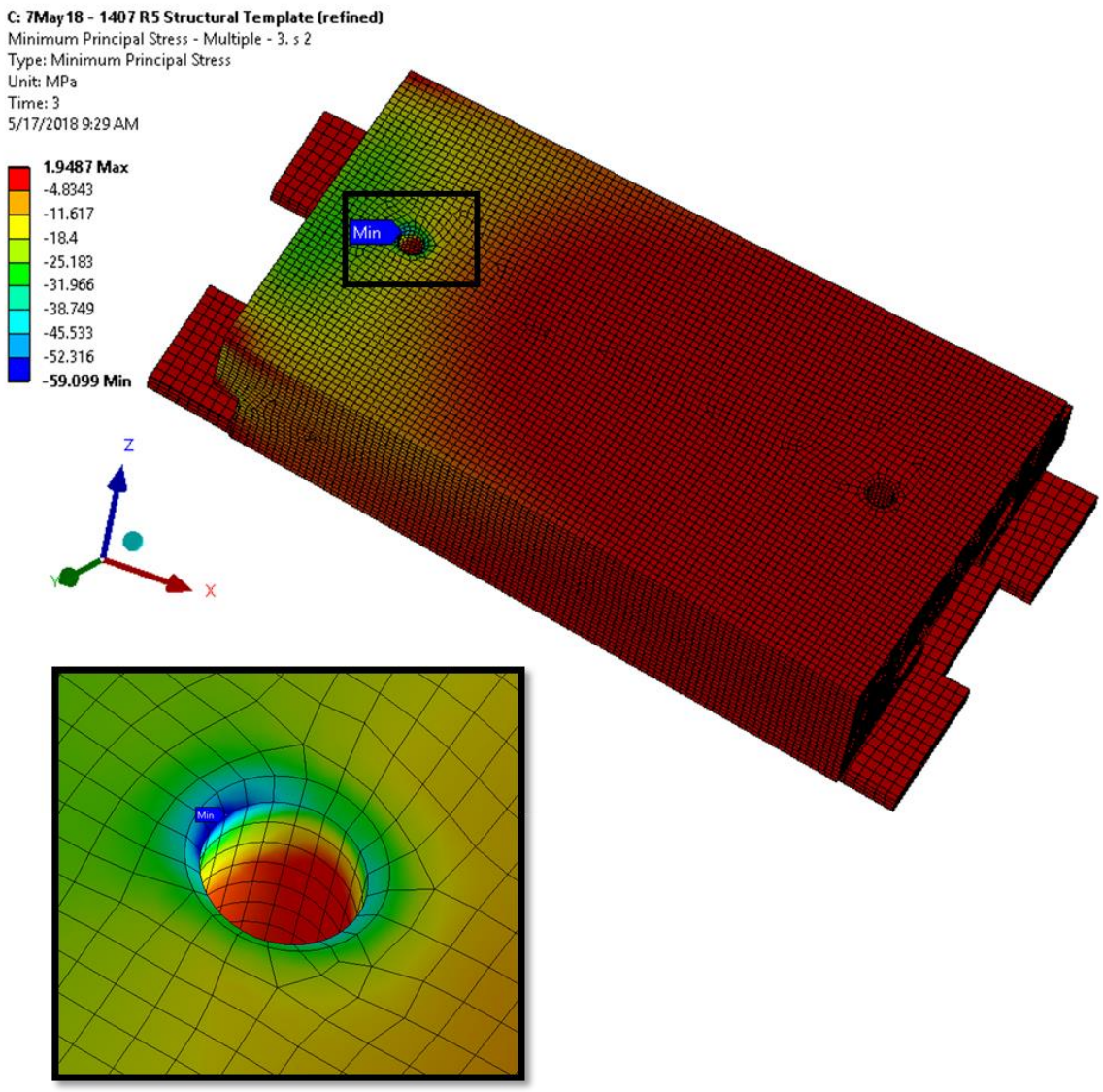


Figure 78: Location of peak minimum stress in graphite tile.

The maximum principal stress occurred in the graphite tile as shown in Figure 60.

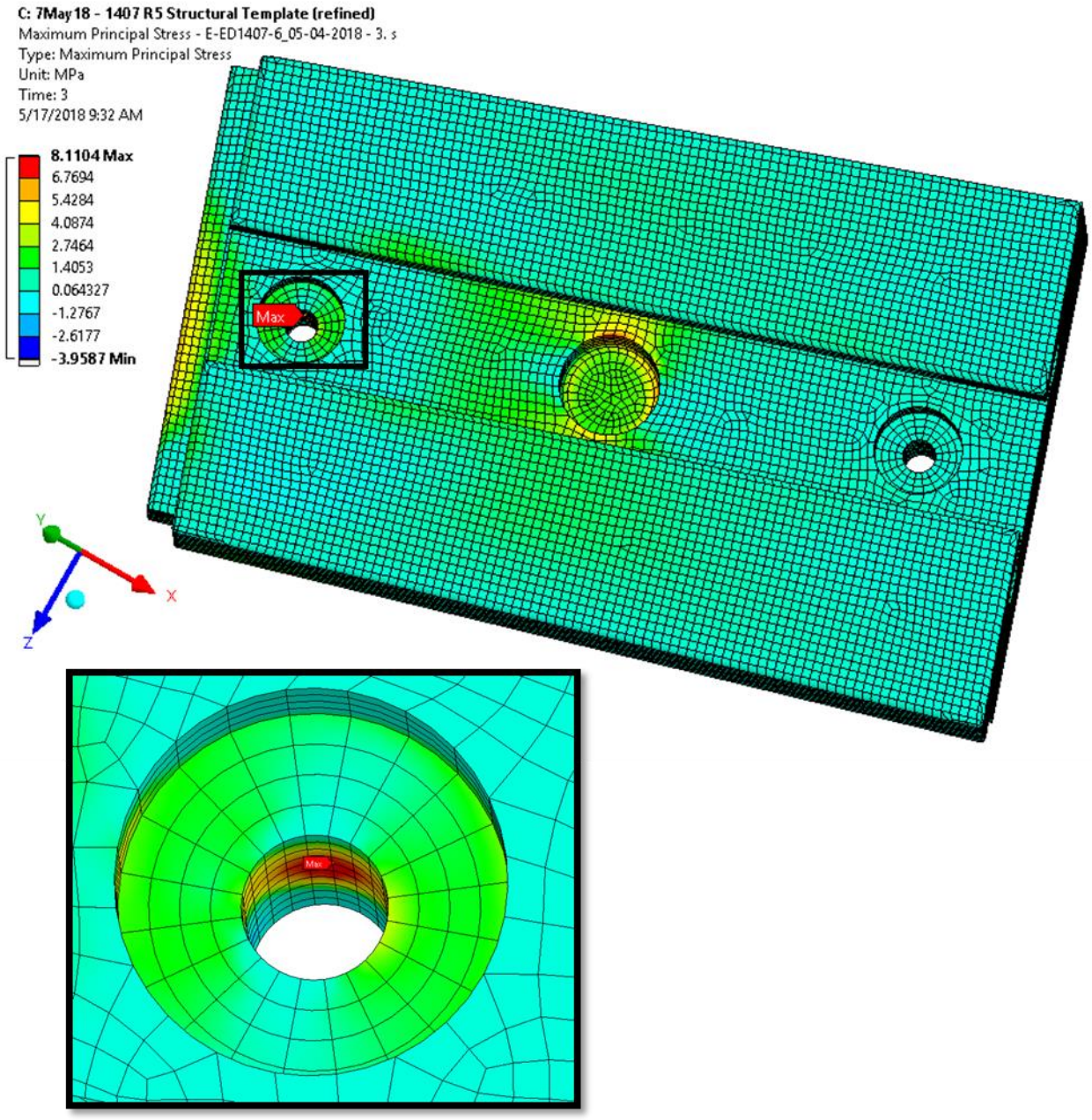


Figure 79: Location of peak maximum principal stress.

The peak equivalent stress for combined loading and for just bolt preload are shown in Figure 61 and Figure 81.

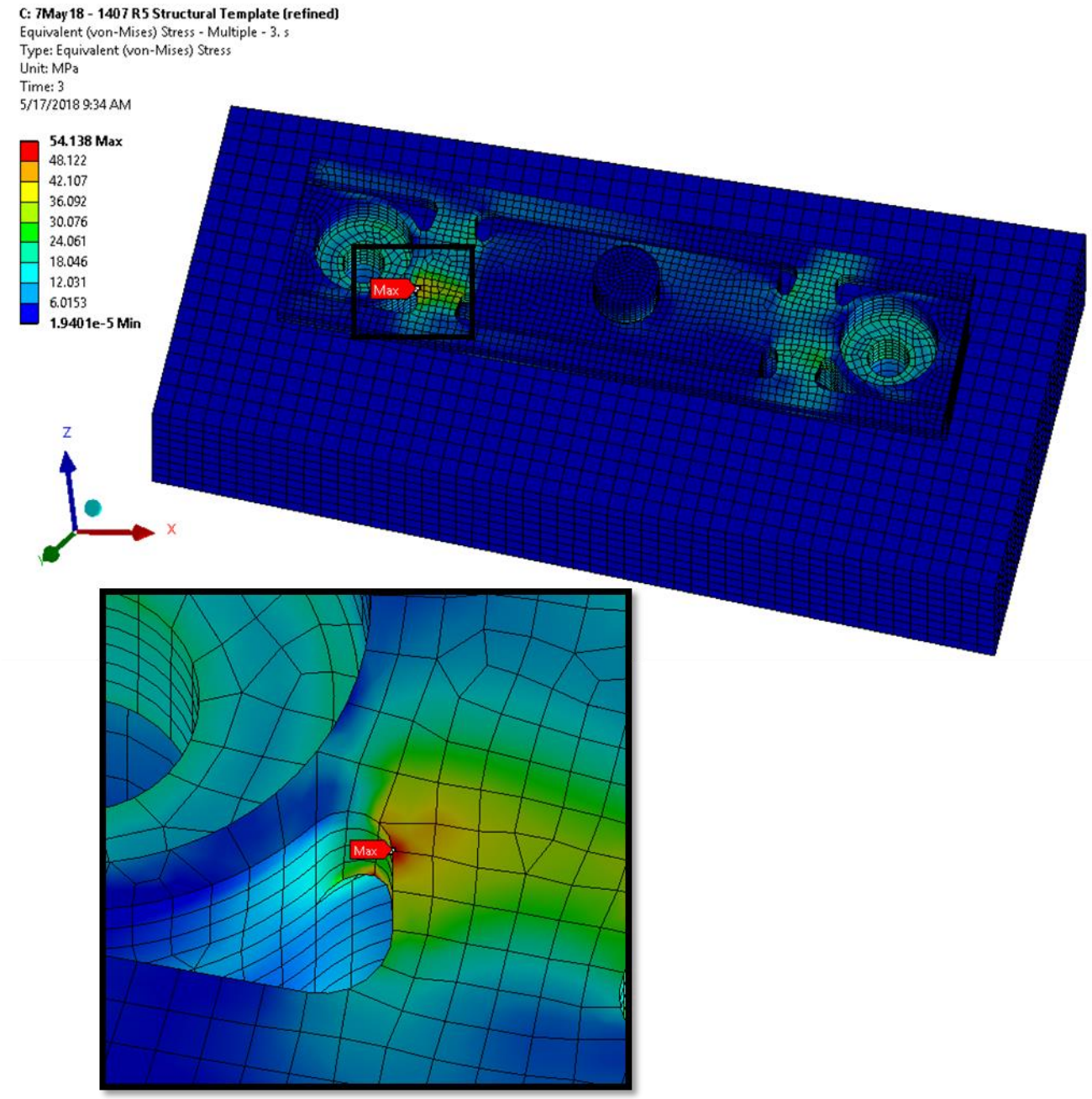


Figure 80: Location of peak equivalent stress for combined loading.

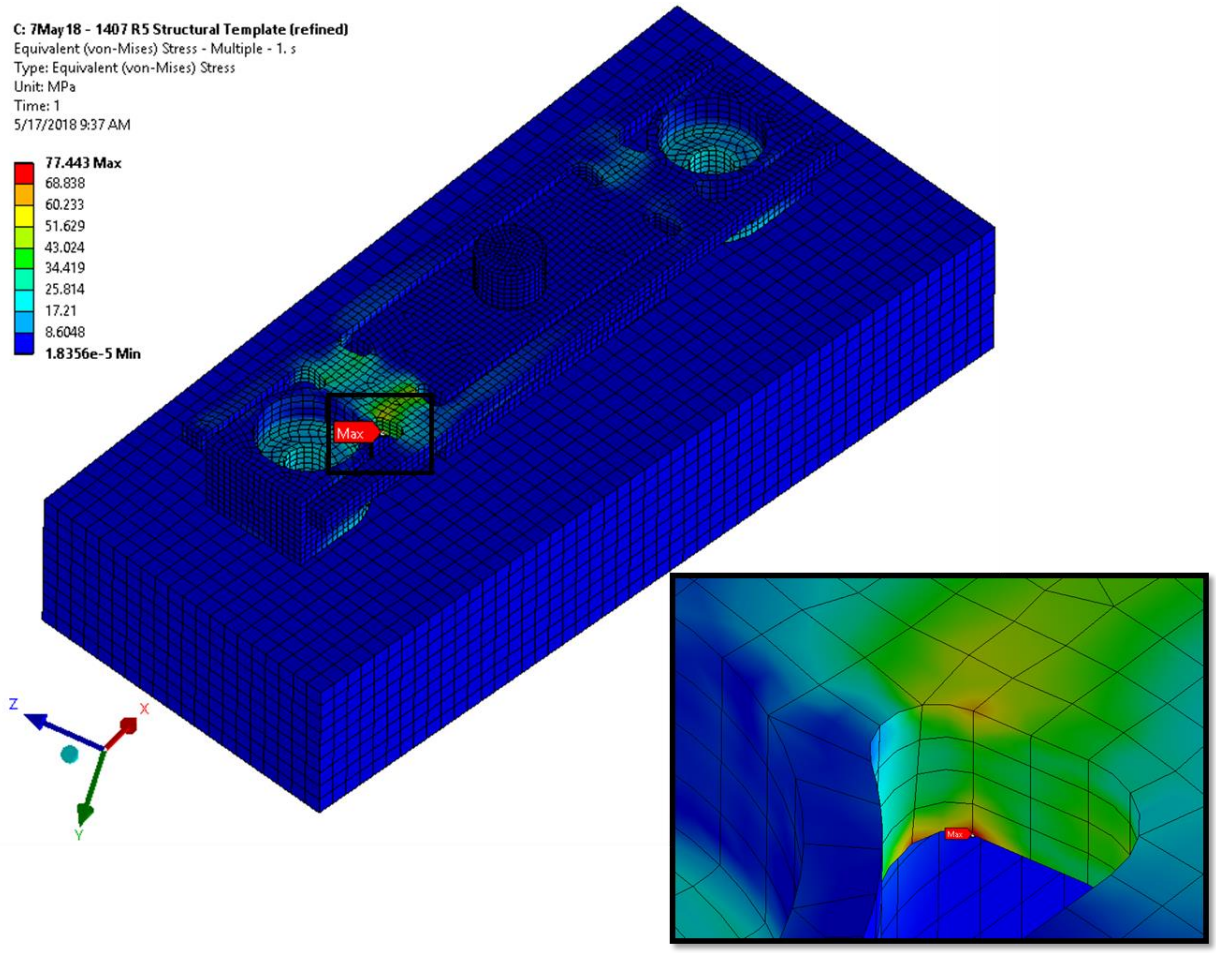


Figure 81: Peak equivalent stress due to bolt preload only.

11 Subreport E-ED1407-8 R5 Style 2 X-Ray Spectrometer Variant

OBD345 R5, S2 round 1 E-ED1407-8 X-ray crystal spectrometer tile

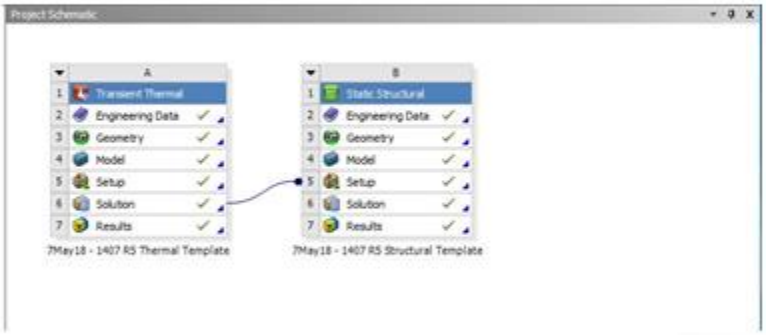
PPPL NSTX-U PFCs

Dennis Youchison
May 18, 2018

ORNL is managed by UT-Battelle for the US Department of Energy

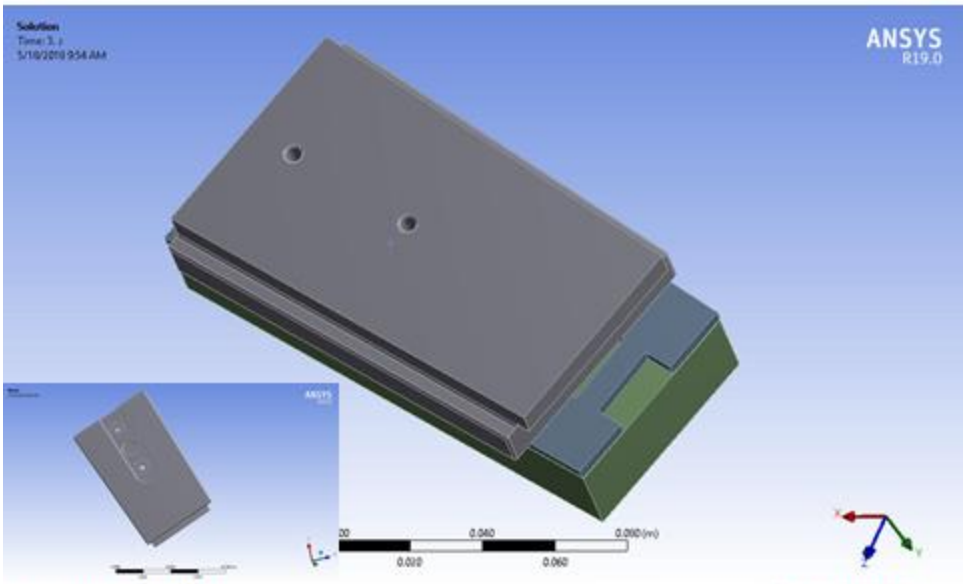
OAK RIDGE National Laboratory

OBD345 R5, S2 round 1 Tile-8, E-ED1407-8, Material T953



OAK RIDGE National Laboratory

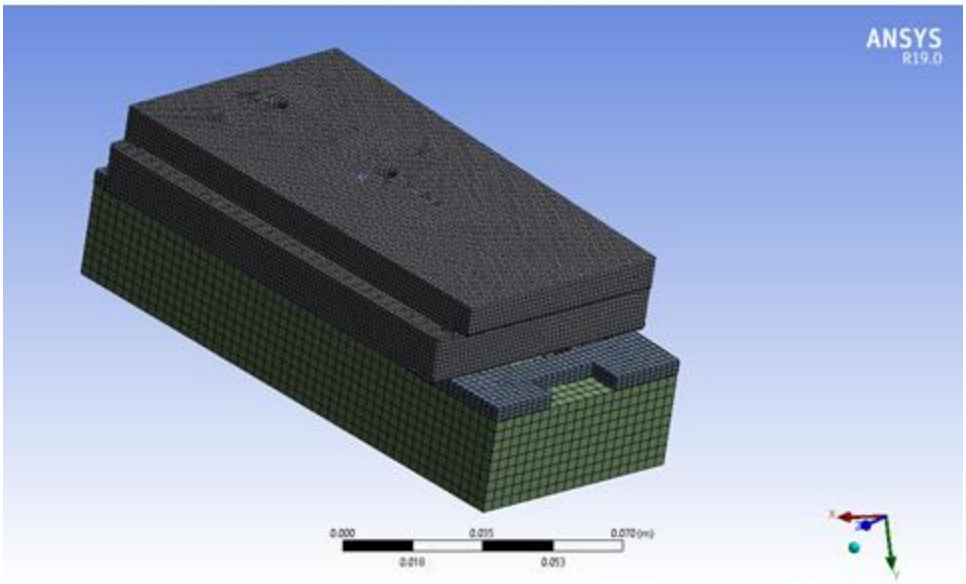
Tile-8 Geometry



X-ray spectrometer

OAK RIDGE National Laboratory

Mesh 138k Hex Dominant



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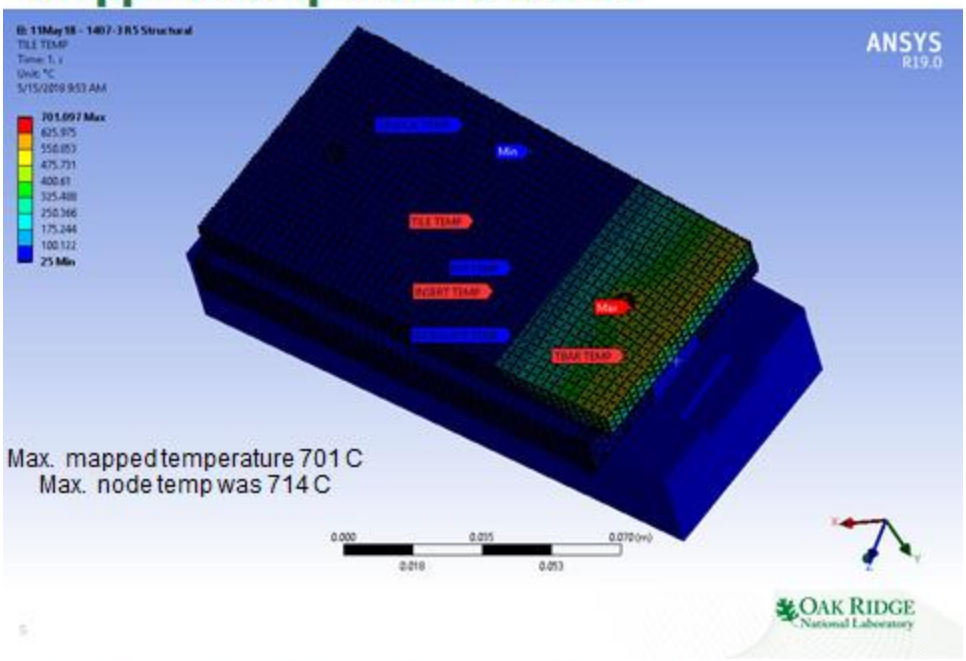
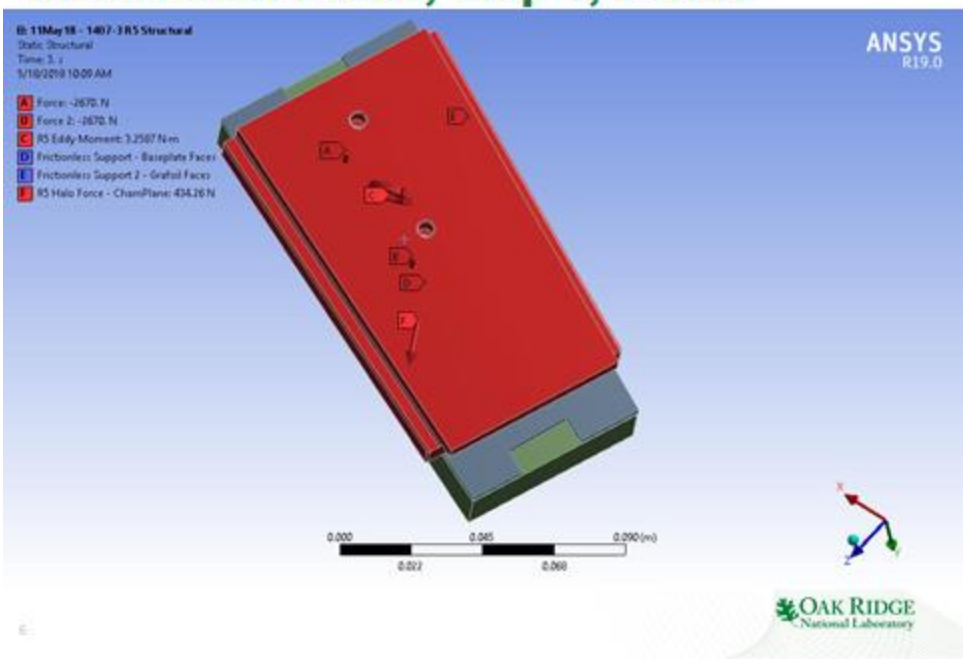
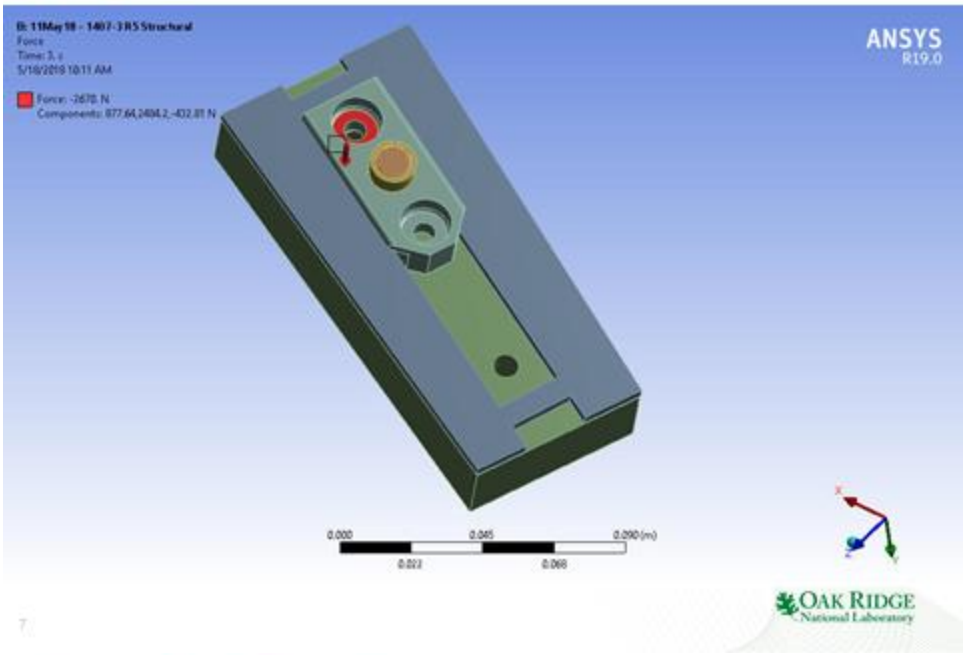
Mapped Temperature Loads



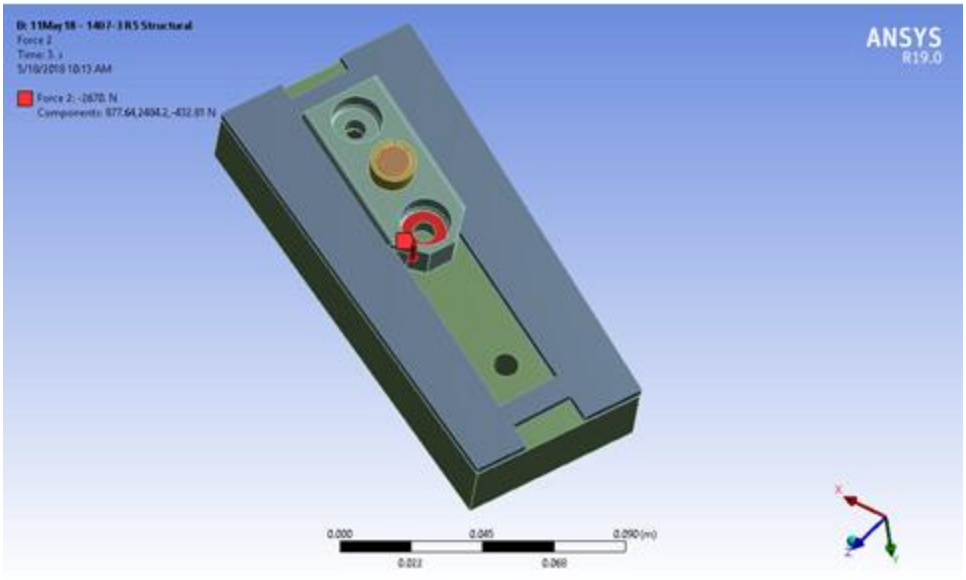
Mechanical Loads, step 3, t=3.0s



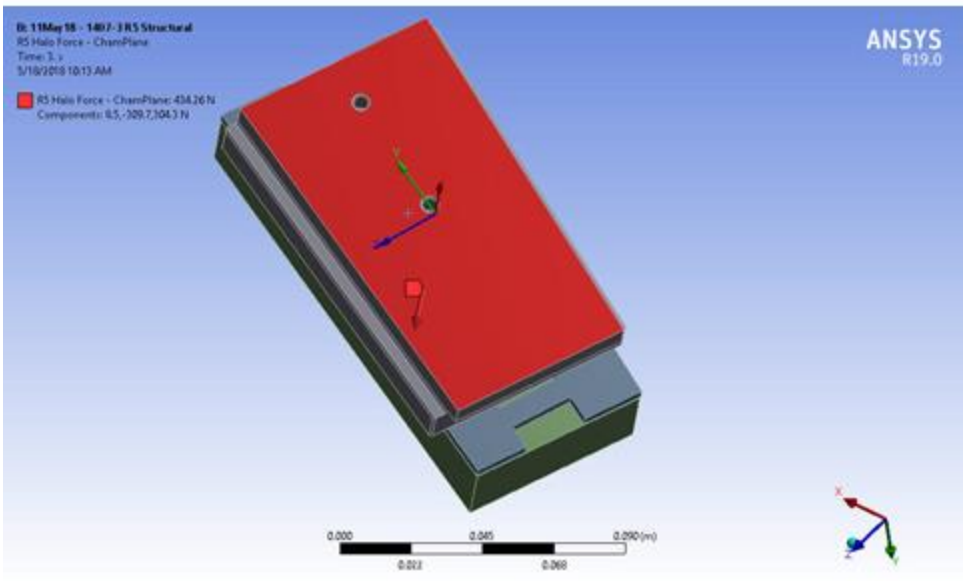
Force 1 defined



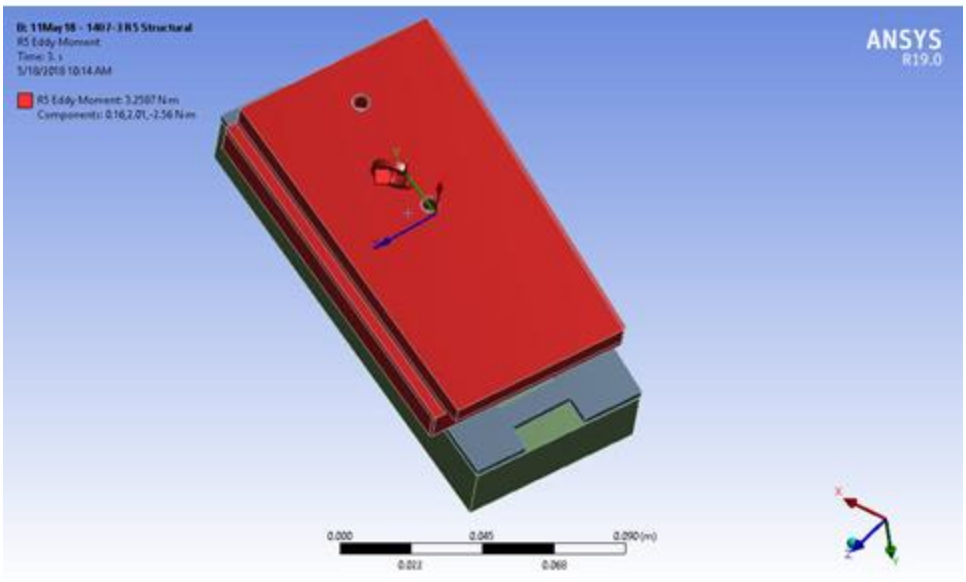
Force 2 defined



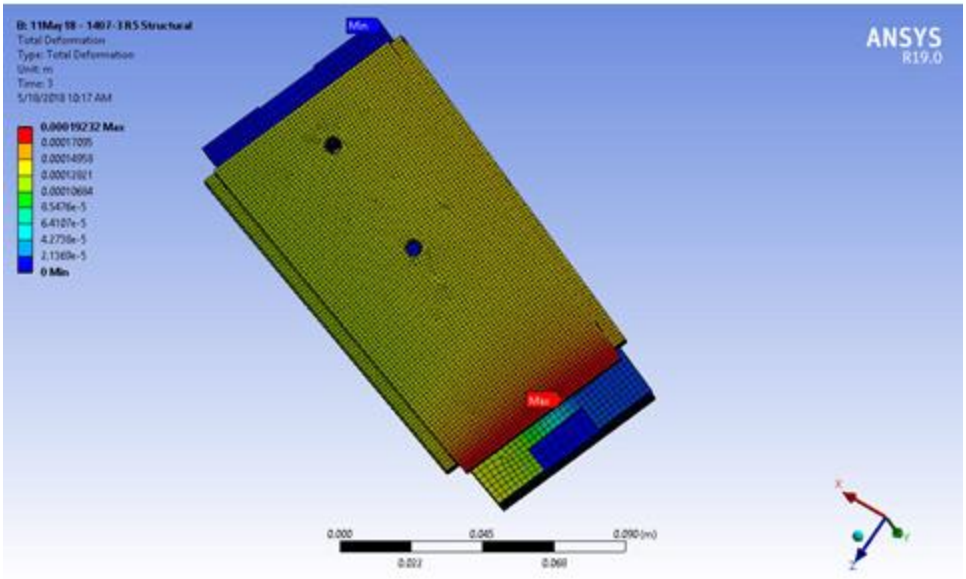
Halo Forces



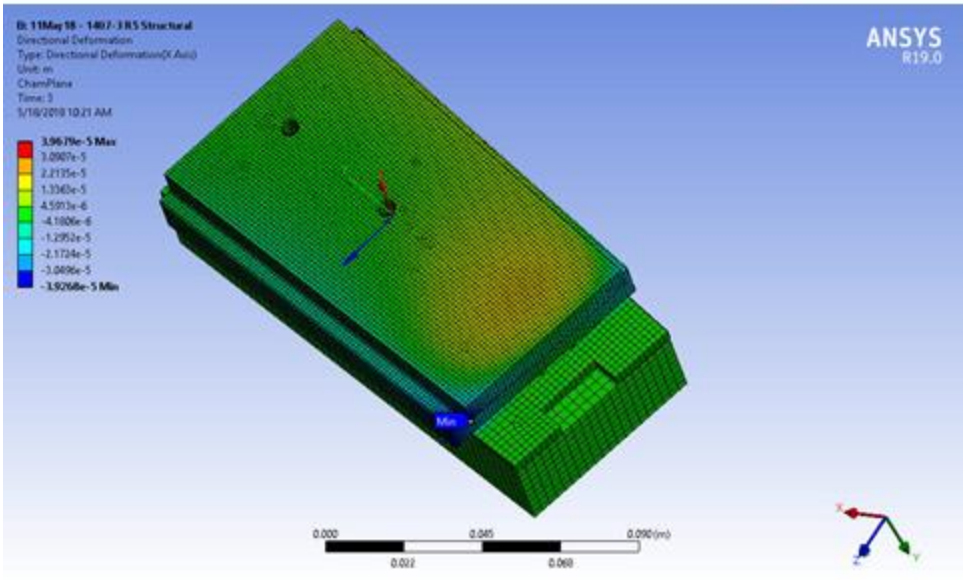
Eddy Moment



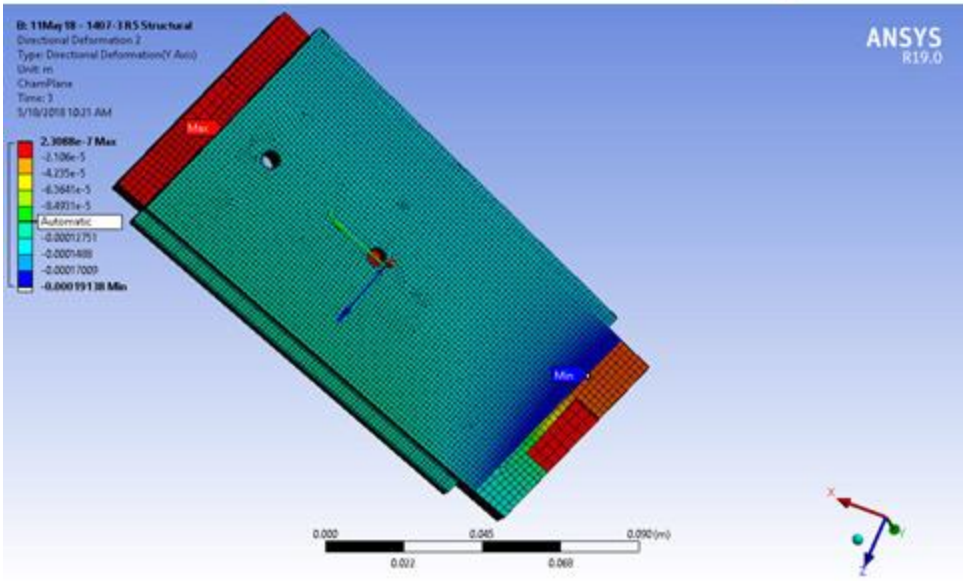
Total Deformation



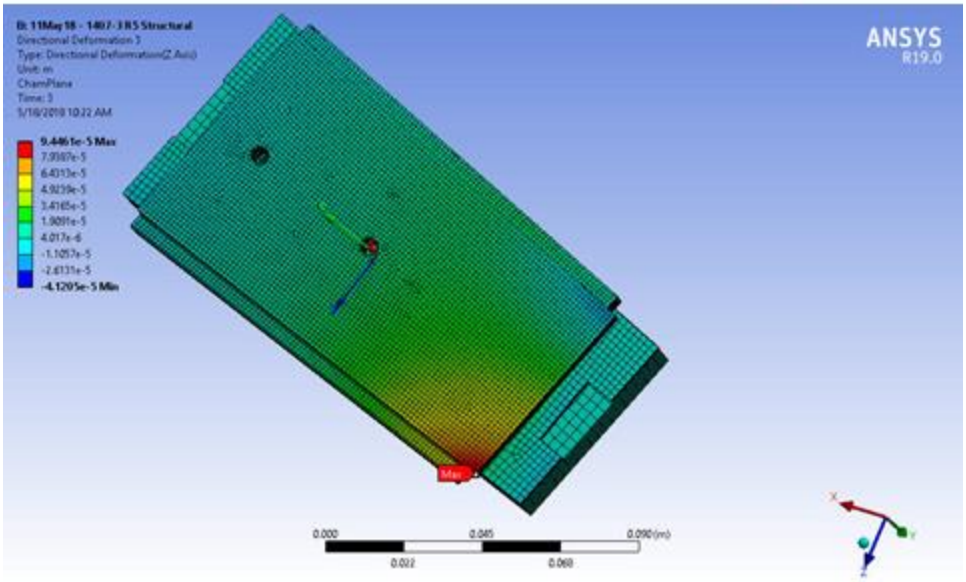
X-deformation from ChamPlane Origin



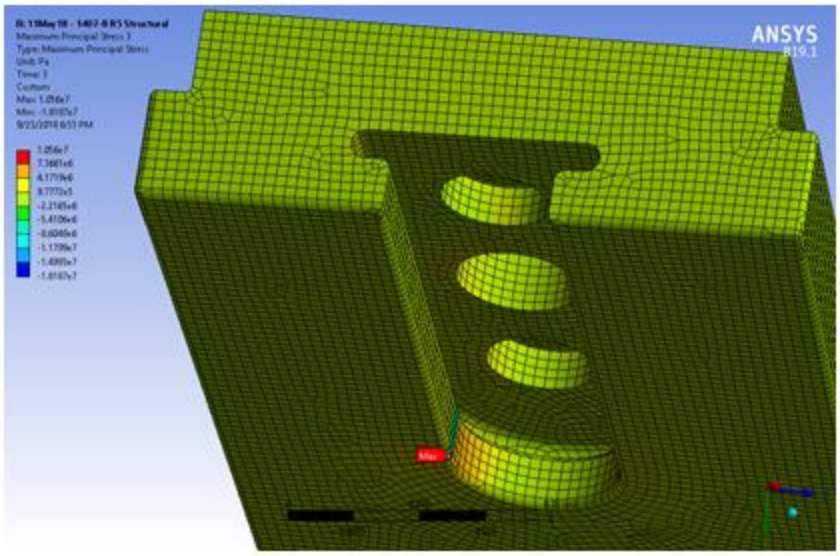
Y-deformation from ChamPlane Origin



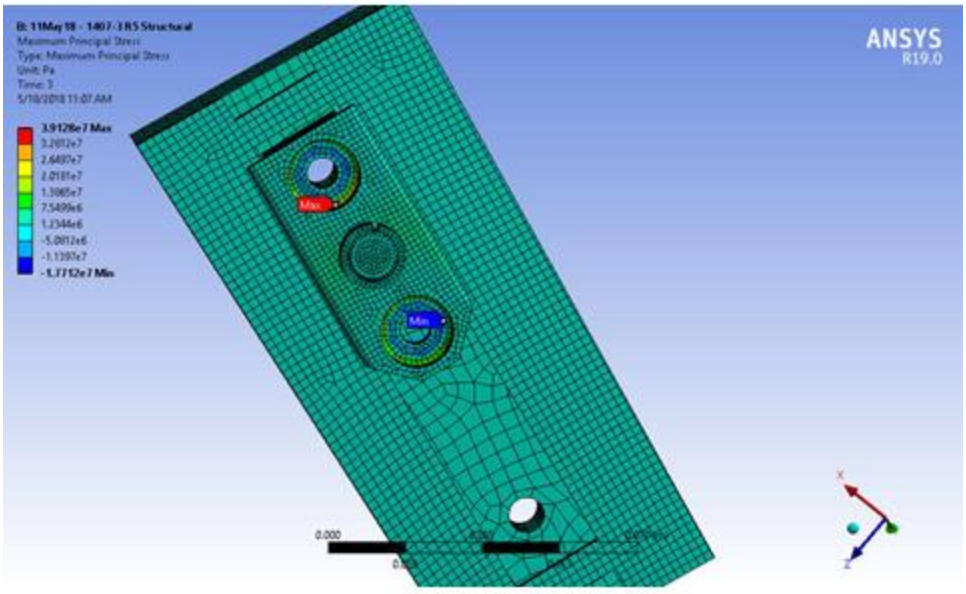
Z-deformation from ChamPlane Origin



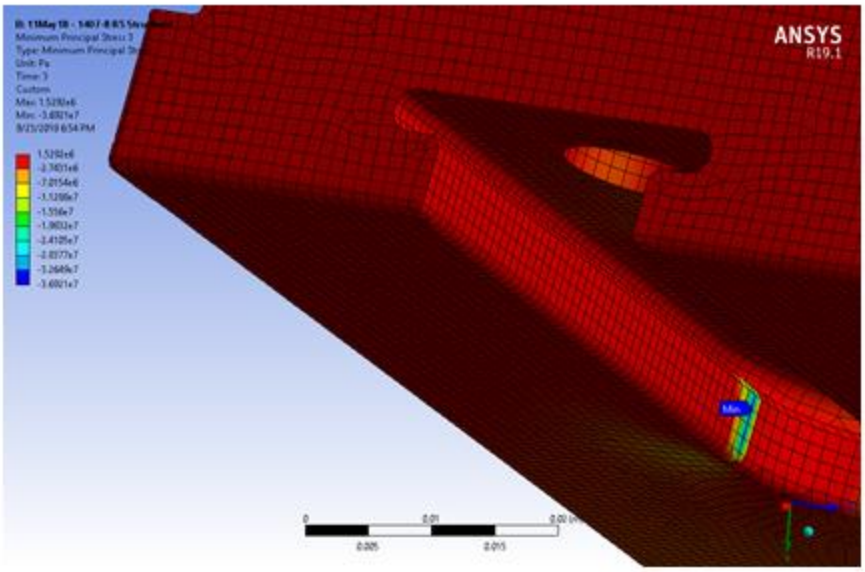
Maximum Principal Stress



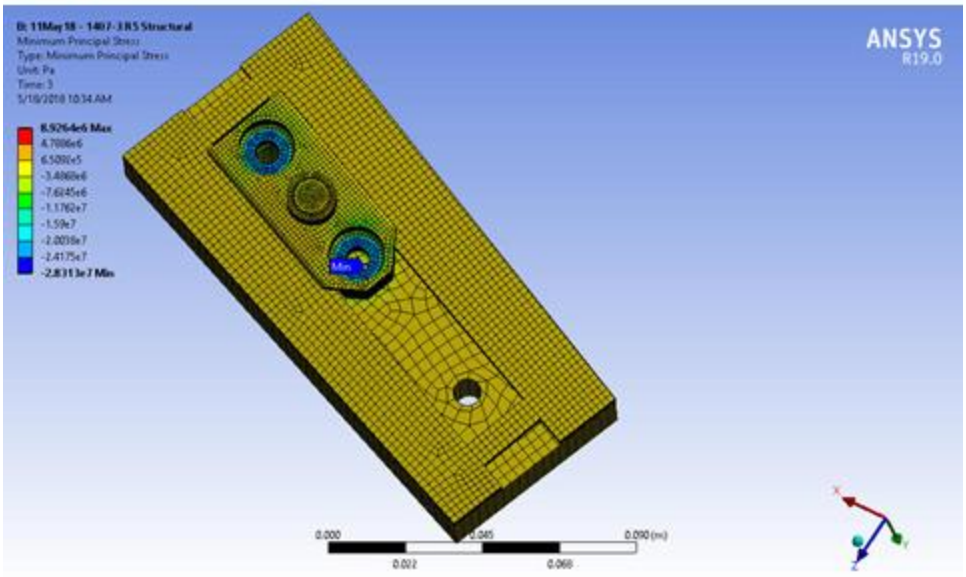
Maximum Principal Stress in Hardware



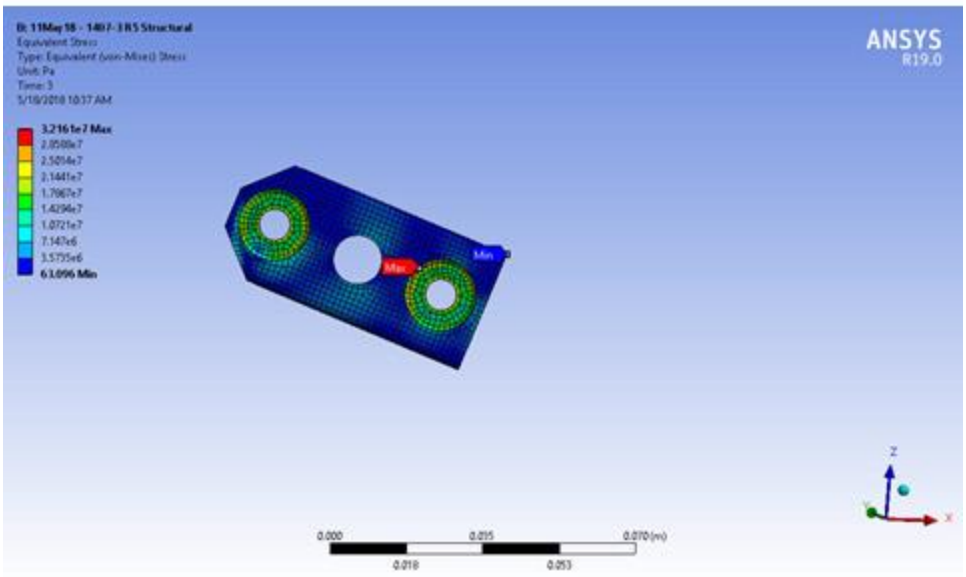
Minimum Principal Stress



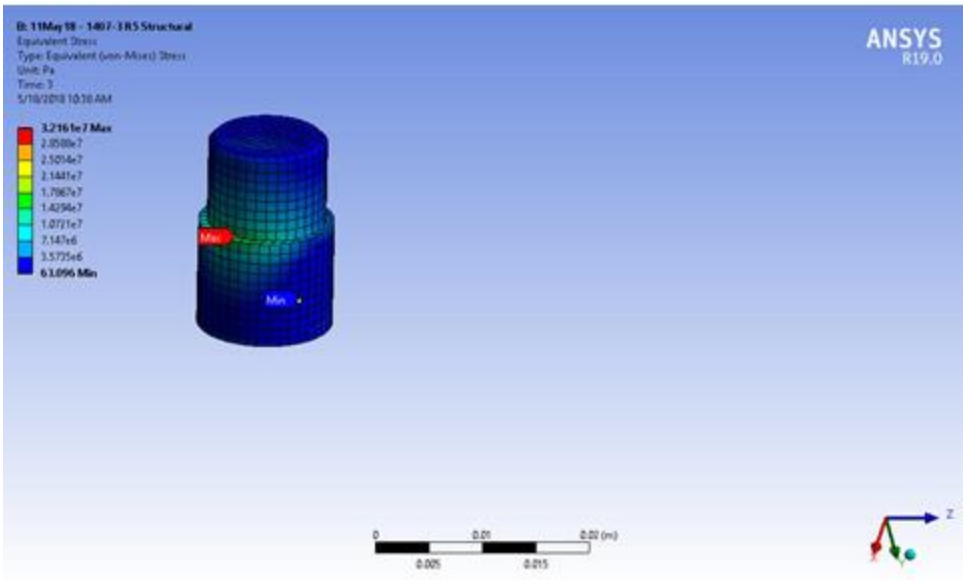
Minimum Principal Stress in Hardware



Von Mises Stress in Teebar



Von Mises Stress in Pin



Summary

Tile
S3 allowable = $1/2\sigma_{UCS}$ T953 = -55 Mpa
S1 allowable = 20 MPa

Max. principal stress was 10.6 MPa and the Min. principal stress was -36.9 MPa
SF~1.9

Teebar
UTS of In625 is 782 MPa
$1/3\sigma_{UTS}$ In625 = 261 MPa
$2/3\sigma_{YS}$ In625 = 266 MPa

Max. von Mises stress was 32.2 MPa: SF~8

12 Subreport E-ED1407-9 R5 Style 2 Diagnostic Gap Chamfered Tile Variant

Subreport E-ED1407-9 not included in Rev0 of this report.

13 Subreport E-ED1407-10 PCHERS Upper Bay Chamfered Variant

13.1 Expected results for E-ED1407-10 made from CFC

The decision to make this tile from CFC was made based on the analysis of the tile design using T953. The subreport for the T953 analysis is presented in the following subsection. The expected thermal-structural response of this tile when made from FMI3D (a grade of CFC) is based on the scaling methodology presented in the subreport for tile E-ED140-10. The scaling is as follows:

Max Temperature = 1170C * 0.72 = 842C
Max S1 = 21.85 MPa * 0.95 = 20.8 MPa
Min S3 = -44.9 MPa * 1.4 *0.47 = -29.5 MPa

13.2 Analysis of E-ED1407-10 with T953 Graphite – FOR INFORMATION ONLY

Analysis performed by ORNL

Summary

The maximum tensile stress in the tbar slot exceeds its allowable. The minimum principal stress in the chamfer of one of the bolt holes exceeds its allowable. See Figure 59. I do not have allowable stress values for pure copper or Inconel 718. Peak stresses in all components are lists in Table 13, Table 14, and Table 15.

The components considered in the analysis are listed below in Figure 43 and Figure 44.

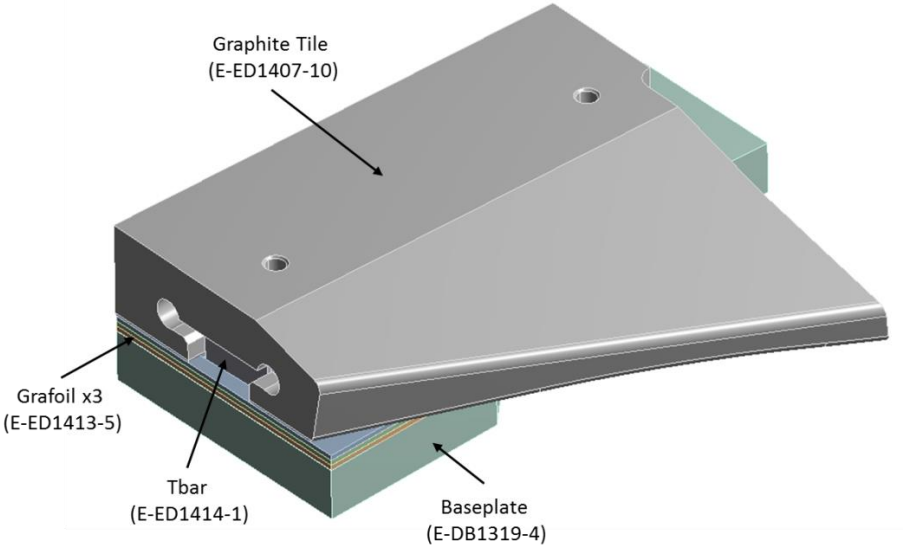


Figure 82: Outboard Diverter Row 5 style 2 variant (1407-10)

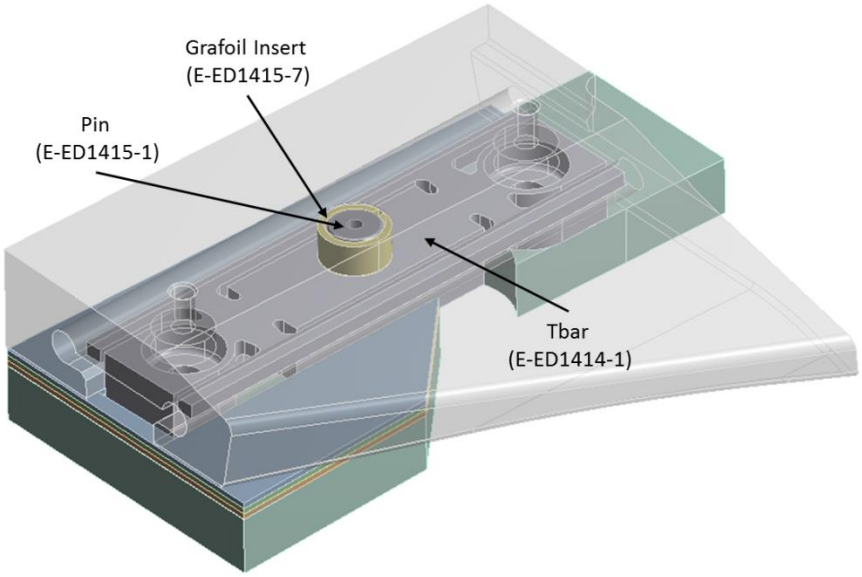


Figure 83: OBD Row 5 style 2 variant (1407-10) components considered.

The total number of elements and nodes for the whole assembly is 794,471 and 1,201,454 respectively. Figure 45 shows the mesh used in the analysis with and without the graphite tile. Figure 46 shows the mesh of the mounting side of the graphite tile.

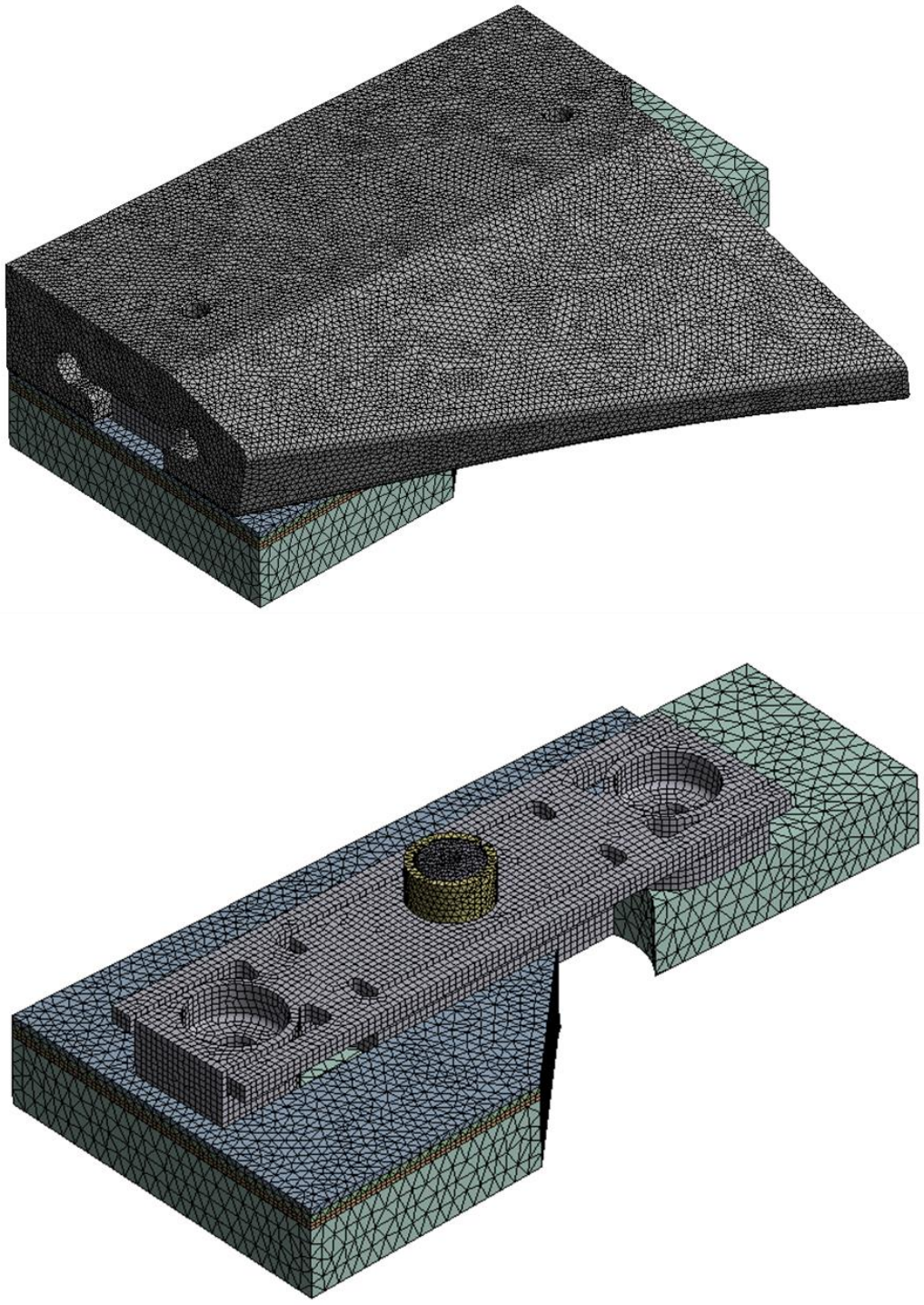


Figure 84: Mesh of the Outboard Diverter Row 5 style 2 variant (1407-10)

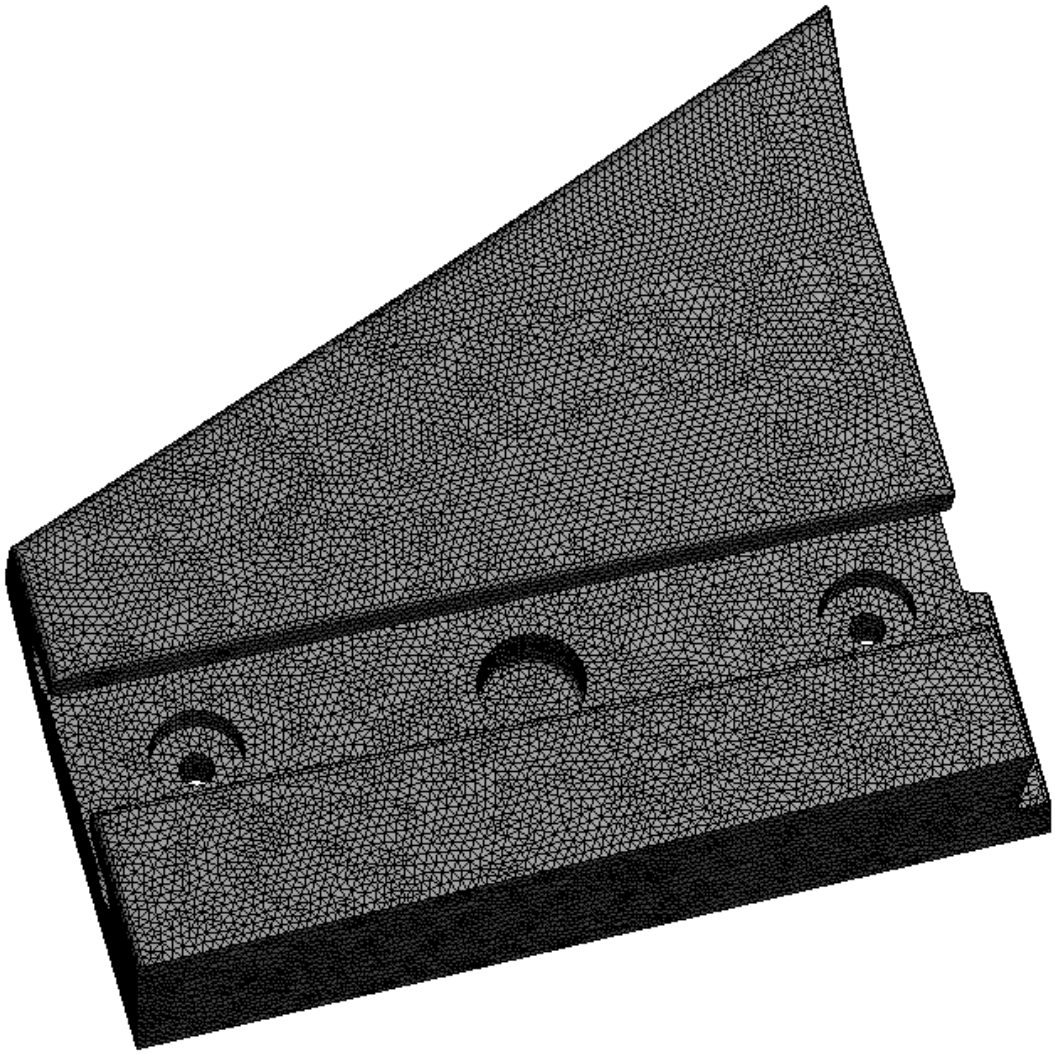


Figure 85: Mounting side of the graphite tile.

Table 11 lists each component of the assembly and its material.

Table 21: Components and their materials.

Component	Material
Graphite Tile (E-ED1407-10)	T953
Grafoil (E-ED1413-5)	Grafoil
Baseplate (E-DB1319-4)	Pure Copper
Grafoil Insert (E-ED1415-7)	Grafoil
Pin (E-ED1415-1)	Inconel 718
Tbar (E-ED1414-1)	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

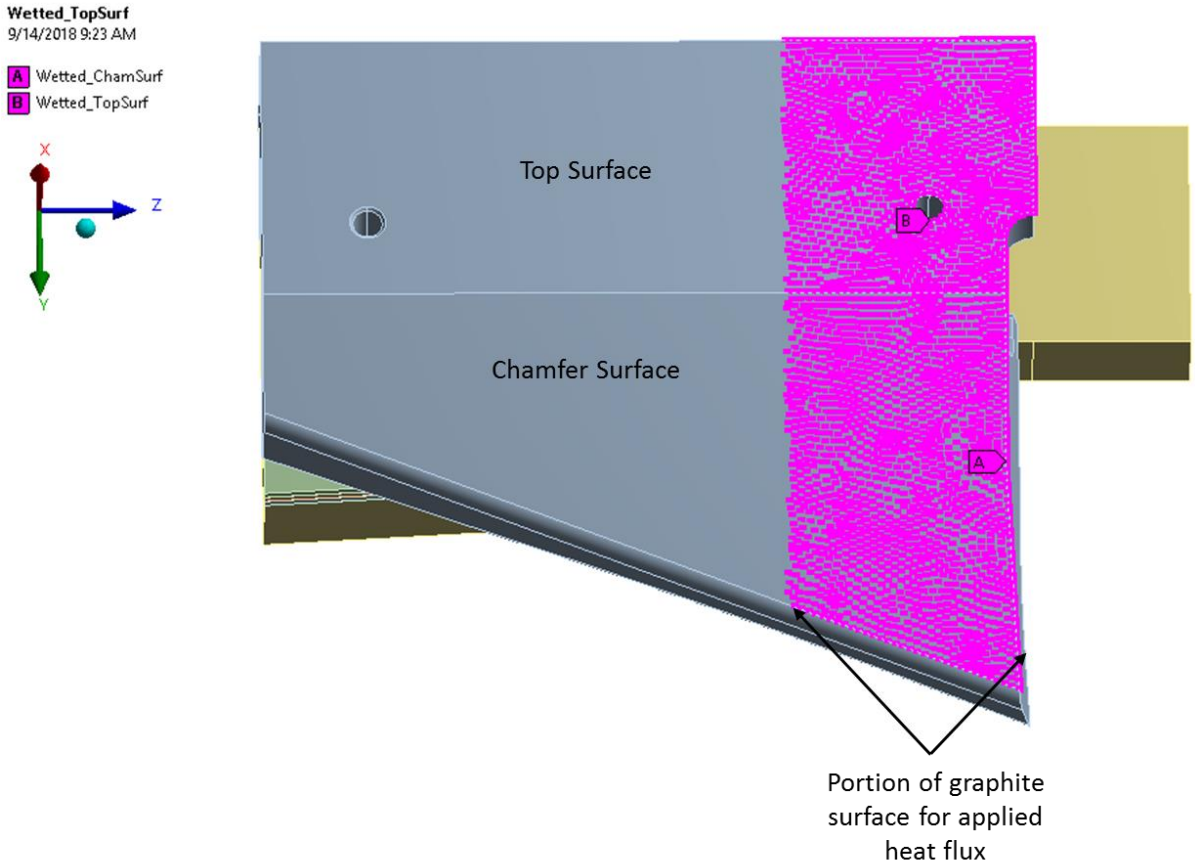


Figure 86: Thermal boundary conditions

Top Surface heat flux = 4,697,997 W/m^2 with a gradient heat flux along the y-direction of –117,449,918 W/m^2/° with the extent being 0.04 m.

Chamfer Surface heat flux = 11,815,287 W/m^2 with a gradient heat flux along the y-direction of -295,382,175 W/m^2/° with the extent being 0.04 m

.

The peak temperature in the assembly was 1170 °C in the graphite tile. Figure 48 and Figure 49 shows the temperature contour because of the applied heat fluxes. Table 12 lists the peak temperature for each component.

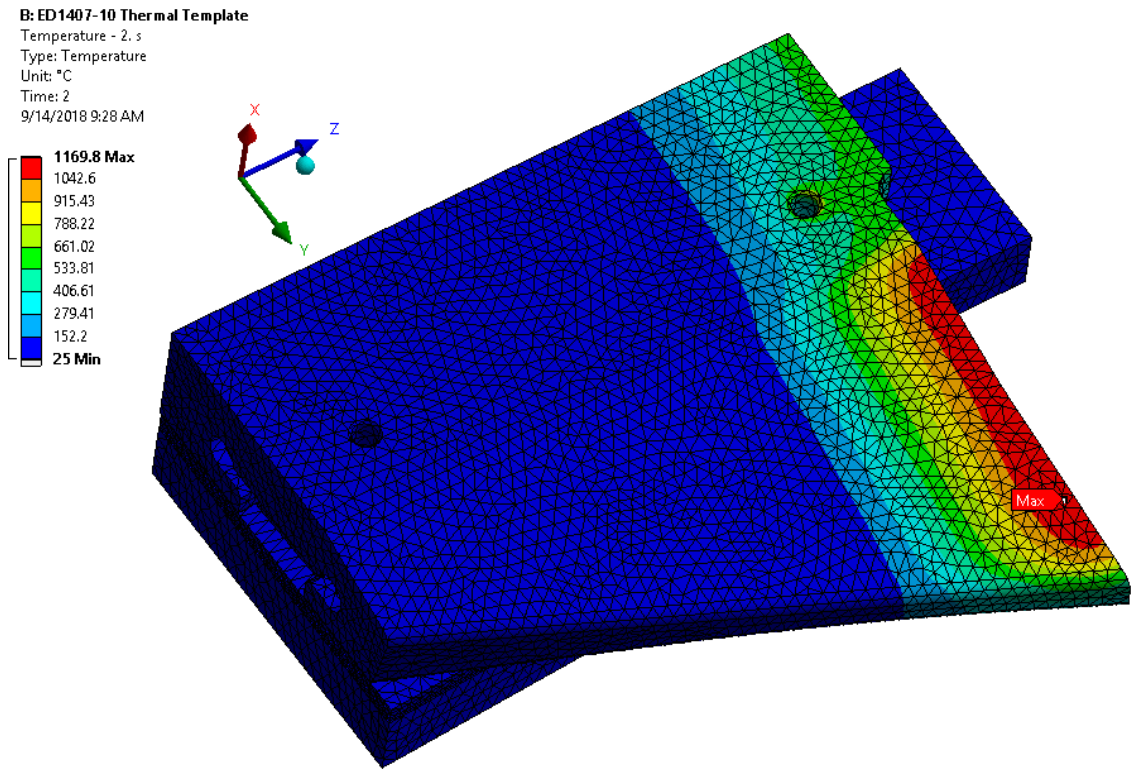


Figure 87: Temperature contour plot of the OBDRow 5 style 2 variant (1407-10)

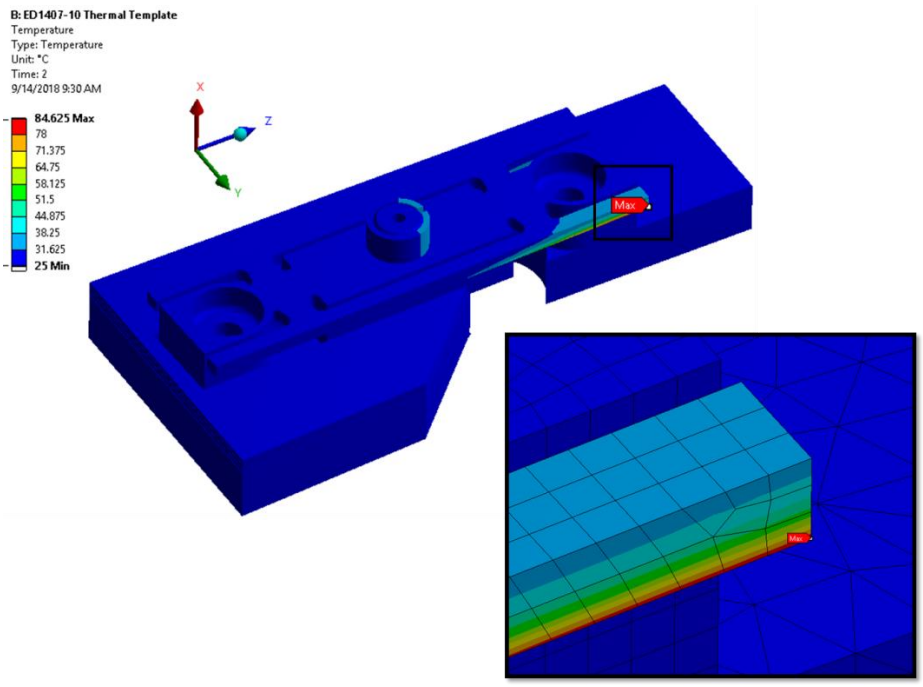


Figure 88: Temperature contour plot of the Outboard Diverter Row 5 style 2 variant (1407-10) without graphite tile

Table 22: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1407-10)	1170
Grafoil (E-ED1413-5)	25
Baseplate (E-DB1319-4)	25
Grafoil Insert (E-ED1415-7)	38
Pin (E-ED1415-1)	25
Tbar (E-ED1414-1)	85

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar (ED1414-1) as shown in Figure 50. Figure 51 and Figure 10 shows the halo force and eddy current loading applied to the graphite tile respectively.

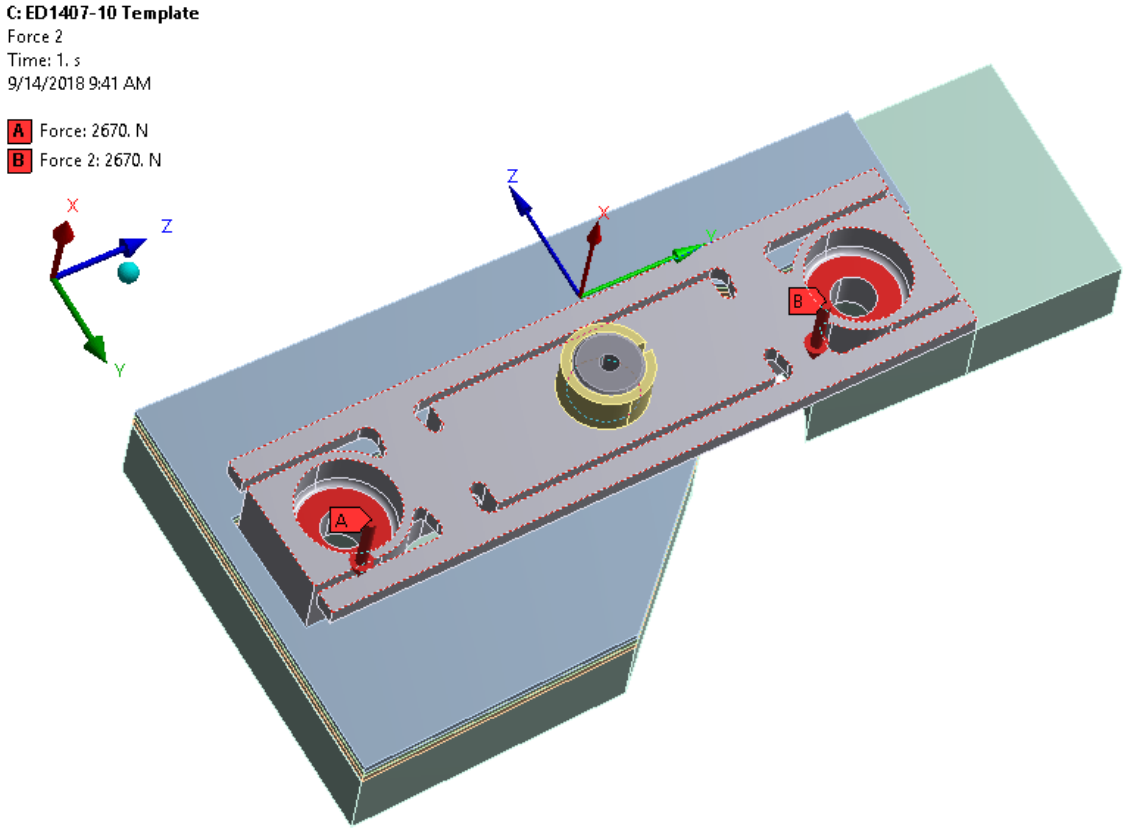


Figure 89: Bolt preload force applied to the Tbar.

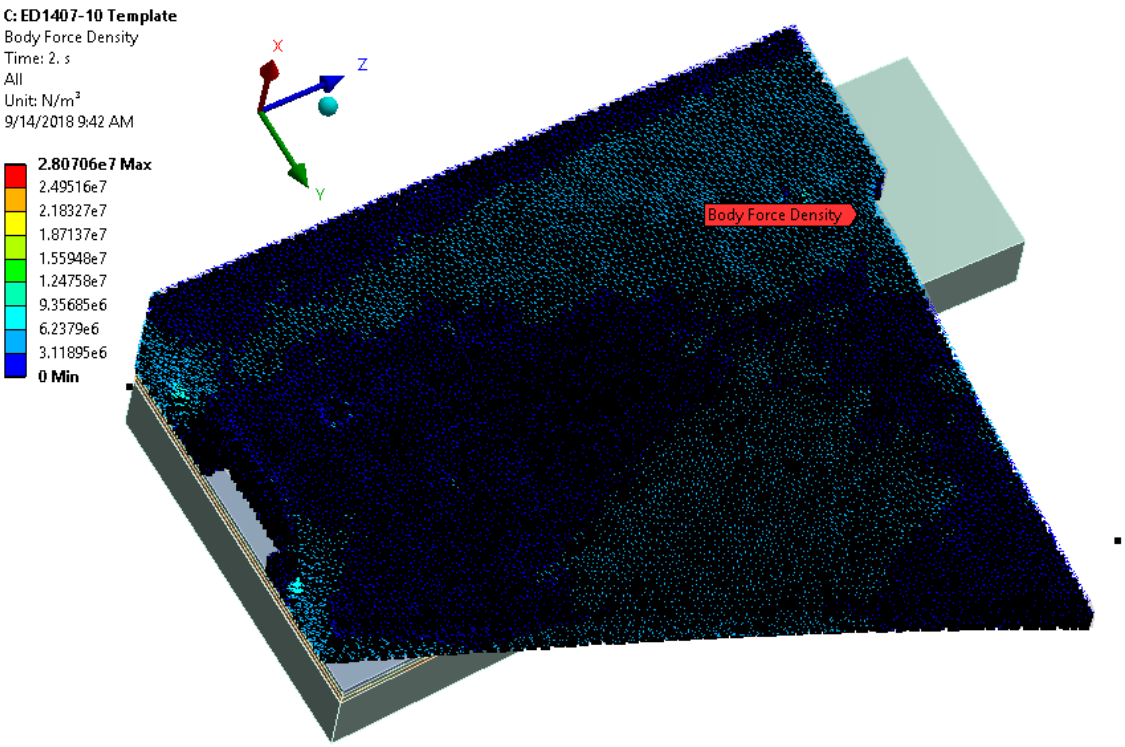


Figure 90: Halo force applied as a body force density to the graphite tile.

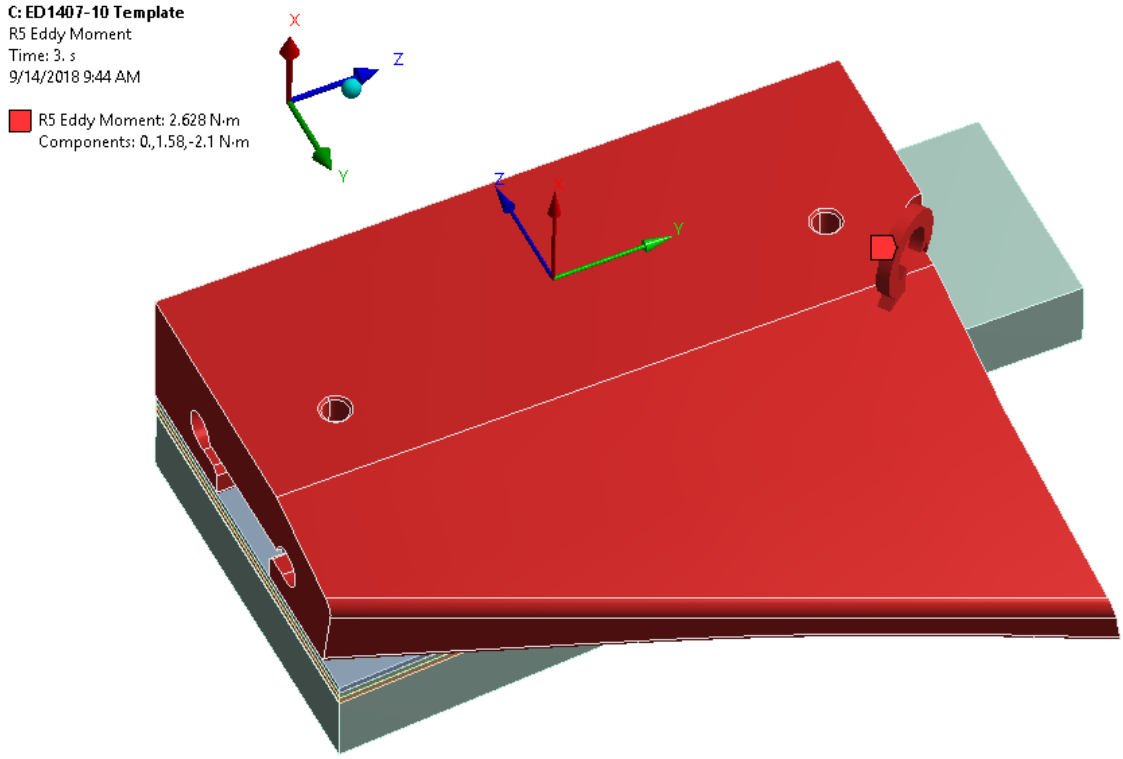


Figure 91: Eddy current load on graphite tile.

Frictionless constraints were applied to one side of the baseplate and two sides of the grafoil. Figure 52 shows the location of these constraints highlighted in blue.

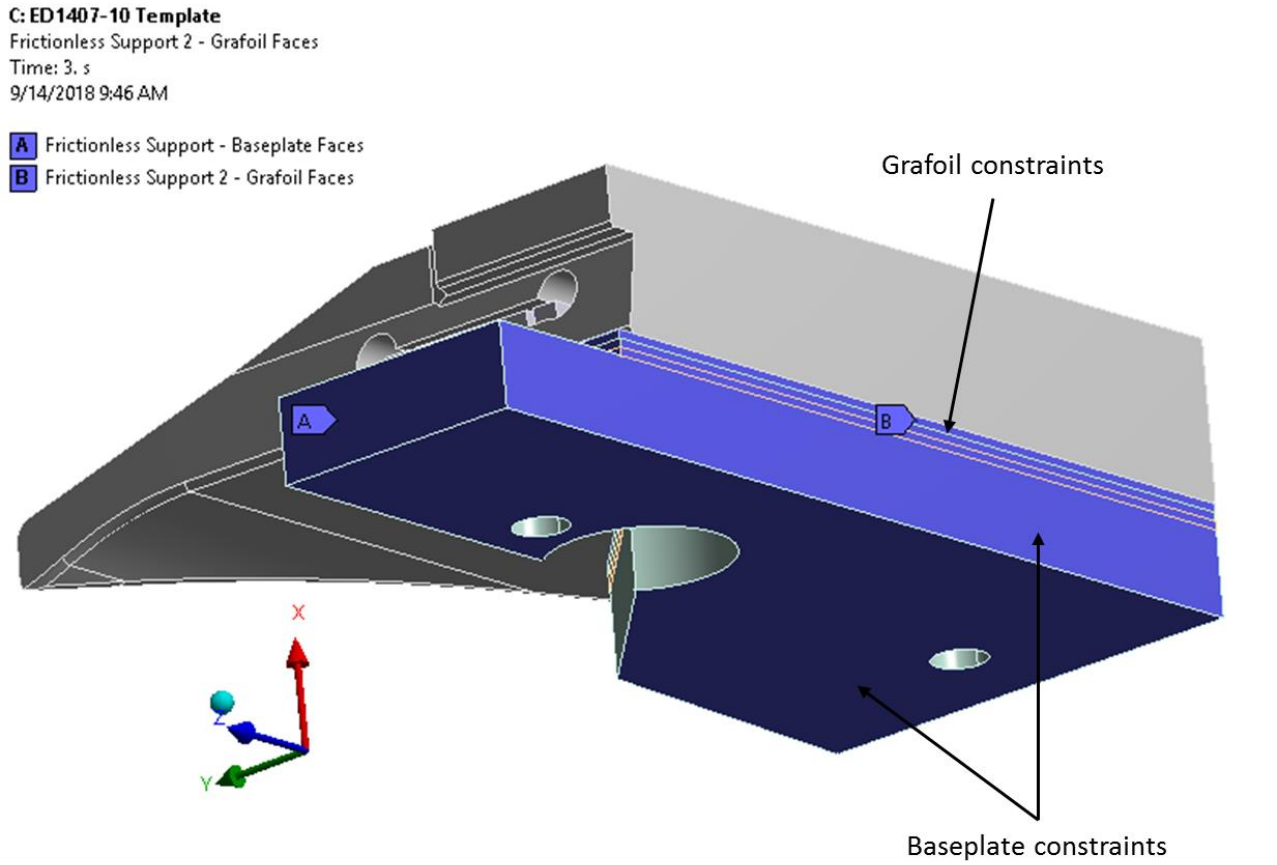


Figure 92: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R45-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1. Figure 53 shows the surfaces in contact with each other labeled A through E.

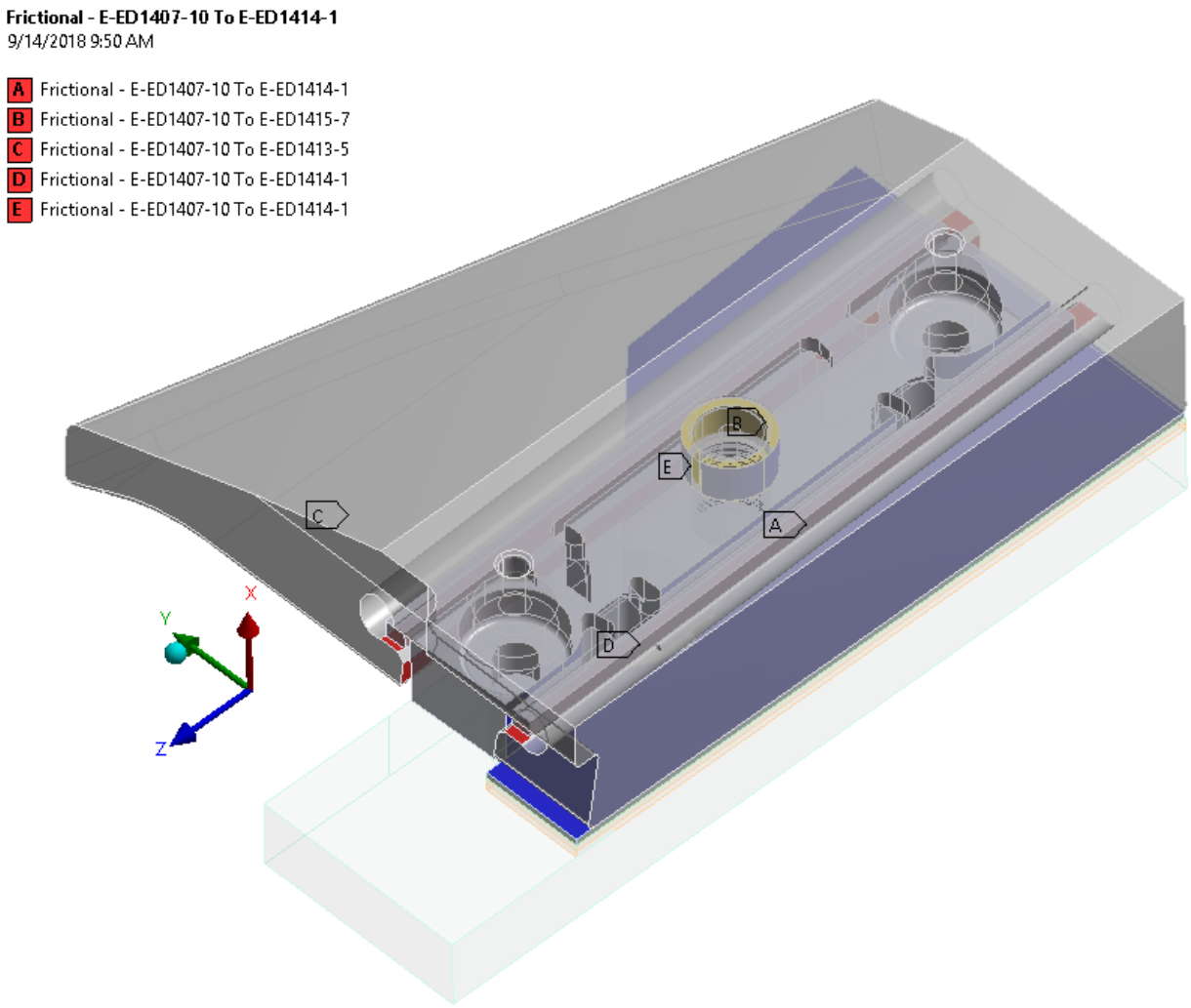


Figure 93: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition. Figure 54 shows the surfaces in contact with each other labeled A through D.

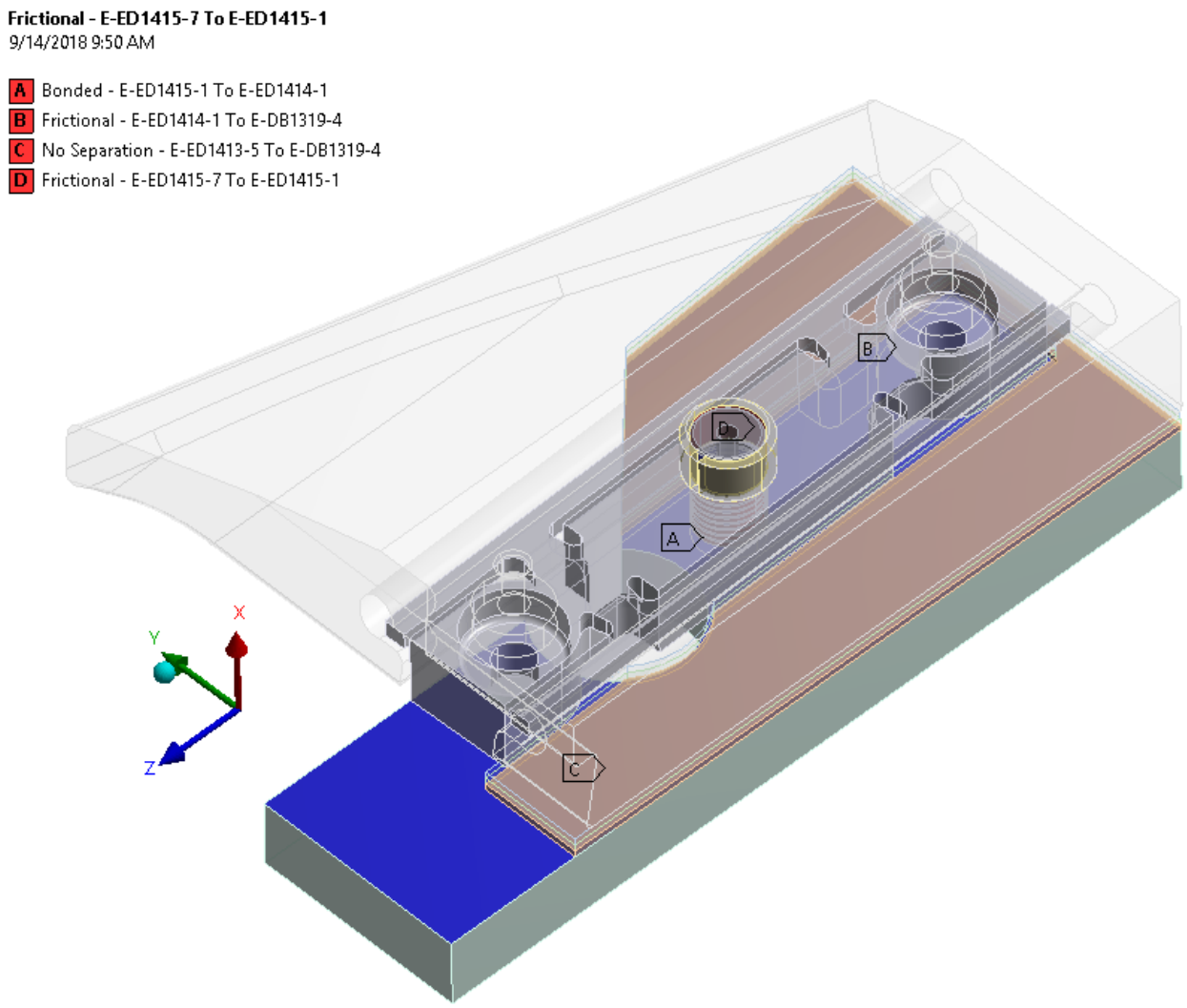


Figure 94: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 55. X, Y, Z deformation contour in the assembly is shown Figure 56, Figure 57, and Figure 58.

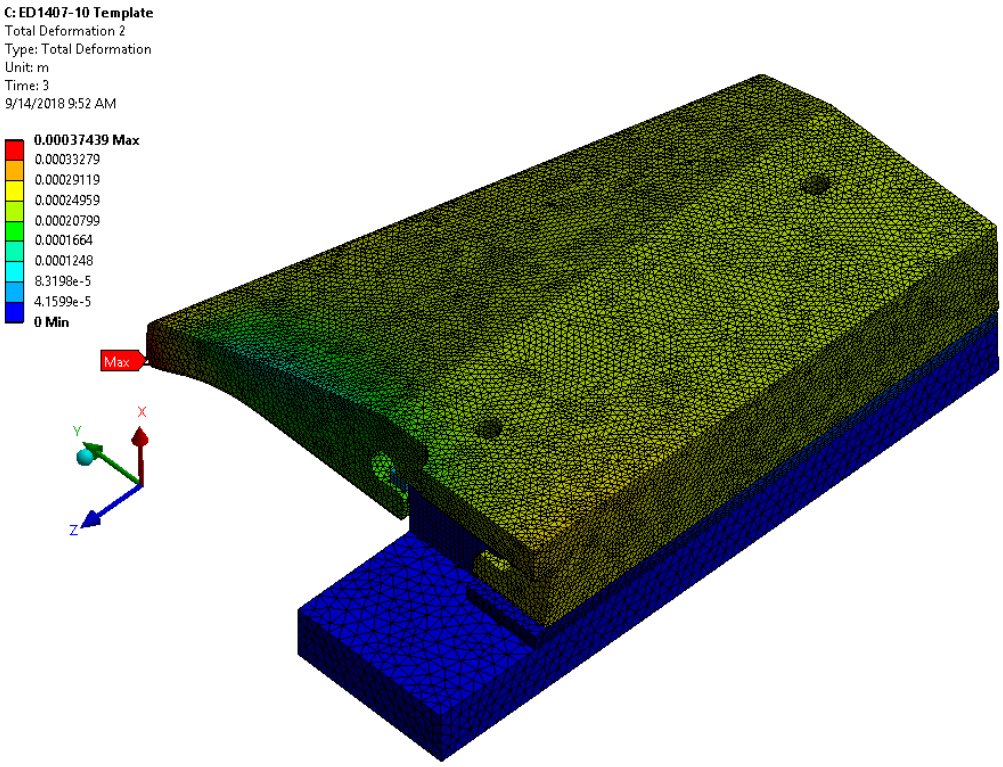


Figure 95: Total deformation of the assembly

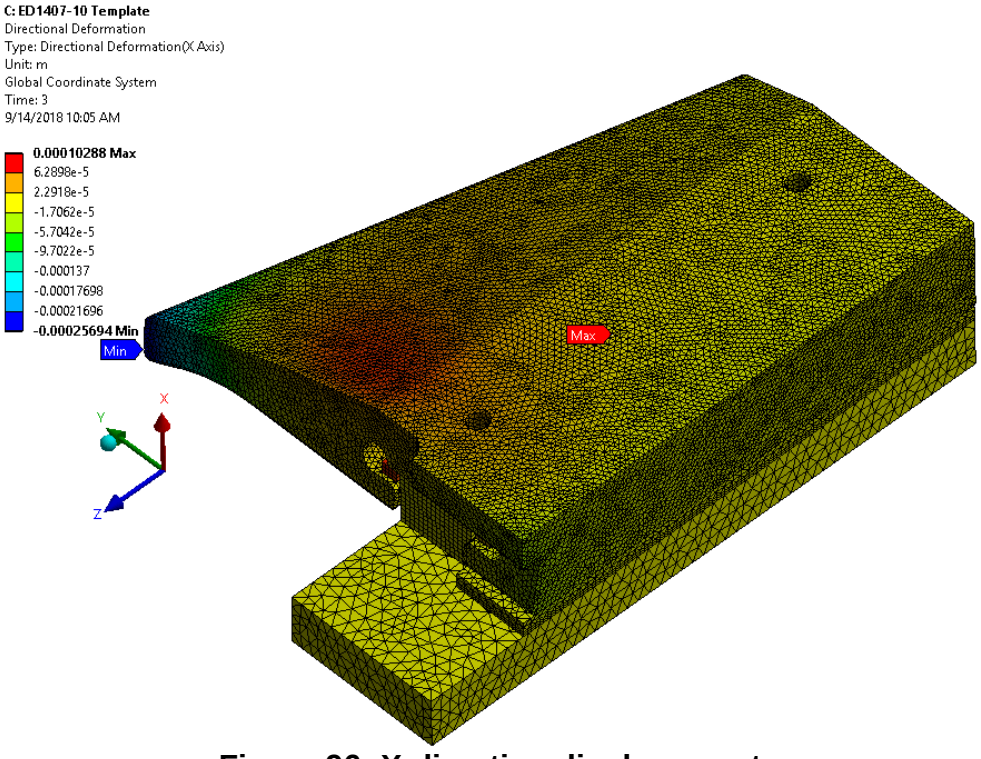


Figure 96: X-direction displacement

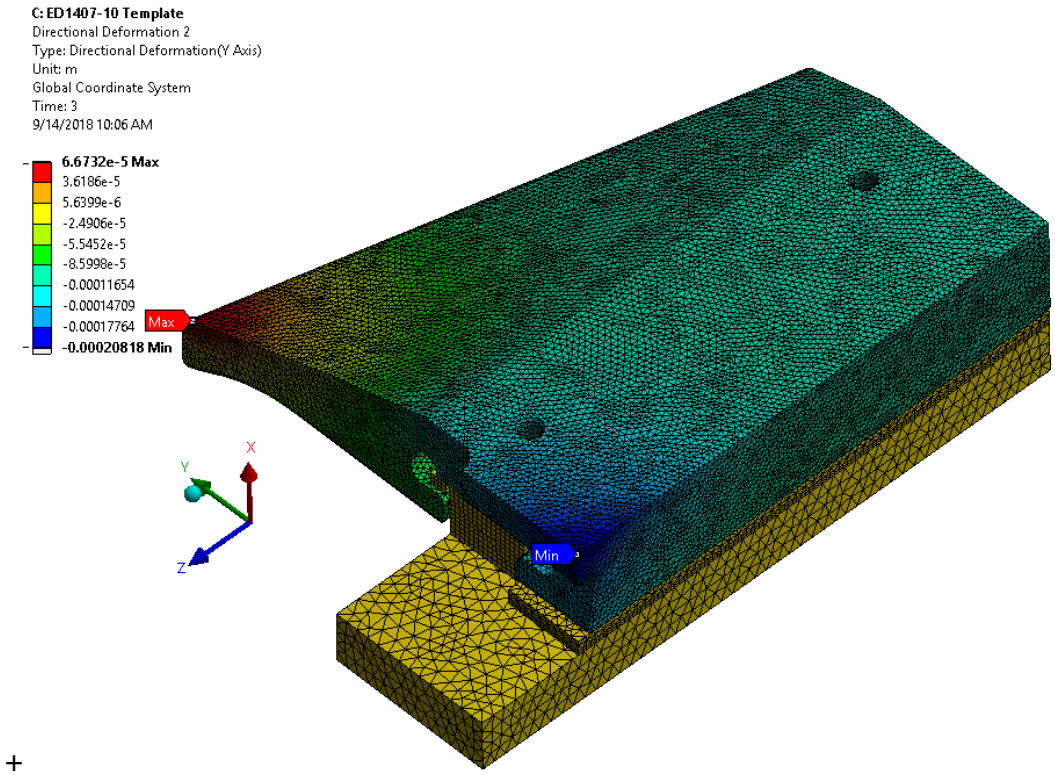


Figure 97: Y-direction displacement

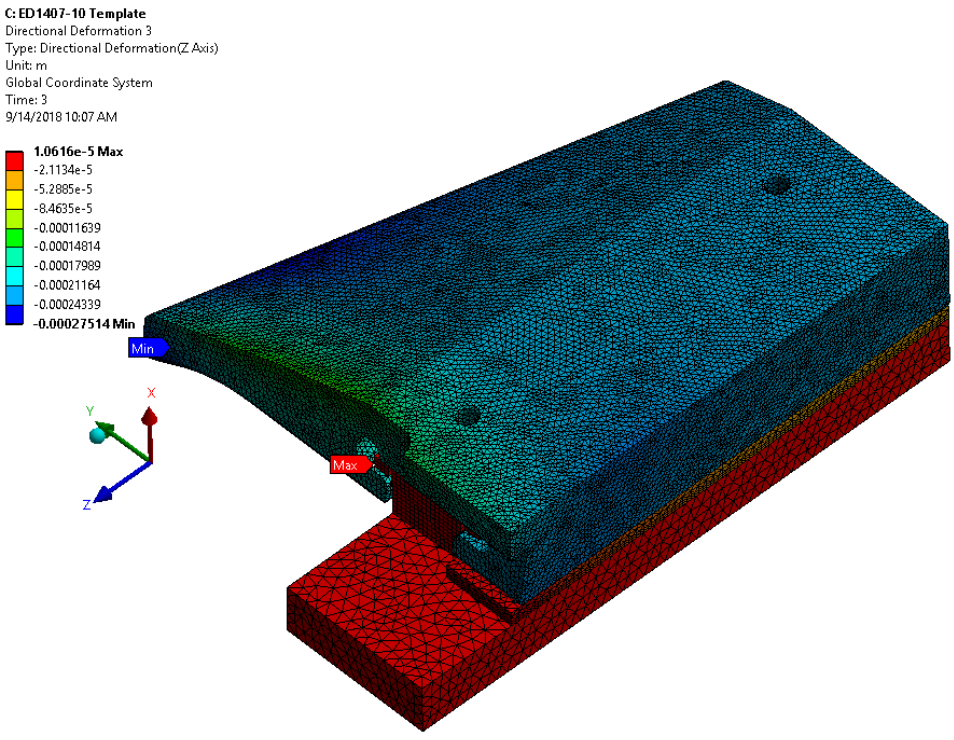


Figure 98: Z-direction displacement

Table 13 and Table 14 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 15 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 23: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-10)	21.85	20	BPL+Halo
Graphite Tile – Tbar Slot	21.85	20	BPL+Halo
Graphite Tile – Shear Pin Hole	9.55	20	BPL+Halo+Eddy
Grafoil (E-ED1413-5)	0.25	20	BPL+Halo
Grafoil Insert (E-ED1415-7)	6.29	20	BPL+Halo+Eddy

Table 24: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-10)	-44.91	-55	BPL+Halo
Graphite Tile – Tbar Slot	-13.14	-55	BPL+Halo+Eddy
Graphite Tile – Shear Pin Hole	-9.03	-55	BPL+Halo+Eddy
Grafoil (E-ED1413-5)	-0.63	-55	BPL+Halo
Grafoil Insert (E-ED1415-7)	-11.32	-55	BPL+Halo+Eddy

Table 25: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate (E-DB1319-4)	12.32	??	BPL
Pin (E-ED1415-1)	34.02	276	BPL+Halo+Eddy
Tbar (E-ED1414-1)	221.38	261	BPL+Halo

All stresses resulted in values below their respective allowables. Figure 59 shows the location of the peak minimum principal stress with bolt preload and the halo load.

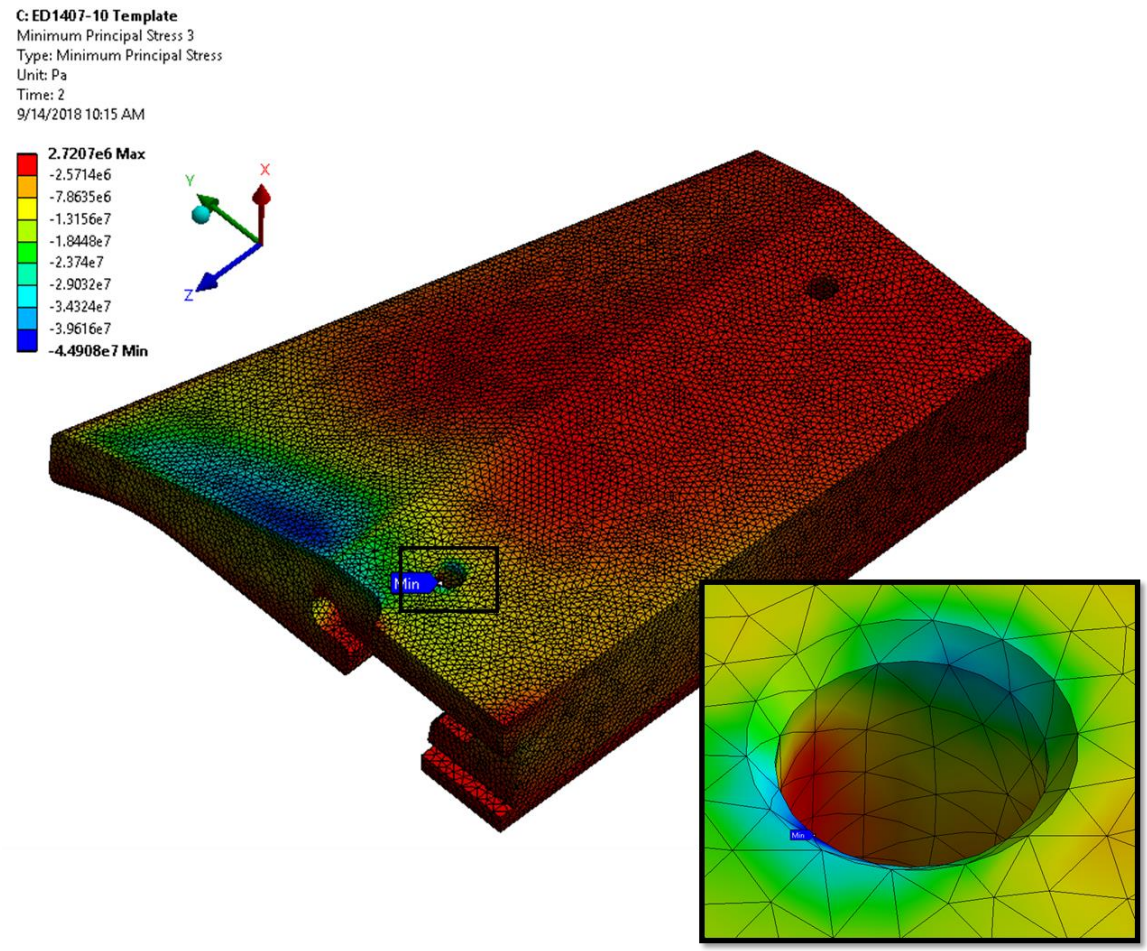


Figure 99: Location of peak minimum stress in OBD Row 5 style 2 -10

The location of maximum principal stress with bolt preload and the halo load is shown in Figure 60.

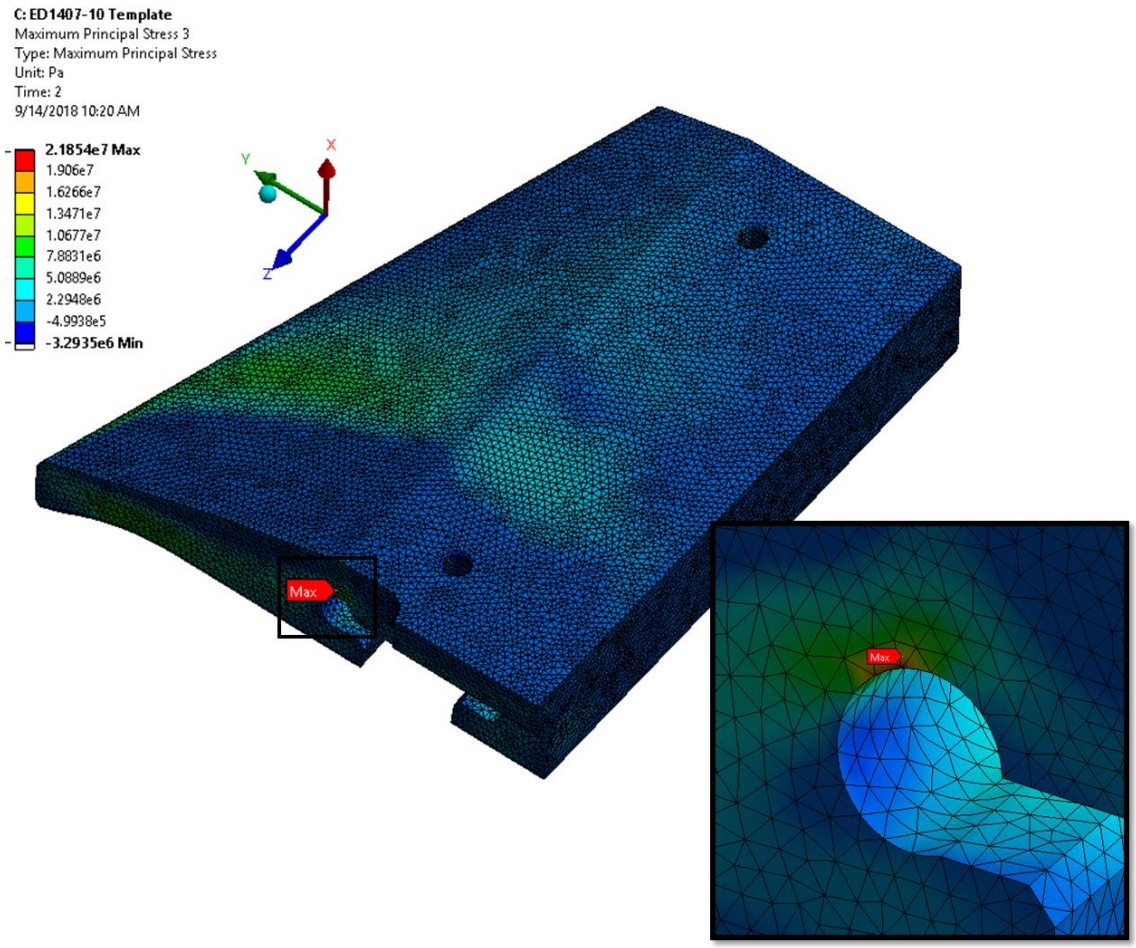


Figure 100: Location of peak maximum principal stress.

The location of peak equivalent stress with bolt preload and the halo load is shown in Figure 61.

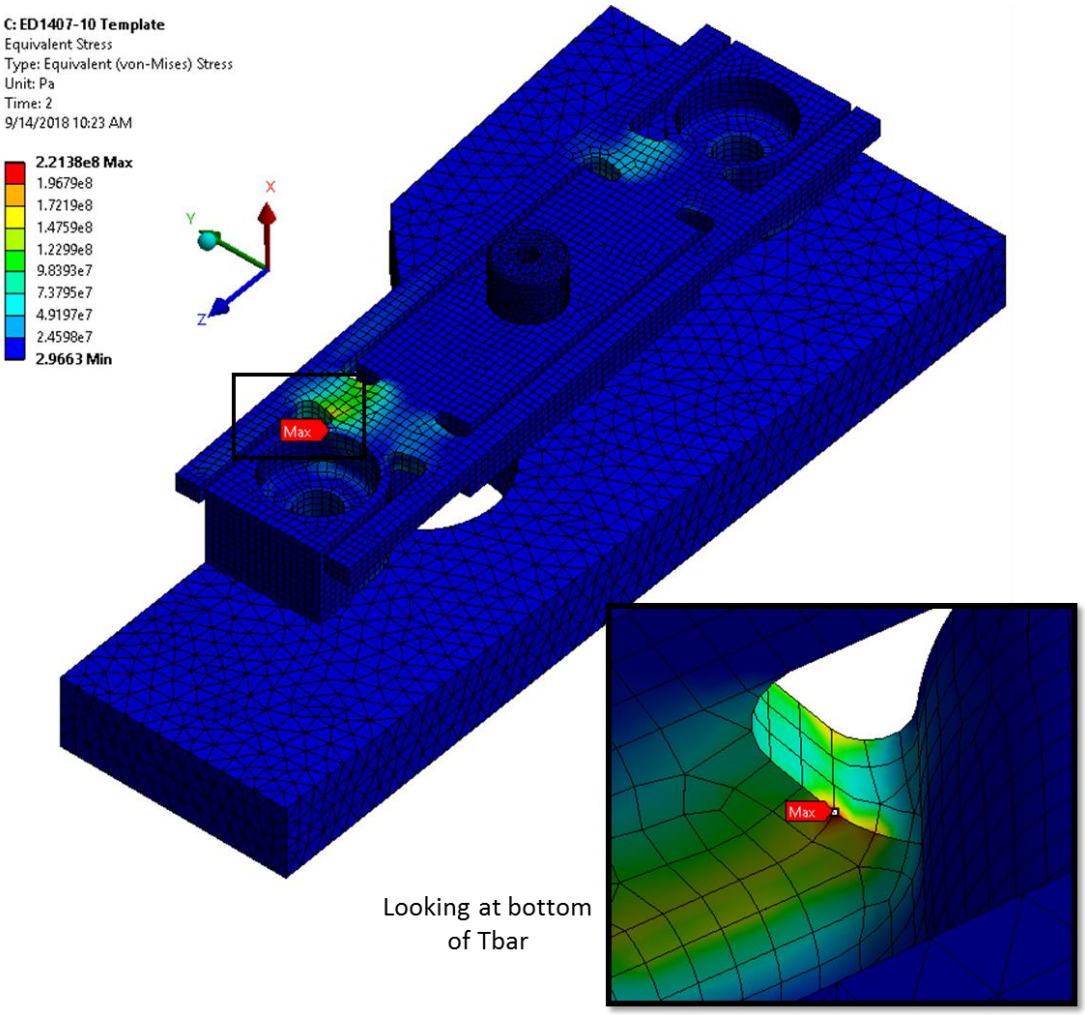


Figure 101: Location of peak equivalent stress for combined loading.

14 Subreport E-ED1407-11 R5 Style 2 Island Tile Variant, Lower Bays B/C and F/G

14.1 Expected results for E-ED1407-11 made from CFC

The decision to make this tile from CFC was made based on the analysis of the tile design using T953. The subreport for the T953 analysis is presented in the following subsection. The expected thermal-structural response of this tile when made from FMI3D (a grade of CFC) is based on the scaling methodology presented in the subreport for tile E-ED140-10. The scaling is as follows:

Max Temperature = 1610C * 0.72 = 1159C
Max S1 = 65 MPa * 0.95 = 61.8 MPa
Min S3 = -85.9 MPa * 1.4 *0.47 = -56.5 MPa

14.2 Analysis of E-ED1407-11 with T953 Graphite – FOR INFORMATION ONLY

Analysis performed by ORNL

The maximum principle stress in the tbar slot exceeds its allowable. The minimum principal stress in the chamfer of one of the bolt holes exceeds its allowable. See Figure 59. I do not have allowable stress values for pure copper or Inconel 718. Peak stresses in all components are lists in Table 13, Table 14, and Table 15.

The components considered in the analysis are listed below in Figure 43 and Figure 44103.

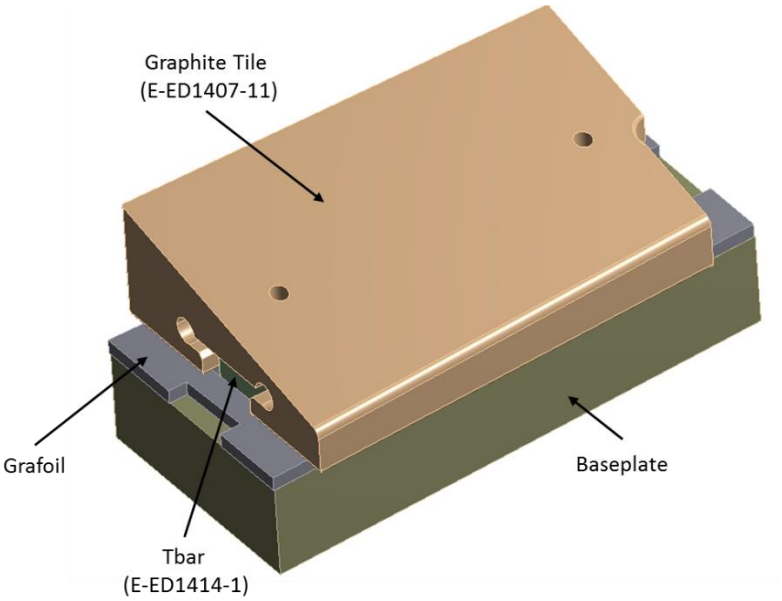


Figure 102: Outboard Diverter Row 5 style 2 variant (1407-11)

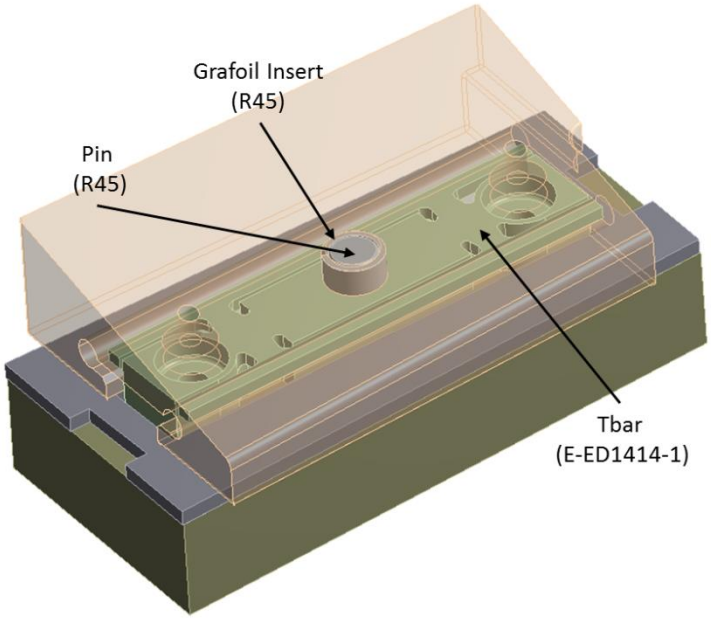


Figure 103: Outboard Diverter Row 5 style 2 variant (1407-11) components considered in analysis.

The total number of elements and nodes for the whole assembly is 145,723 and 558,025 respectively. Figure 45103 shows the mesh used in the analysis with and without the graphite tile. Figure 46104 shows the mesh of the mounting side of the graphite tile.

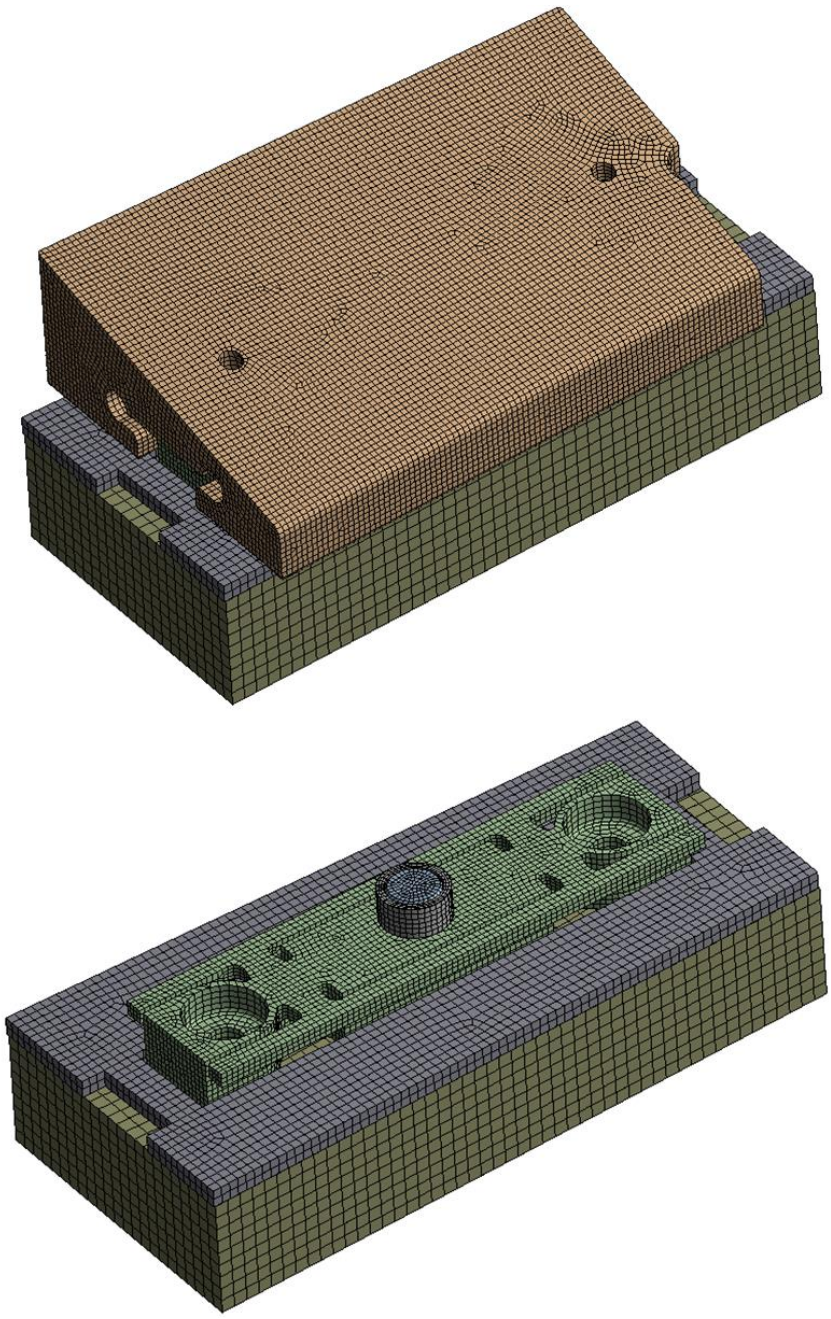


Figure 104: Mesh of the Outboard Diverter Row 5 style 2 variant (1407-11)

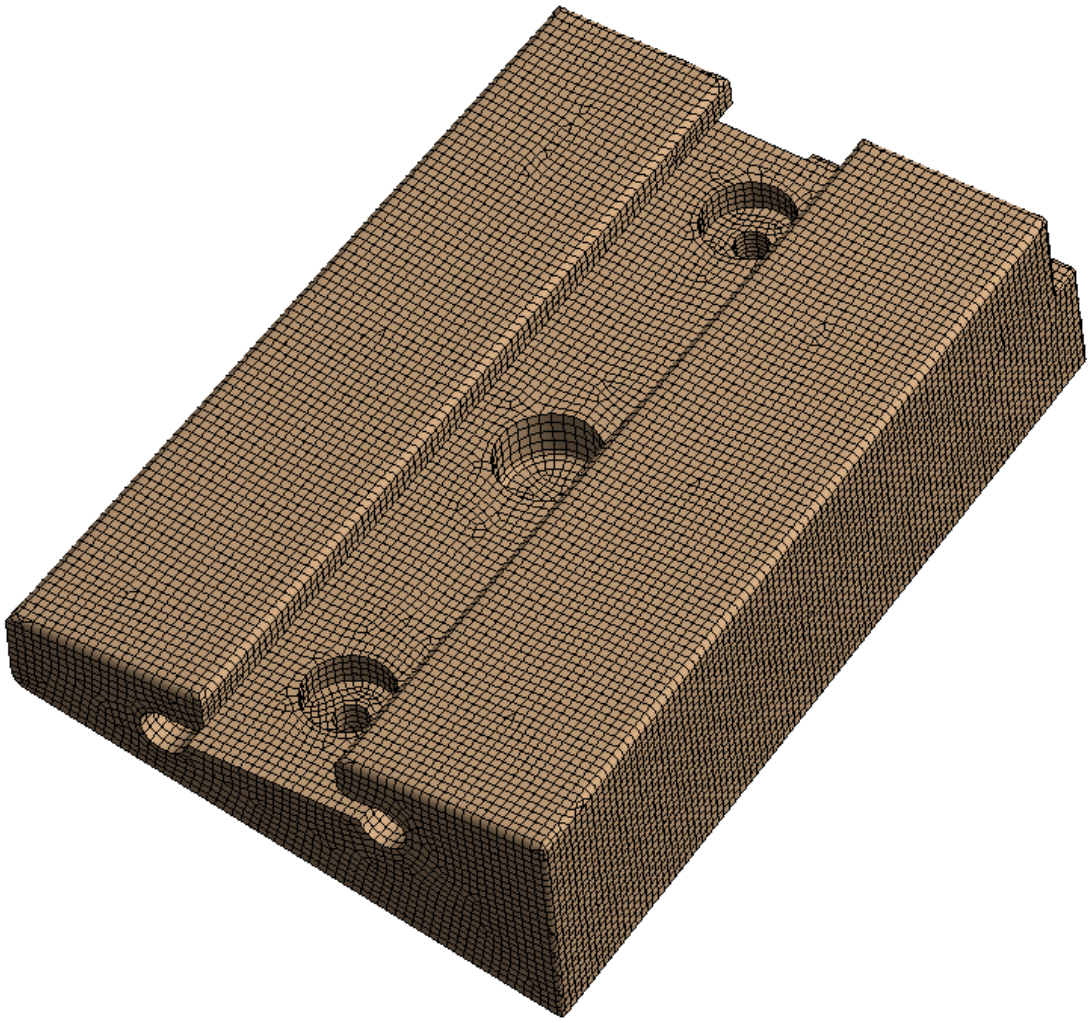


Figure 105: Mounting side of the graphite tile.

Table 11 lists each component of the assembly and its material.

Table 26: Components and their materials.

Component	Material
Graphite Tile (E-ED1407-11)	T953
Grafoil	Grafoil
Baseplate	Pure Copper
Grafoil Insert (R45)	Grafoil
Pin (R45)	Inconel 718
Tbar (E-ED1414-1)	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

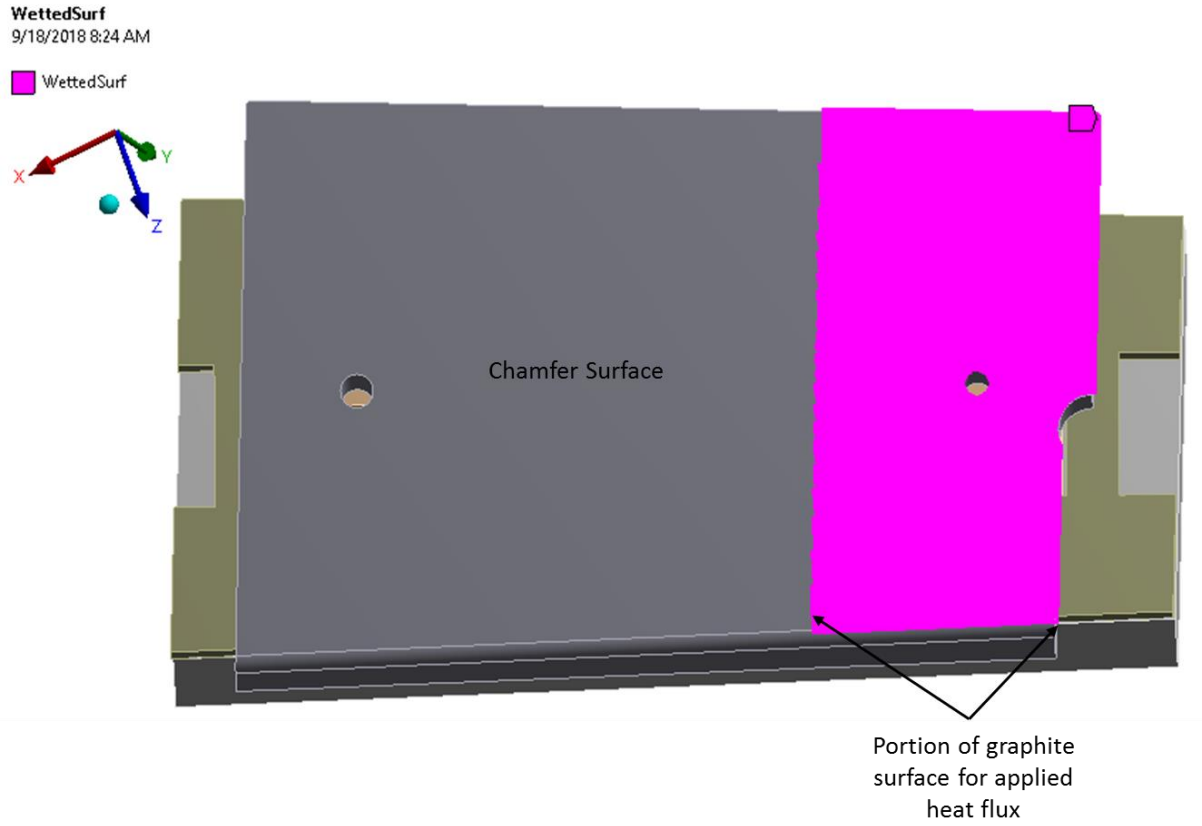


Figure 106: Thermal boundary conditions

Chamfer Surface heat flux = 10,595,056 W/m^2 with a gradient heat flux along the y-direction of –96,318,695 W/m^2/° with the extent being 0.04 m.

The peak temperature in the assembly was 1610 °C in the graphite tile. Figure 48106 and Figure 49 shows the temperature contour because of the applied heat fluxes. Table 12 lists the peak temperature for each component.

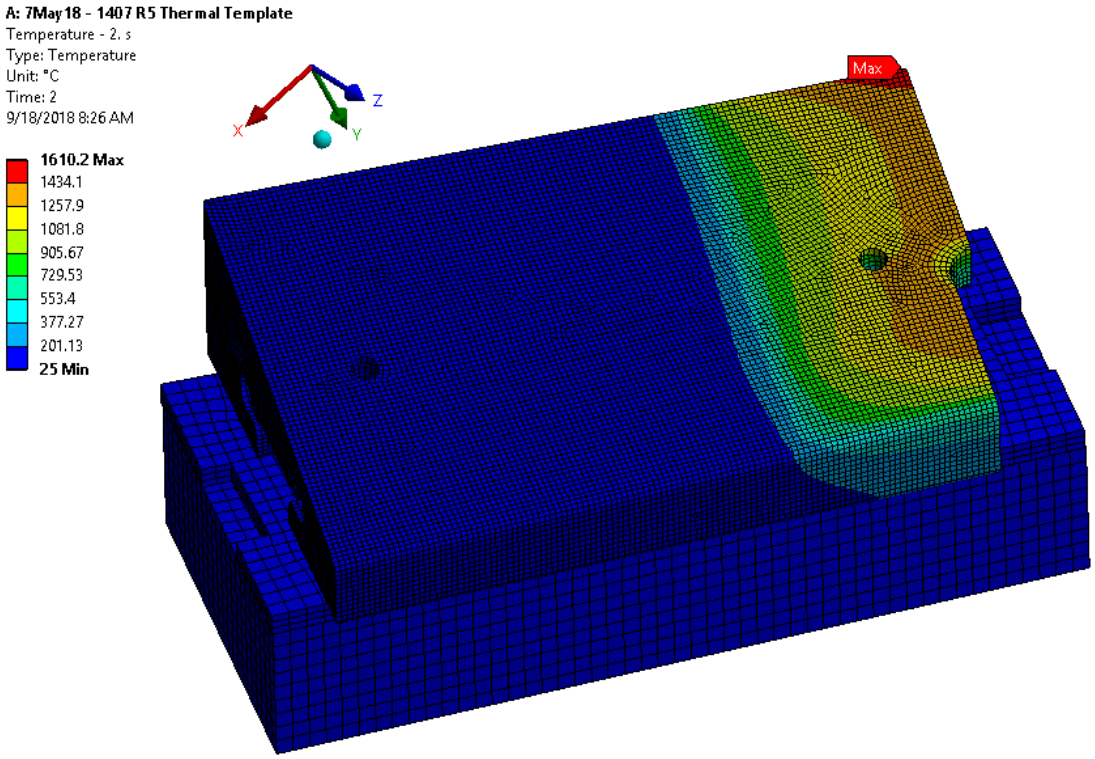


Figure 107: Temperature contour plot of the OBD Row 5 style 2 variant (1407-11)

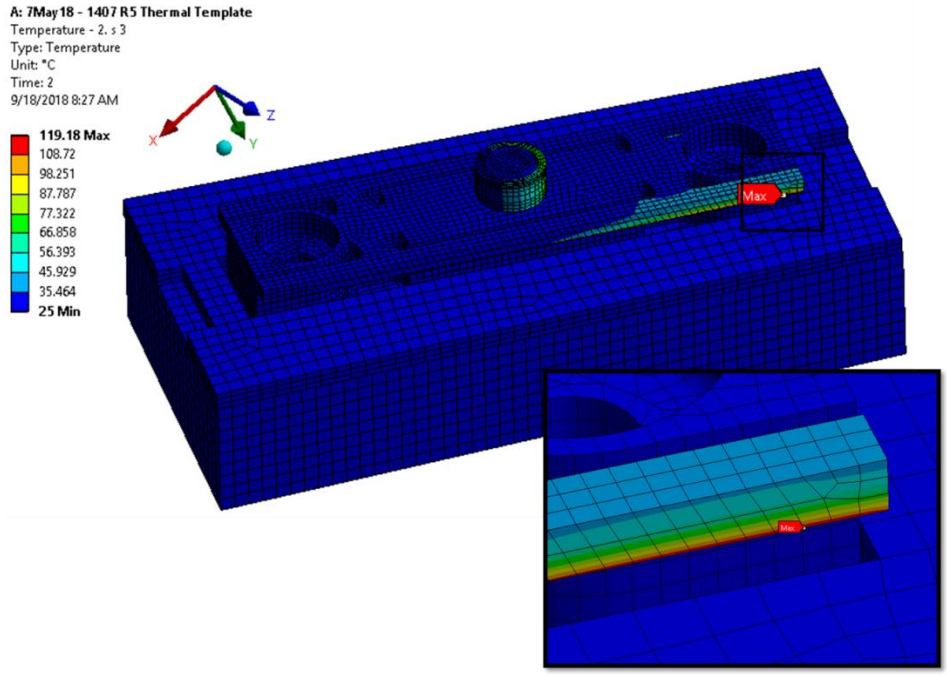


Figure 108: Temperature contour plot of the Outboard Diverter Row 5 style 2 variant (1407-11) without graphite tile

Table 27: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1407-11)	1610
Grafoil	25
Baseplate	25
Grafoil Insert (R45)	78
Pin (R45)	25
Tbar (E-ED1414-1)	119

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar (ED1414-1) as shown in Figure 50. Figure 51 and Figure 1011 shows the halo force and eddy current loading applied to the graphite tile respectively.

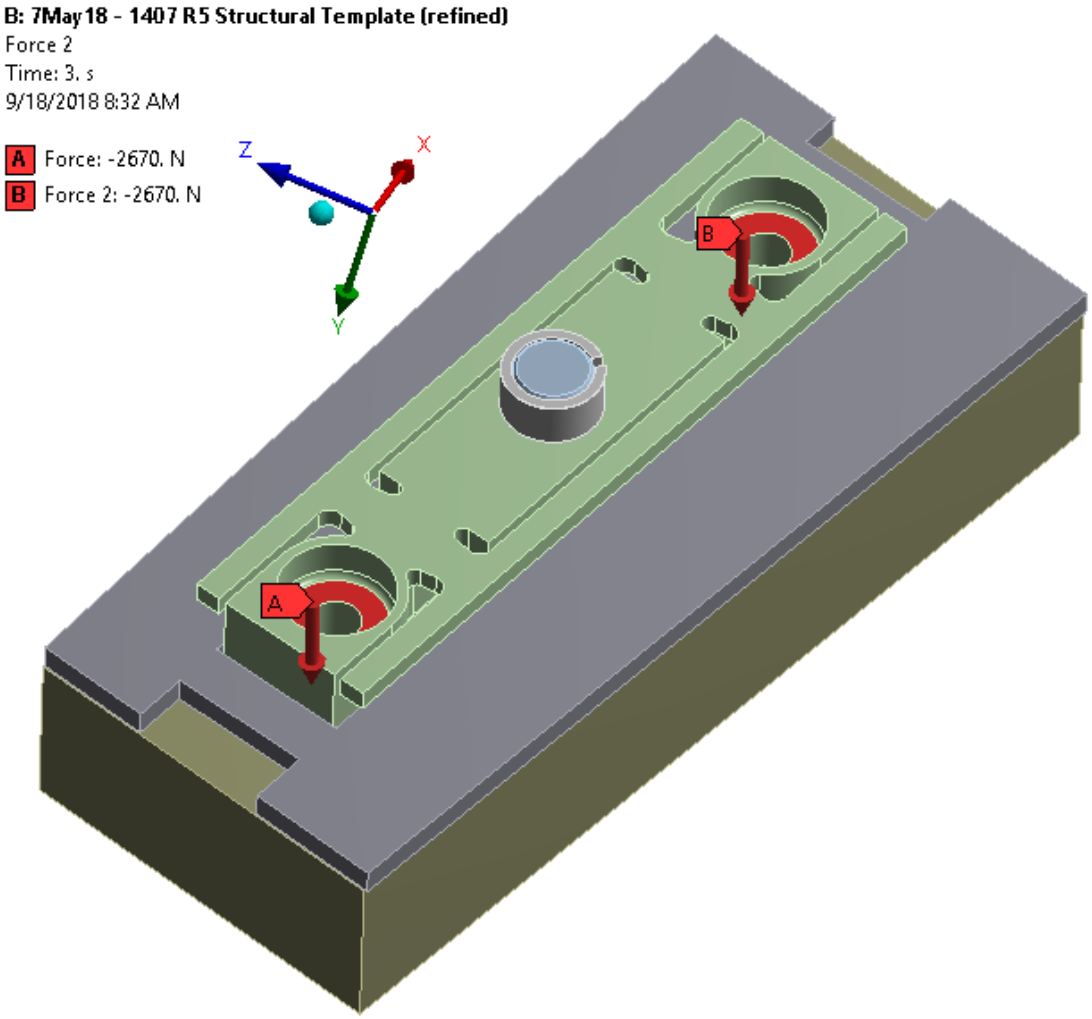


Figure 109: Bolt preload force applied to the Tbar.

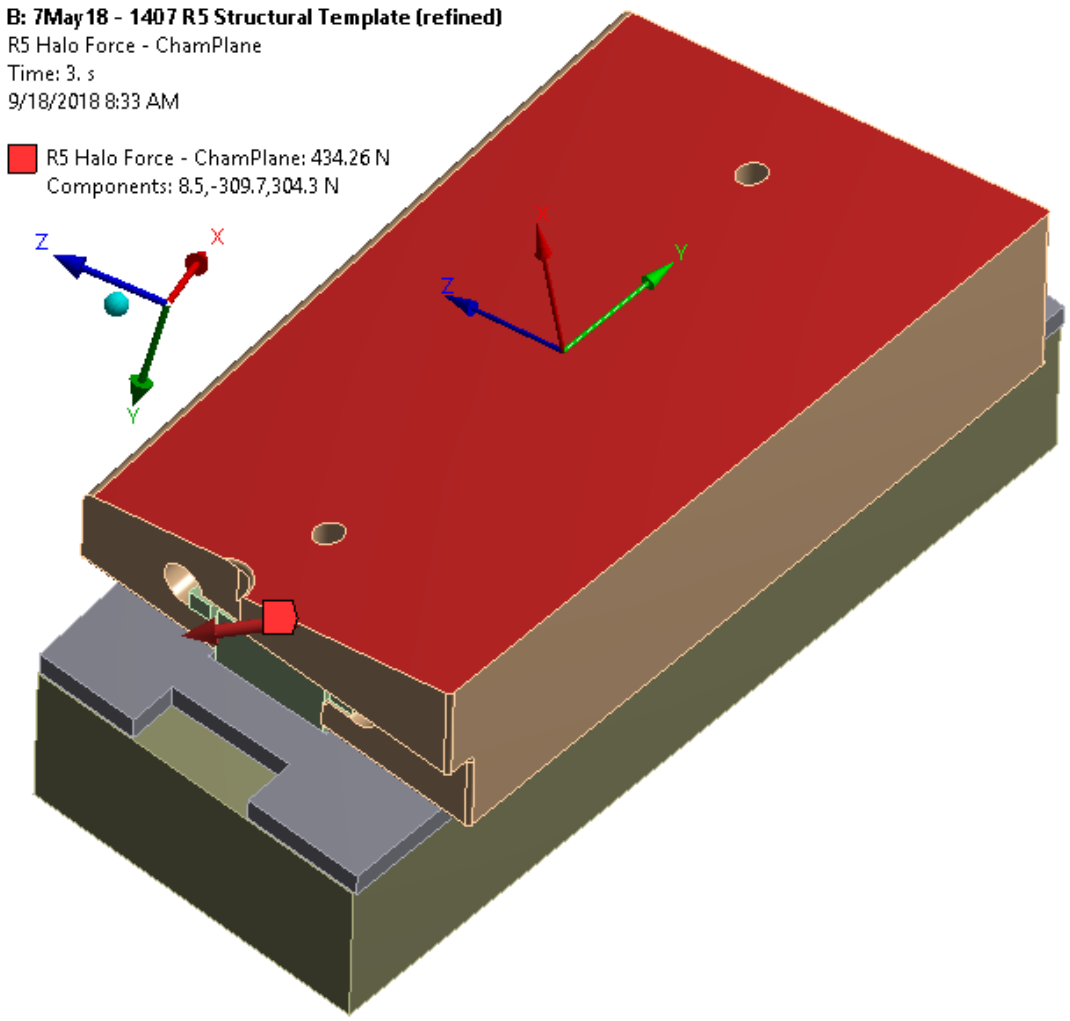


Figure 110: Halo force applied as a body force density to the graphite tile.

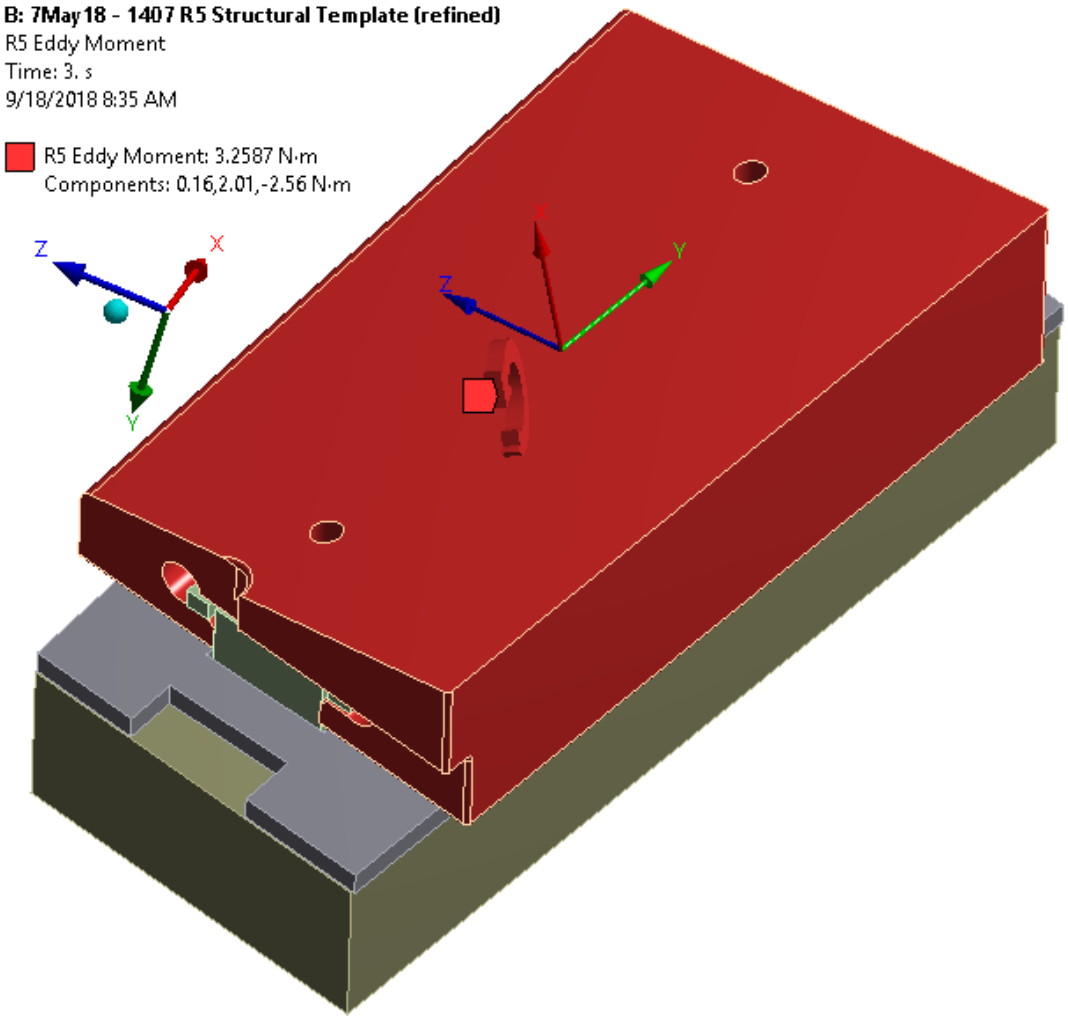


Figure 111: Eddy current load on graphite tile.

Frictionless constraints were applied to one side of the baseplate and two sides of the grafoil. Figure 52 shows the location of these constraints highlighted in blue.

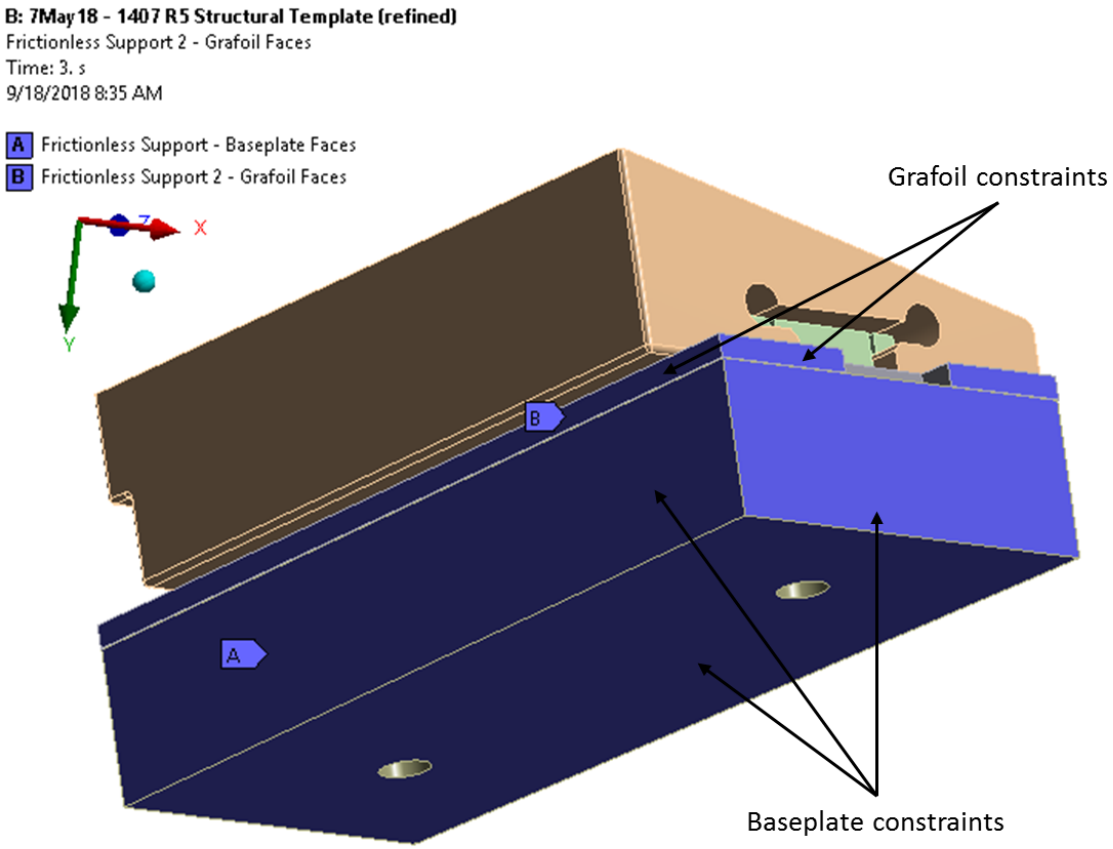


Figure 112: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R45-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1. Figure 53 shows the surfaces in contact with each other labeled A through E.

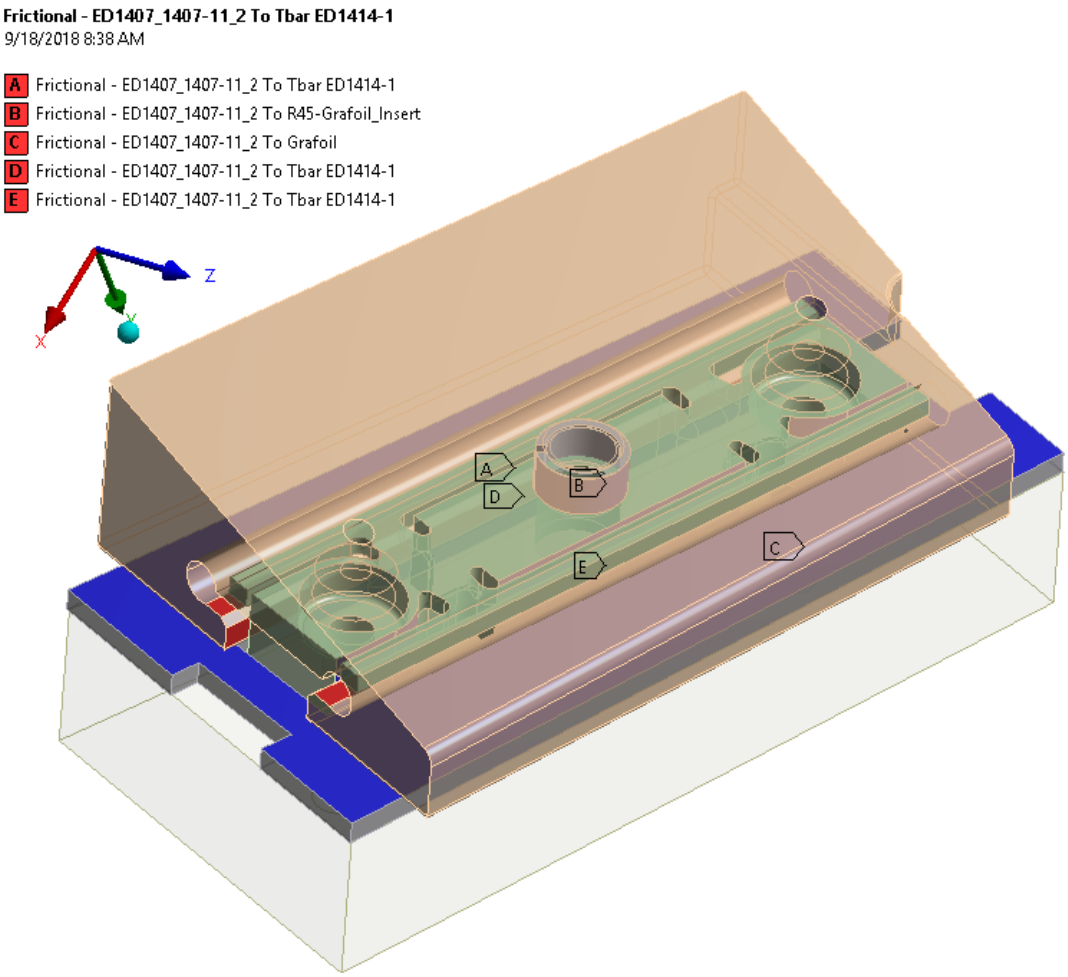


Figure 113: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition. Figure 54 shows the surfaces in contact with each other labeled A through D.

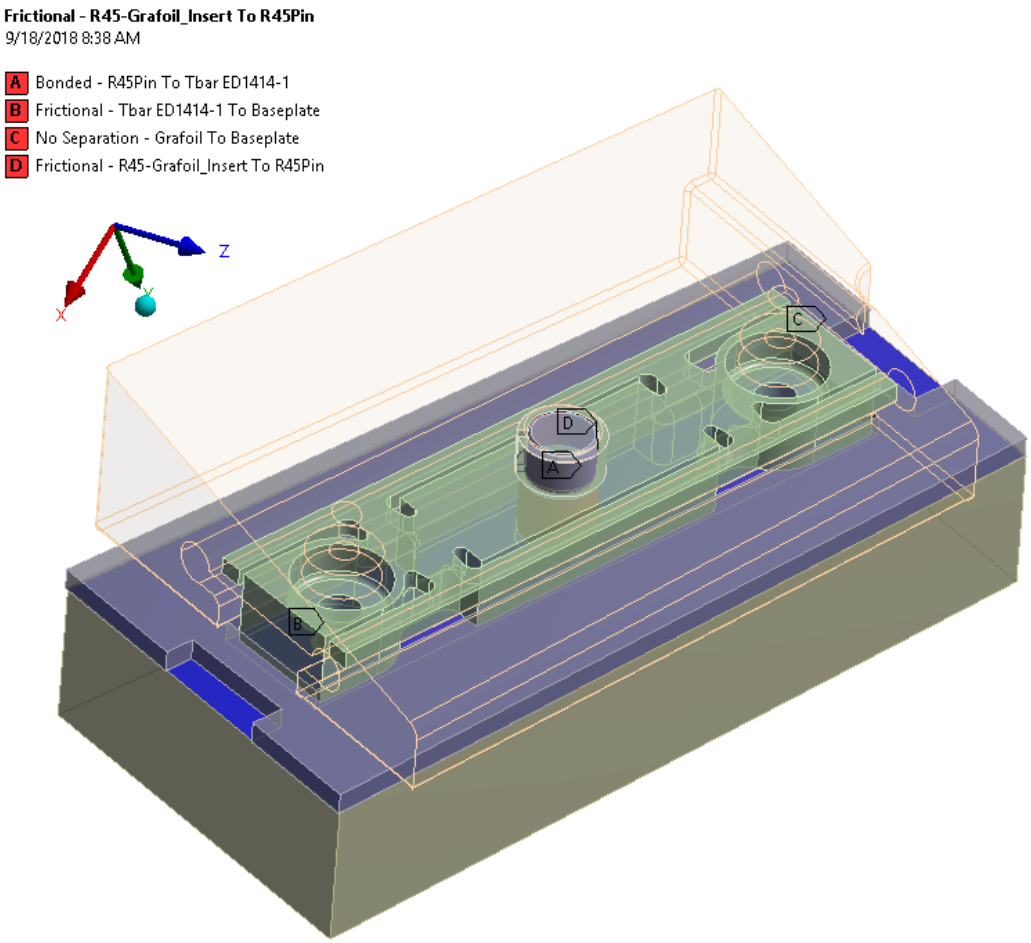


Figure 114: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 115. X, Y, Z deformation contour in the assembly is shown Figure 56, Figure 57, and Figure 58.

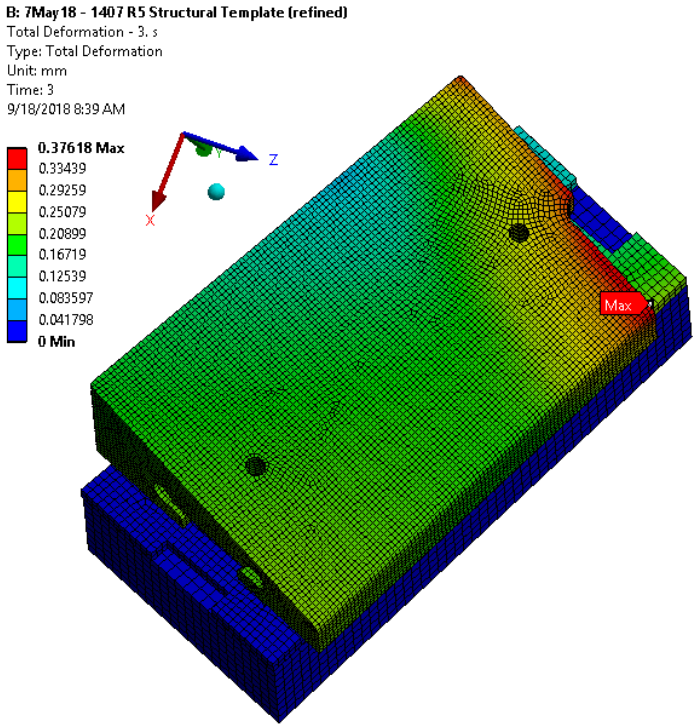


Figure 115: Total deformation of the assembly

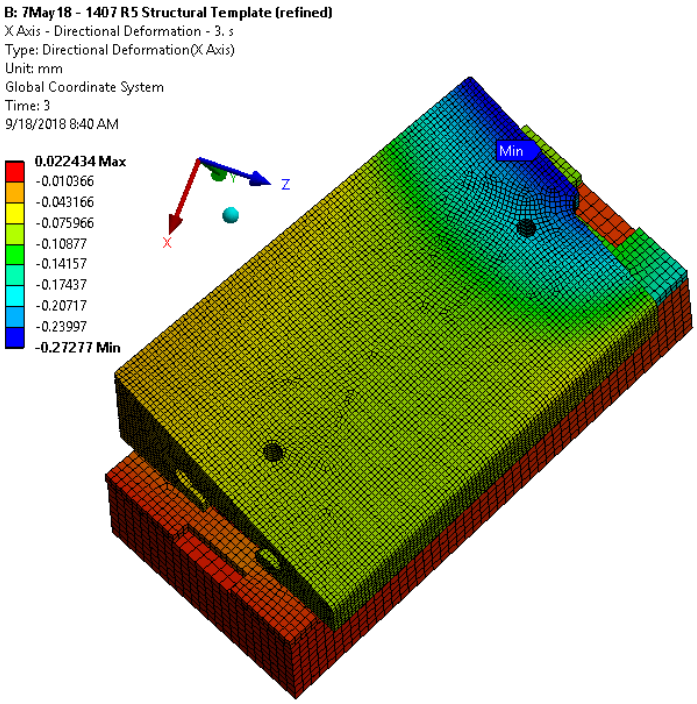


Figure 116: X-direction displacement

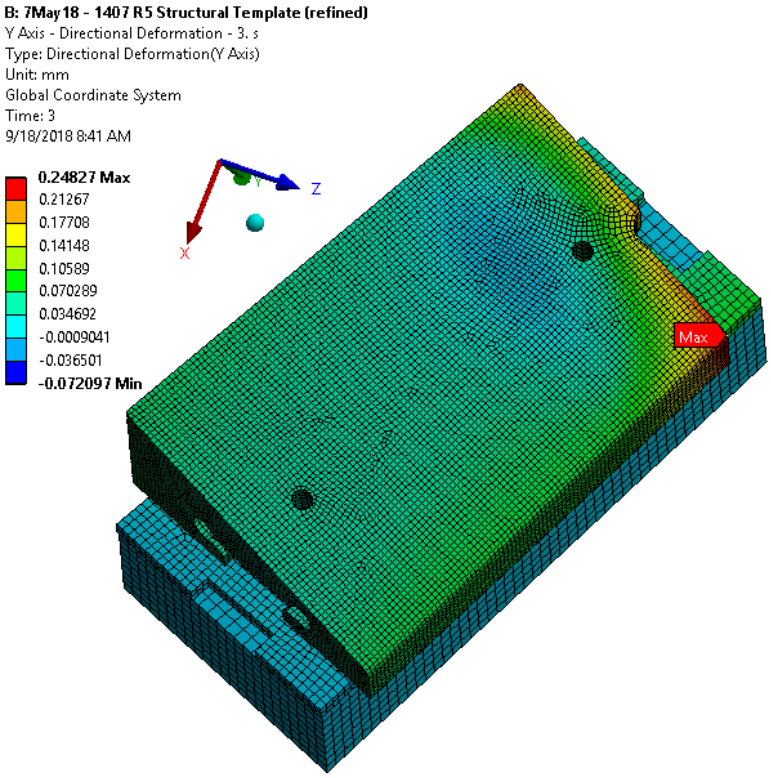


Figure 117: Y-direction displacement

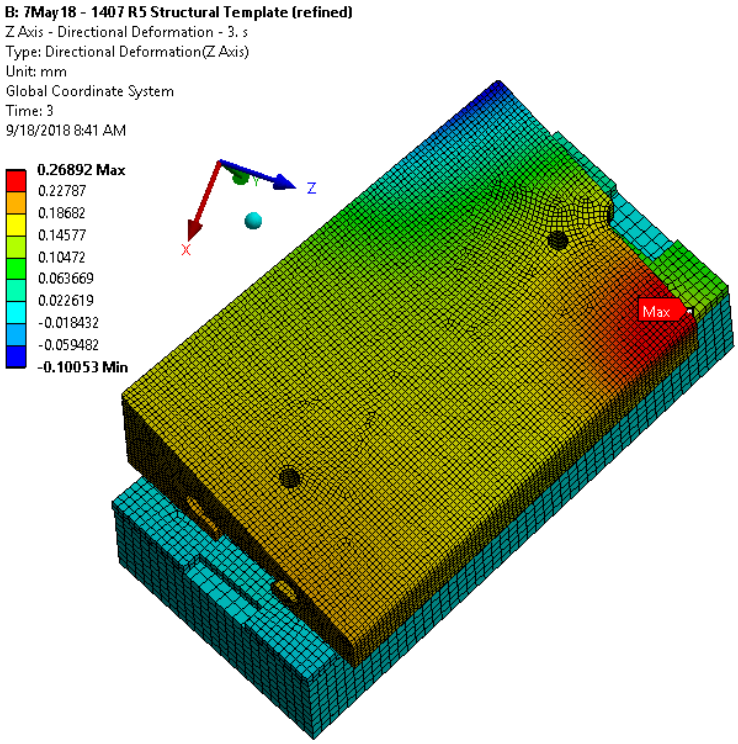


Figure 118: Z-direction displacement

Table 28 and Table 1429 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 15 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 28: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-11)	65.03	20	BPL
Graphite Tile – Tbar Slot	65.03	20	BPL
Graphite Tile – Shear Pin Hole	12.05	20	BPL
Grafoil	1.05	20	BPL+Halo
Grafoil Insert (R45)	3.19	20	BPL+Halo+Eddy

Table 29: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1407-11)	-85.90	-55	BPL+Halo
Graphite Tile – Tbar Slot	-43.71	-55	BPL+Halo+Eddy
Graphite Tile – Shear Pin Hole	-5.49	-55	BPL+Halo+Eddy
Grafoil	-2.57	-55	BPL+Halo+Eddy
Grafoil Insert (R45)	-11.94	-55	BPL+Halo+Eddy

Table 30: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	15.28	??	BPL+Halo
Pin (R45)	23.37	276	BPL+Halo+Eddy
Tbar (E-ED1414-1)	252.83	261	BPL

Both the peak maximum and minimum principal stresses exceeded their allowable values in the graphite tile. All other components resulting stress was below their respective allowable. Figure 59119 shows the location of the peak minimum principal stress with bolt preload and the halo load. This peak minimum stress is localized and can possibly be mitigated with a chamfer around the bolt hole.

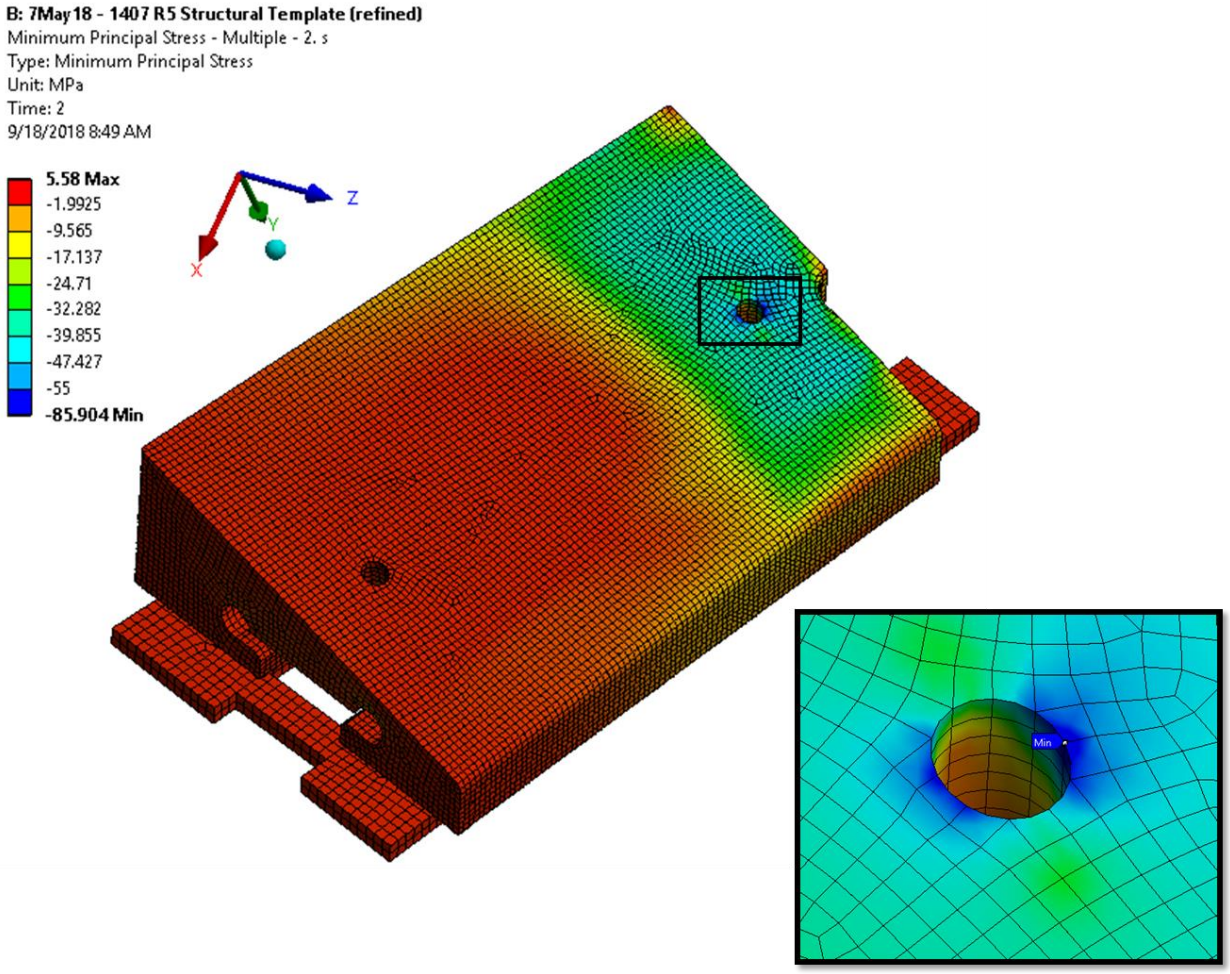


Figure 119: Location of peak minimum stress in OBD Row 5 style 2 -11

The location of maximum principal stress with bolt preload and the halo load is shown in Figure 60.

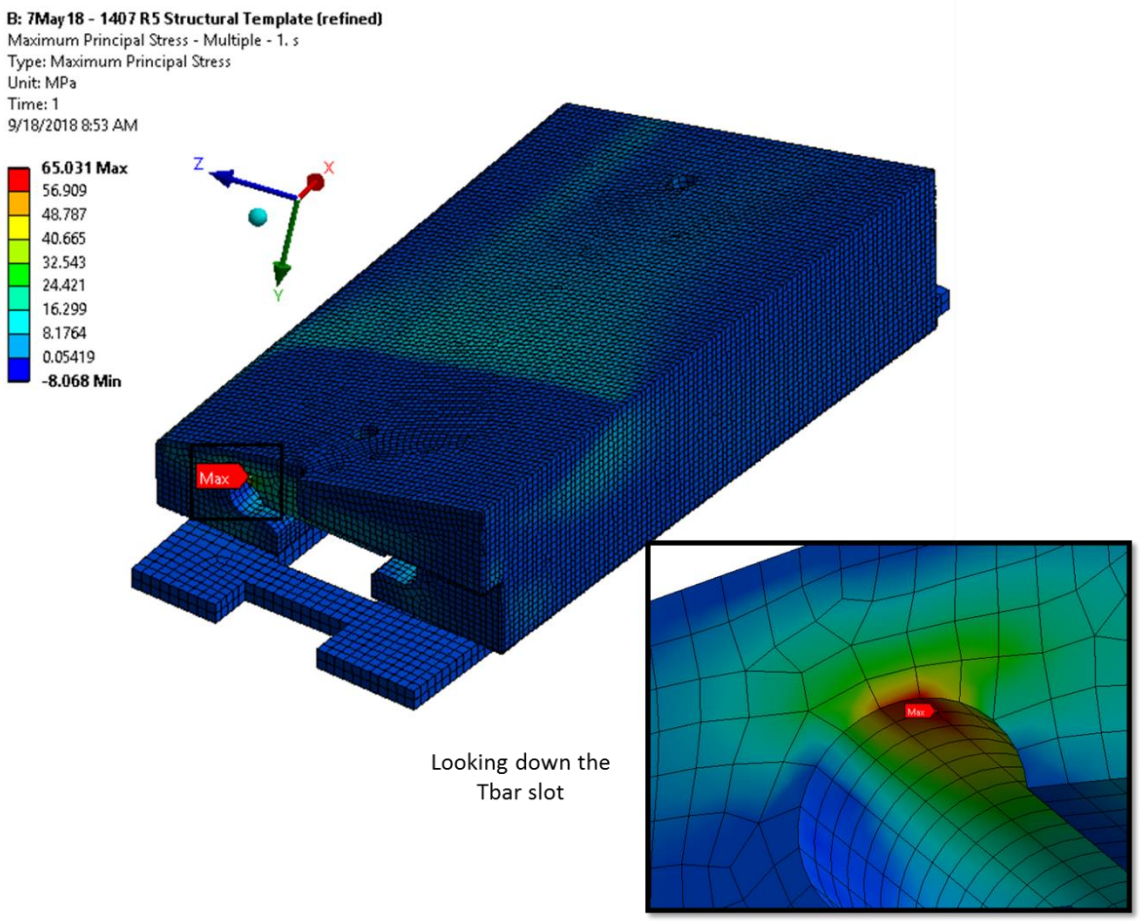


Figure 120: Location of peak maximum principal stress.

The location of peak equivalent stress with bolt preload and the halo load is shown in Figure 61.

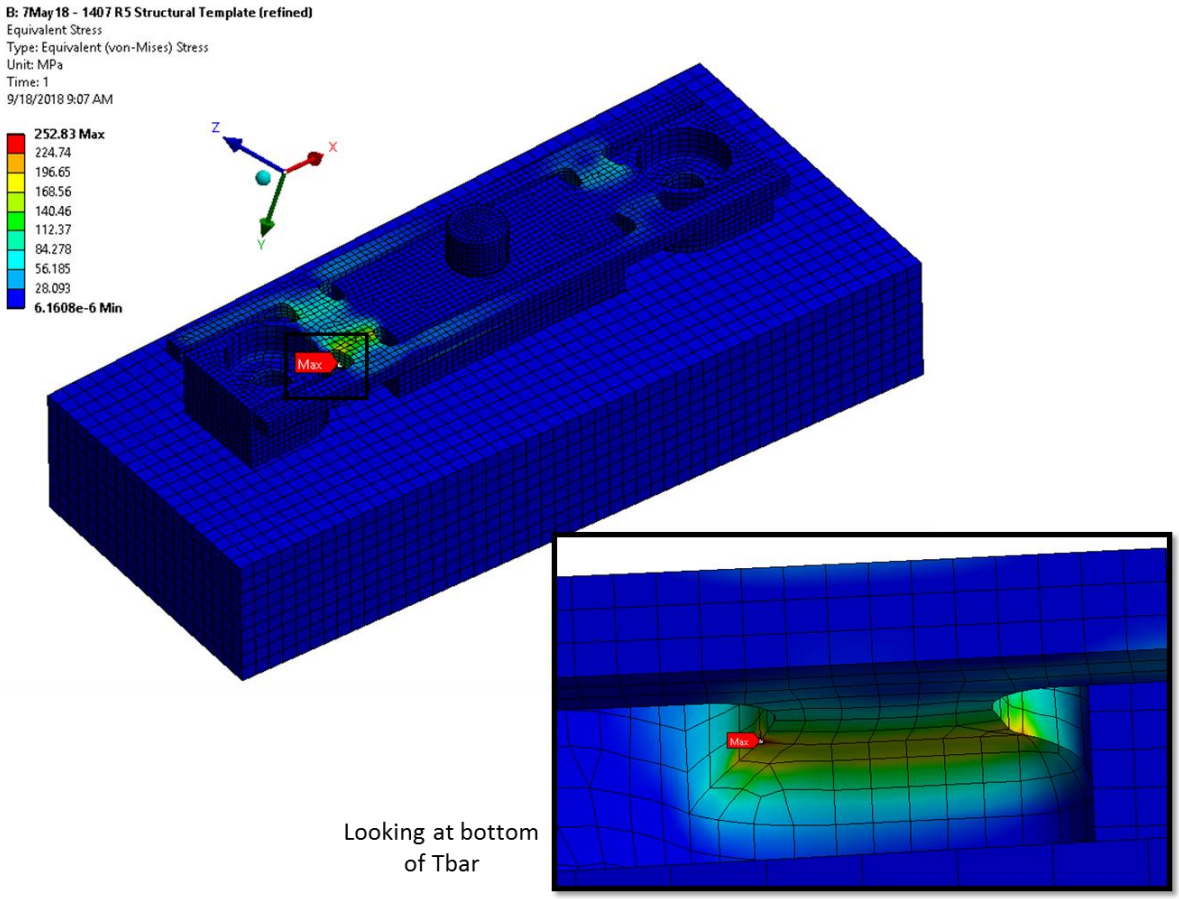


Figure 121: Location of peak equivalent stress for combined loading.