Calculation No: NSTXU-CALC-011-18-00   **Revision No: 0**

PFCs Analysis of the IBDH Tiles

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

Calculate the structural response of the Inboard Divertor Horizontal tiles.

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

ANSYS v19.1

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

1) GENERAL REQUIREMENTS DOCUMENT NSTX-U-RQMT-GRD-001-02
2) NSTX-U SYSTEM REQUIREMENTS DOCUMENT Plasma Facing Components NSTX-U-RQMT-SRD-003-01 July 14, 2018
3) NSTX-U Disruption Analysis Requirements NSTX-U-RQMT-RD-003-02 7/23/18
4) NSTXU Recovery Global Heat Balance Calculations, NSTXU-CALC-10-06-00, by H Zhang

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

The tile is assumed to be made of Sigrafine R6510 with a layer of Grafoil between it and the underlying cooling plate. All supports (cooling plate and frame) and hardware (rods & pins) are Inconel 718.

Calculation (Calculation is either documented here or attached)

See attached report sections “Method of Analysis” and “Results”

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

The analysis has shown the tile temperatures are within the allowables but is has identified several areas where high stresses exist. The spherical connection of the pins to the rods show high contact stresses though hand calculations suggest it should be acceptable. It is recommended that the connection be tested to demonstrate acceptable life. Also, the reverse helicity case results in high surface compression for the prescribe 1 MW/m2 for 1 sec. The recommendation is to relax these requirements if possible. Finally, the diagnostic tile with cutouts for the Langmuir Probes show high stresses at the one location where it is in the middle of a castellation whereas the other 4 locations between castellations are acceptable

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

Preparer’s printed name, signature and date

Art Brooks Digitally signed by Art Brooks Date: 2018.09.27 13:24:44 -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

Moheb Thomas Digitally signed by Moheb Thomas Date: 2018.09.27 15:17:09 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

PFCs Analysis of the IBDH Tiles

NSTXU-CALC-011-18_00

September 18, 2018

Prepared By:

Art Brooks Digitally signed by Art Brooks Date: 2018.09.27 13:25:10 -04'00'

Art Brooks, Engineering Analyst

Reviewed By:

Moheb Thomas Digitally signed by Moheb Thomas Date: 2018.09.27 15:27:04 -04'00'

Moe Thomas, Engineering Analyst

Reviewed By:

Michael Jaworski Digitally signed by Michael Jaworski Date: 2018.09.28 23:32:48 -04'00'

Michael Jaworski, RE

Checks for Calculation No: NSTXU-CALC-011-18 Revision No: 0

PFCs Analysis of the IBDH Tiles

Component was checked against latest design

All required load cases are included and current

Discuss method used in the calculation

Discuss how the calculation was checked (*)

List issue identified and how they were resolved

Checker's name:

Technical Authority:____(sign and date)

(*) independent calculations can be appended

Minimum Requirements for Checking Calculations

1. Assure that inputs were correctly selected and incorporated into the design.

2. Calculation considers, as appropriate:

   - Performance Requirements (capacity, rating, system output)
   - Design Conditions (pressure, temperature, voltage, etc.)
   - Load Conditions (Electromagnetic (Lorentz Force), seismic, wind, thermal, dynamic)
   - Environmental Conditions (radiation zone, hazardous material, etc.)
   - Material Requirements
   - Structural Requirements (foundations, pipe supports, etc.)
   - Hydraulic Requirements (NPSH, pressure drops, etc.)
   - Chemistry Requirements
   - Electrical Requirements (power source, volts, raceway, and insulation)
   - Equipment Reliability (FMEA)
   - Failure Effects on Surrounding Equipment
   - Tolerance Buildup

3. Assumptions necessary to perform the design activity are adequately described and reasonable.

4. An appropriate calculation method was used.

5. The results are reasonable compared to the inputs.

6. Error bars (range) for inputs used, results / conclusions, assumptions, have been considered and are acceptable.

NOTE: IT IS THE RESPONSIBILITY OF THE CHECKER TO USE METHODS THAT WILL SUBSTANTIATE TO HIS/HER PROFESSIONAL SATISFACTION THAT THE CALCULATION IS CORRECT.

BY SIGNING CALCULATION, CHECKER ACKNOWLEDGES THAT THE CALCULATION HAS BEEN APPROPRIATELY CHECKED AND THAT THE APPLICABLE ITEMS LISTED ABOVE HAVE BEEN INCLUDED AS PART OF THE CHECK.

NSTX-U CALCULATION

Record of Changes

Rev.	8	Description of Changes	Revised by
0	09/17/18	Initial Release	

PFCs Analysis of the IBDH Tiles

Executive Summary

The analysis has shown the tile temperatures are within the allowables but is has identified several areas where high stresses exist. The spherical connection of the pins to the rods show high contact stresses in the ANSYS model but hand calculations show acceptable stresses. It is recommended that the connection be tested to demonstrate acceptable life. Also, the reverse helicity case results in high surface compression for the prescribed 1 MW/m2 for 1 sec. The recommendation is to relax these requirements if possible. Finally, the diagnostic tile with cutouts for the Langmuir Probes show high stresses at the one location where it is in the middle of a castellation (the other 4 locations between castellations are acceptable). The recommendation is to eliminate the Langmuir Probe at this location.

The qualification of the IBDH tiles is premised on the project accepting these recommendations as it has indicated it will.

Introduction

The Inboard Divertor Horizontal (IBDH) Tiles are part of the High Heat Flux (HHF) tiles exposed to the highest surface heating from the plasma. As with the other HHF tiles it is both castellated to reduce thermal stresses and fishscaled to eliminate edge heating during normal (forward) helicity operation. They are held in place by Inconel rods at the base of the castellations that are shielded by the tiles from the heat flux carried along magnetic field lines. The rods are held in place by pins that connect to the rods through a spherical contact which can be engaged by turning the rods, eliminating the need for accessing bolts from the surface of the tile as originally designed.

The IBDH tiles have a number of variations in the design to accommodate diagnostics. (The analysis of the baseline tile without diagnostic cutouts was performed by ORNL and appears as Appendix I to this report and serves as a basis for the analysis of the diagnostic tiles in the body of this report.) Rather than analyze all the diagnostic tiles separately a single model was created containing most of the cutouts that exist in the different tiles in one ‘super tile’. This includes cutouts for a Mirnov coil, Langmuir probes and thermocouples. A separate model was still required for the line of sight tile due to the presence of the large view port.

Assumptions

The tile is assumed to be made of Sigrafine R6510 with a layer of Grafoil between it and the underlying cooling plate. The tile is cooled by radiation to the interior of the VV and other PFCs with an assumed emissivity of 0.7 and by cooling at the base from the cooling plate. The initial temperatures and radiation sink temperatures are based on the global heat balance given in Ref 4. All supports (cooling plate and frame) and hardware (rods & pins) are Inconel 718.

Method of Analysis

PFCs Analysis of the IBDH Tiles

The ANSYS Workbench version 19.1 is used to analyze the thermal and structural response to the applied preload, heat fluxes and electromagnetic (EM) loads as specified in Ref 1.

The preload developed between the rods and the pins due to the Belleville washers is modeled as a constant force on the pins and an opposing force on the support frame. A 750 N force is applied to the outer radius pins while only a 500 N force is applied to the inner radius pins to better balance the stresses at the rod-tile interfaces.
Several Heating scenarios are given in the requirements and are repeated below.

Table 1 IBDH Heat Flux Requirements

IBDH	Case # ->	1	2	3	4
Range of Application	m	0.47 < R < 0.6		R < 0.6	R < 0.47
Extent	cm	15	full	full	full
Max Angle	degrees	1.0	5.0	-1	4.0
Min Angle	degrees	1.0	5.0	-5	1.0
Heat Flux	MW/m^2	6.5	5.4	1	3.5
Duration	sec	1.5	5	1	5
Reference Scenario	---	Stationary High Ip/Bt w/ large poloidal flux expansion	High Ip/Bt Long Pulse Swept Case	Reversed Helicity Requirement	Spill Over From HHF Regions

The heat fluxes in the requirements are the axisymmetric averaged values. The values are enhanced or amplified by tile shaping which is needed to protect leading edges formed by gaps between discrete tiles and the castellations within tiles. The enhancement factor is given by f=sin(alp+beta)/sin(alp) where alp is the angle of the field line (tabulated above) and beta is the angle of the tile surface. For each of the cases tabulated above the highest value of f occurs at the Min (field) Angle tabulated. Note the tile surface angle was determined for each tile based on the Max Angle and the tile geometry and tolerances to protect leading edges from direct impingement.

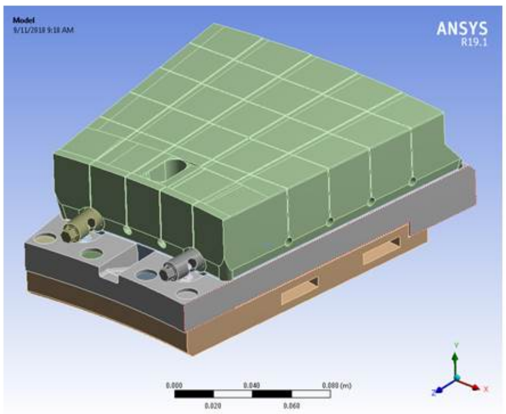
Note all these cases were run for the baseline tile and are documented in Appendix I. Based on those results only a subset of the cases were run for the diagnostic tiles. In particle, for the Line of Sight (LOS) tile, cases 2 and 4 were run concurrently which was deemed worse than case 1. The reverse helicity was also run on that tile. The Super tile was run for just the combined case 2 and 4.

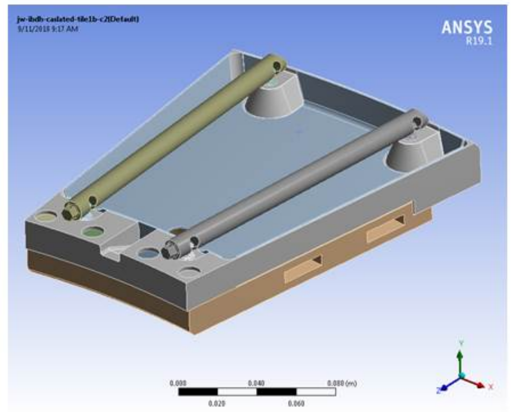
The EM loads are calculated using field data (B and dB/dt) from Ref 2 which in turn were developed from Ref 1. The Halo Forces are assumed evenly distributed amongst all the nodes of the tiles. The toroidal and poloidal Eddy Current Moments are applied as opposing surface shear forces on the tiles.

The analysis flow within ANSYS Workbench starts with a static structural response of the preload with EM loads to simulate a disruption early in the pulse when the tile is still cold. This is followed by a transient thermal analysis of using the heat flux and pulse durations from Table I. The initial fully ratcheted temperature of 122 C is taken from Ref 4.

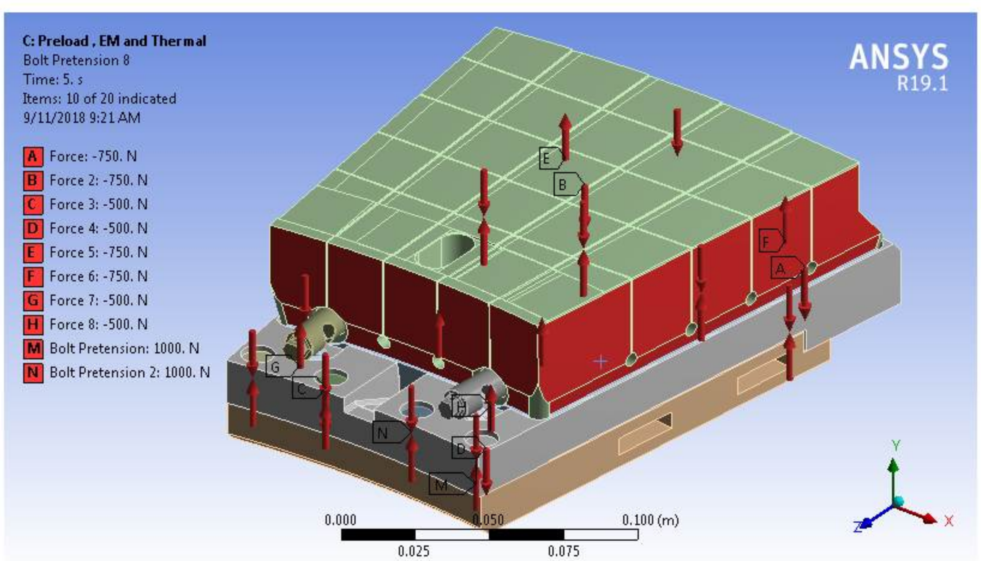
Results - <u>Line of Sight Tile</u>

Line of Sight IBDH Tile Analysis

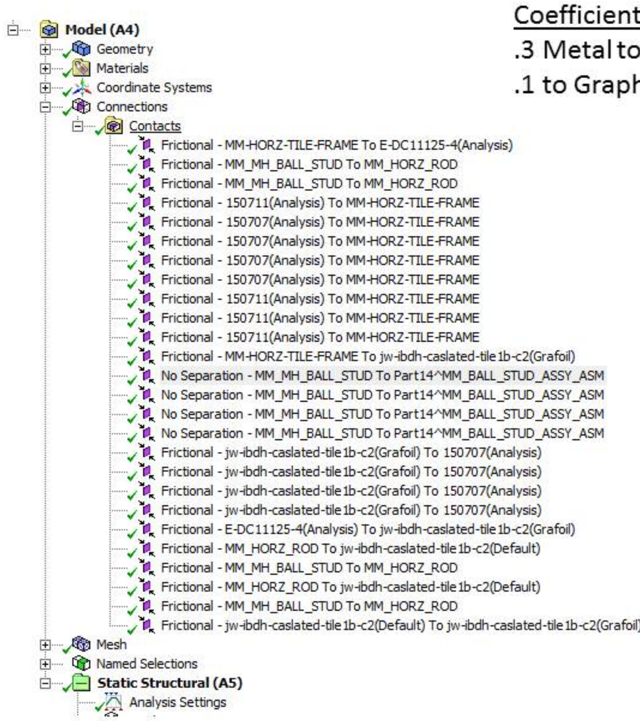




Applied Forces – Preloads



Contacts

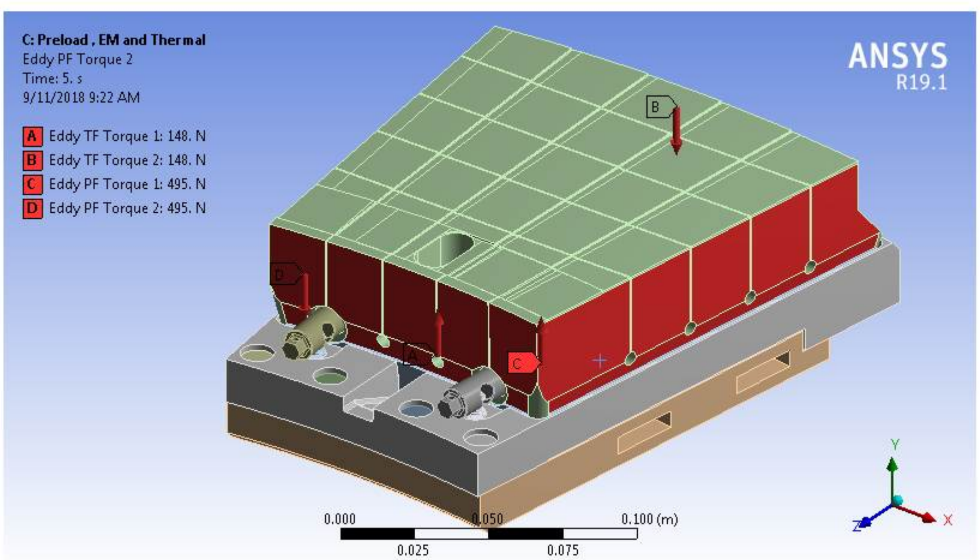


Coefficient of friction

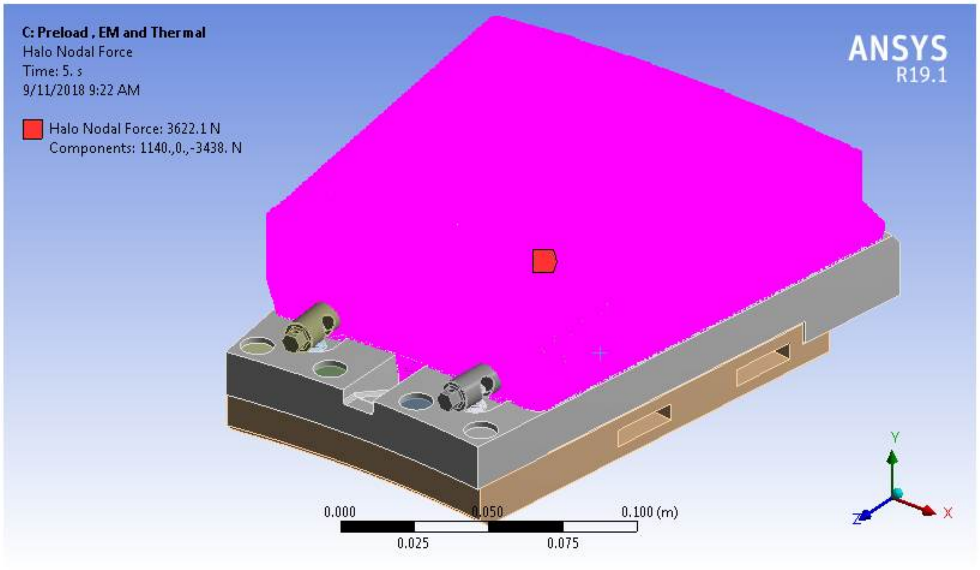
.3 Metal to Metal

.1 to Graphite and Grafoil

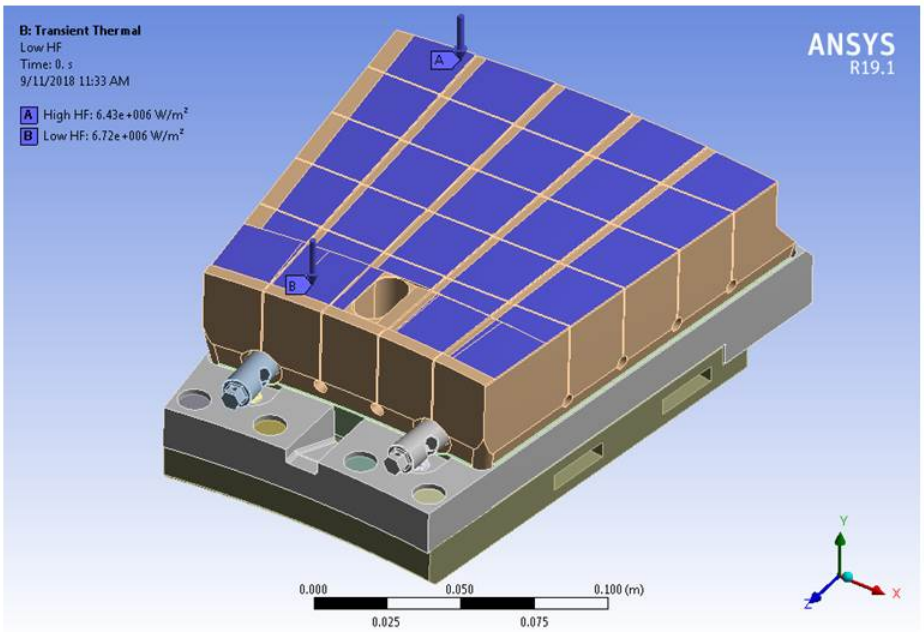
Applied Loads – Halo Forces



Applied Loads – Halo Forces



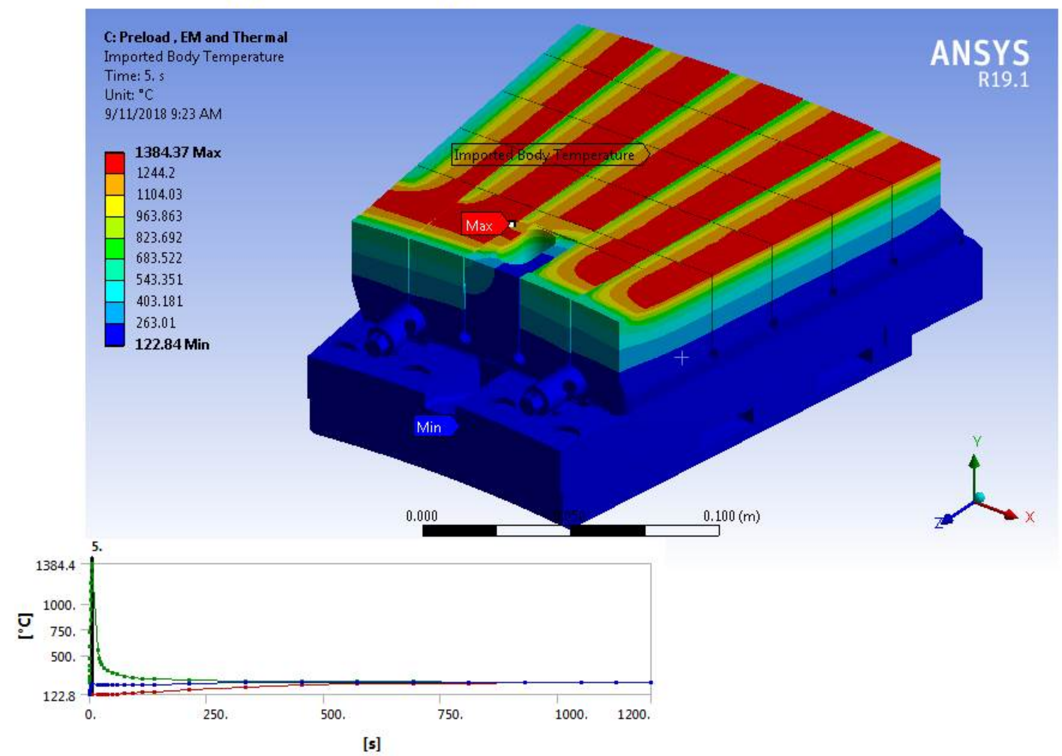
Applied Heat Fluxes



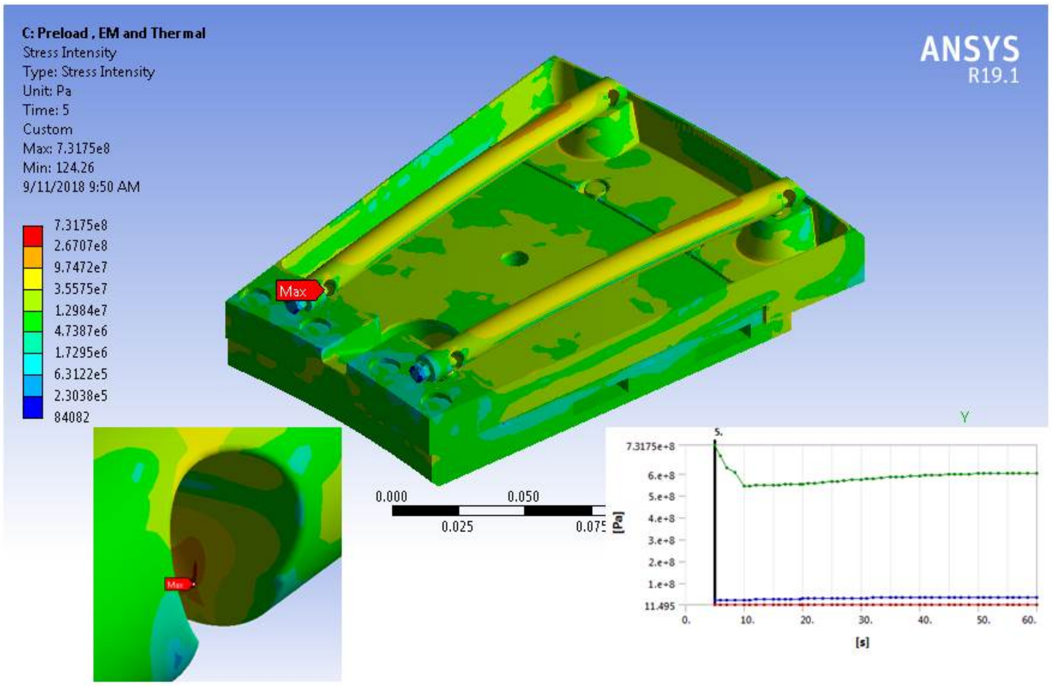
Simulation of end of day pulse using repulse ratcheted temperature of 123 C
Cooling by Radiation only to ratcheted ambient temperature of 123 C

Combined
Case 2 - High Ip/Bp Long Pulse Swept
and Case 4 - Spill over from HHF region

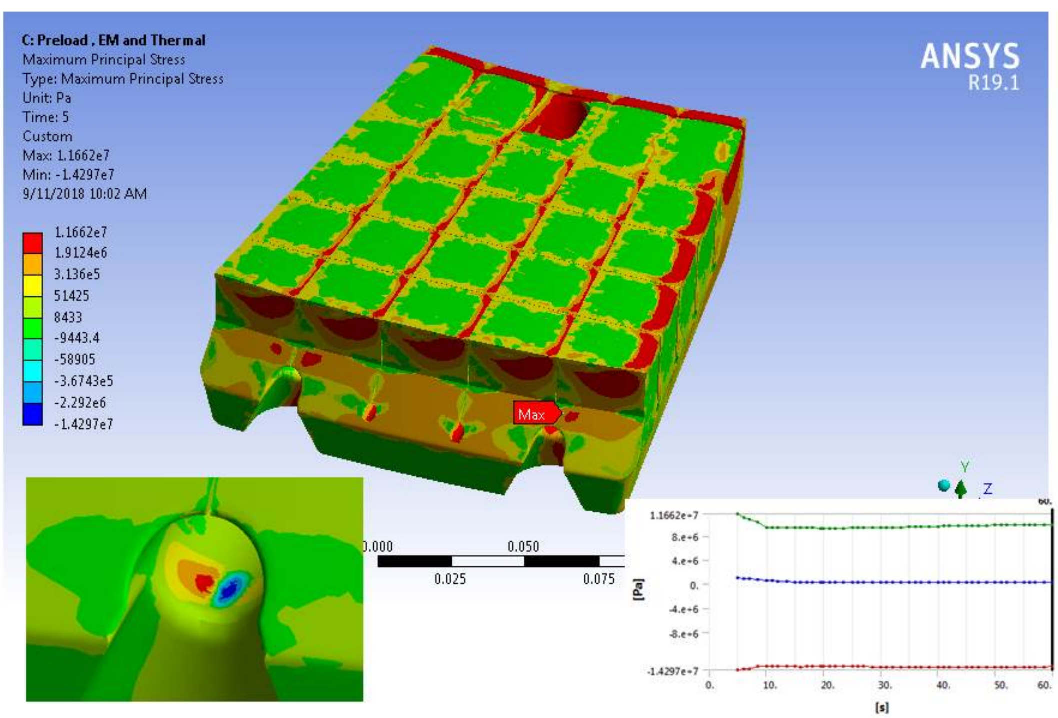
Max Applied Temperature – End of 5 sec Pulse



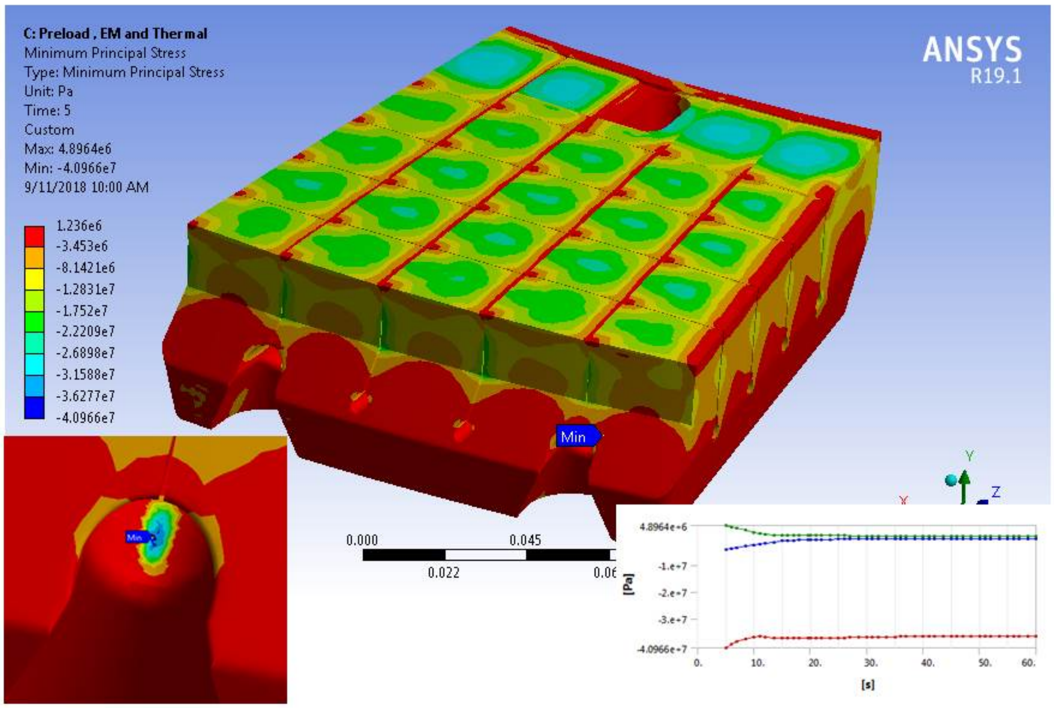
Max Stress Intensity Inconel 718 Structures 732 MPa



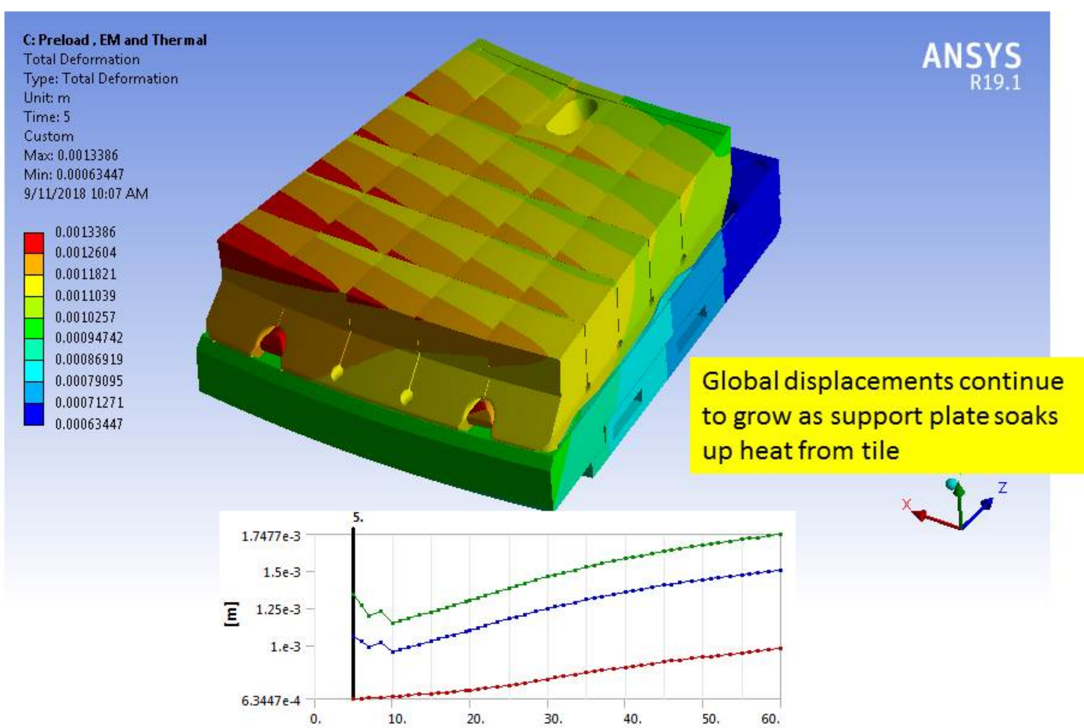
Max Principal Stress (Tension) in Graphite 11.7 MPa



Min Principal Stress (Compression) in Graphite 41.0 MPa

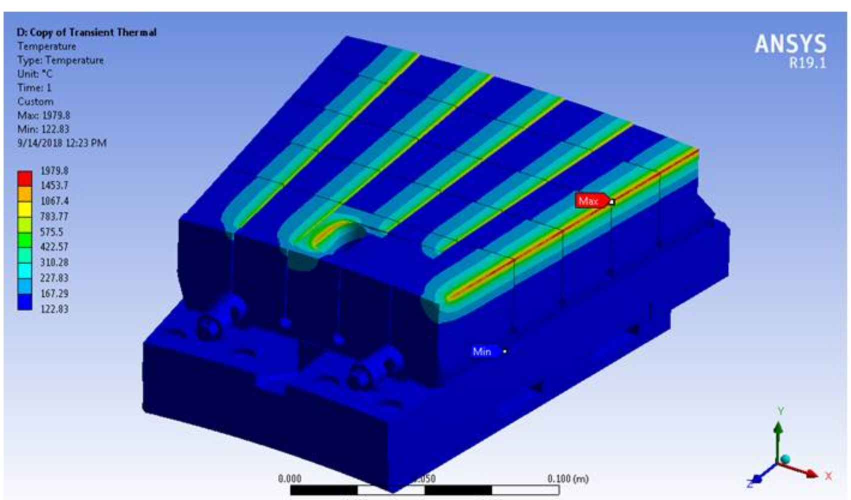


Displacements

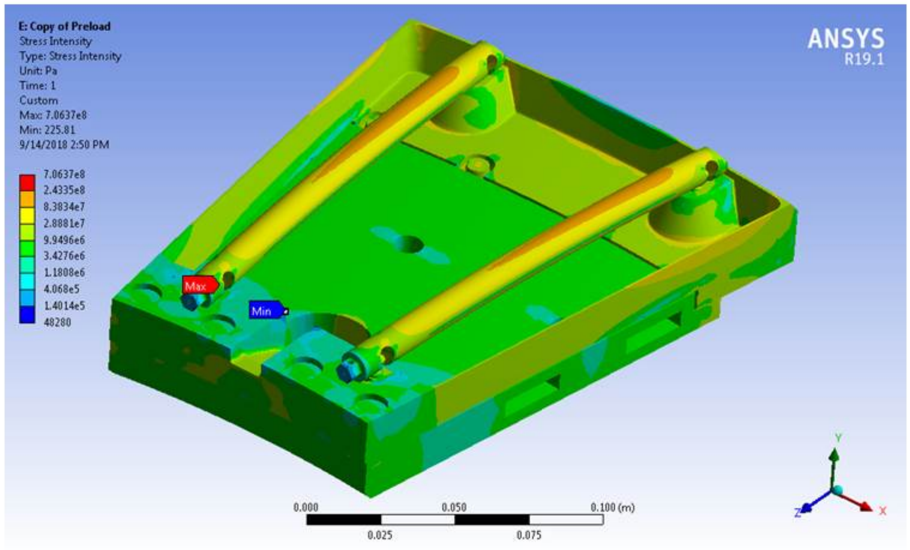


Case 3 Reverse Helicity

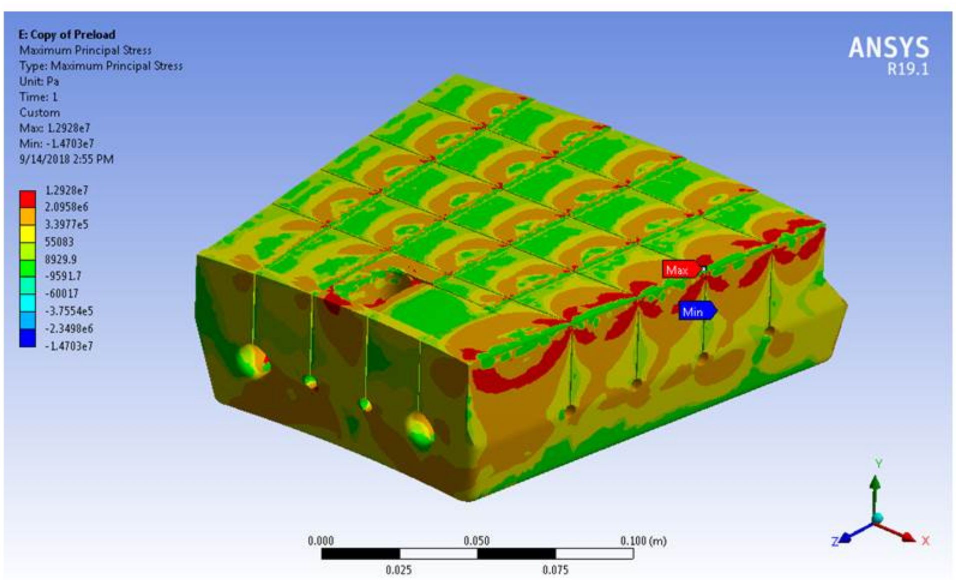
Max Applied Temperature – End of 1 sec Pulse



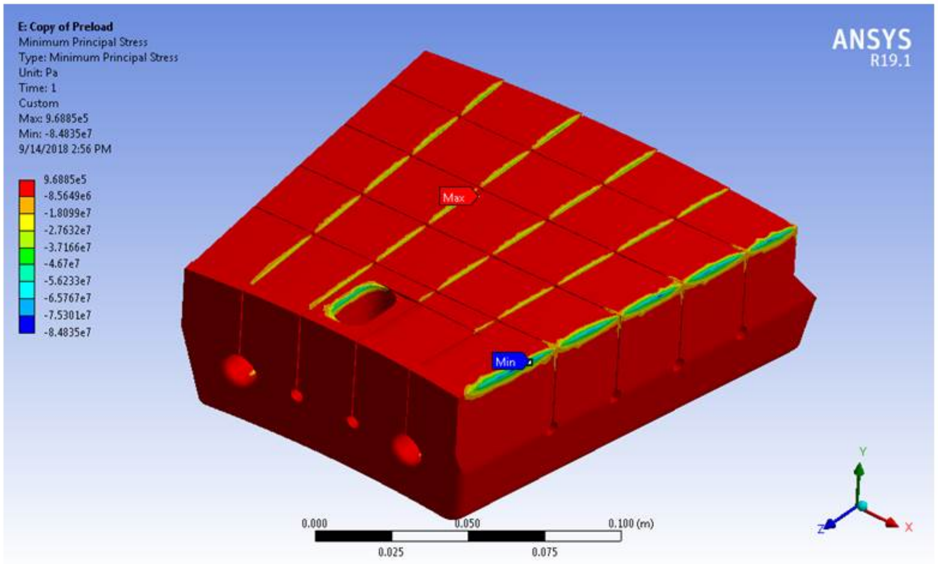
Max Stress Intensity Inconel 718 Structures 706 MPa



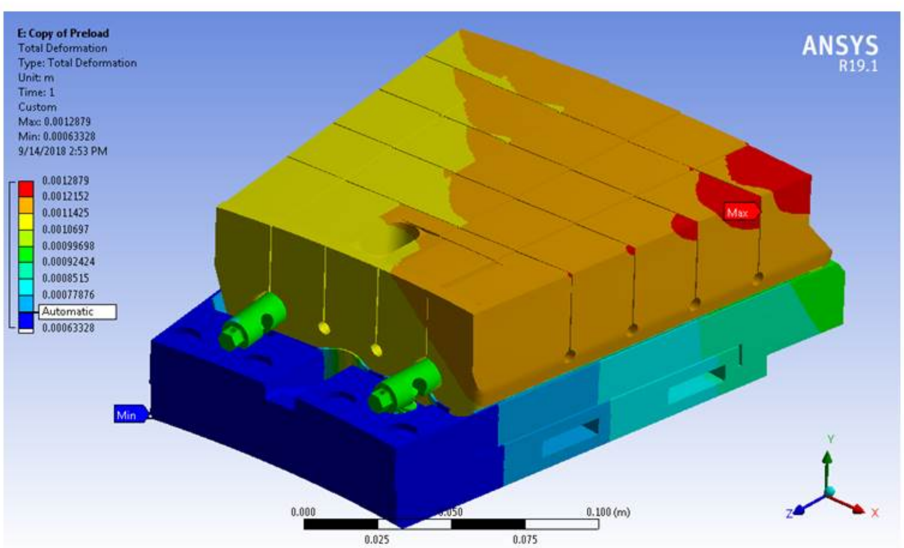
Max Principal Stress (Tension) in Graphite 12.9 MPa



Min Principal Stress (Compression) in Graphite 84.8 MPa

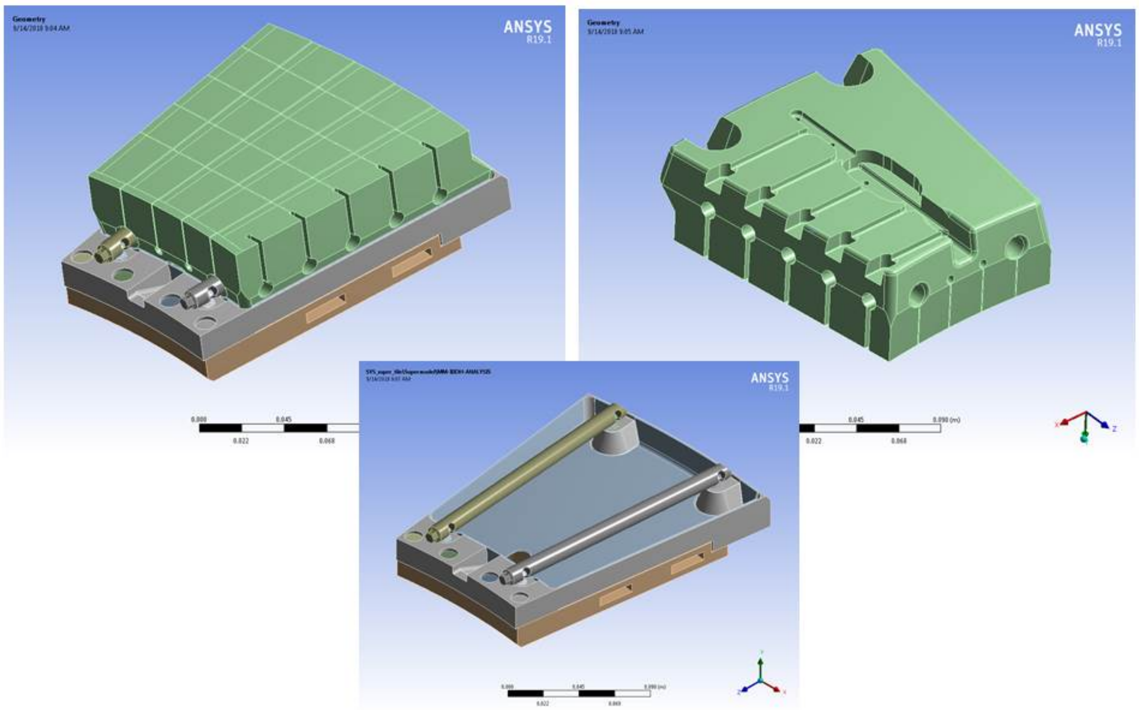


Displacements

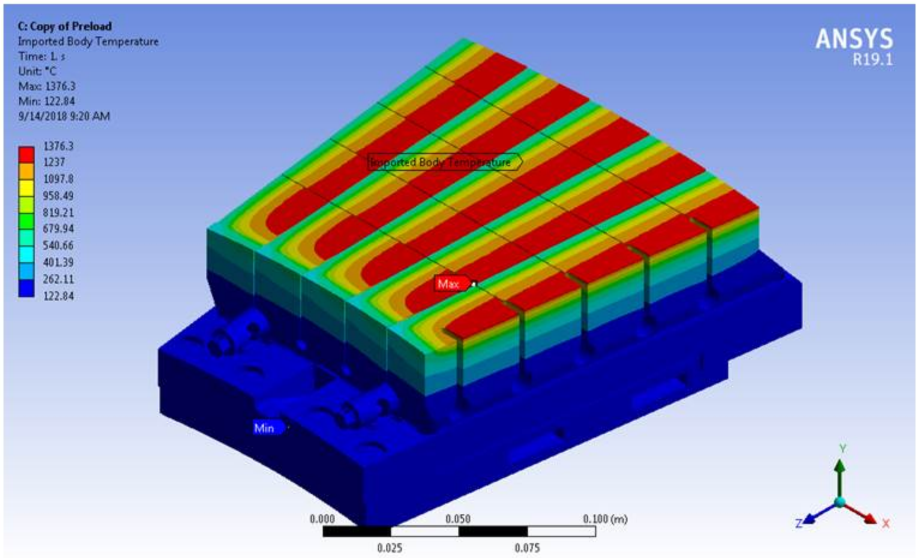


Results - **<u>Super Tile</u>**

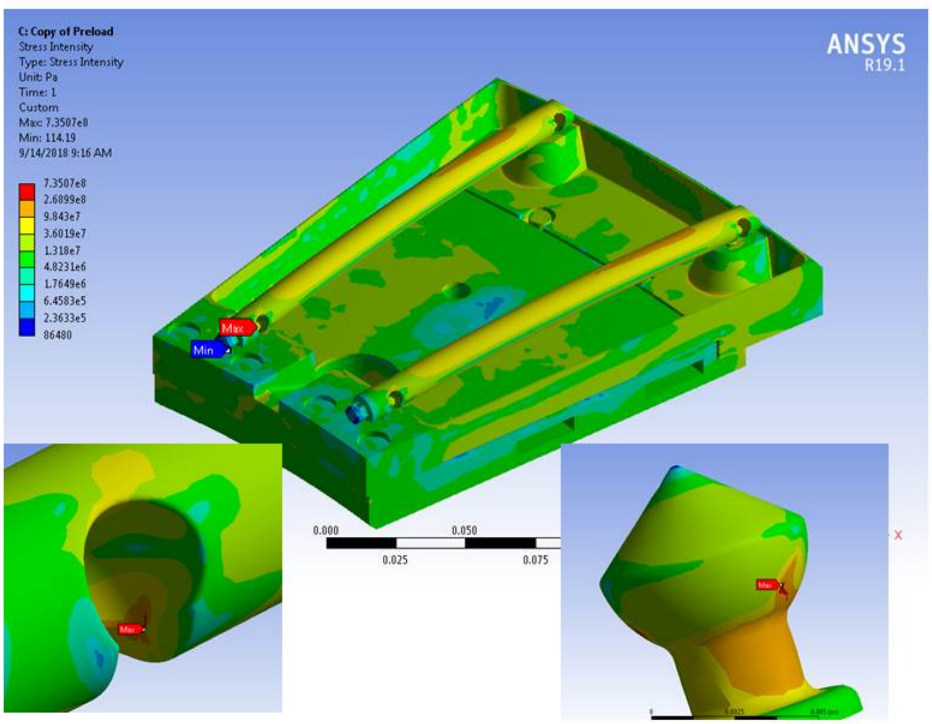
'Super' Tile with all Diagnostic Cutouts



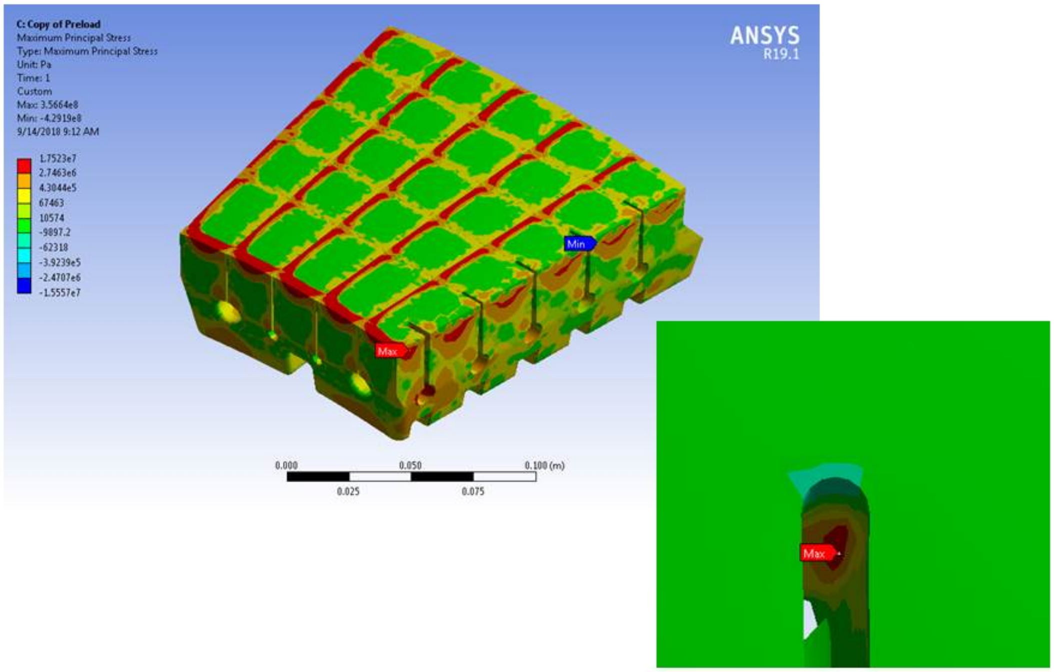
Max Applied Temperature – End of 5 sec Pulse



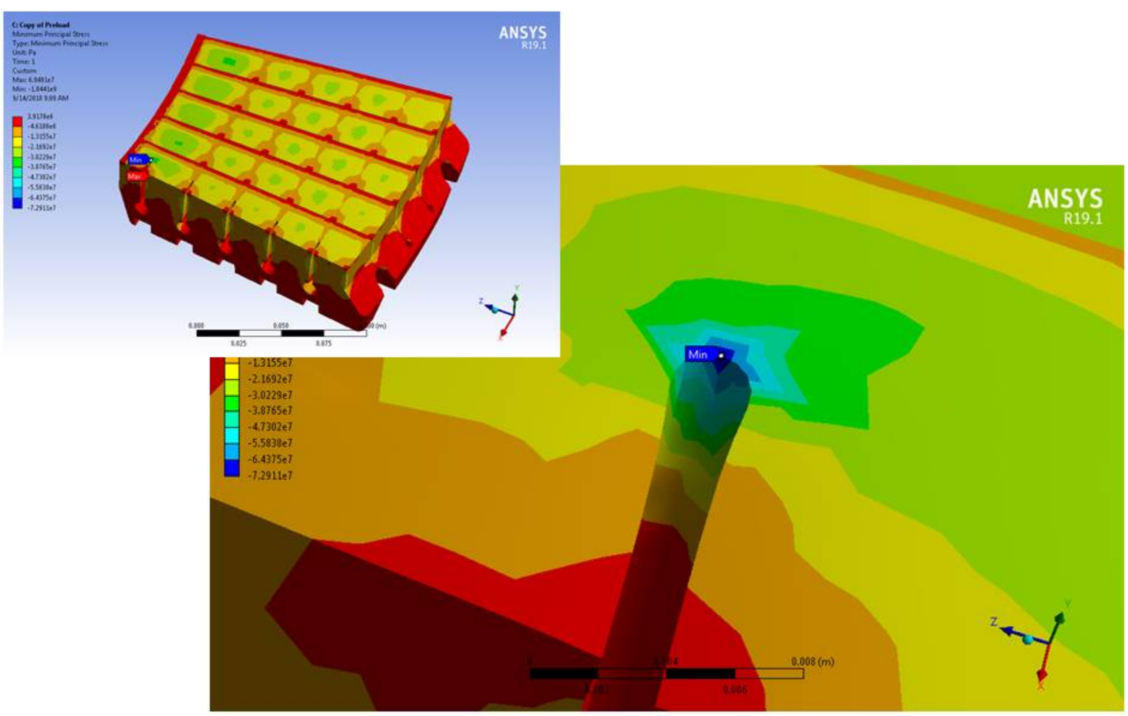
Max Stress Intensity Inconel 718 Structures 735 MPa



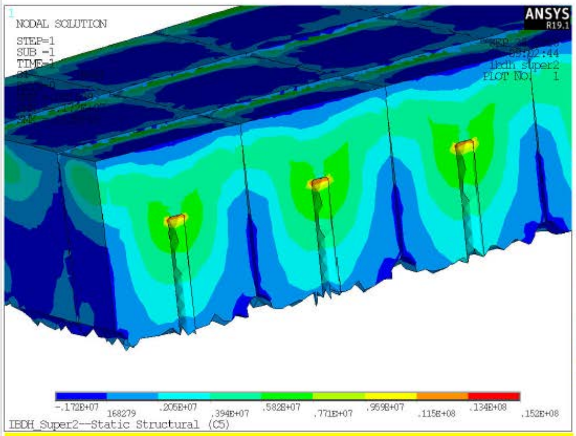
Max Principal Stress (Tension) in Graphite 17.5 MPa



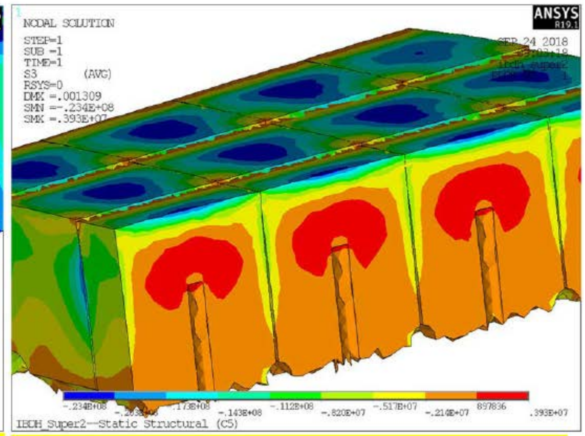
Min Principal Stress (Compression) in Graphite 72.9 MPa



Principal Stresses in Graphite
Away From Rod Contact and Inner Langmuir Probe

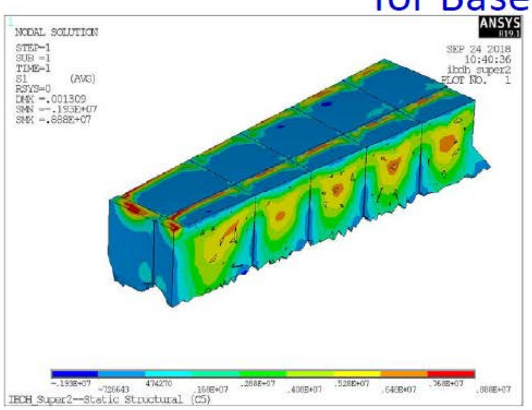


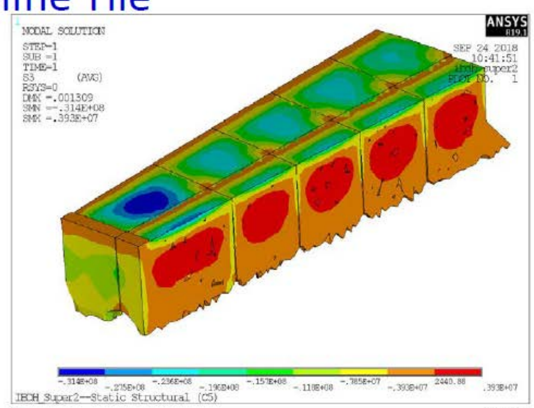
Peak Tension now at thermocouples 15.2 MPa



Peak Compression now on surface -23.4 MPa

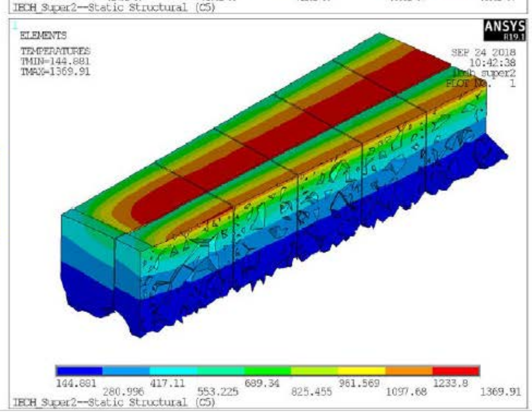
Principal Stresses in Graphite
for Baseline Tile



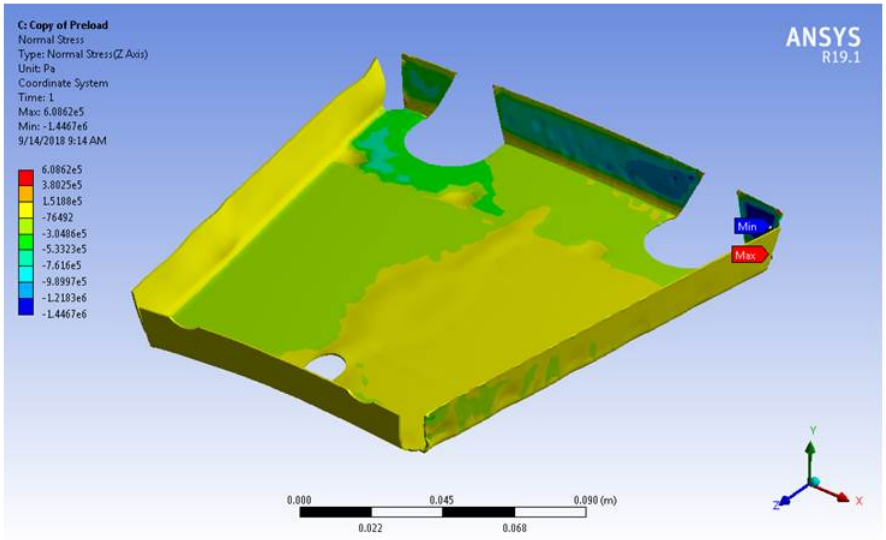


Peak Tension now at unheated region of surface 8.9 MPa

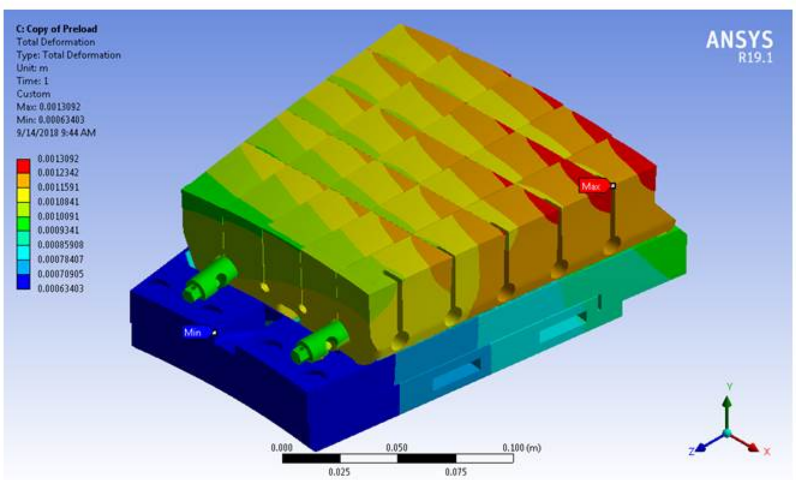
Peak Compression now on surface of inner castellation (higher heating) -31.4 MPa



Grafoil Normal Stresses



Displacements



Summary

	Line of Sight Tile		'Super' Tile		Comments
	Case 2&4	Case 3	Case 2&4		
Tile Max Temperature, C	1384	1980	1376		
Rod&Pin Peak Stress, MPa	732	706	735		
Tile Max Principle Tension, MPa	11.7	12.9	17.5		At Langmuir Probe
			15.2		Away from Languir Probe at Thermocouple
Tile Min Principle Compression, MPa	-41	-84.8	-72.9		At Langmuir Probe
			-23.4		Away from Languir Probe at Surface
Relative Displacement at Castellation, in			0.0054		

The results show the tile temperatures are within the allowables but is has identified several areas where high stresses exist. The spherical connection of the pins to the rods show high contact stresses though hand calculations suggest it should be acceptable. It is recommended that the connection be tested to demonstrate acceptable life. Also, the reverse helicity case results in high surface compression for the prescribed 1 MW/m2 for 1 sec. The recommendation is to relax these requirements if possible. Finally, the diagnostic tile with cutouts for the Langmuir Probes show high stresses at the one location where it is in the middle of a castellation whereas the other 4 locations between castellations are acceptable.

References

1) GENERAL REQUIREMENTS DOCUMENT NSTX-U-RQMT-GRD-001-02
2) NSTX-U SYSTEM REQUIREMENTS DOCUMENT Plasma Facing Components NSTX-U-RQMT-SRD-003-01 July 14, 2018
3) NSTX-U Disruption Analysis Requirements NSTX-U-RQMT-RD-003-02 7/23/18

4) NSTXU Recovery Global Heat Balance Calculations, NSTXU-CALC-10-06-00, by H Zhang

Appendix I

Analysis of Inboard Divertor Horizontal Basetile – q” cases 2 & 4

ORNL
Dennis Youchison

Summary:
The ANSYS Workbench project diagram appears in Figure 1 below. It included an initial static structural analysis of the IBDH base tile with TC slot. It also included a 5s heat on/ 120 s heat off transient thermal analysis followed by a static structural analysis with thermal loading at 5s and 120 s. Data was saved every second during heat up and every 10 s during cooldown. Also, at the peak temperature of 5s, the EM force loads from halo and eddy currents were applied. These results are presented below.

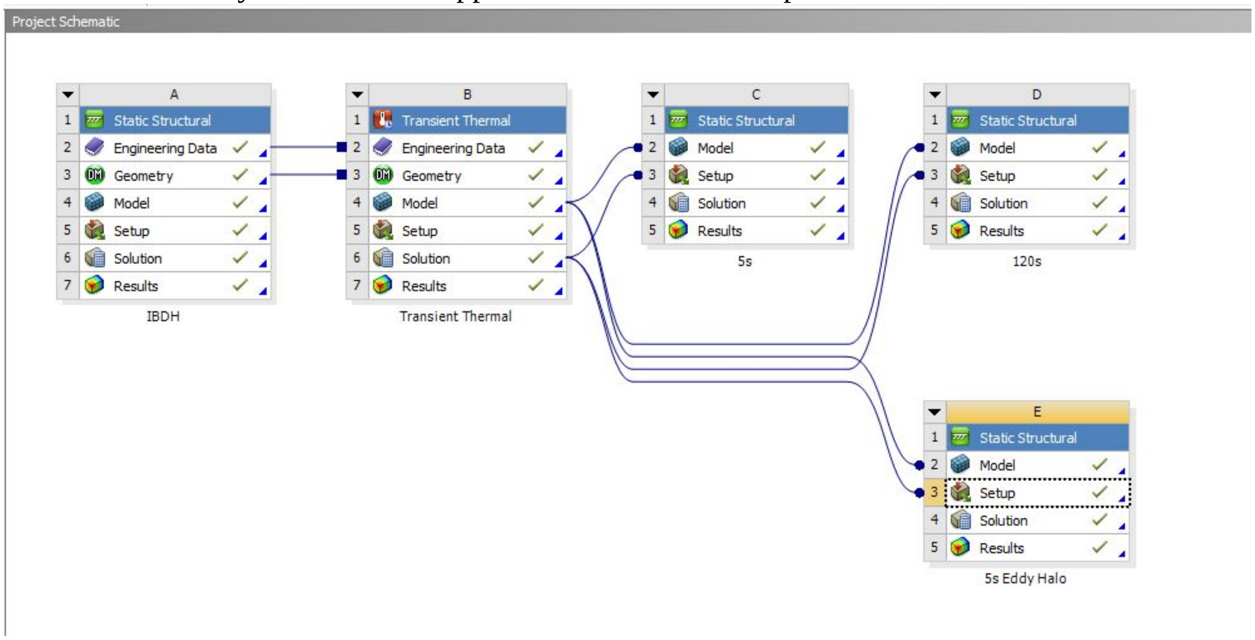


Figure 1. ANSYS Workbench workflow

N.B. *There are localized hot spots particularly at the interface between the horizontal rods and the large bolts which I refer to as locking pins or studs. These hot spots exceed allowables for principal stresses in many cases, but are in small isolated areas.*
The components considered in the analysis are listed below in Figure 2 and Figure 3.

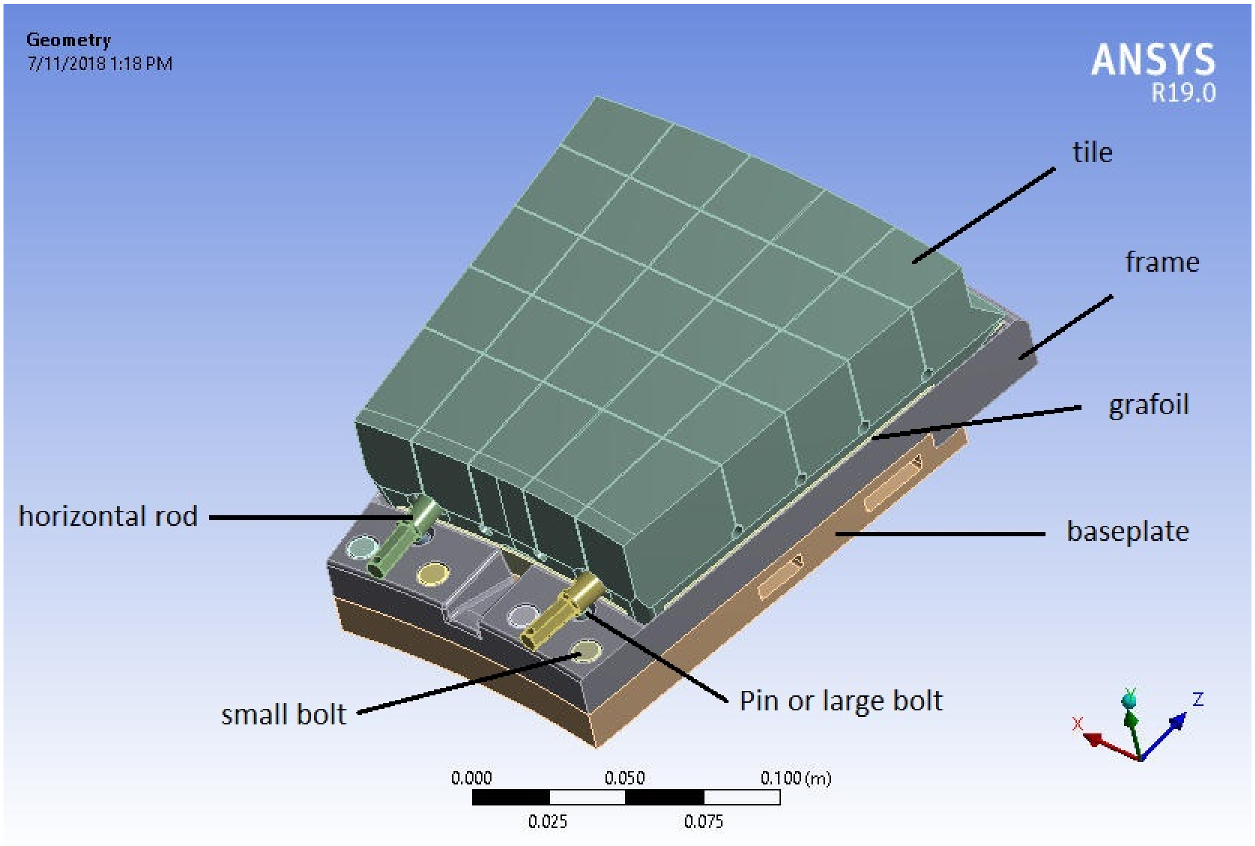


Figure 2: Inboard Divertor Horizontal TC variant

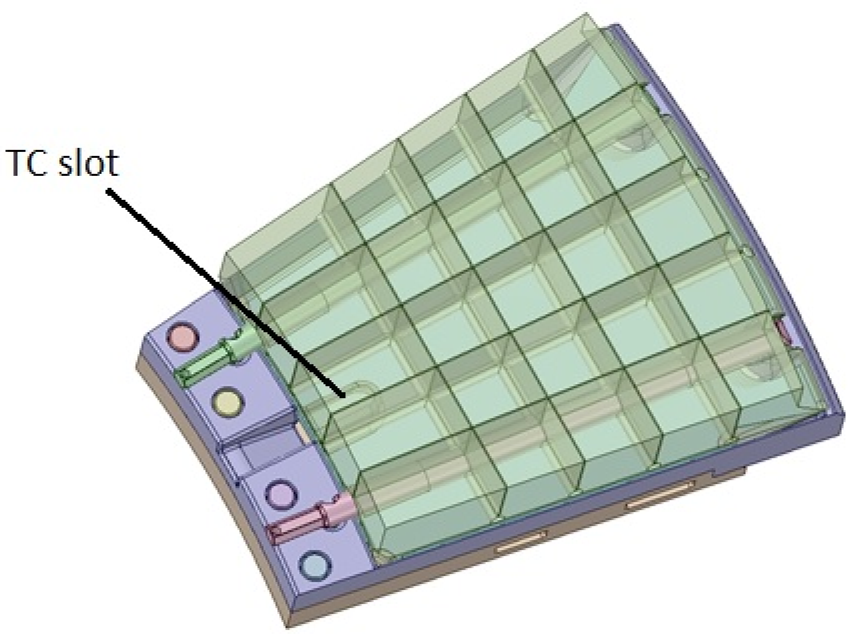


Figure 3: Inboard Diverter Horizontal Hardware Components with TC slot visible.

The total number of elements and nodes for the whole assembly is 944,201 and 1,516,177, respectively. Figure 4 shows the mesh used in the analysis with the graphite tile. Figure 5 and Figure 6 show the mesh on the mounting hardware only. The mesh was refined on the horizontal mounting rods and inside the tile holes mating to the rods. Figure 7 shows the mesh on the bottom side of the graphite tile and the TC cutout slot.

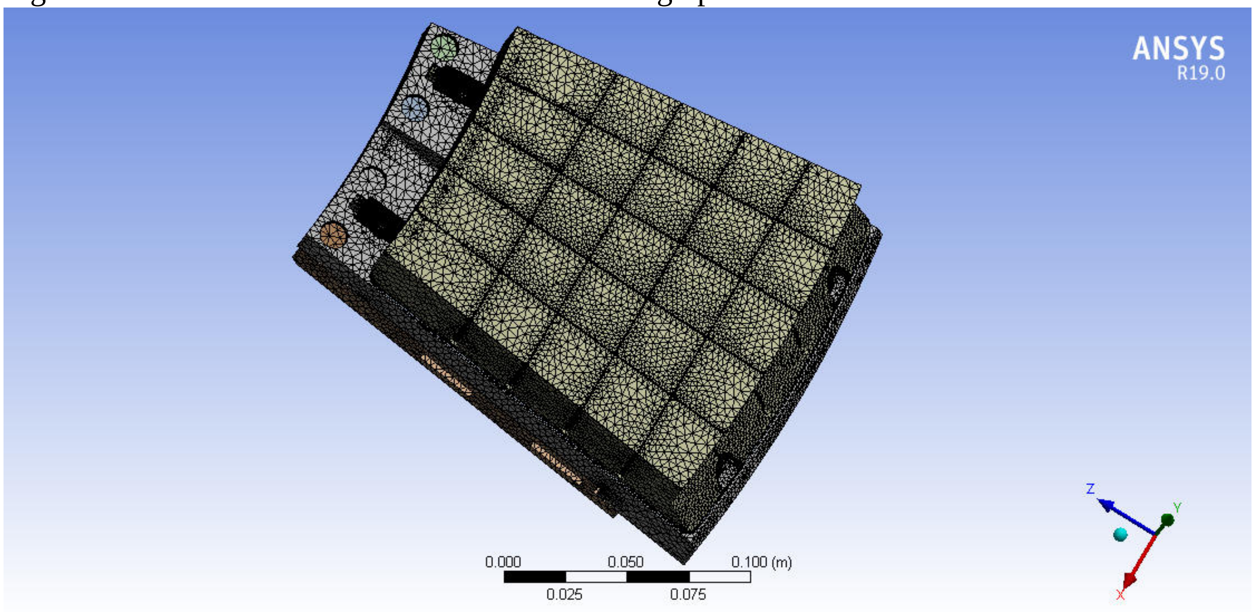


Figure 4: Mesh of the IBDH base assembly

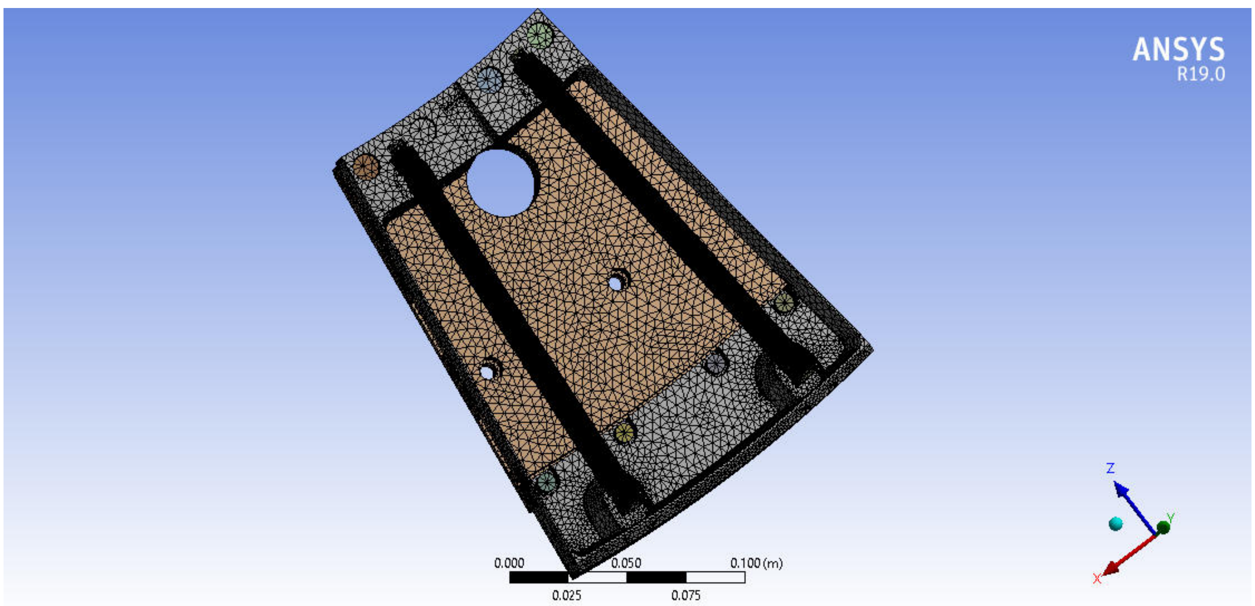


Figure 5. Mesh of mounting hardware.

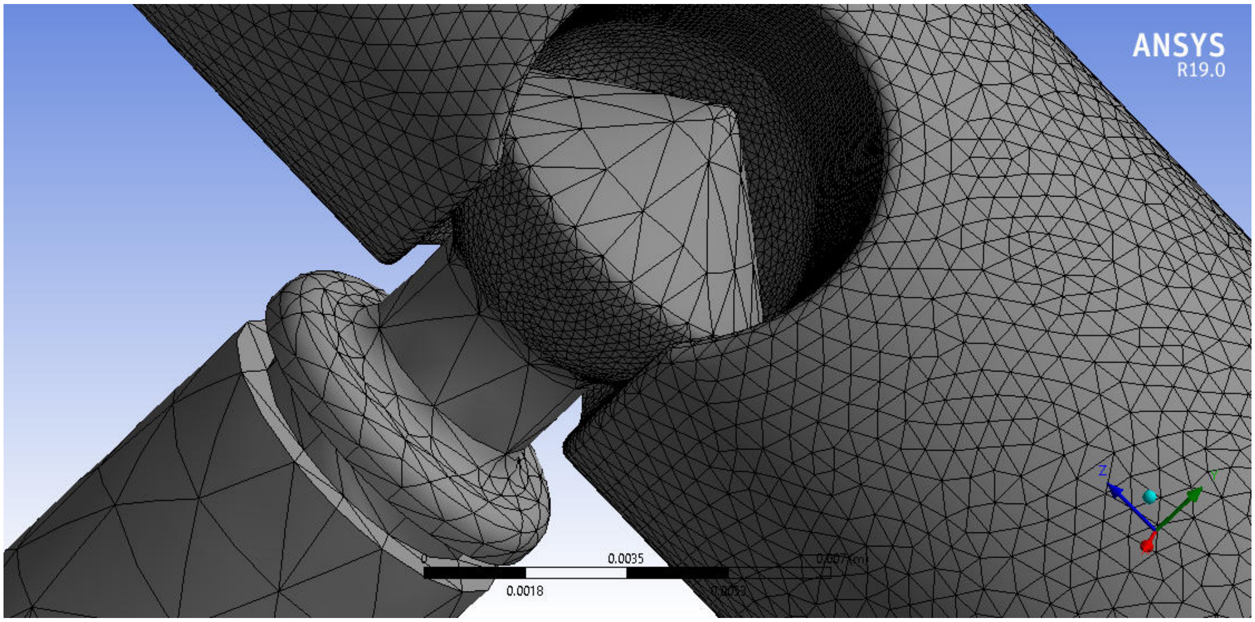


Figure 6. Refined mesh on mounting rods and stud interface

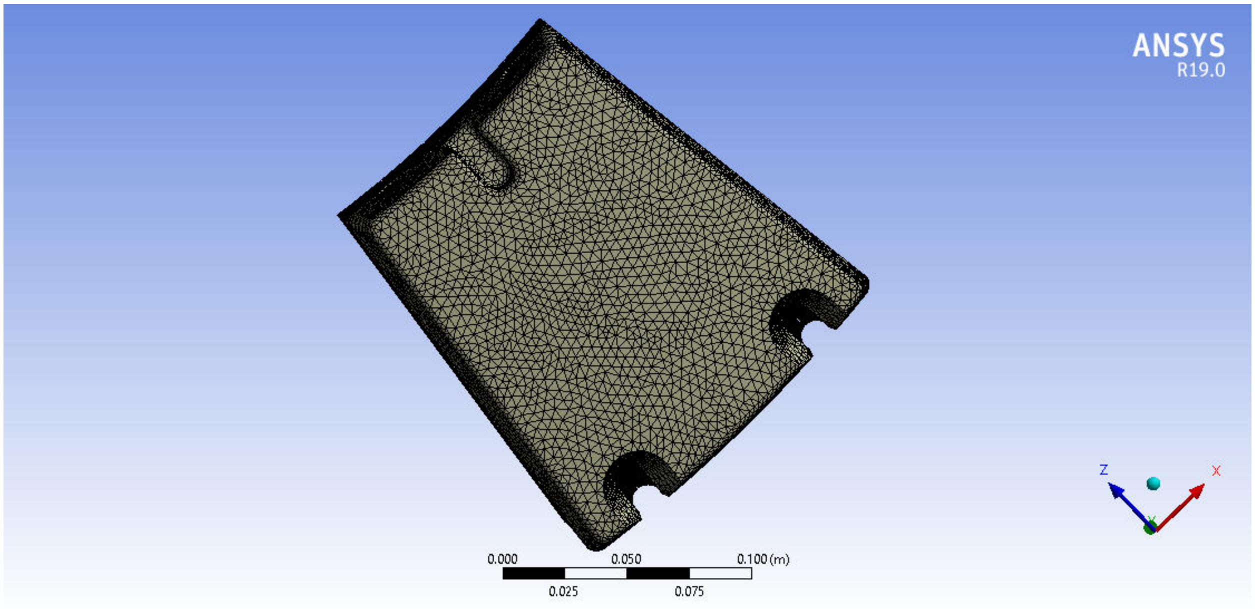


Figure 7: Mounting side of the graphite tile showing cutout.

Table 1 lists each component of the assembly and its material.

Table 2: Components and their materials.

Component	Material
IBDH Graphite Tile	Sigrafine 6510
Grafoil	Grafoil
Grafoil Insert Rings	Grafoil
Baseplate	Inconel 718
Horizontal rods	Inconel 718
Large bolts	Inconel 718
Small bolts	Inconel 718

Static Structural Analysis

The following boundary conditions were used for the static analysis. Reaction forces of 750 N were applied to the pins that hold down the horizontal rods and graphite tile. Bolt pretensions of 1000 N were applied to the 8 inconel-718 bolts that hold the frame to the baseplate. The frame to bolt contacts were set to frictionless. However, all the other contacts were specified as frictional with a friction coefficient of 0.1 and a thermal contact conductance of 1000 W/m^{2}K.

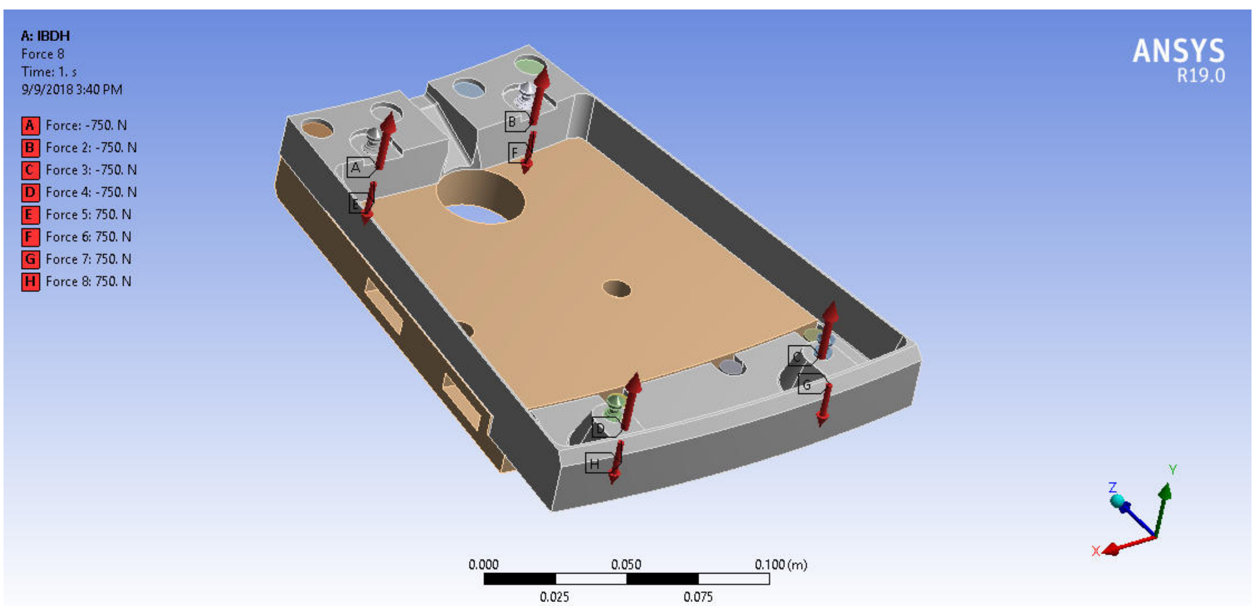


Figure 8. Structural loads – reaction forces applied between pins and frame

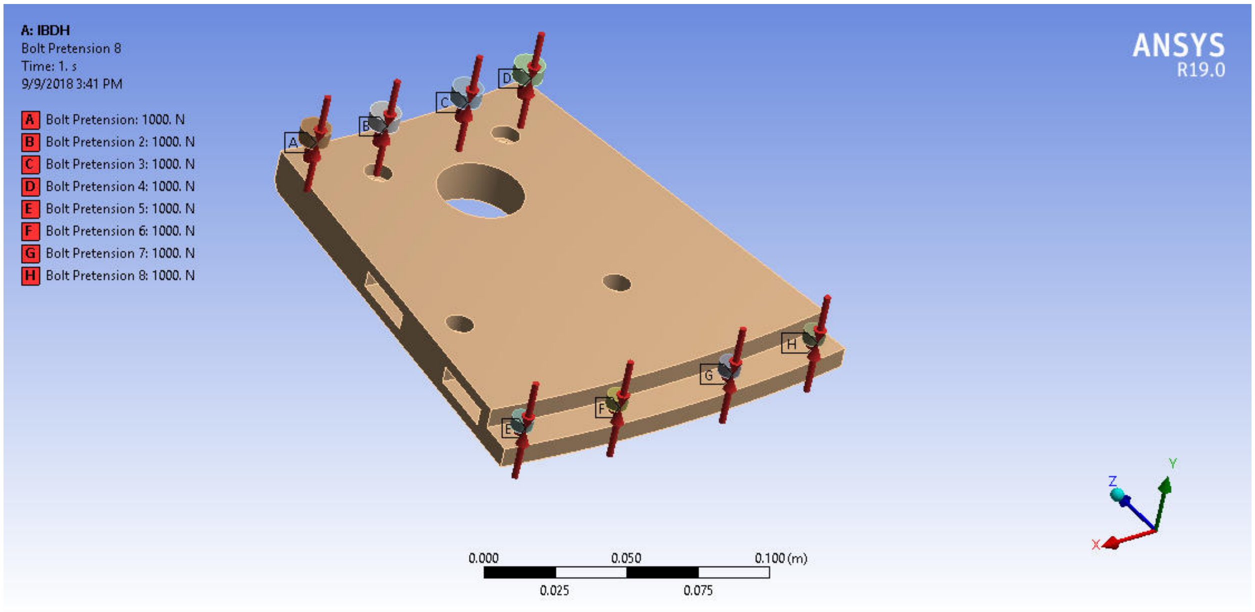


Figure 9: structural loads – bolt pretension included

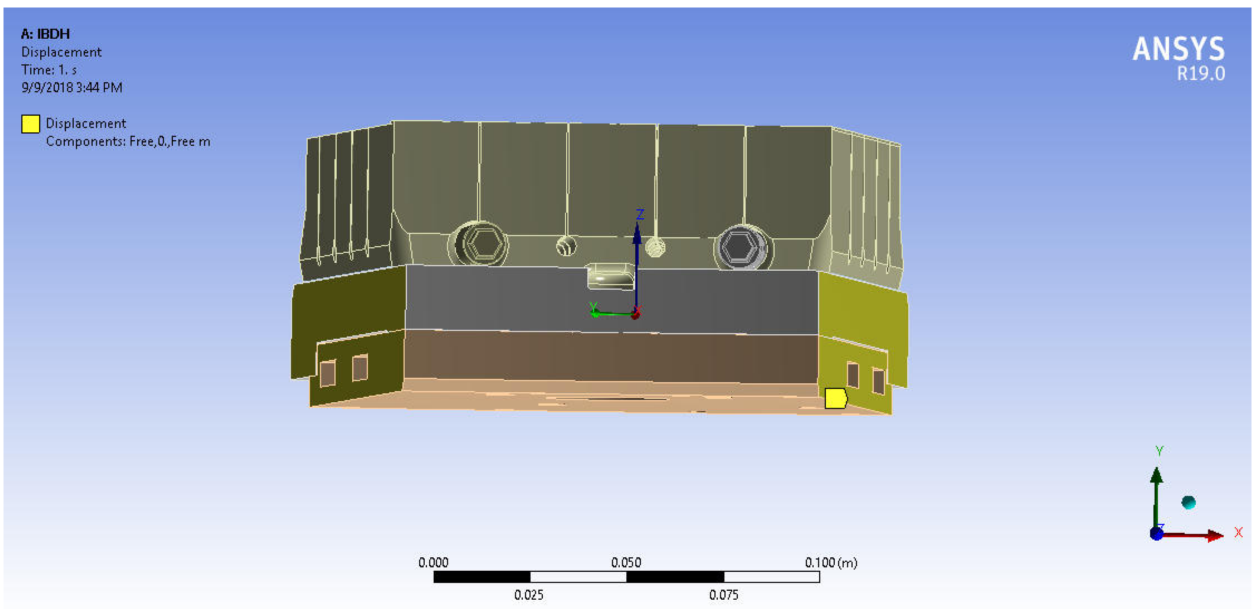


Figure 10. Displacement condition on frame sides limit rotation

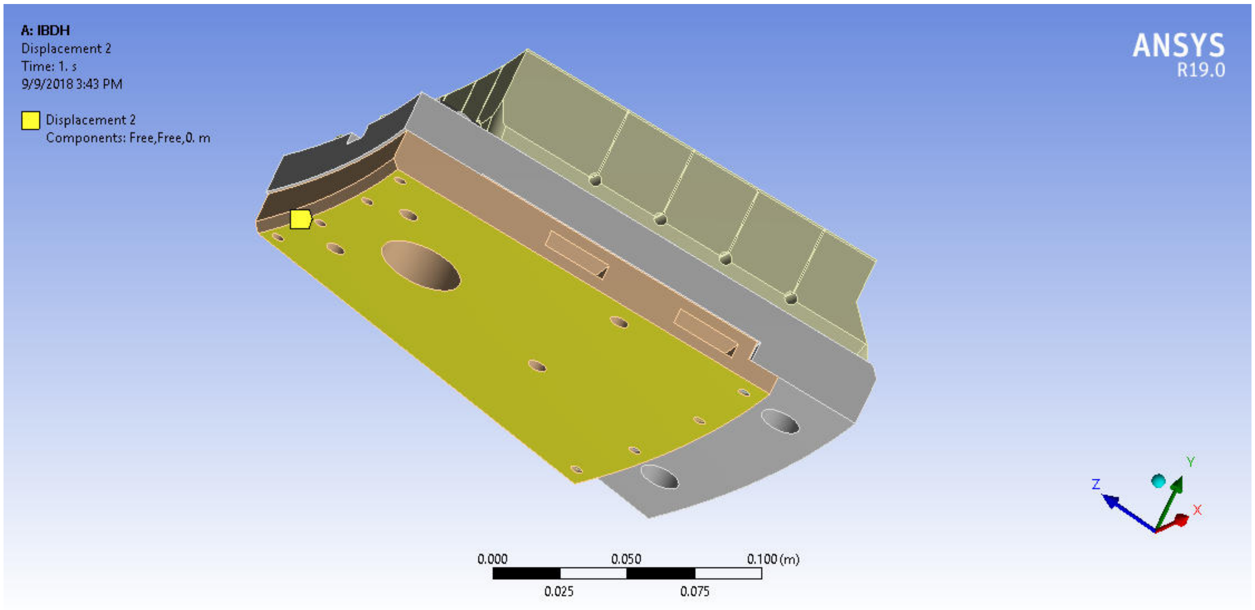


Figure 11. Displacement boundary conditions limits motion in z direction and fixes bottom face.

The total deformation of the assembly under static pretension is shown in Figure 12. Figure 13 indicates that the horizontal rods experience more deformation on the outboard side of the tile (-z) than the inboard and load the outboard side of the tile more.

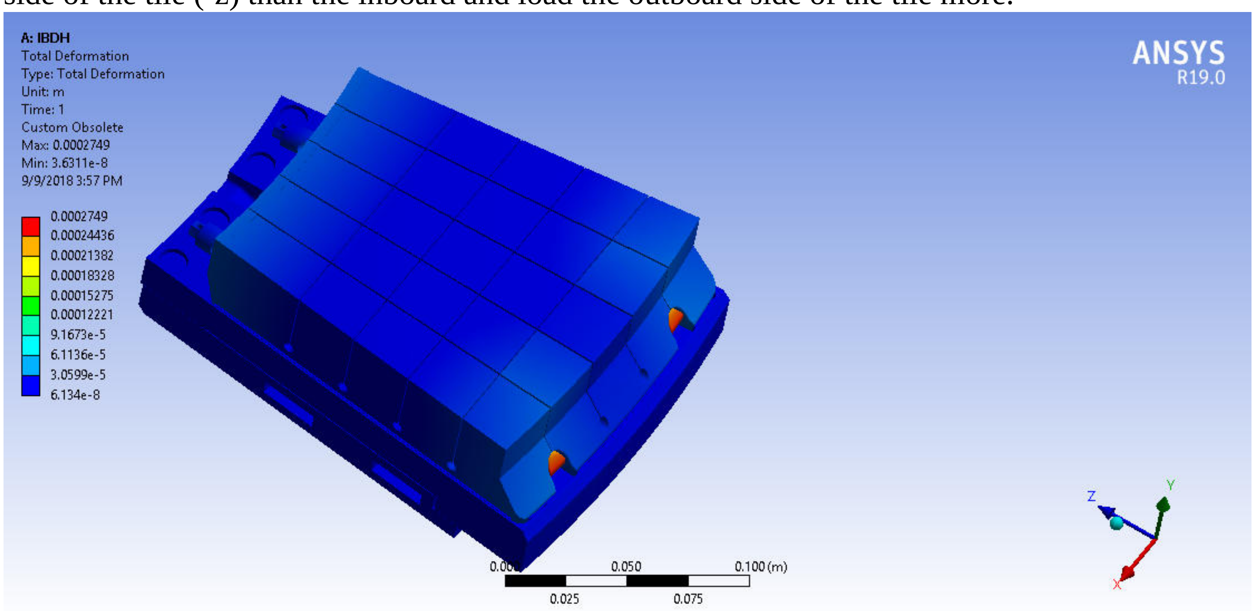


Figure 12. total deformation from pretension loads only.

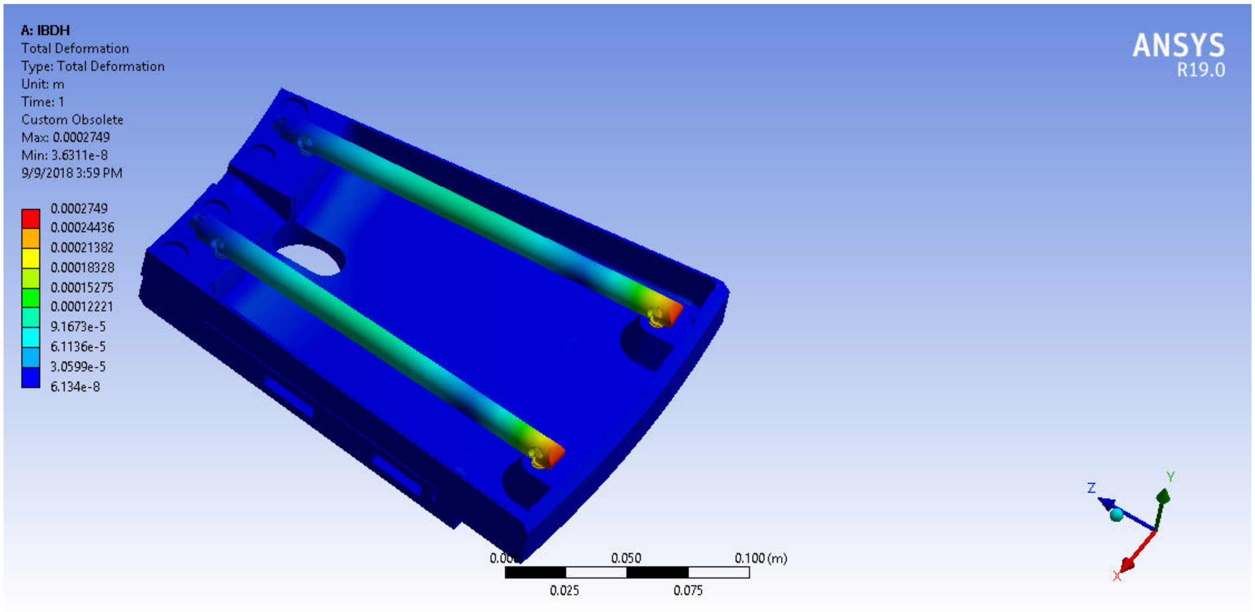


Figure 13. z-direction deformation in horizontal rods

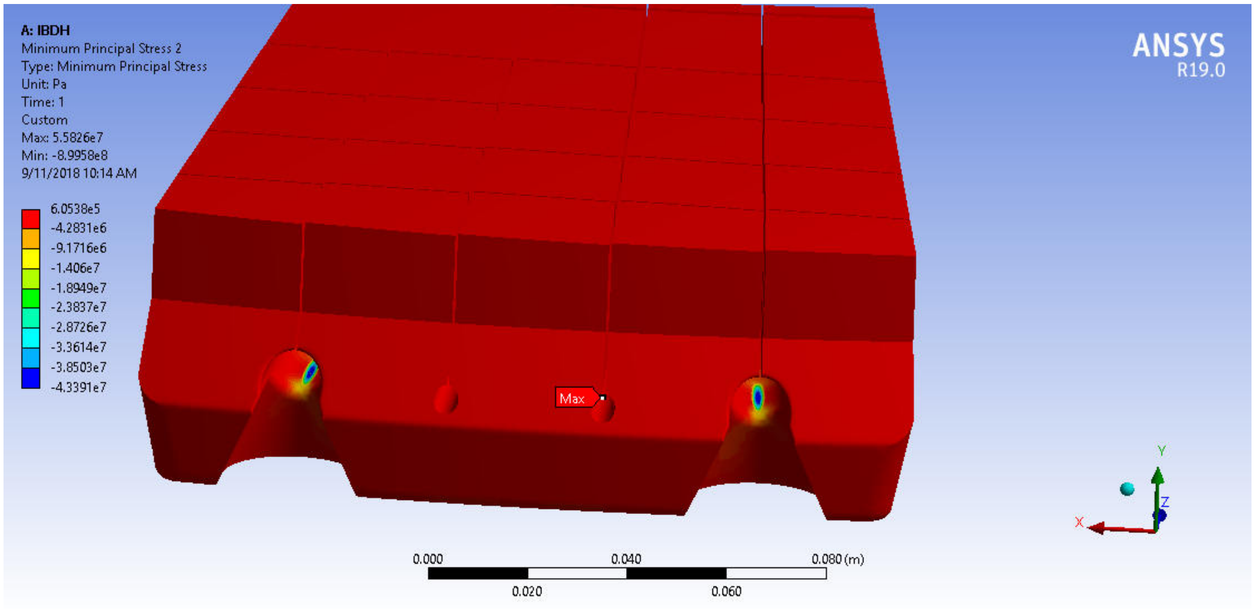


Figure 14. Minimum principal stresses appear highest on outboard side of tile.

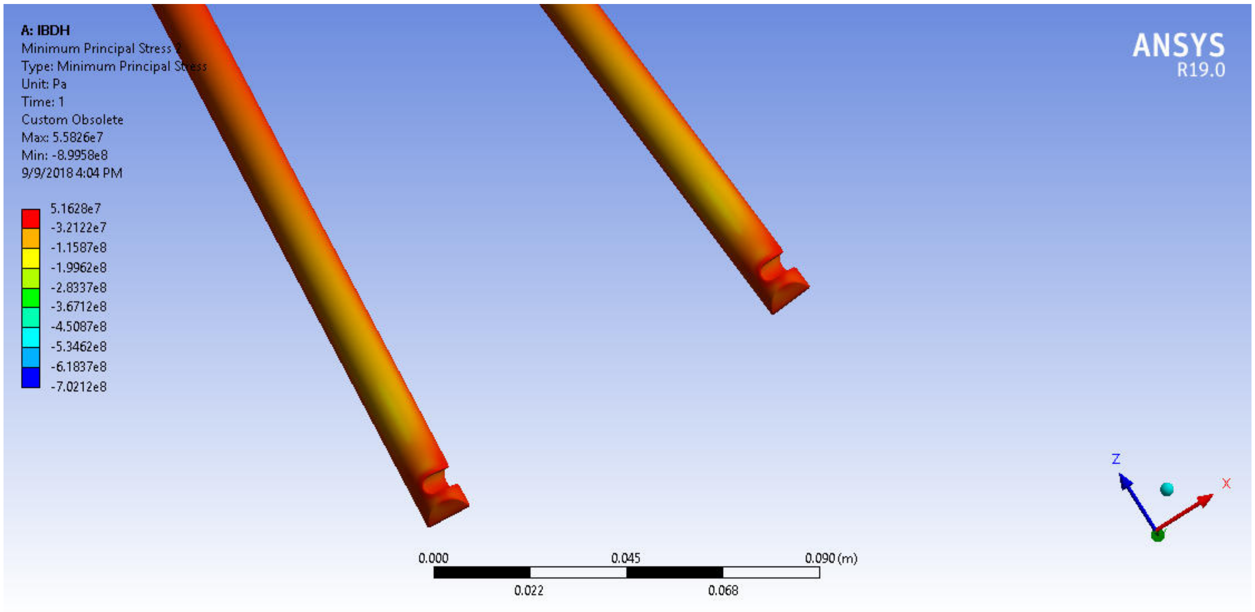


Figure 15. Largest minimum principal stresses appear at rod-pin contacts and along the rod bottoms

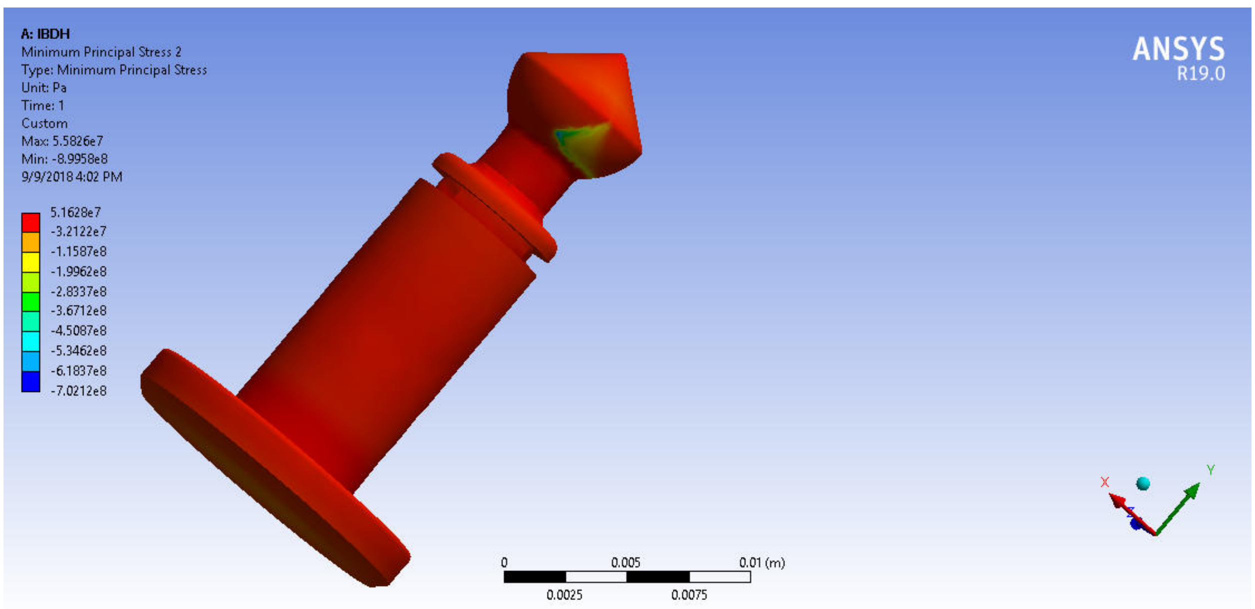


Figure 16. Locking pins also have a large minimum principal stress

Figure 17 presents the maximum principal stresses in the mounting studs.

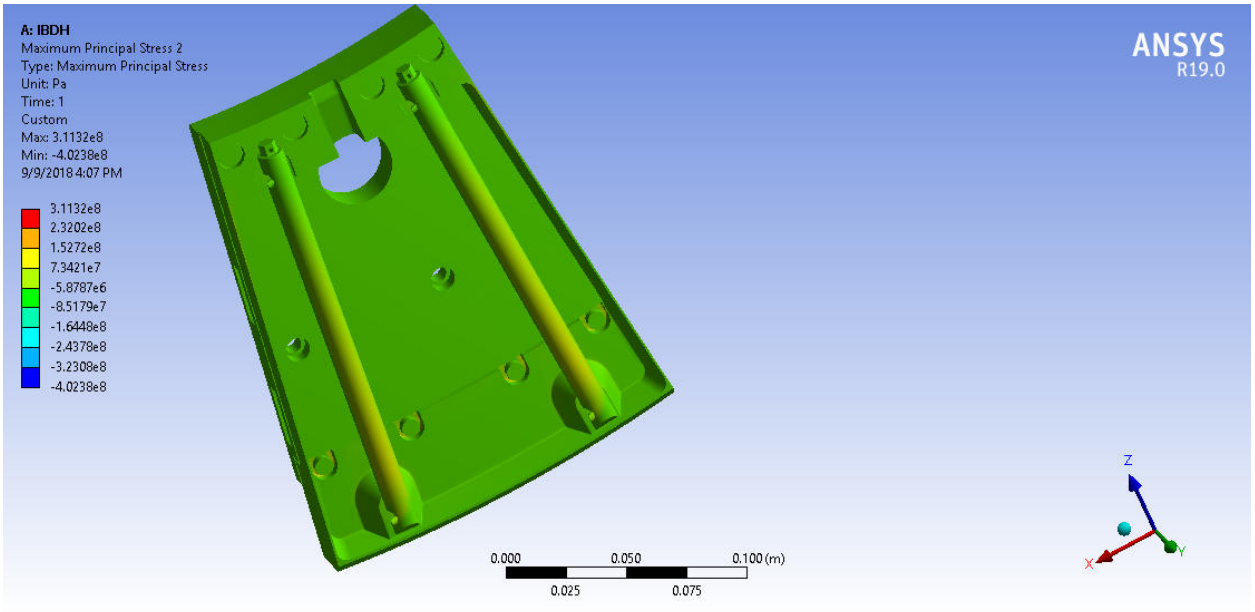


Figure 17. Maximum principal stress in mounting hardware

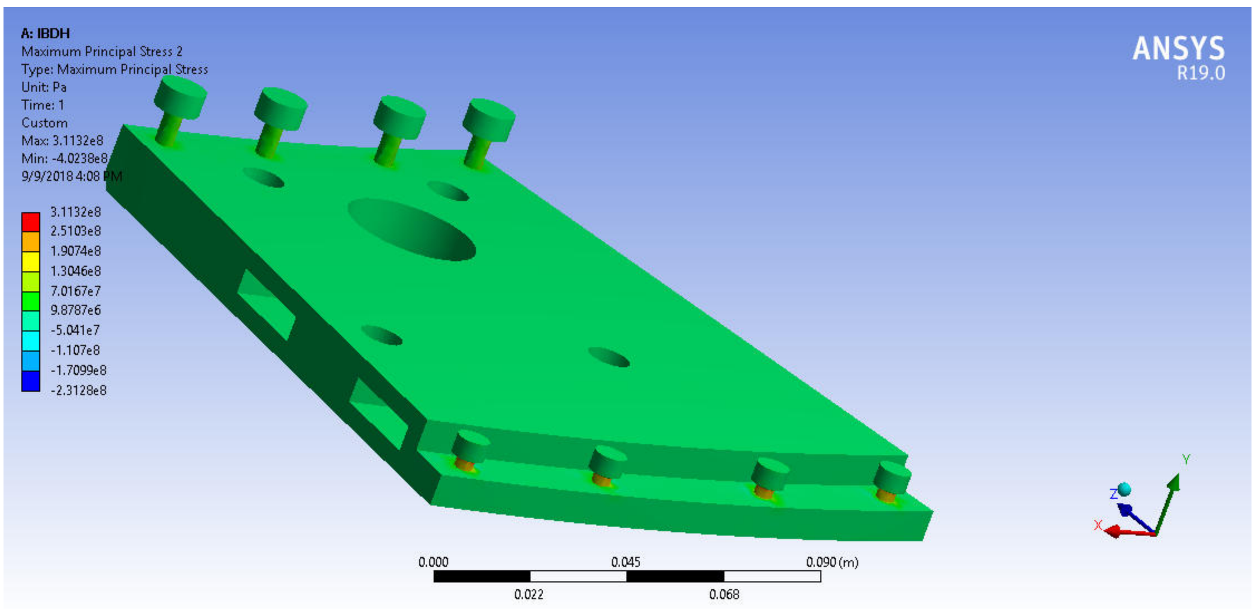


Figure 18. Maximum principal stresses in base plate.

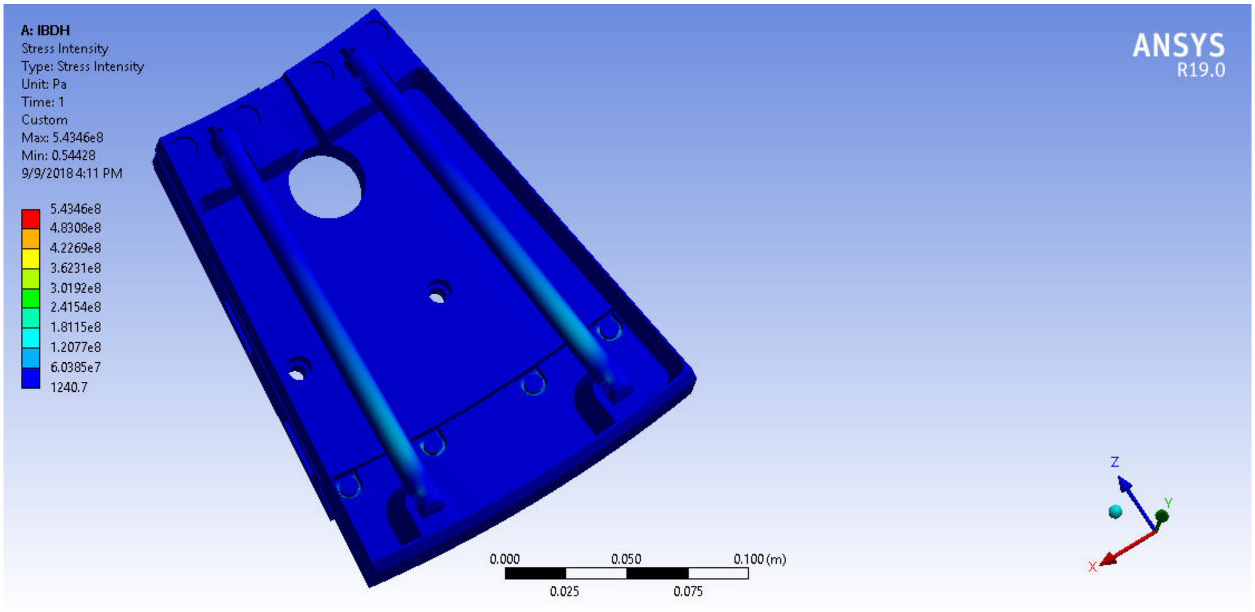


Figure 19. Stress intensity from preload only

Transient-Thermal Analysis

A transient thermal analysis was performed with an initial ambient temperature of 116 ^{o}C for a 5s heat flux pulse mapped over specified areas of the tile, corresponding to case 2 and case 4 heating. For case 2, the heat flux was 6.43 MW/m^2, and for case 4, it was 6.72 MW/m^2. This was followed by a 115 s cooldown period. Helium cooling using 25 C helium in the baseplate was assumed with a convective heat transfer coefficient of 300 W/m^{2}K. This is not entirely consistent with a 116 ^{o}C environment temperature due to ratcheting, unless the helium flow starts at the beginning of the pulse. Radiation was included for the top tile surface only, since all other have no open viewfactor. The emissivity was 0.7 and the reference background temperature was 52 ^{o}C. The model boundary conditions appear in Figure 20.

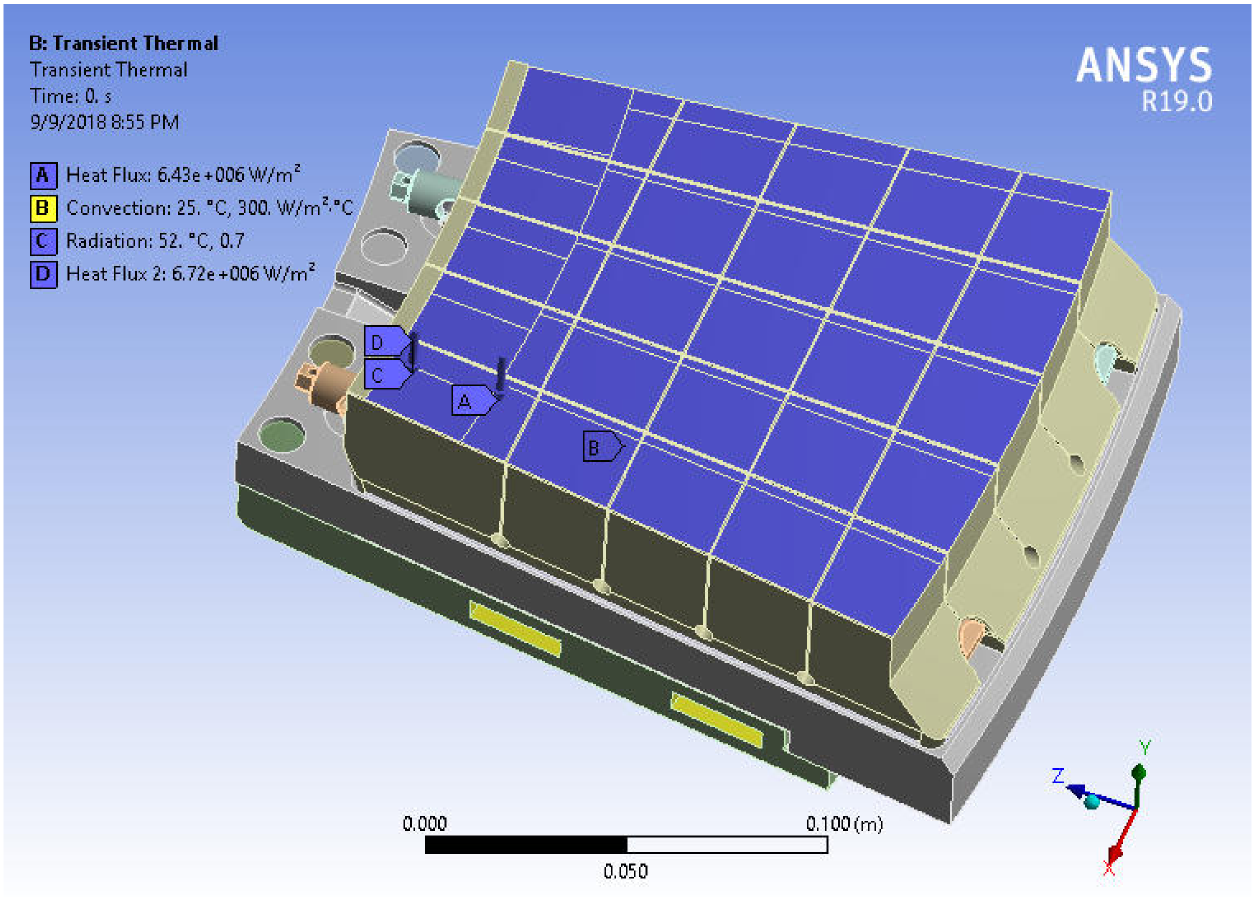


Figure 20. Transient thermal boundary conditions at end of 5 s pulse.

The maximum global temperature response appears in Figure 21 for this scenario.

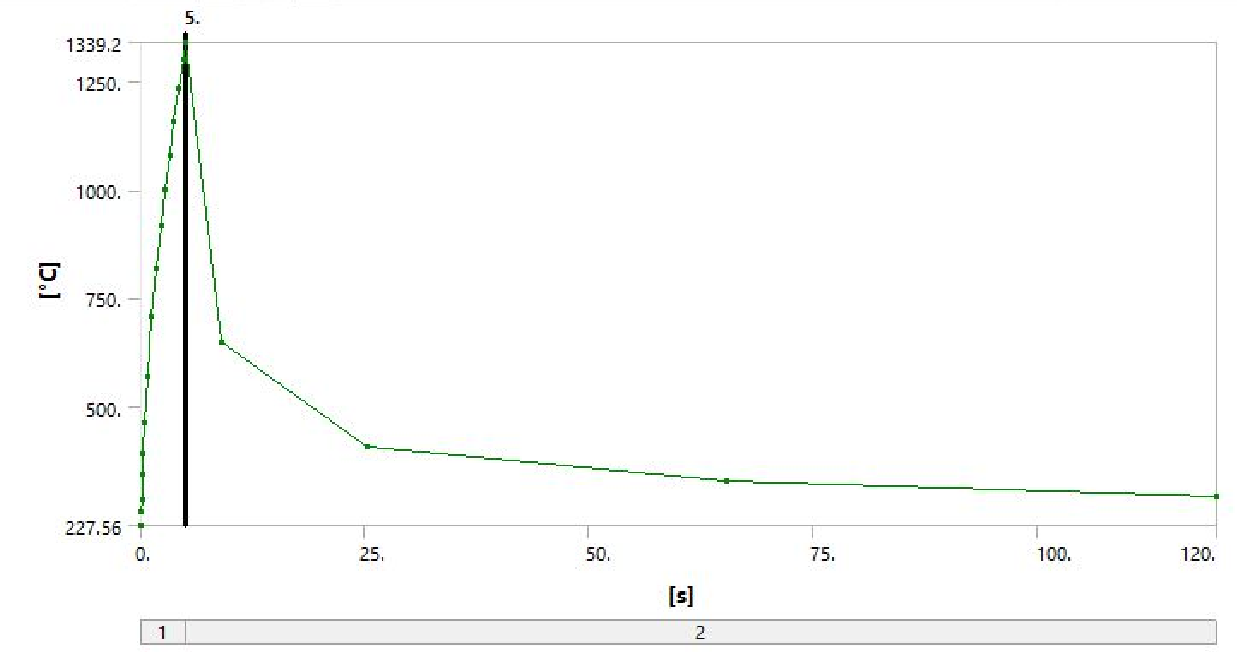


Figure 21. Maximum global temperature response.

The temperature distribution at 5s, 25 s and 120 s appear in Figure 22, Figure 23 and Figure 24, respectively. At 25 s, the thermal wave has almost reached the bottom of the tile. At 120 s, the tile is still cooling.

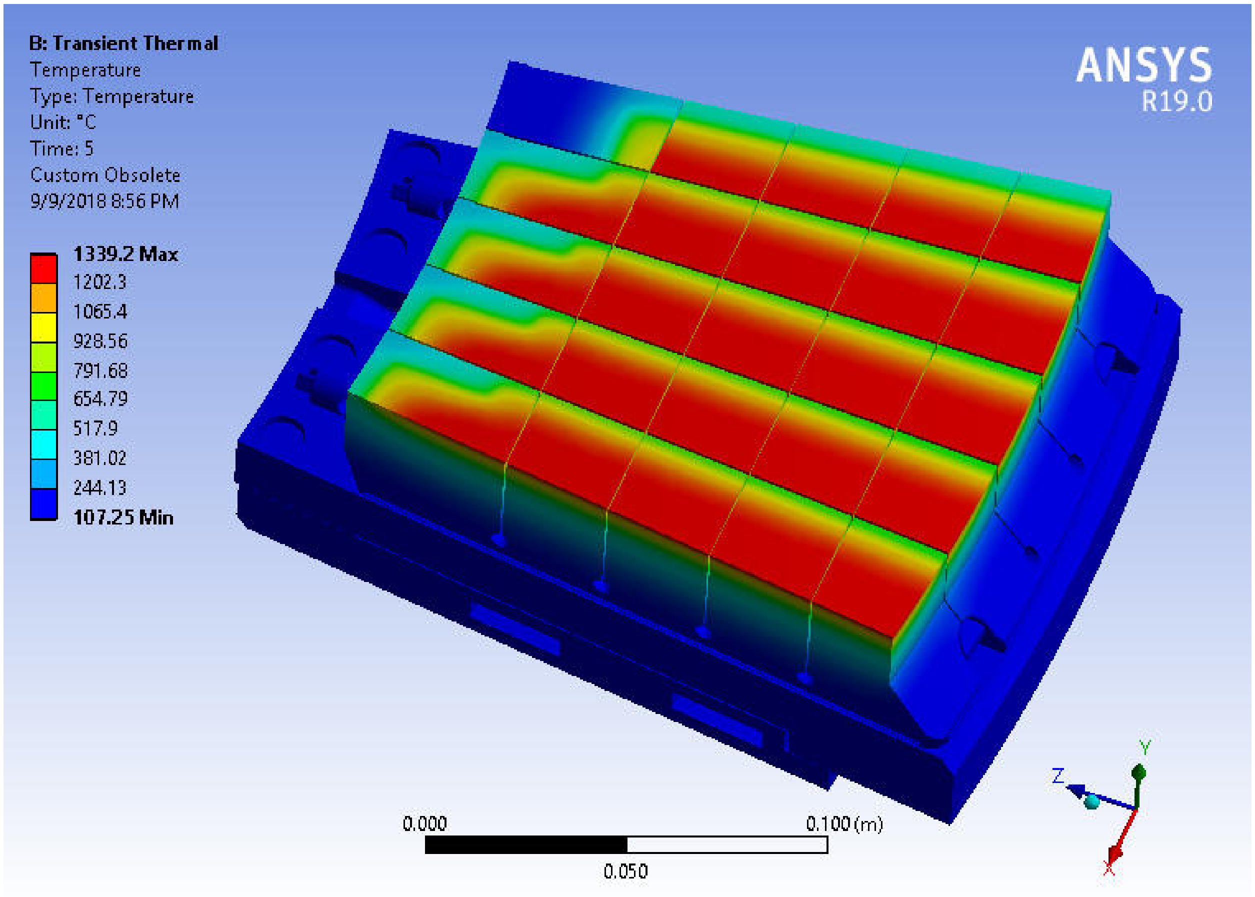


Figure 22. Temperature distribution at 5 s.

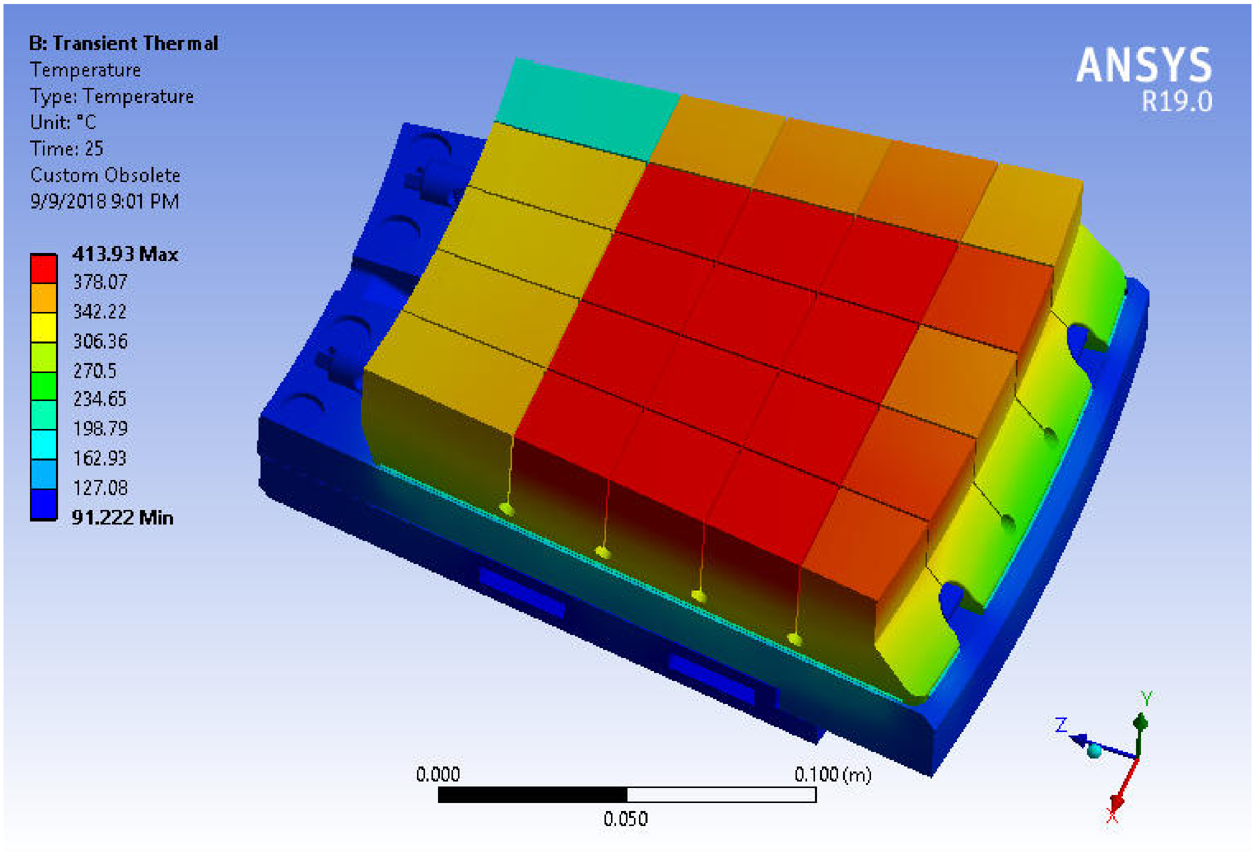


Figure 23 Temperature distribution at 25 s.

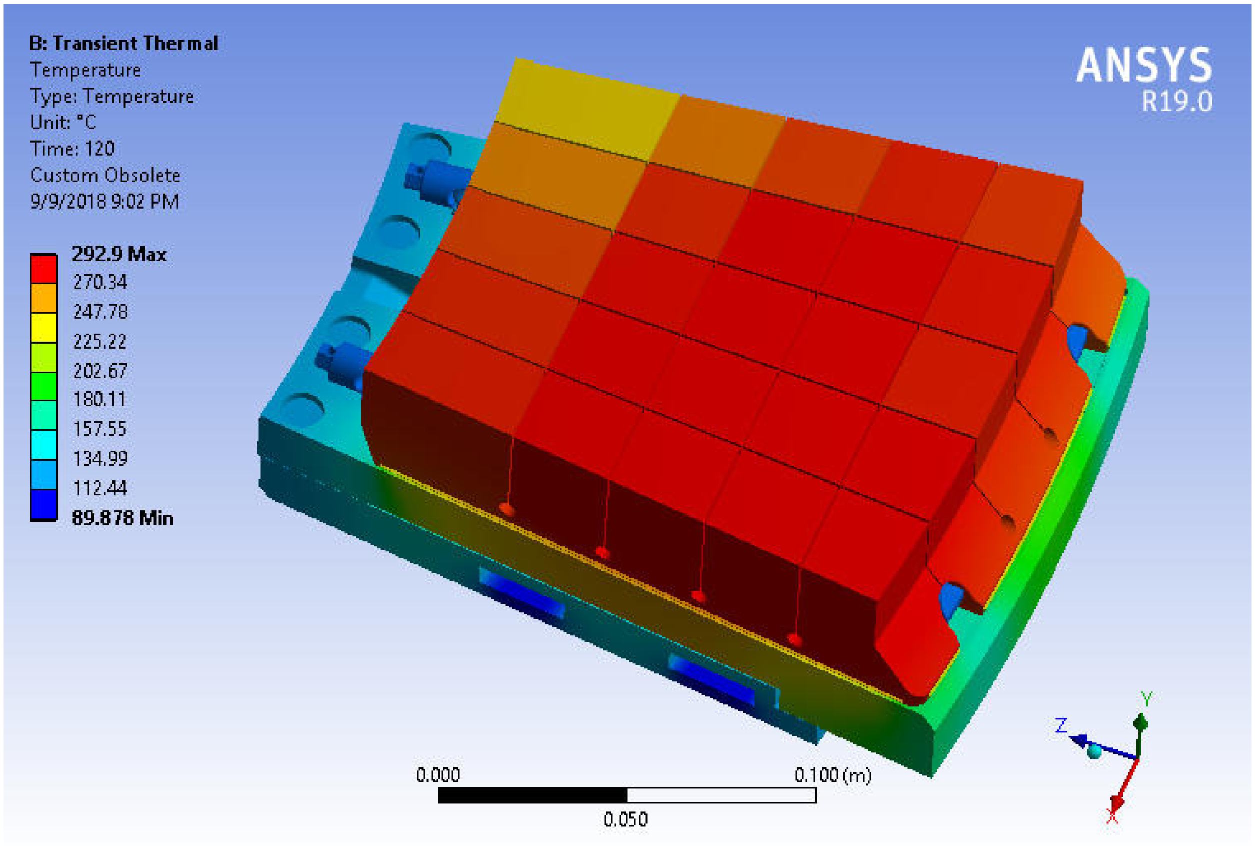


Figure 24. Temperature distribution at 120 s.

Table 2 lists the peak temperature for each component throughout the entire cycle.

Table 3: Peak temperature for each component

Component	Peak Temperature (°C)	Time (s)
Graphite Tile (Sigrafine 6510)	1339	5
Grafoil	264	120
Baseplate	194	120
Inconel pins	131	120
Inconel horizontal rods	118	120
Inconel Frame	259	120

Structural-Thermal Analysis

Preload forces and bolt pretension used previously in Figure 9 were combined with the imported temperature load at 5 s shown in Figure 25 and a static structural analysis was performed.

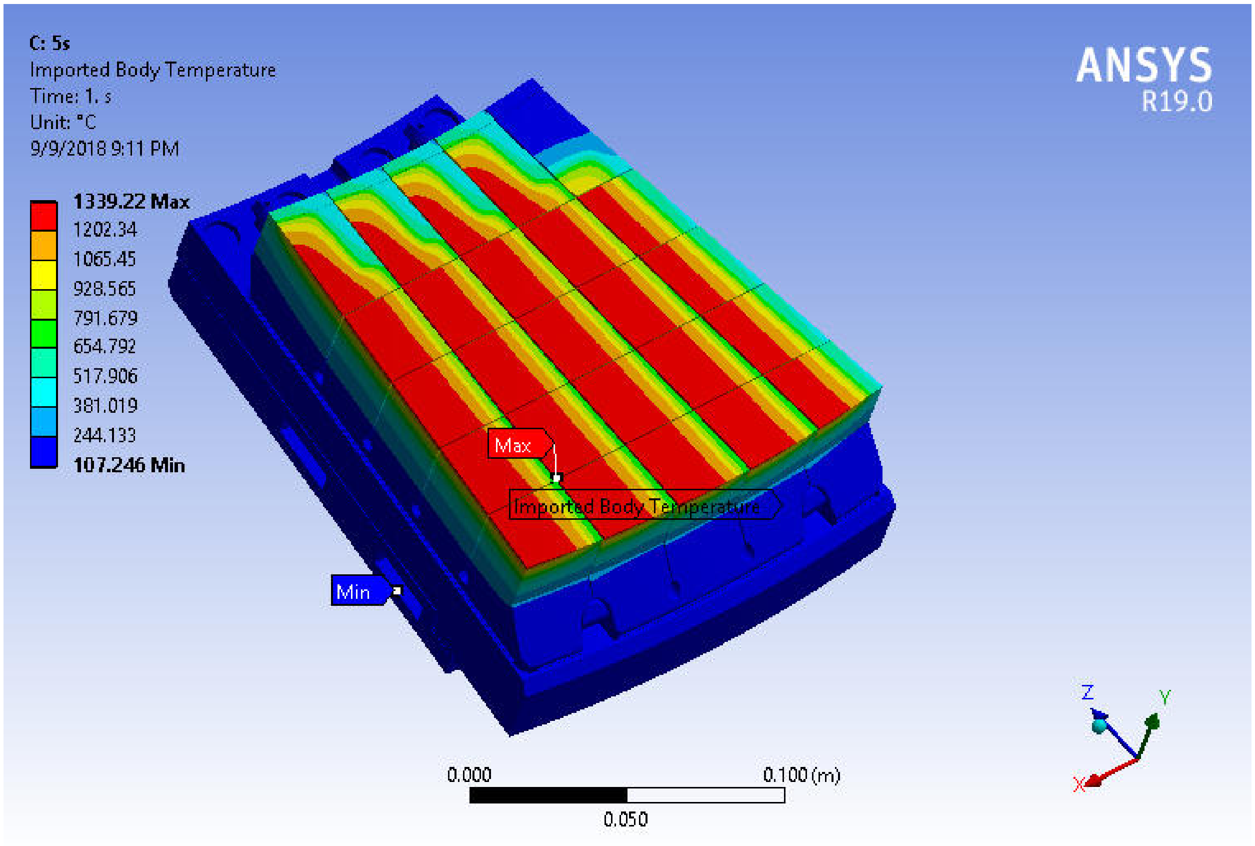


Figure 25. Imported temperature distribution at end of 5s pulse.

Results

Total deformation contour plot of the assembly is shown in Figure 26 and the deformation perpendicular to the tile surface is shown in Figure 27. The reaction force is shown in Figure 28.

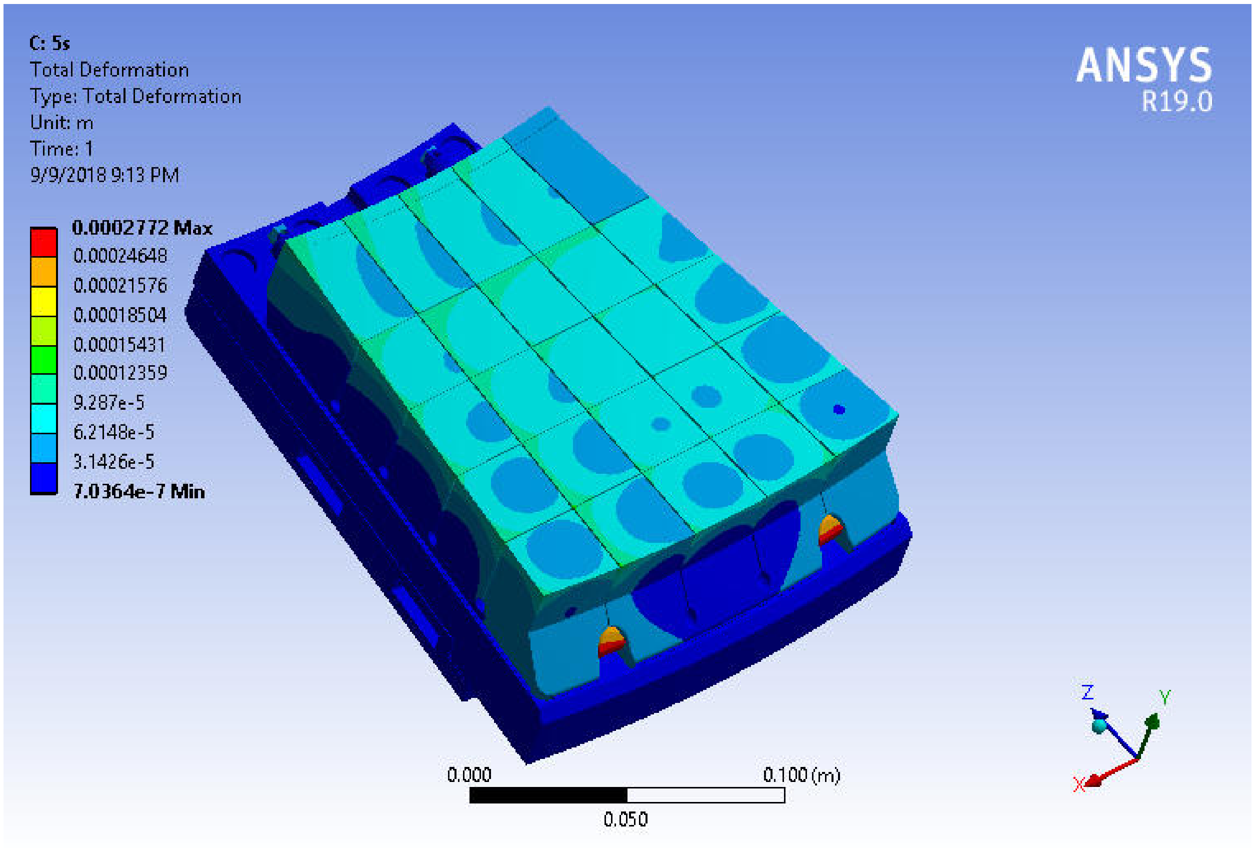


Figure 26 Total Deformation at end of 5s pulse.

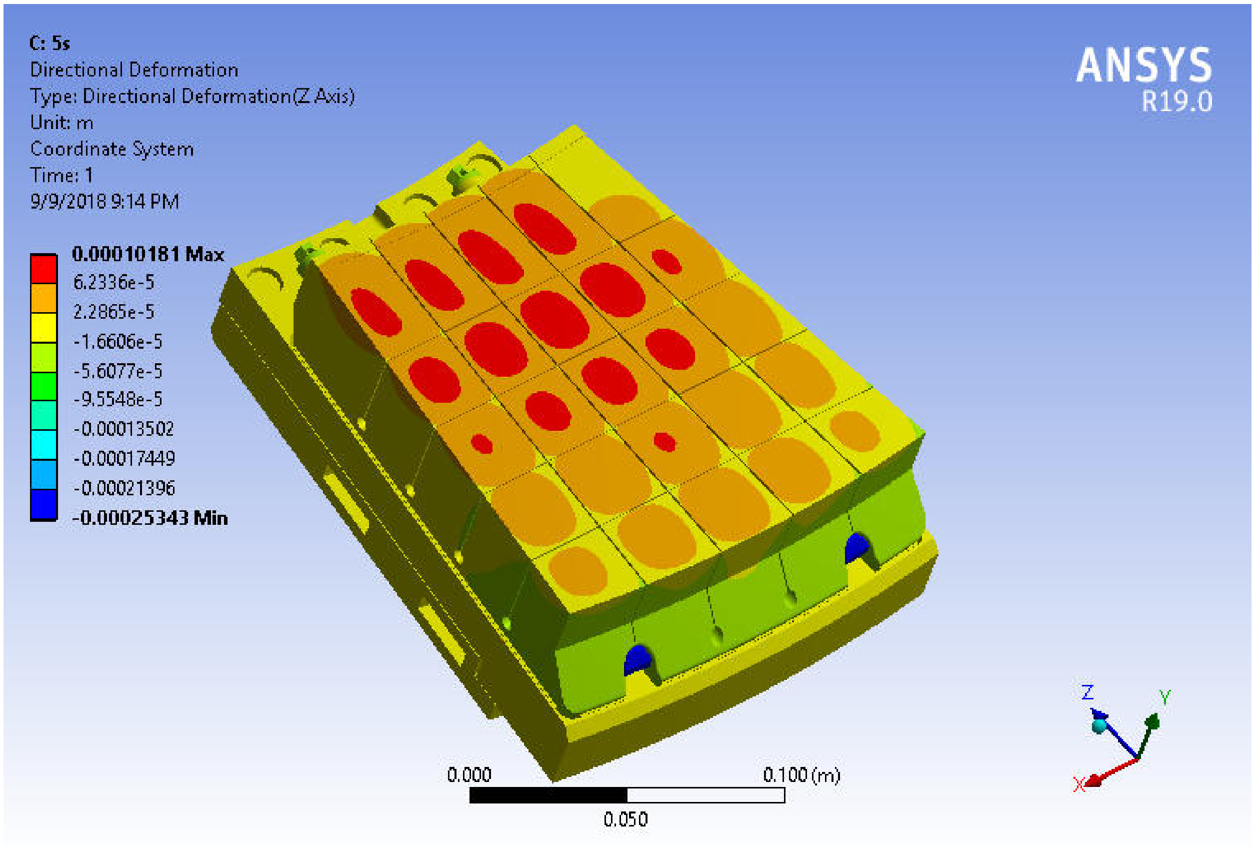


Figure 27. Directional deformation perpendicular to tile surface at end of 5s pulse.

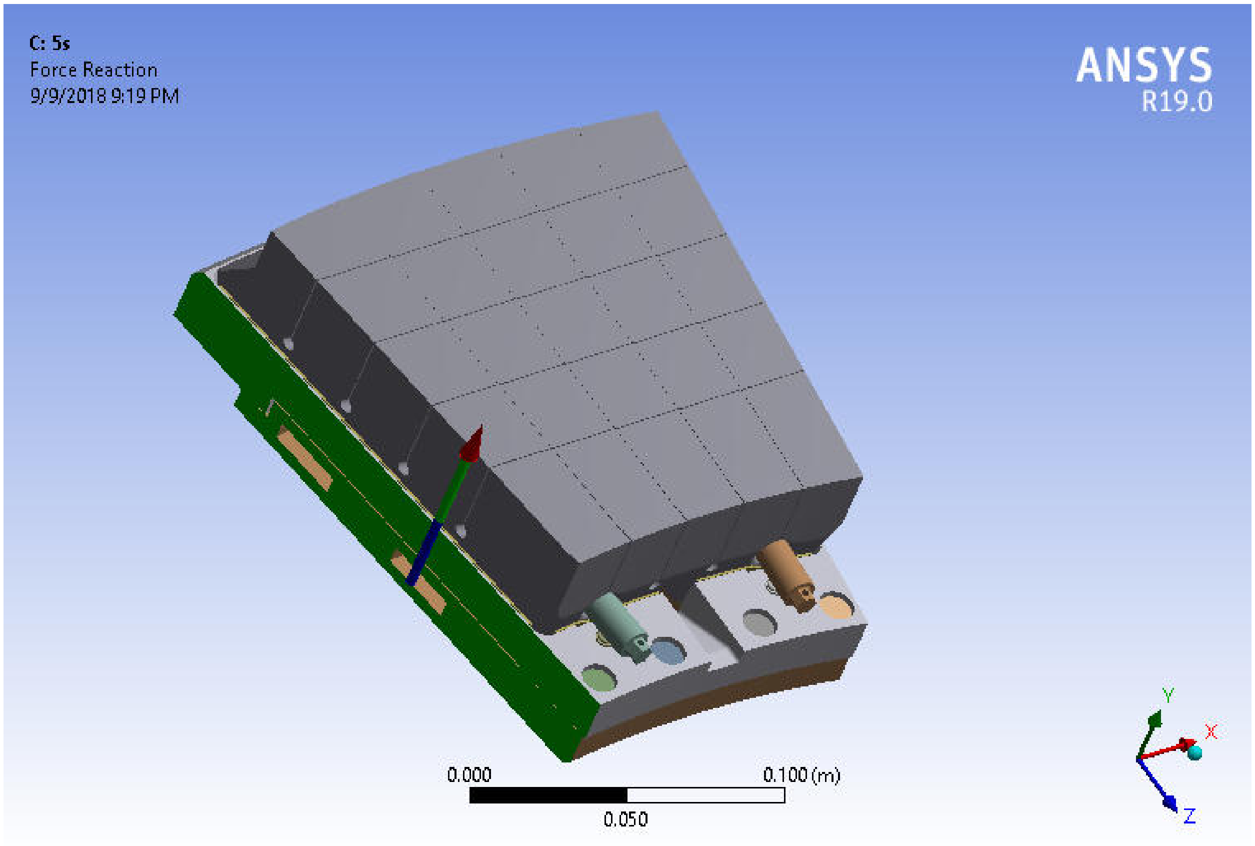


Figure 28. Reaction force due to loads at end of 5s pulse.

Figure 29 and Figure 30 display the maximum and minimum principal stresses in the assembly. The maximum principal stress at 5 s is 308 MPa over a very localized area at the rod/stud contact. The minimum principal stress at 5s is 166 MPa in the horizontal rod. Again, very small isolated areas of larger values appear in the horizontal rods at the stud contacts. The stress intensity at the bottom of the rods is 163 MPa.

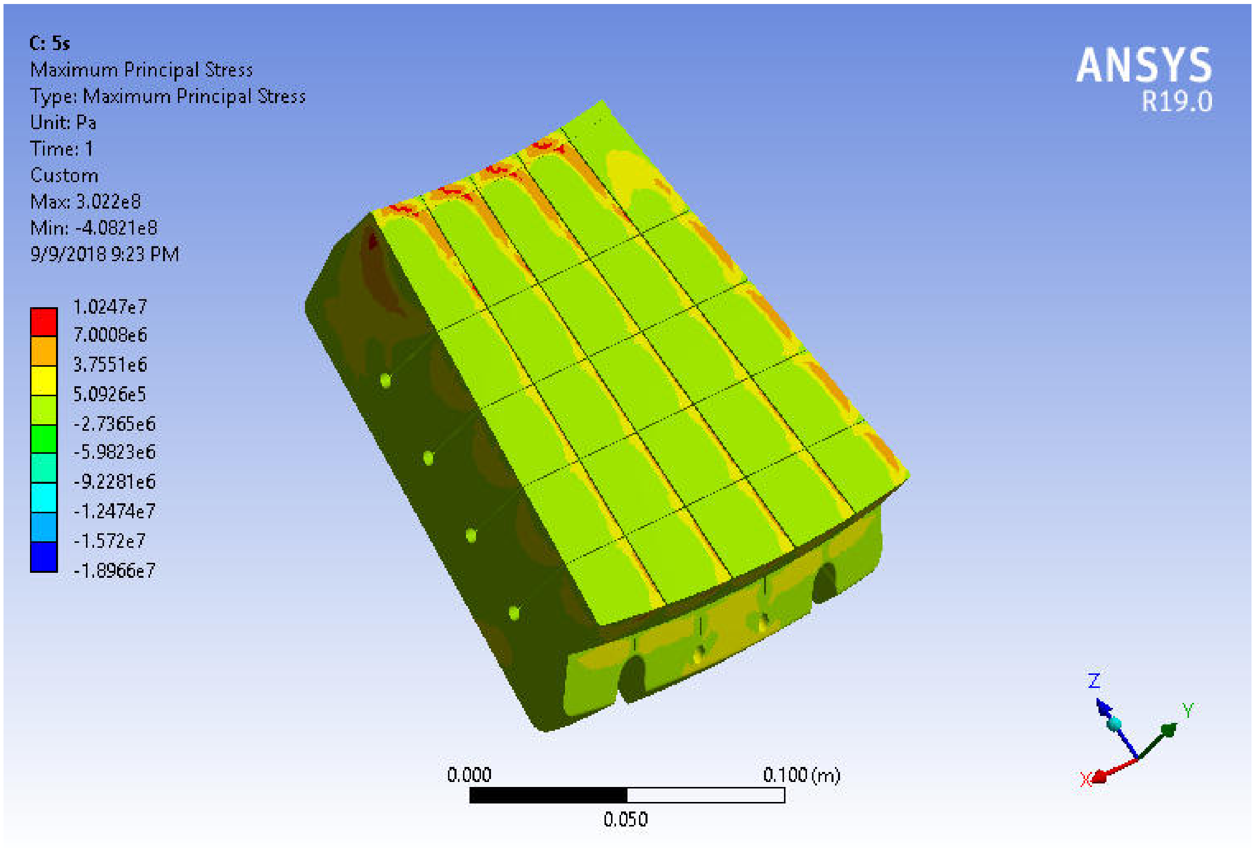


Figure 29. Maximum principal stress at end of 5s pulse.

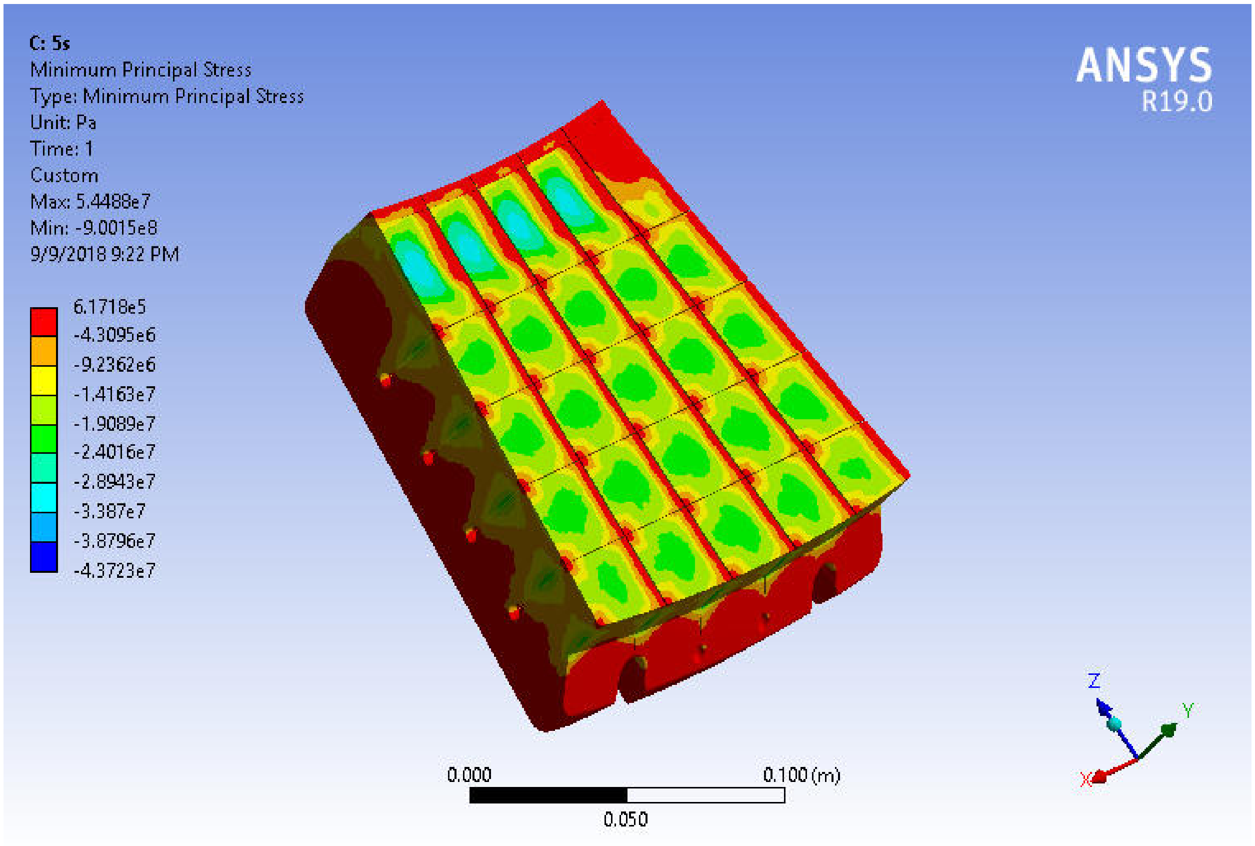


Figure 30. Minimum principal stress at end of 5s pulse.

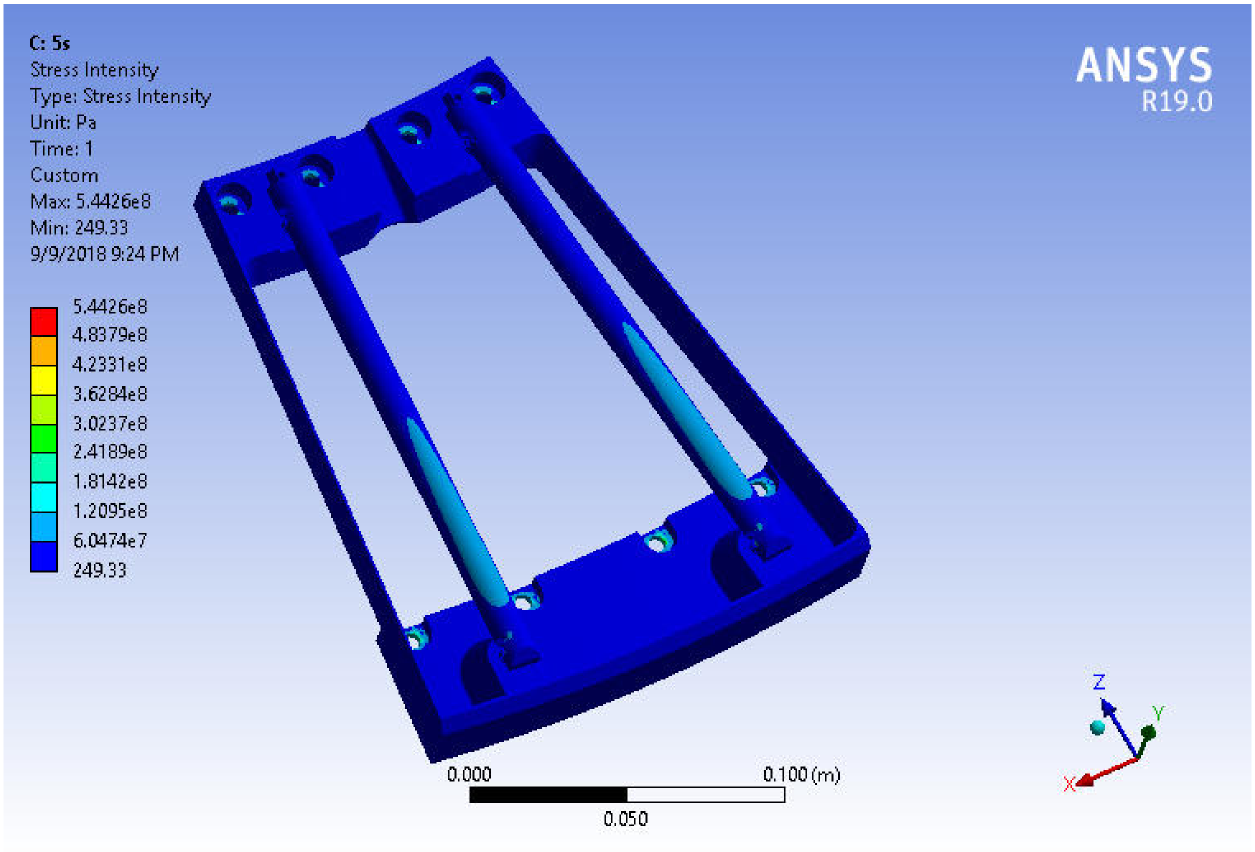


Figure 31. Stress intensity highest in pins and horizontal rods at end of 5s.

A similar thermal-structural analysis was conducted at 120 s during the cooldown phase. Figure 32 displays the imported temperature distribution at 120s. The mechanical loads and boundary conditions are identical to Figure 9.

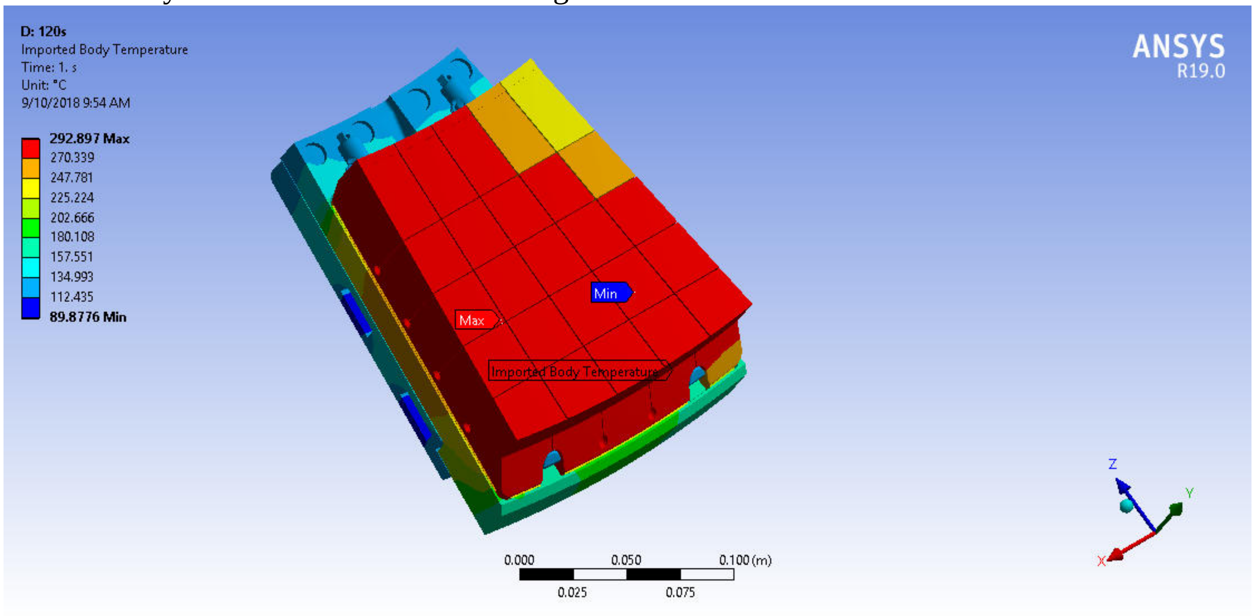


Figure 32. Imported temperature distribution at 120 s.

The total deformation is shown in Figure 33 at 120s.

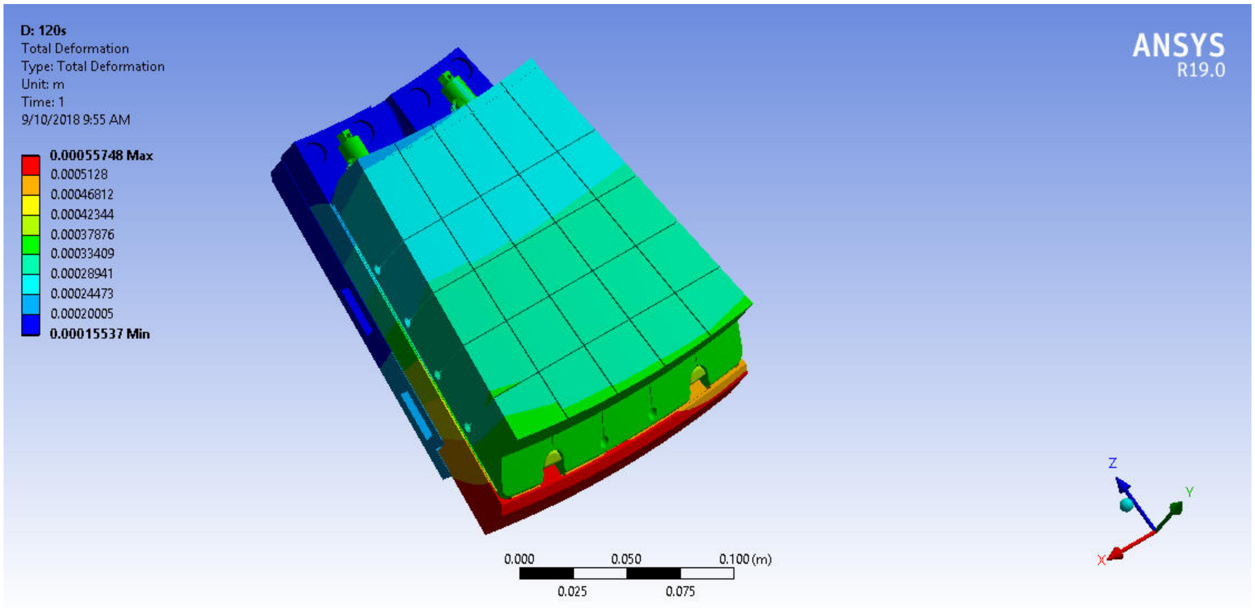


Figure 33. Total deformation at 120 s

The directional deformation perpendicular to the tile surface appears in Figure 34.

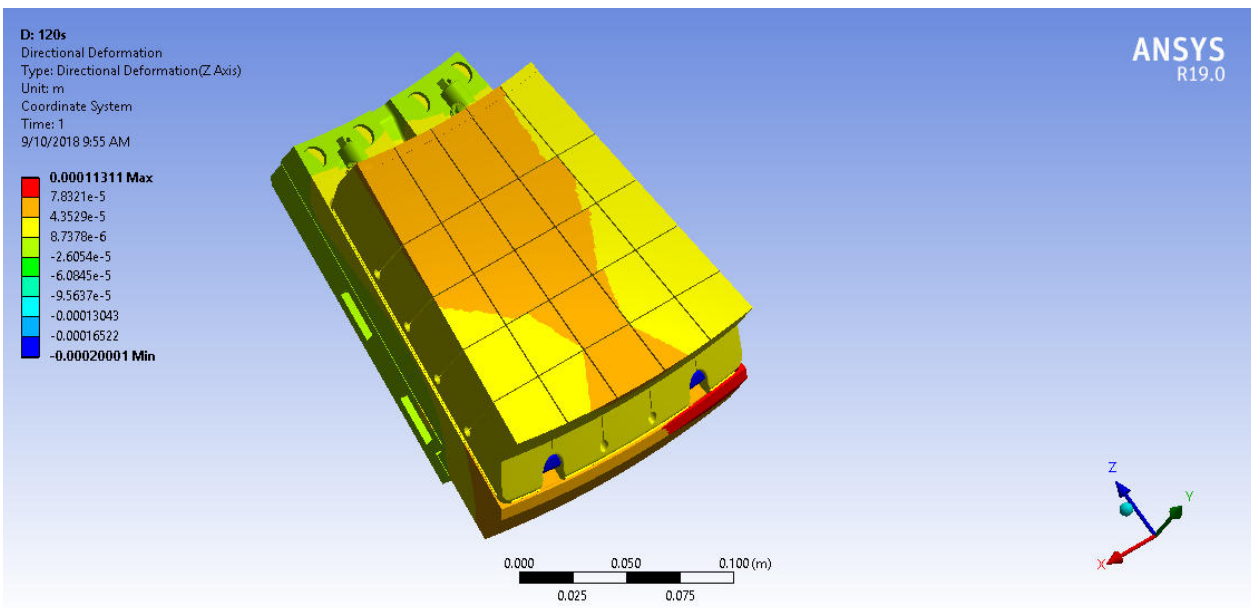


Figure 34. Directional deformation perpendicular to tile surface at 120 s.

The stress intensity in the hardware is very modest at 120s as shown in Figure 35.

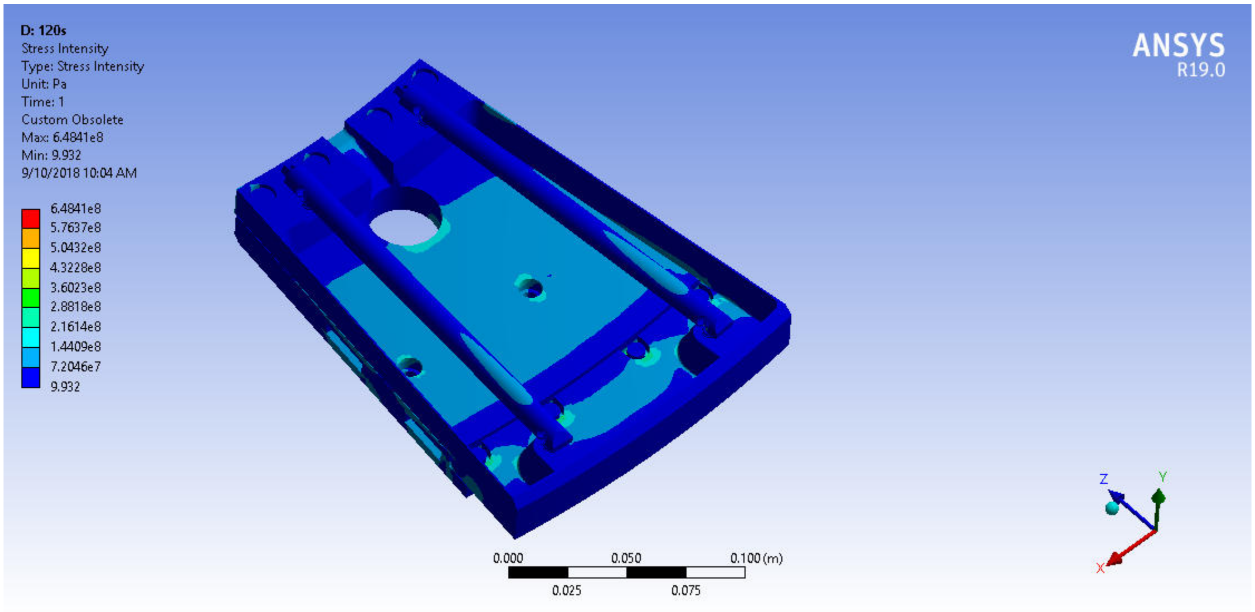


Figure 35. Stress intensity in the IBDH hardware at 120 s.

The maximum principal stress distribution is shown in Figure 36 at 120 s.

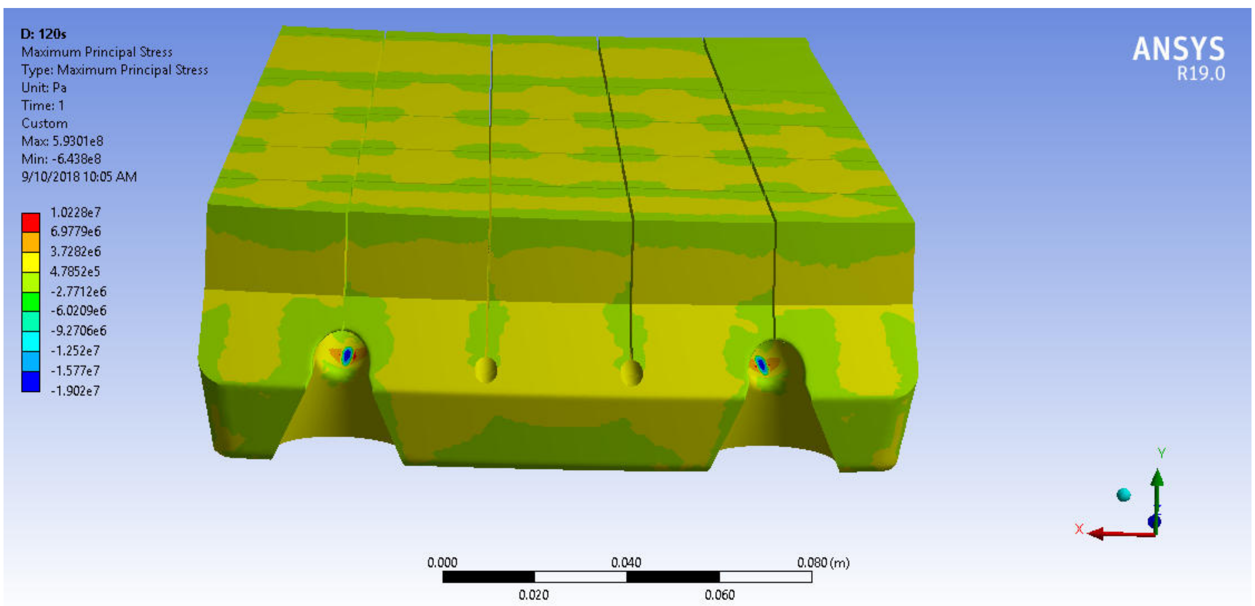


Figure 36. Maximum principal stress distribution at 120 s.

The minimum principal stress distribution appears in Figure 37 for the assembly. The extremes are shown in Figure 38 and Figure 39 for the mounting hardware.

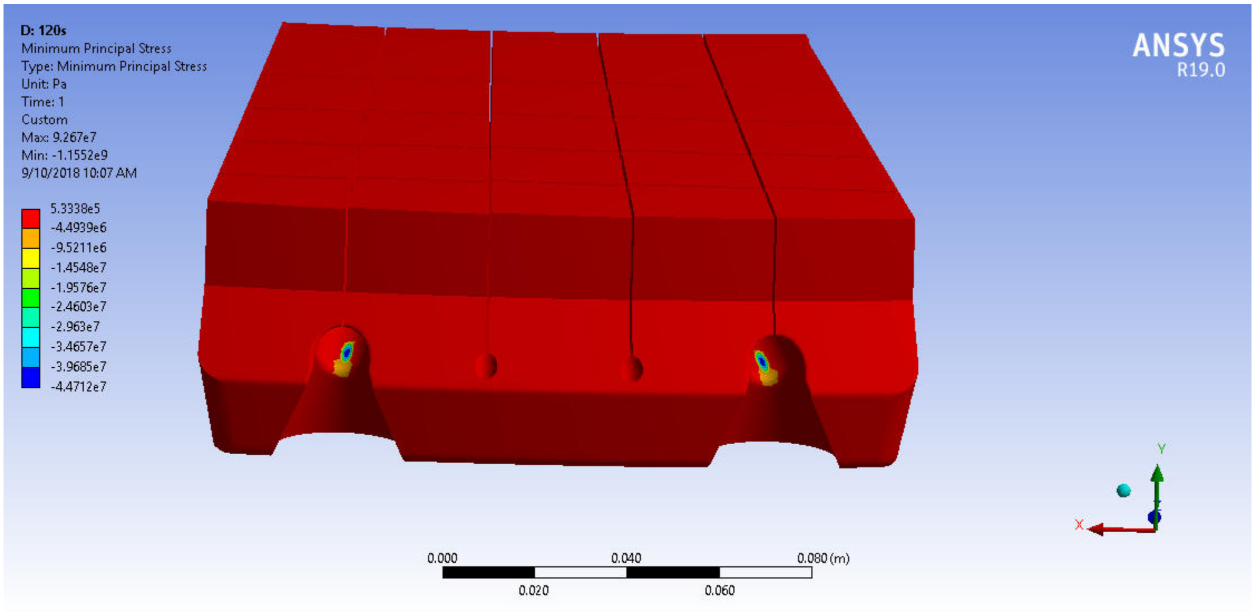


Figure 37Minimum principal stress distribution in the assembly

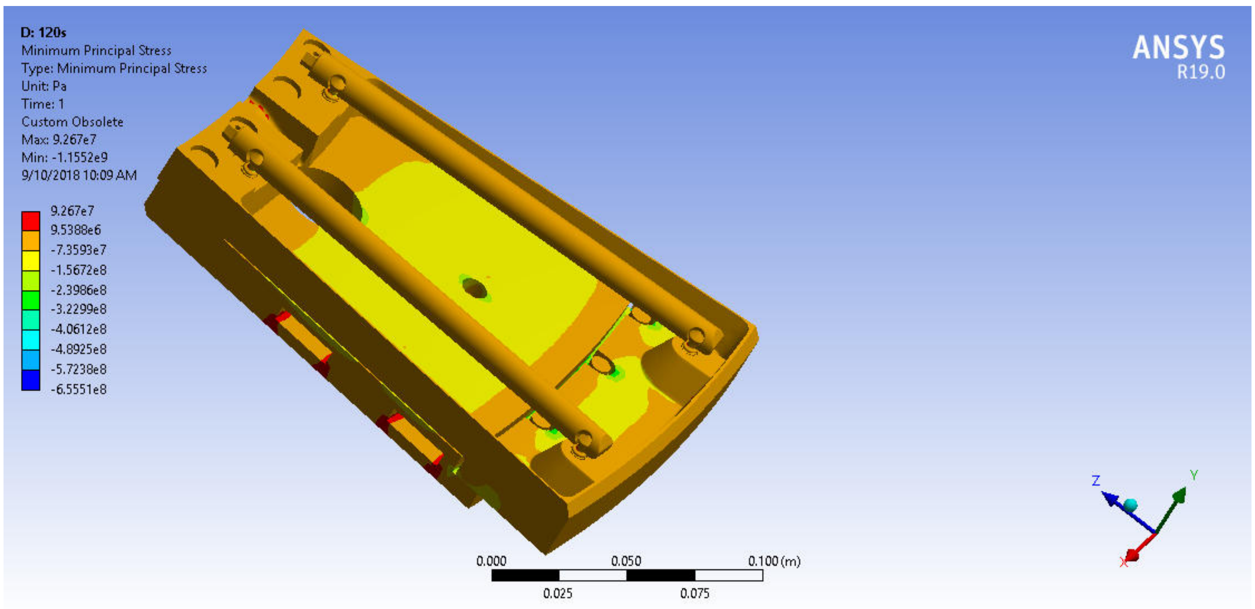


Figure 38. Minimum principal stress distribution in the hardware.

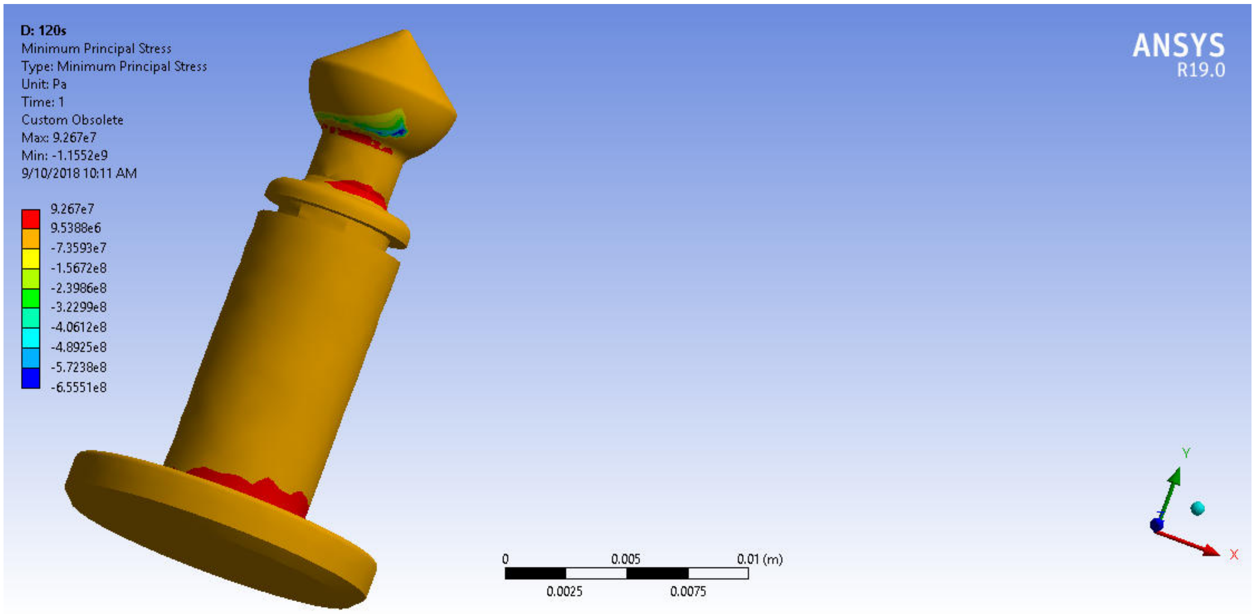


Figure 39. Minimum principal stress distribution in the pins

Thermal structural + Halo and Eddy Loads

Next a thermal structural analysis was carried out at 5s including the halo forces and eddy forces from disruptions. Bulk forces from halo currents were entered as nodal forces on the tile only and those from eddy currents as face loads. These constant values were obtained for worst cases from previous EM analyses on NSTX-U disruption plasmas. The EM loads appear in Figure 40. The bulk halo forces were applied to the 1,162,278 nodes in the tile body, while the eddy loads were applied to opposite sides of the tile as shown. The same temperature distribution from the 5s end of pulse as shown in Figure 25 was imported as a temperature load. The total deformation appears in Figure 41 and the z-deformation is shown in Figure 42.

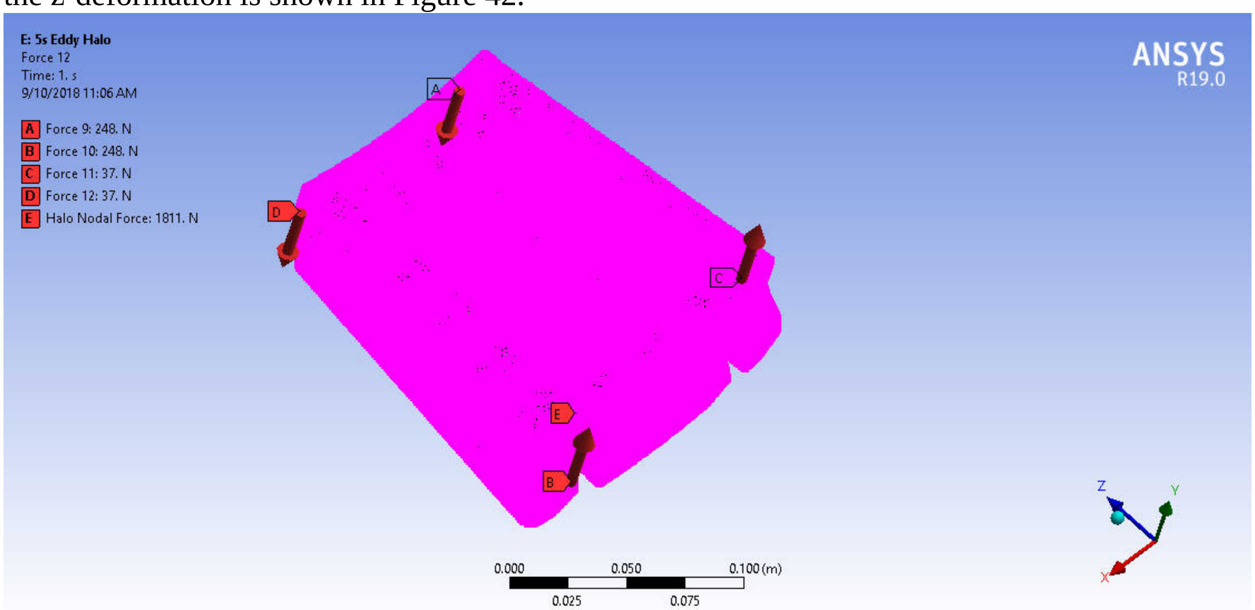


Figure 40. Applied EM loads

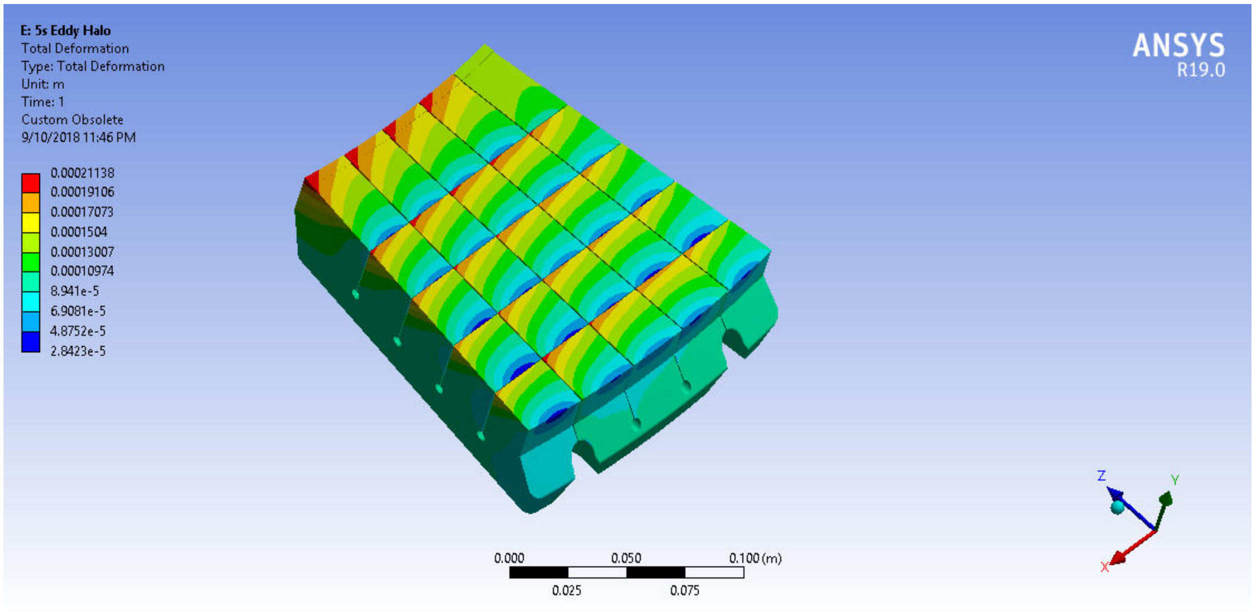


Figure 41. Total deformation at 5s including EM loads.

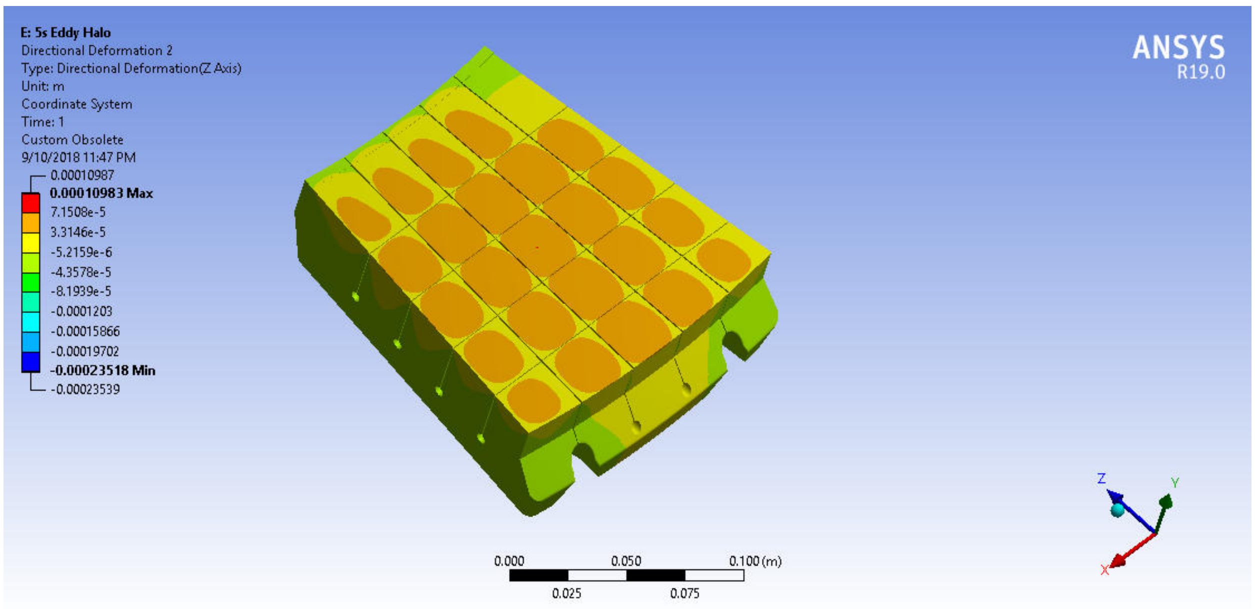


Figure 42. Deformation perpendicular to the tile surface is little affected by the EM loads.

The minimum principal stresses including EM loads in the tile appears in Figure 43. The minimum principal stresses at the rod contact points appears in Figure 44. The minimum principals in the mounting hardware are shown in Figure 45. The maximum principal stresses with EM loads on the tile appears in Figure 46. Likewise, the maximum principal stress in the horizontal mounting rods appears in Figure 47.

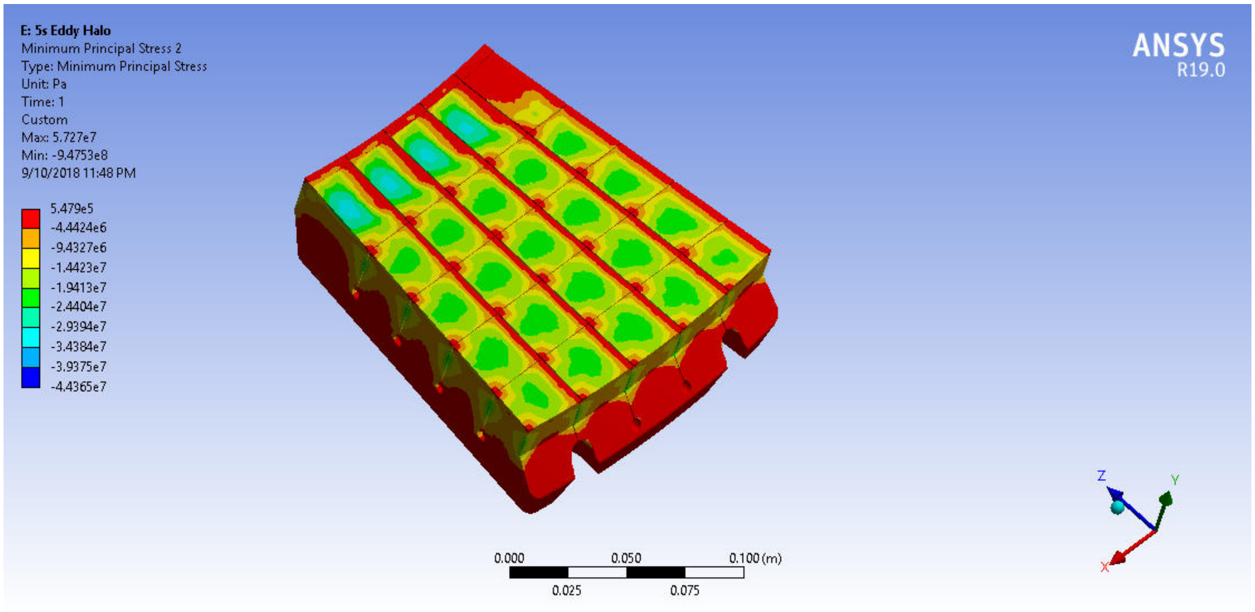


Figure 43. Minimum principal stresses in the tile

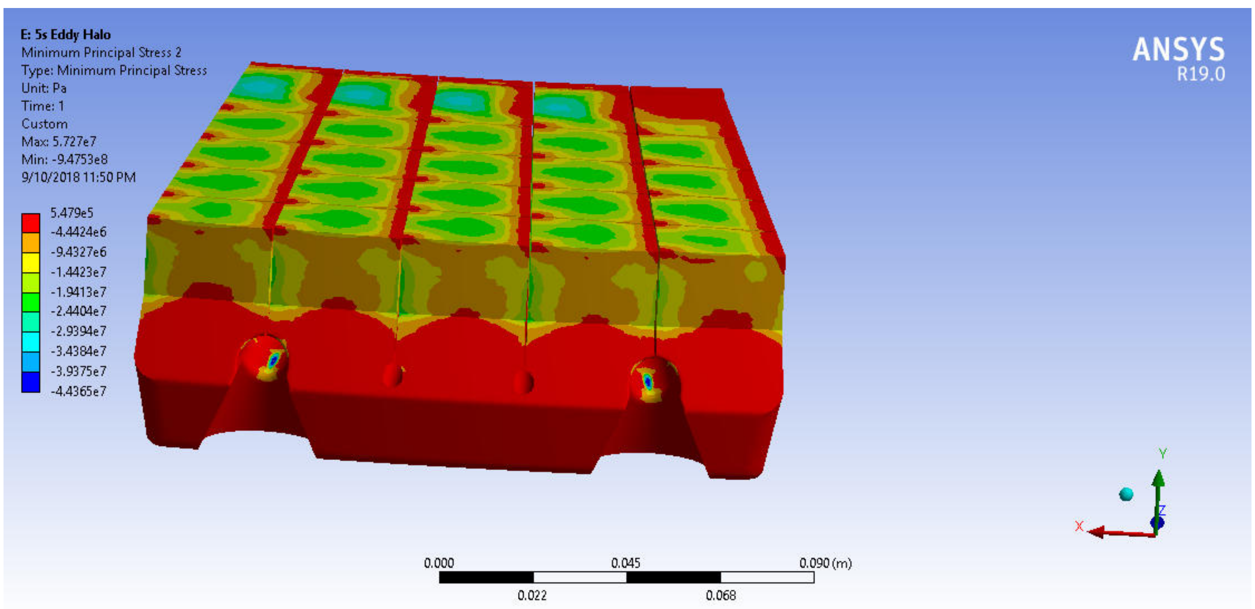


Figure 44. Minimum Principal stress at 5s at rod contact points

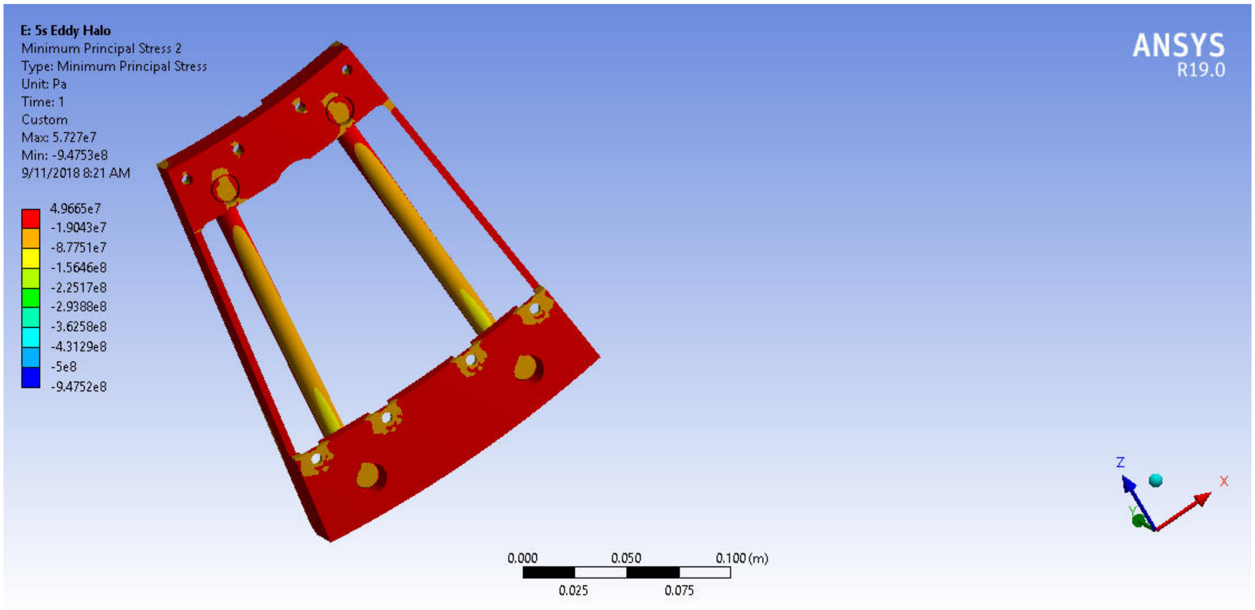


Figure 45. Minimum principal stresses in the mounting hardware.

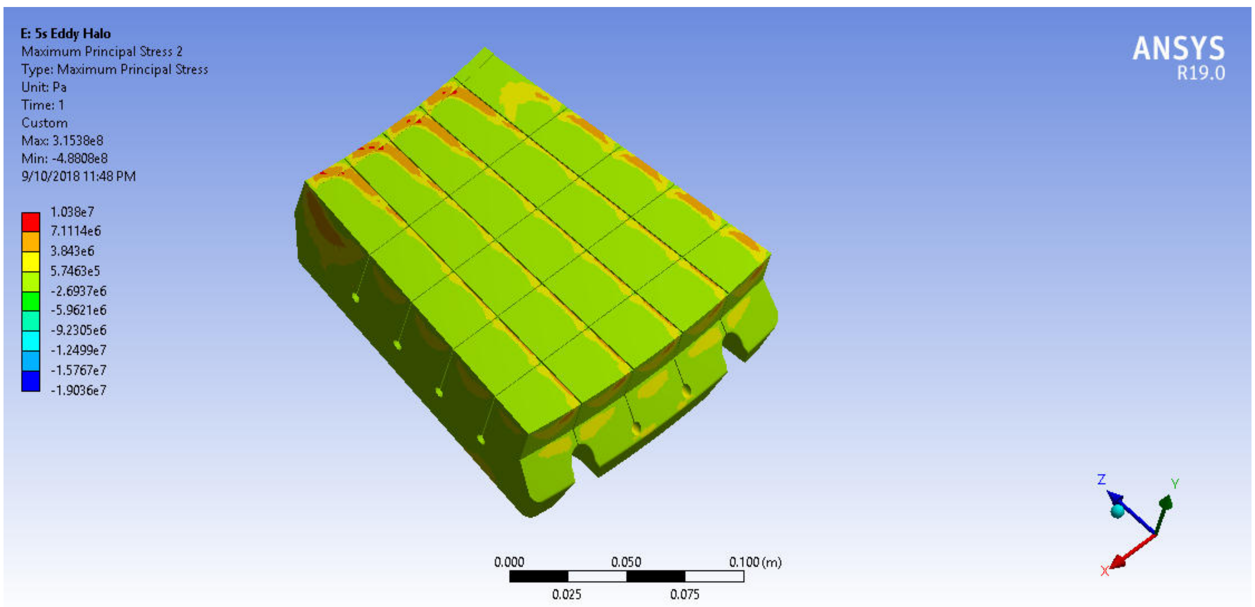


Figure 46. Maximum principal stress at 5 s in the tile including EM loads

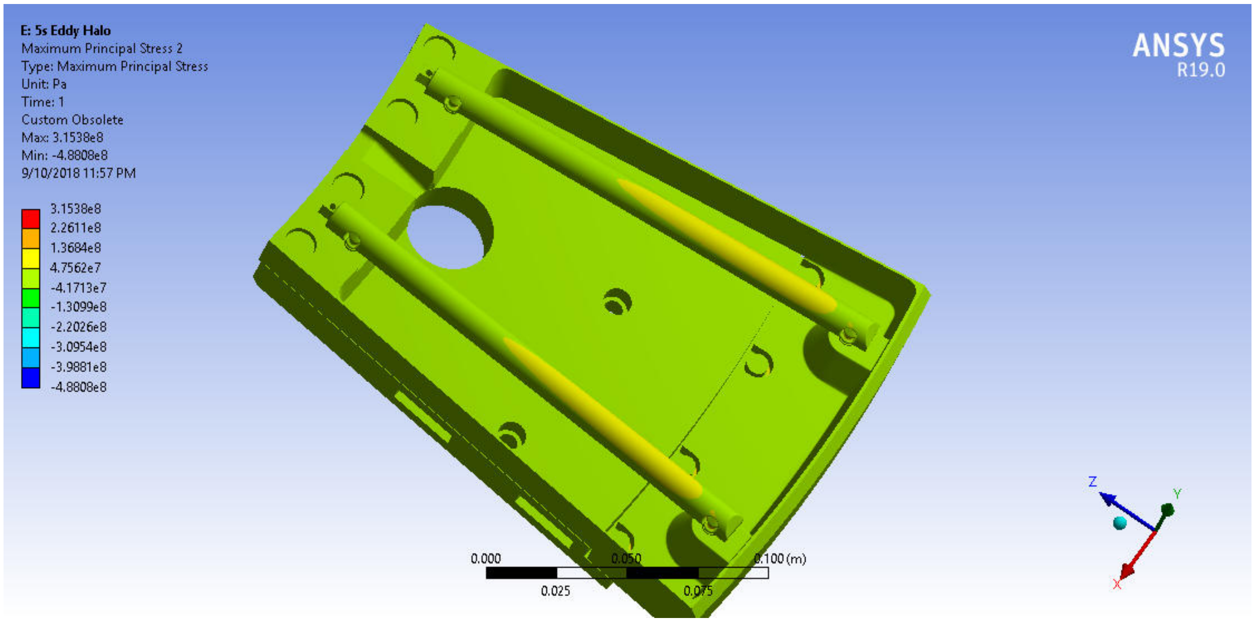


Figure 47. Maximum principal stress in the horizontal mounting rods.

The maximum stress intensity in the horizontal mounting rods is 130 MPa as shown in Figure 48. The reaction force corresponding to the toroidal displacement BC of zero displacement appears in Figure 49; whereas, the reaction force for the baseplate displacement BC is shown in Figure 50.

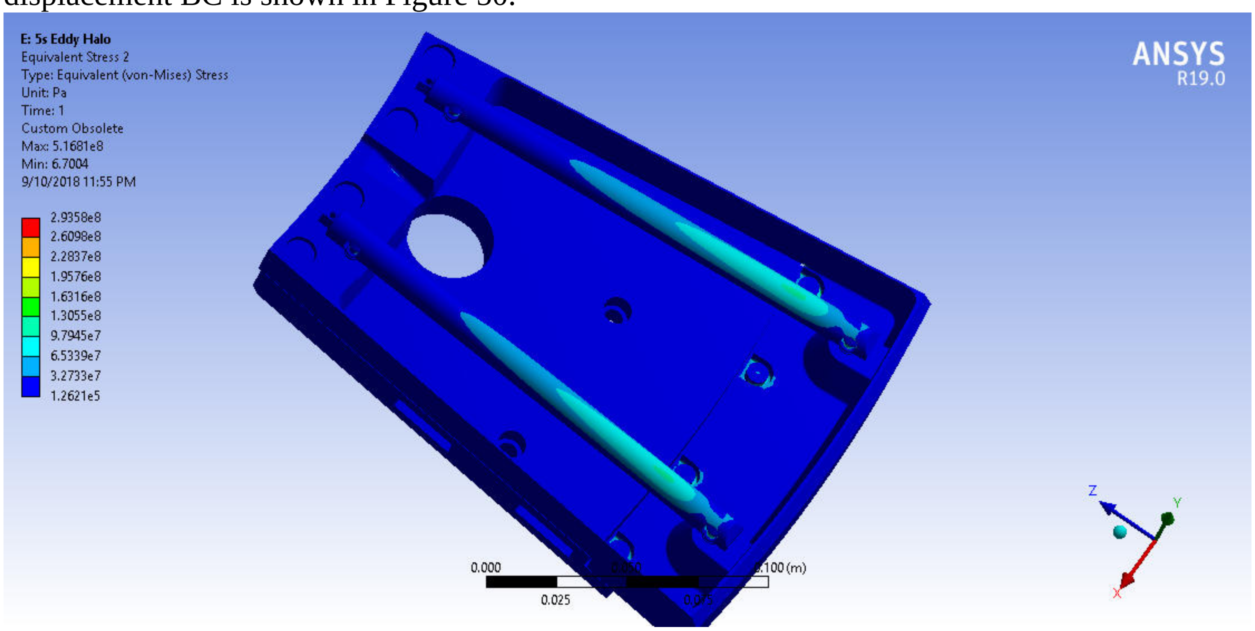


Figure 48. Stress intensity highest in horizontal rods.at 5 s including EM loads.

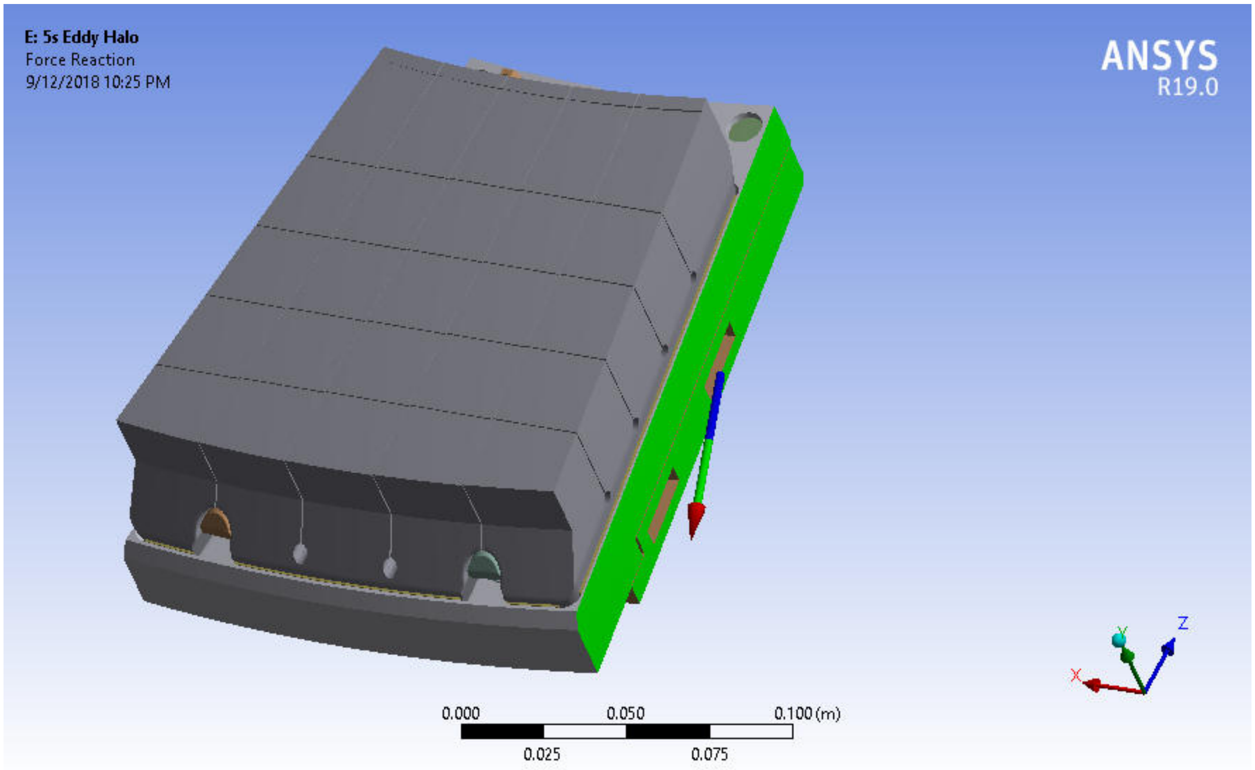


Figure 49. Reaction force provided by limiting displacement.in the toroidal direction.

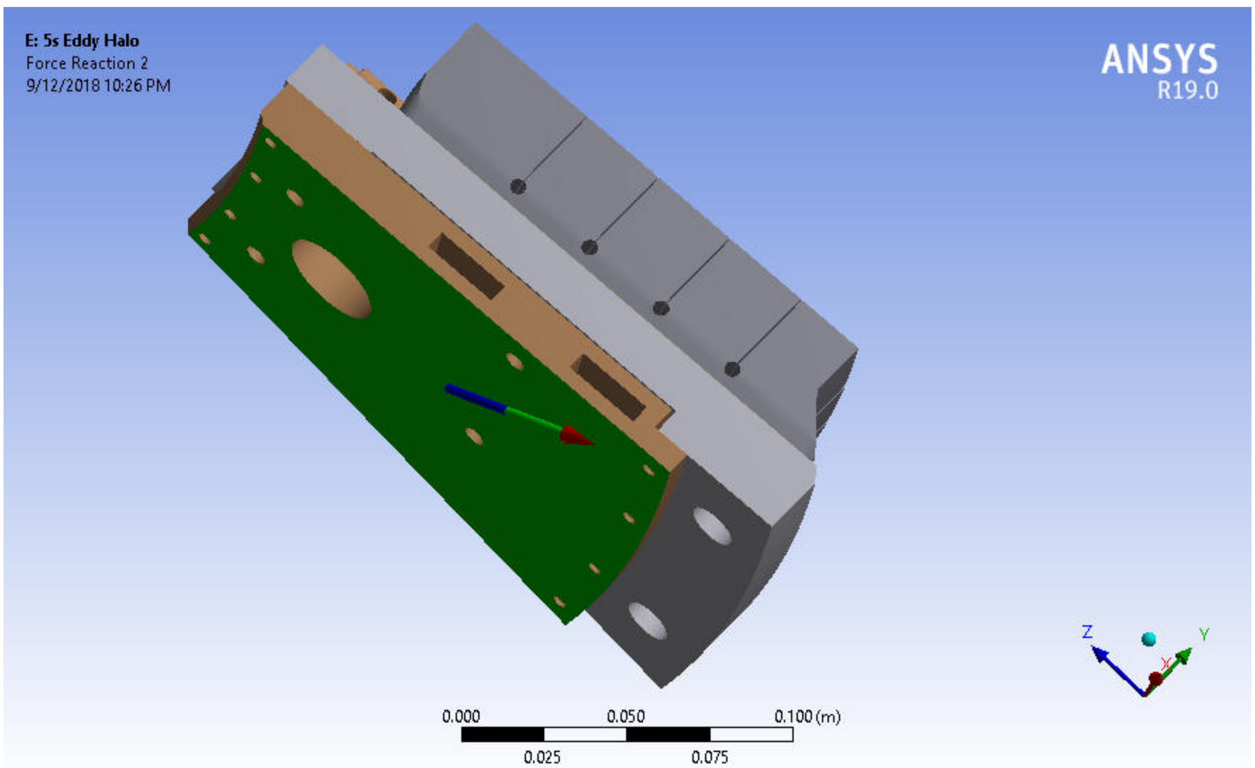


Figure 50. Reaction force provided by displacement2 boundary condition on the bottom of the baseplate at 5s.

Table 3 and Table 4 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite at the end of the 5s pulse. The bolt holes in the frame exhibit a maximum of 190 MPa equivalent stress in localized areas. Table 5 lists the peak equivalent stress and the corresponding allowable for the components made from Inconel718. The minimum safety factor is 1.5 in the Inconel stud and the graphite tile. The horizontal rods have a safety factor of 1.6. All other parts have a safety factor greater than 3.0. The small bolts have localized equivalent stresses as high as 232 MPa. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced forces.

Table 4: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (jw-ibdh-caslated-tile 1b-c1)	10.4	30	BPL+Halo+Eddy
Grafoil	1.4	25	BPL+Halo+Eddy

Table 5: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (jw-ibdh-caslated-tile 1b-c1)	-44.4	-65	BPL+Halo+Eddy
Grafoil	-3.2	-55	BPL+Halo+Eddy

Table 6: Equivalent Stress of Inconel-718 components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	14	276	BPL+Halo+Eddy
Frame	95	276	BPL+Halo+Eddy
Pin	132	276	BPL+Halo+Eddy
Horizontal Rods	172	276	BPL+Halo+Eddy

Analysis of Inboard Divertor Horizontal Basetile – q" case 3

ORNL
Dennis Youchison
Summary:

Transient-Thermal Analysis

A transient thermal analysis was performed with an initial ambient temperature of 116 ^{o}C for a 1s heat flux pulse mapped on the edge of the tile, corresponding to case 3 heating. For case 3, the heat flux was 57.29 MW/m^2 applied to the radial leading edge of the tile. This was followed by a 119 s cooldown period. Helium cooling using 25 C helium in the baseplate was assumed with a convective heat transfer coefficient of 300 W/m^{2}K. This is not entirely consistent with a 116 ^{o}C environment temperature due to ratcheting, unless the helium flow starts at the beginning of the pulse. Radiation was included for the top tile surface only, since all others have no open viewfactor. The emissivity was 0.7 and the reference background temperature was 52 ^{o}C. The model boundary conditions appear in Figure 51

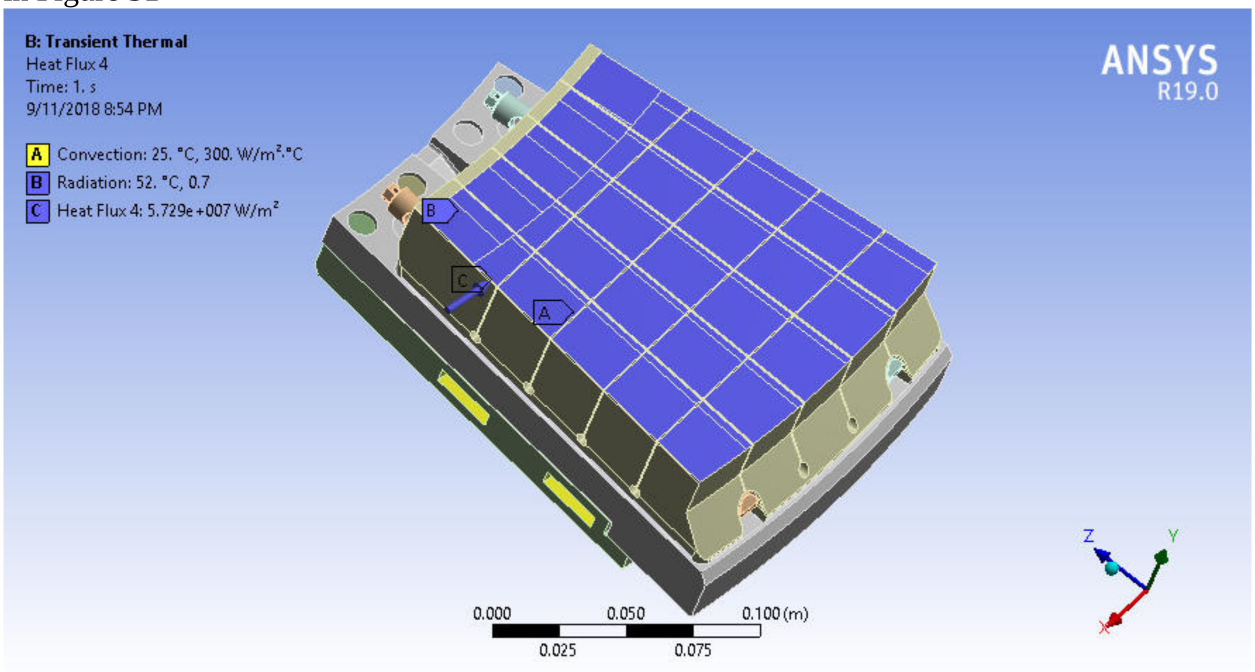


Figure 51. Transient thermal boundary conditions during 1 s pulse.

The maximum global temperature response appears in Figure 52 for this scenario.

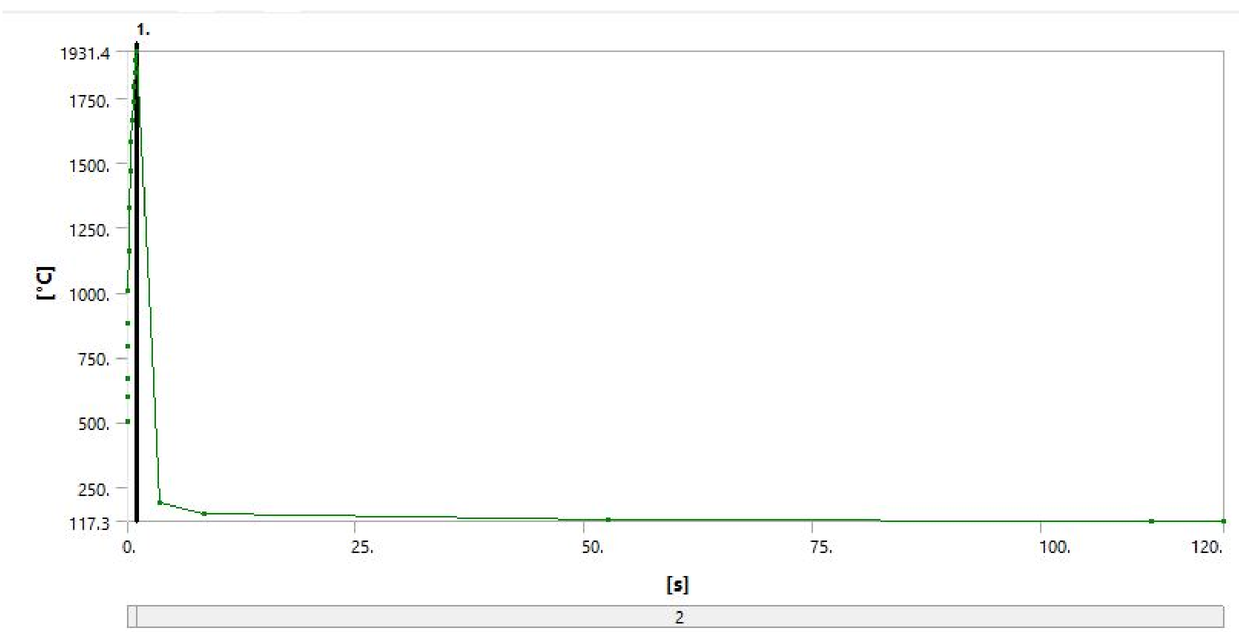


Figure 52. Maximum global temperature response.

The temperature distribution at 1s, 25 s and 120 s appear in Figure 53, Figure 54 and Figure 55, respectively. At 25 s, the thermal wave has almost reached the bottom of the tile. At 120 s, the tile is still cooling.

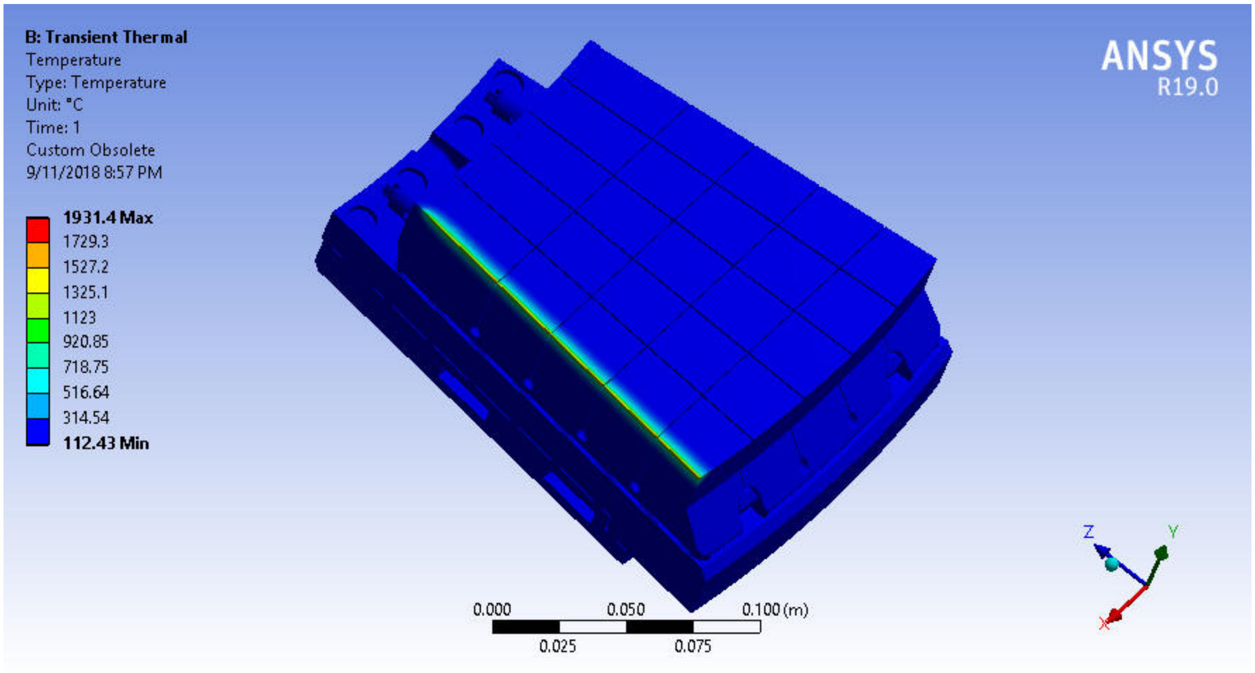


Figure 53. Temperature distribution at 1 s.

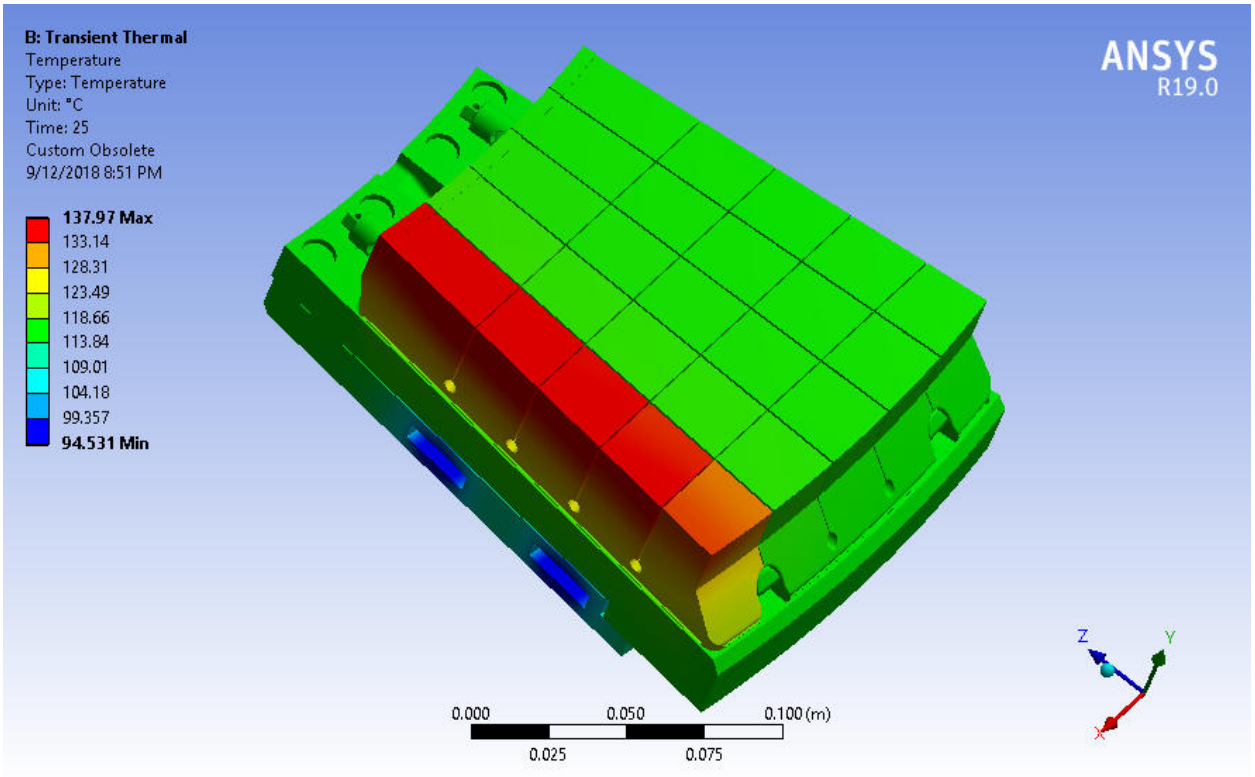


Figure 54 Temperature distribution at 25 s.

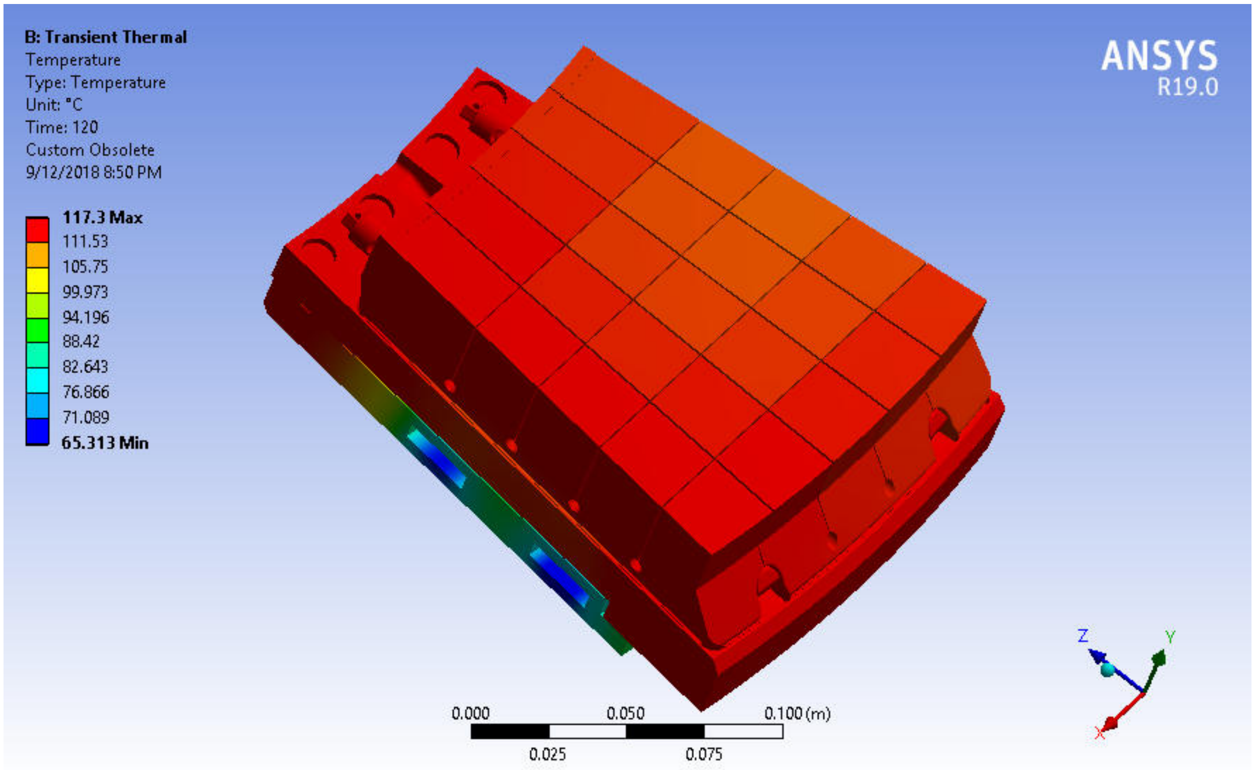


Figure 55. Temperature distribution at 120 s.

Table 2 lists the peak temperature for each component throughout the entire cycle.

Table 7: Peak temperature for each component

Component	Peak Temperature (°C)	Time (s)
Graphite Tile (Sigrafine 6510)	1931	1
Grafoil	117	120
Baseplate	117	120
Inconel pins	117	120
Inconel horizontal rods	117	120
Inconel Frame	117	120

Structural-Thermal Analysis

Preload forces and bolt pretension used previously in Figure 9 were combined with the imported temperature load at 1 s shown in Figure 56 and a static structural analysis was performed.

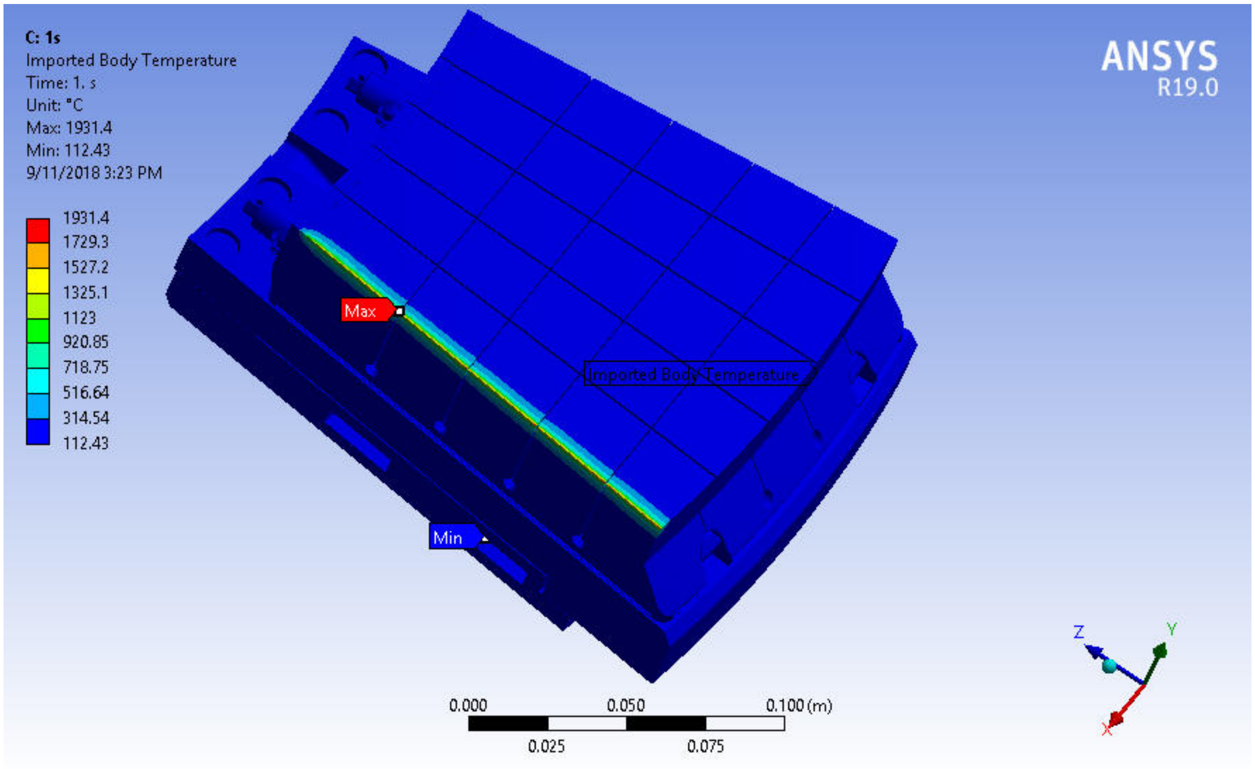


Figure 56. Imported temperature distribution at end of 1s pulse.

Results

Total deformation contour plot of the assembly is shown in Figure 57 and the deformation perpendicular to the tile surface is shown in Figure 58. The reaction force is shown in Figure 59.

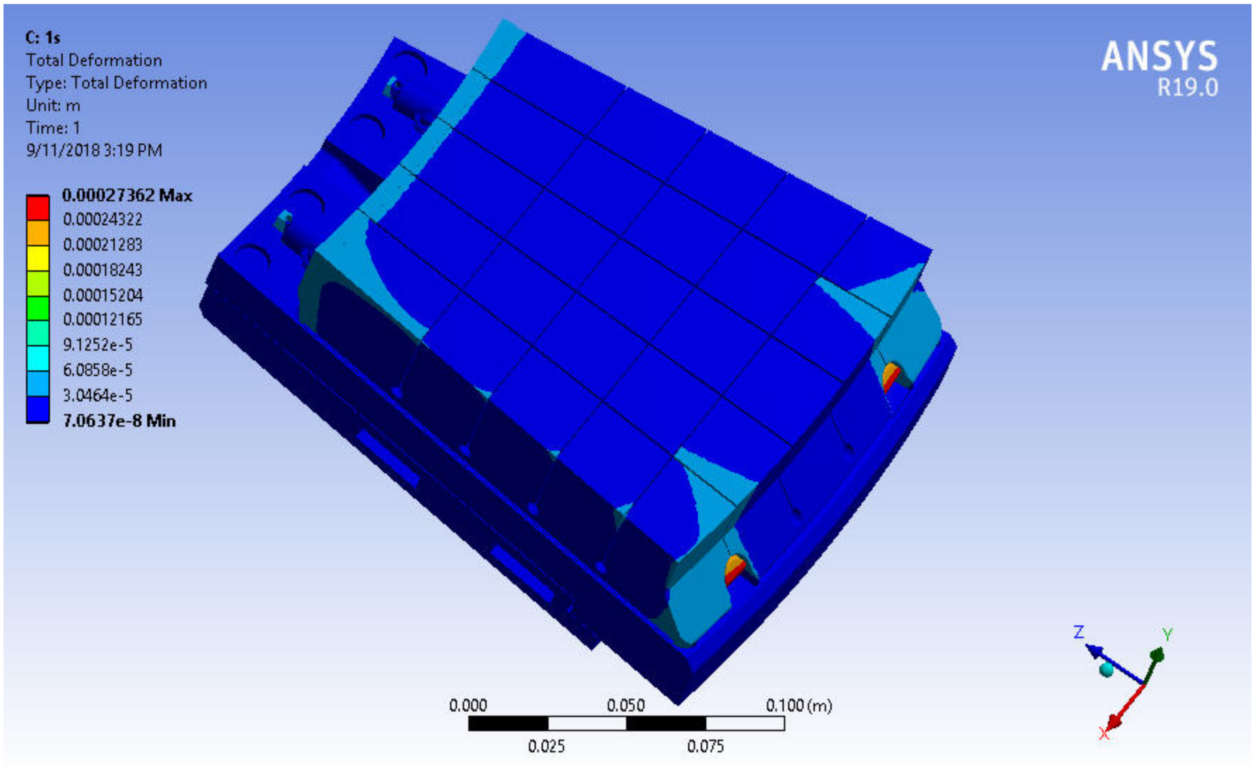


Figure 57 Total Deformation at end of 1s pulse.

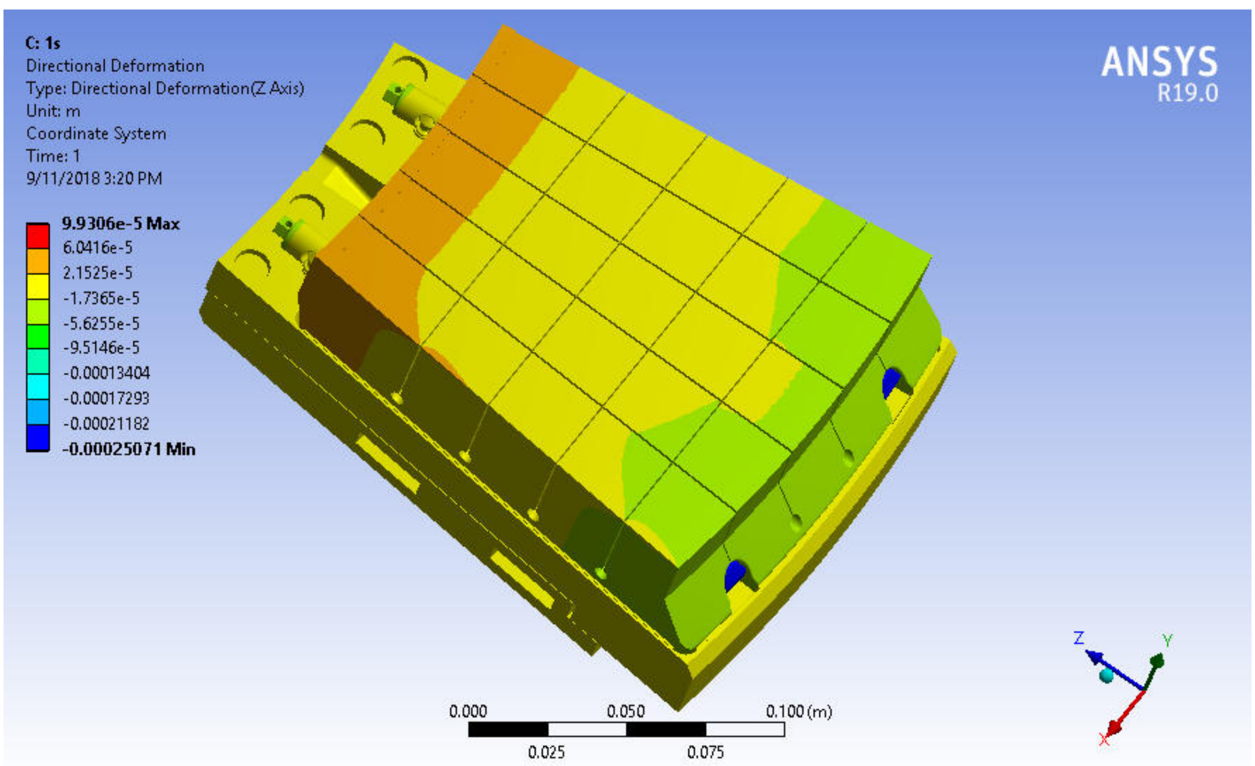


Figure 58. Directional deformation perpendicular to tile surface at end of 1s pulse.

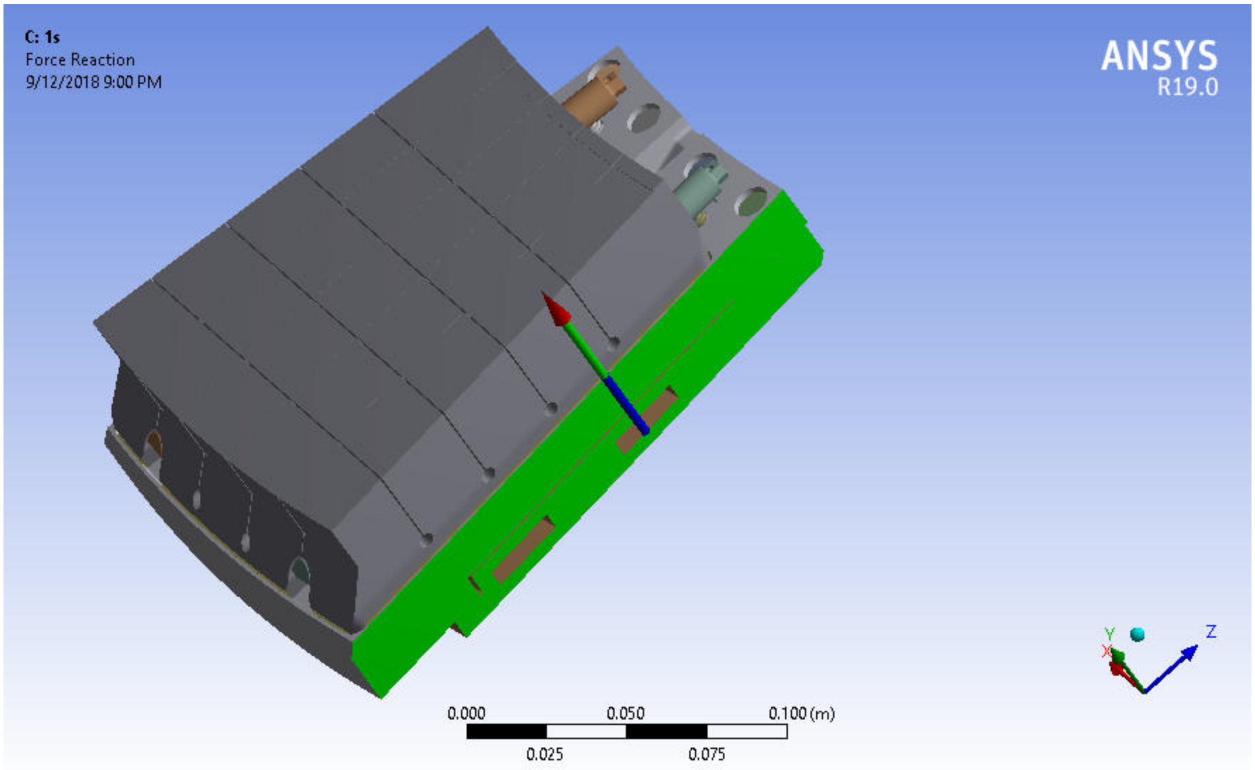


Figure 59. Reaction force due to loads at end of 1s pulse.

Figure 60 and Figure 61 display the maximum and minimum principal stresses in the assembly. The maximum principal stress at 1 s is 308 MPa over a very localized area at the rod/pin contact. The minimum principal stress at 1 s is 166 MPa in the horizontal rod. Again, very small isolated areas of larger values appear in the horizontal rods at the pin contacts. The stress intensity shown in Figure 62 at the bottom of the rods is 163 MPa.

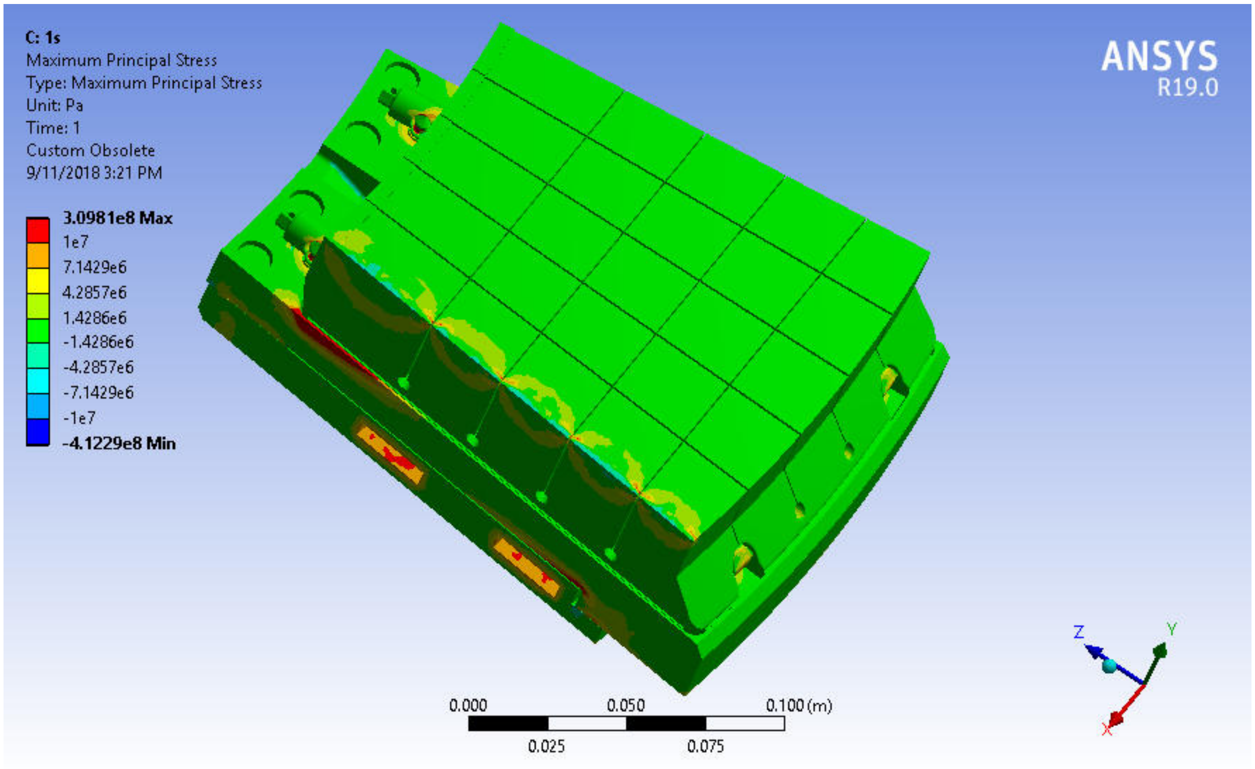


Figure 60. Maximum principal stress at end of 1s pulse.

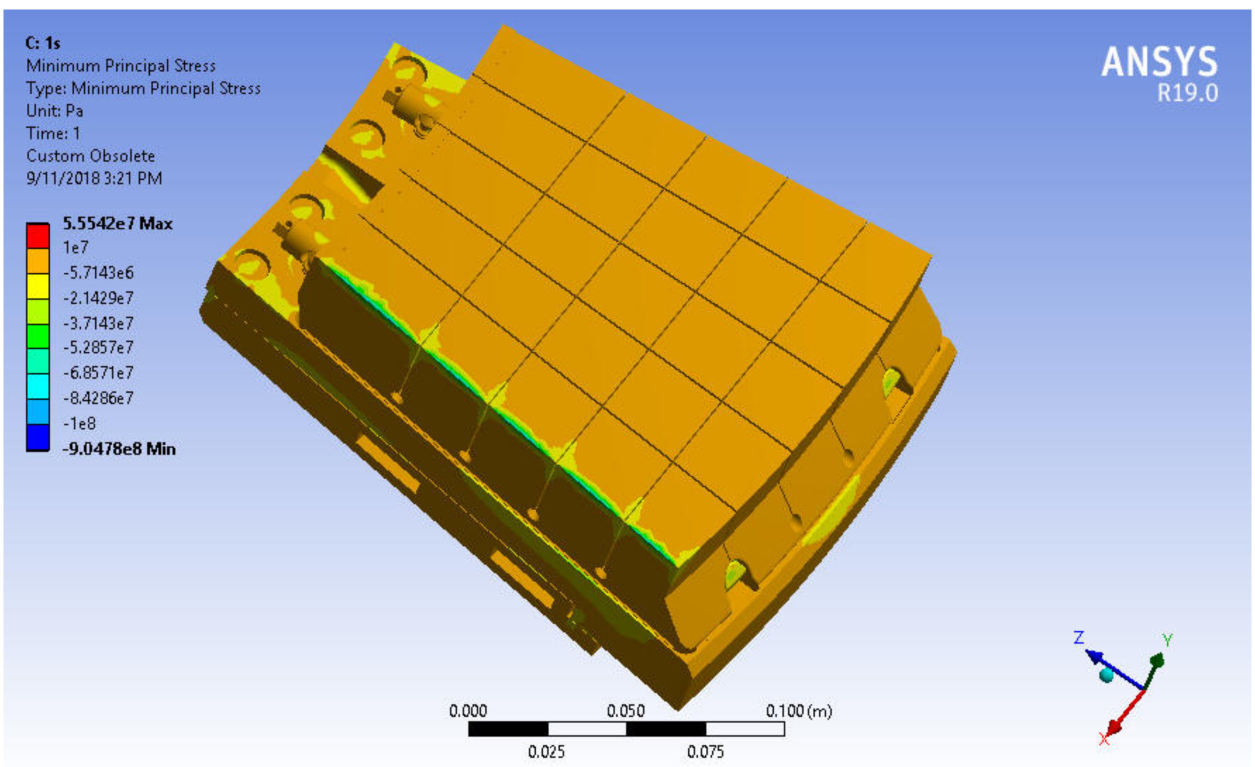


Figure 61. Minimum principal stress at end of 1s pulse.

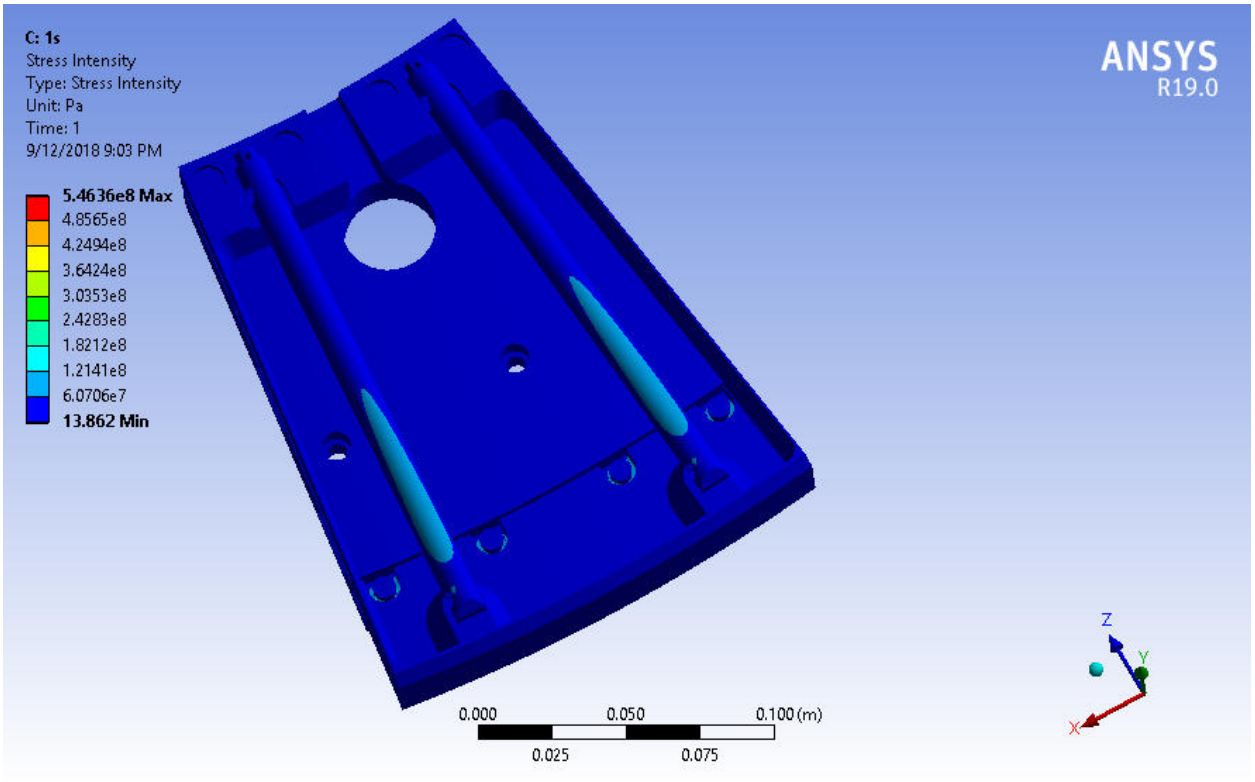


Figure 62. Stress intensity highest in pins and horizontal rods at end of 1s.

A similar thermal-structural analysis was conducted at 120 s during the cooldown phase. Figure 63 displays the imported temperature distribution at 120s. The mechanical loads and boundary conditions are identical to Figure 9.

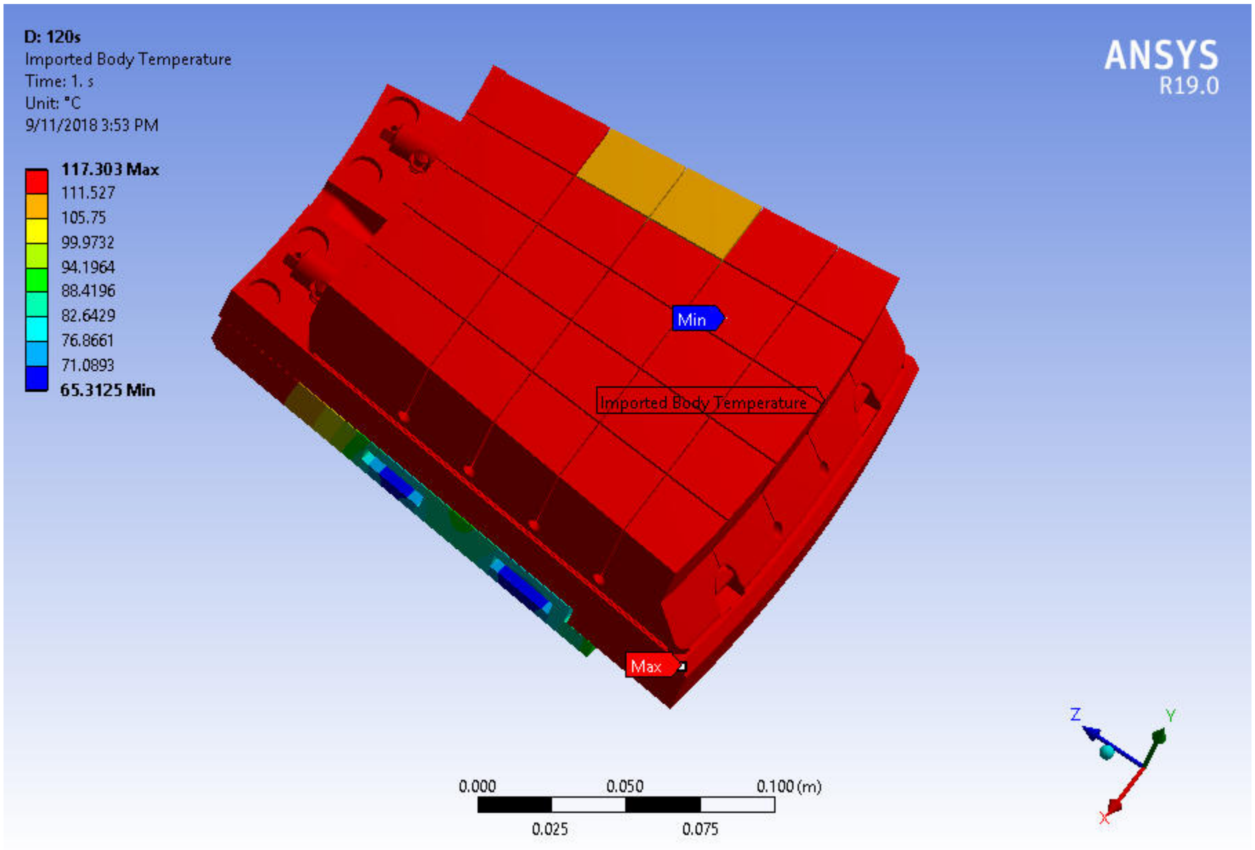


Figure 63. Imported temperature distribution at 120 s.

The total deformation is shown in Figure 64 at 120s.

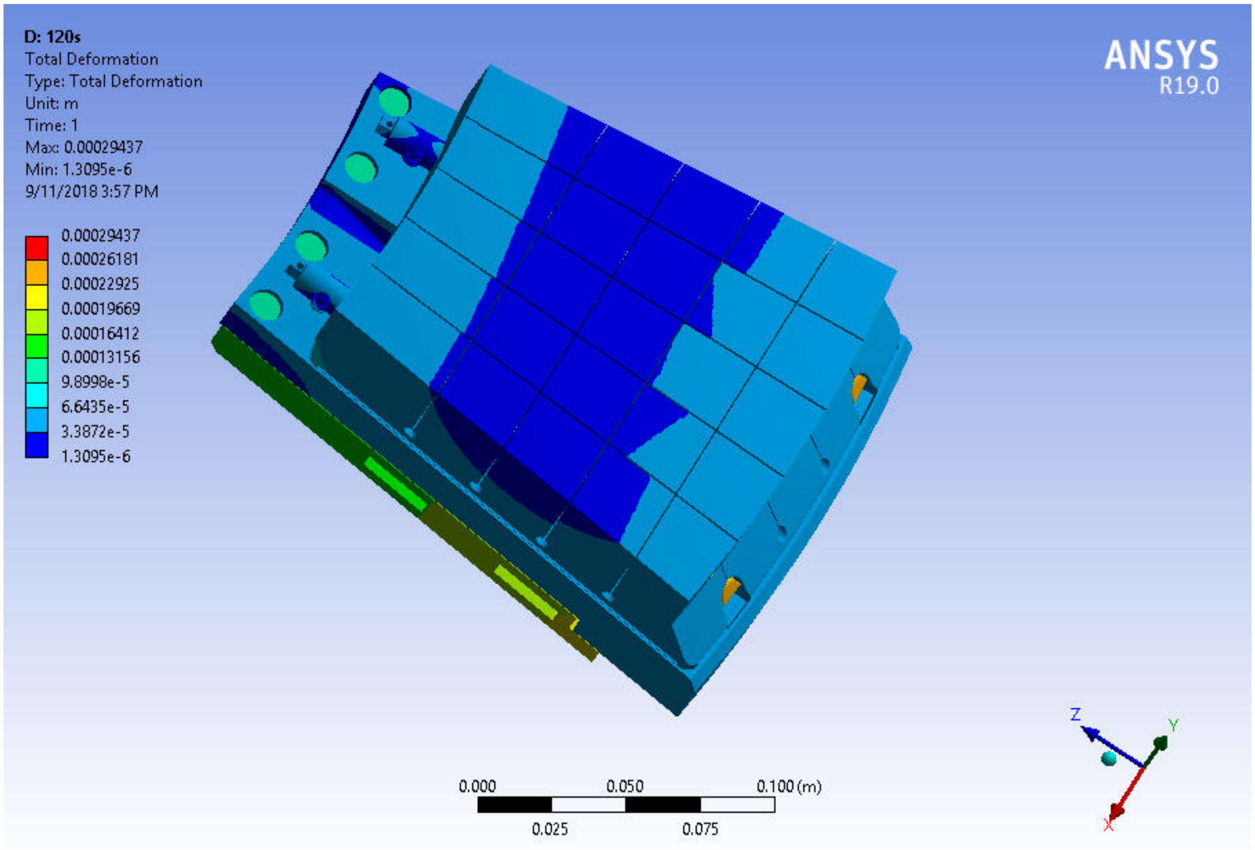


Figure 64. Total deformation at 120 s

The directional deformation perpendicular to the tile surface appears in Figure 65.

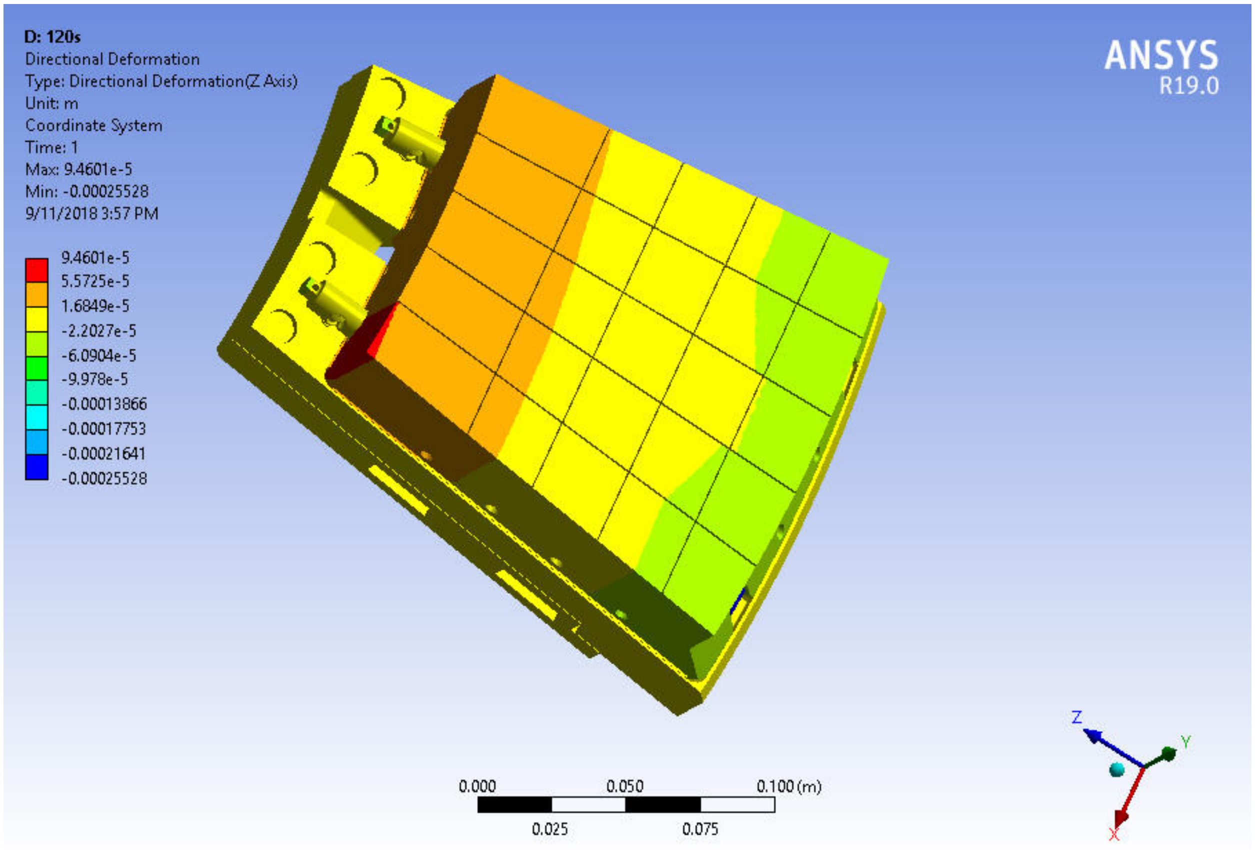


Figure 65. Directional deformation perpendicular to tile surface at 120 s.

The stress intensity in the hardware is very modest at 120s as shown in Figure 66.

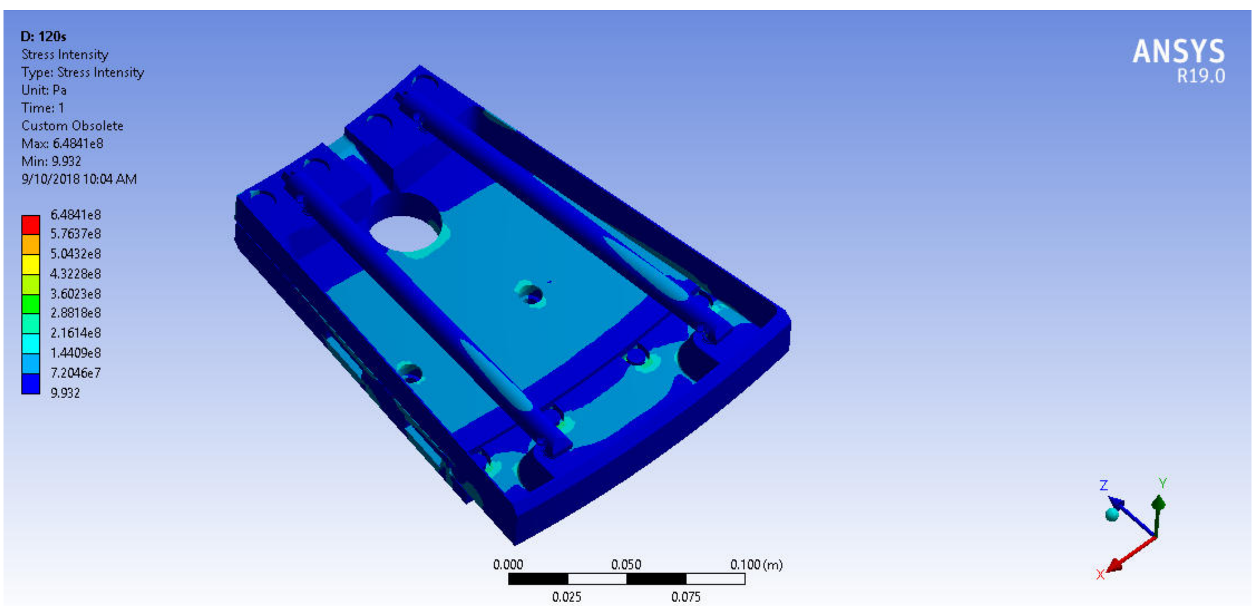


Figure 66. Stress intensity in the IBDH hardware at 120 s.

The maximum principal stress distribution is shown in Figure 67 at 120 s.

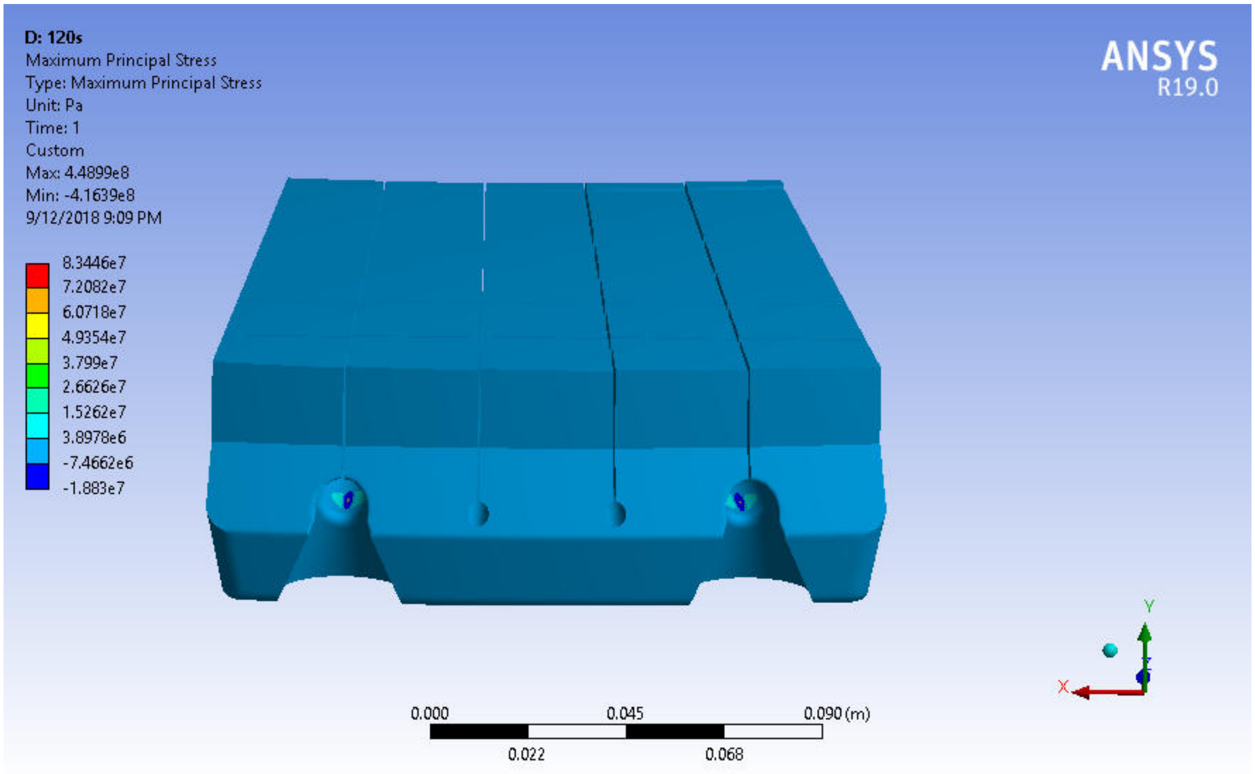


Figure 67. Maximum principal stress distribution in tile at 120 s.

The minimum principal stress distribution appears in Figure 68 for the assembly. The extremes are shown in Figure 69 and Figure 70 for the mounting hardware.

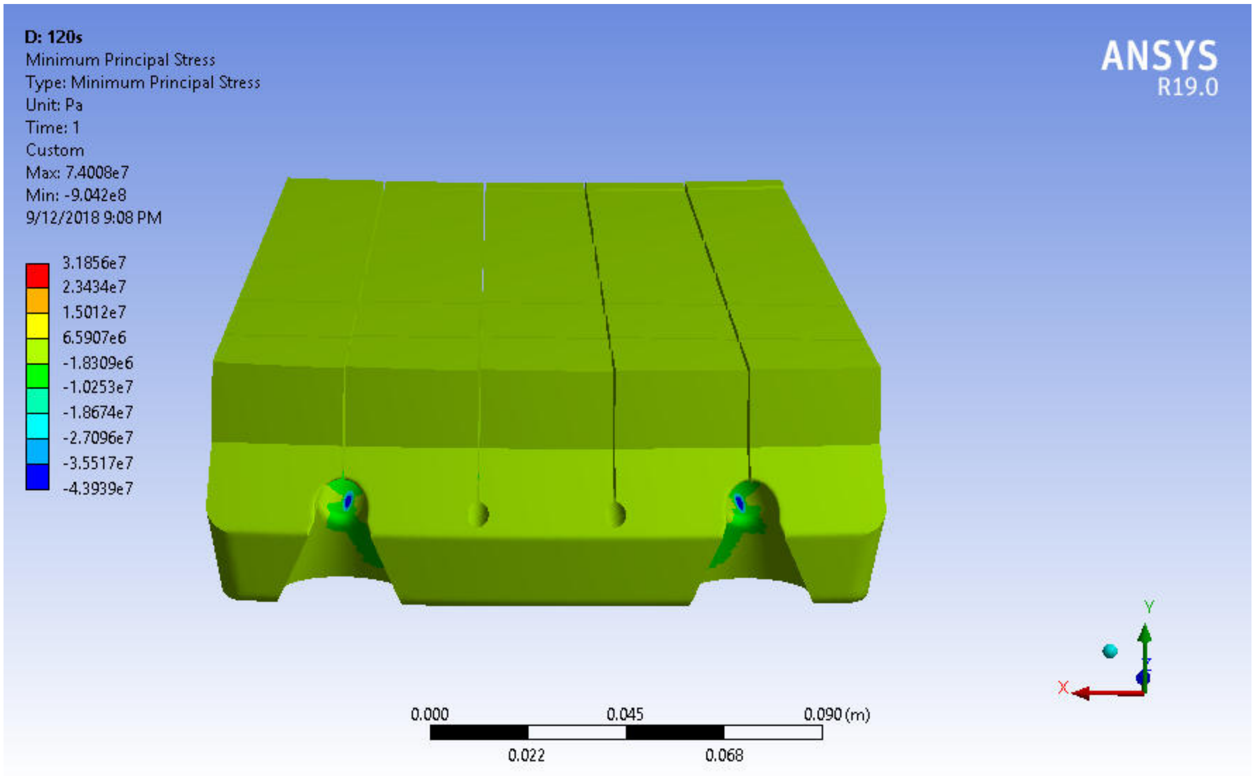


Figure 68 Minimum principal stress distribution in the tile at 120 s.

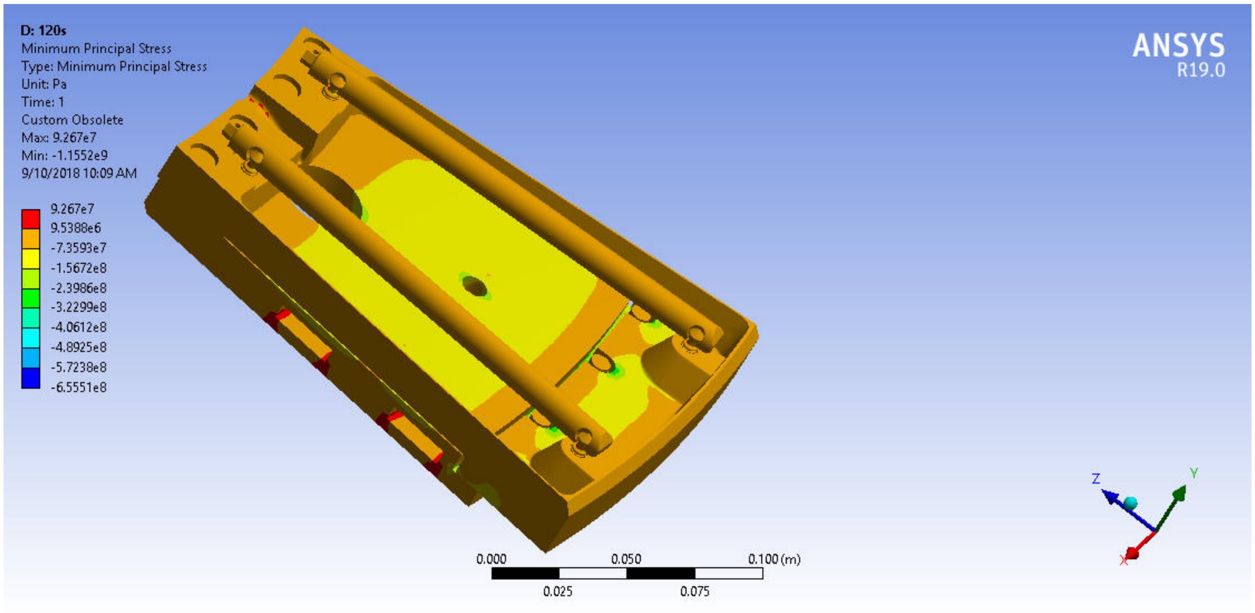


Figure 69. Minimum principal stress distribution in the hardware at 120 s.

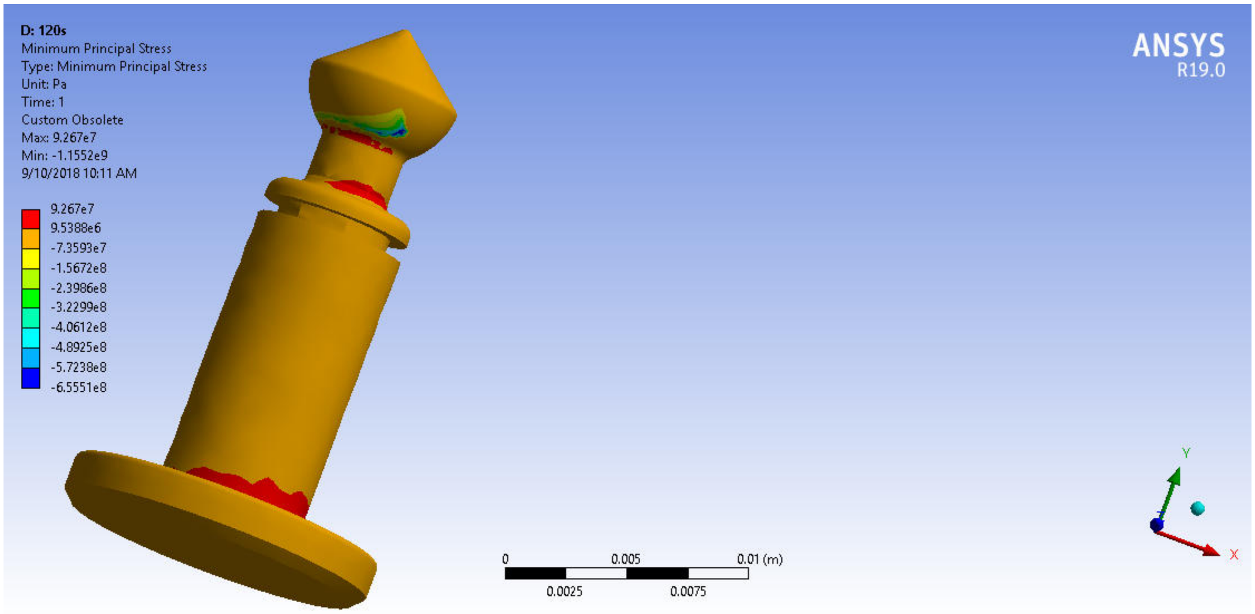


Figure 70. Minimum principal stress distribution in the pins at 120 s.

Thermal structural + Halo and Eddy Loads

Next a thermal structural analysis was carried out at 1s including the halo forces and eddy forces from disruptions. Bulk forces from halo currents were entered as nodal forces on the tile only and those from eddy currents as face loads. These constant values were obtained for worst cases from previous EM analyses on NSTX-U disruption plasmas. The EM loads appear in Figure 71. The bulk halo forces were applied to the 1,162,278 nodes in the tile body, while the eddy loads were applied to opposite sides of the tile as shown. The same temperature distribution from the 1s end of pulse as shown in Figure 53 was imported as a temperature load. The total deformation appears in Figure 72 and the z-deformation is shown in Figure 73.

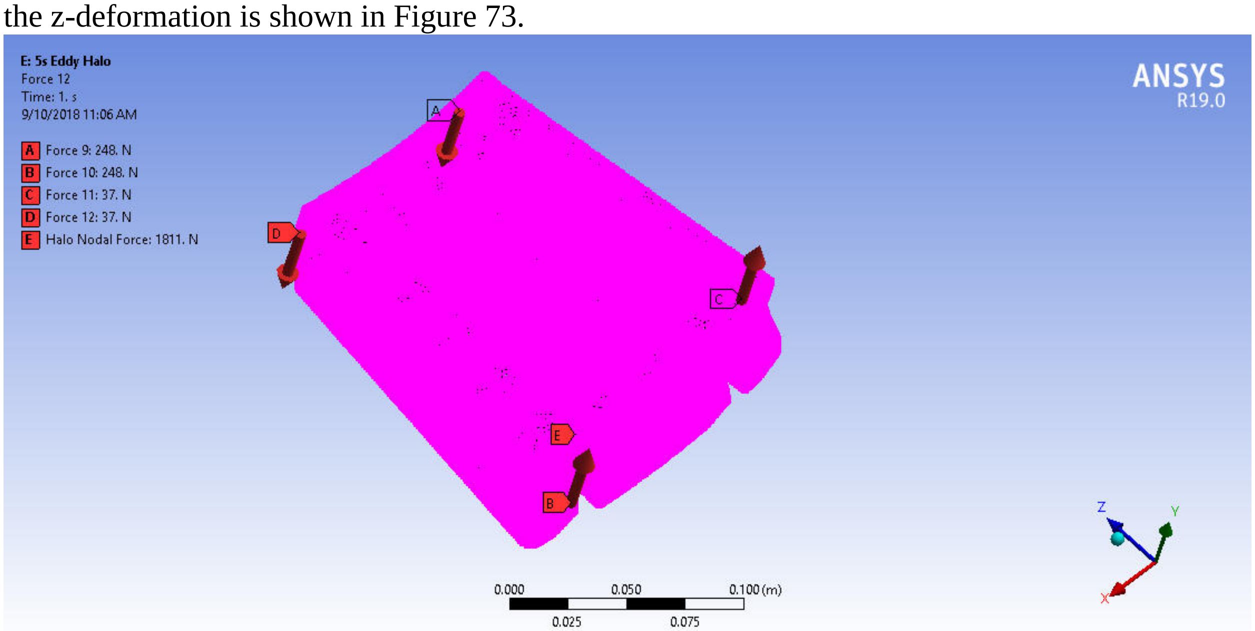


Figure 71. Applied EM loads

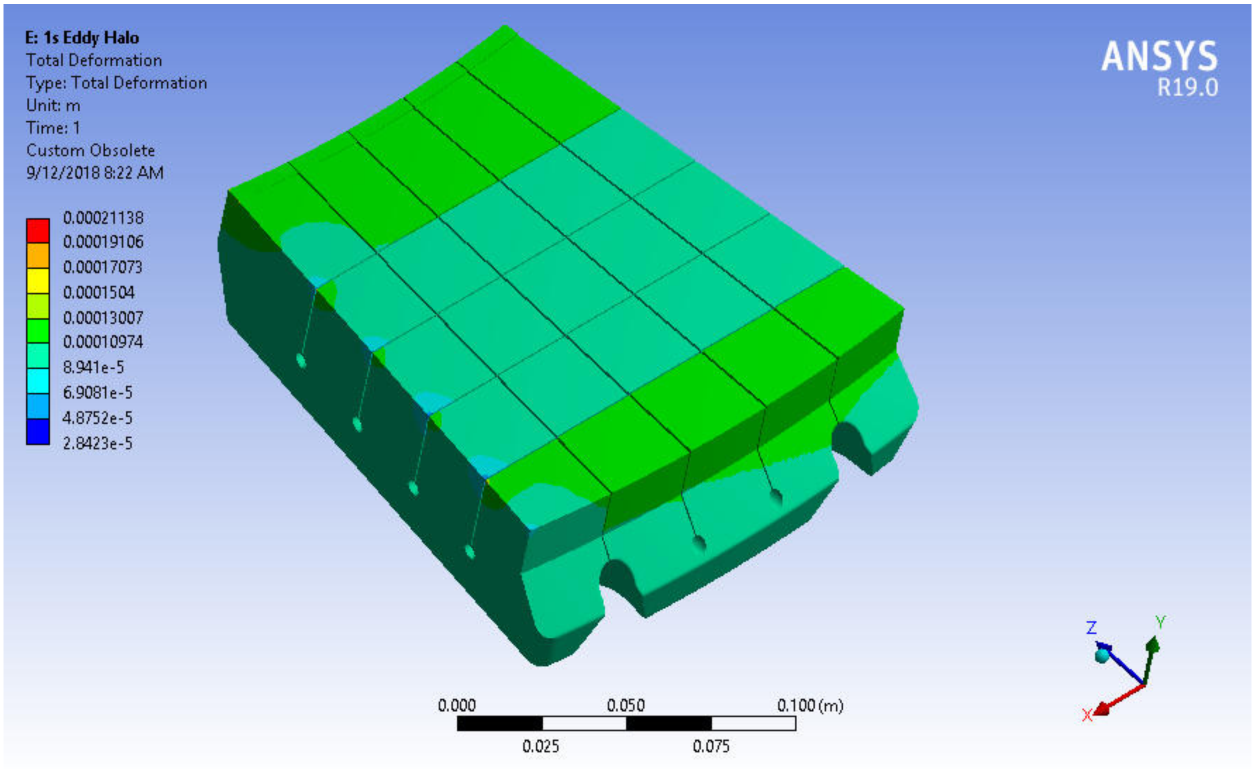


Figure 72. Total deformation at 1s including EM loads.

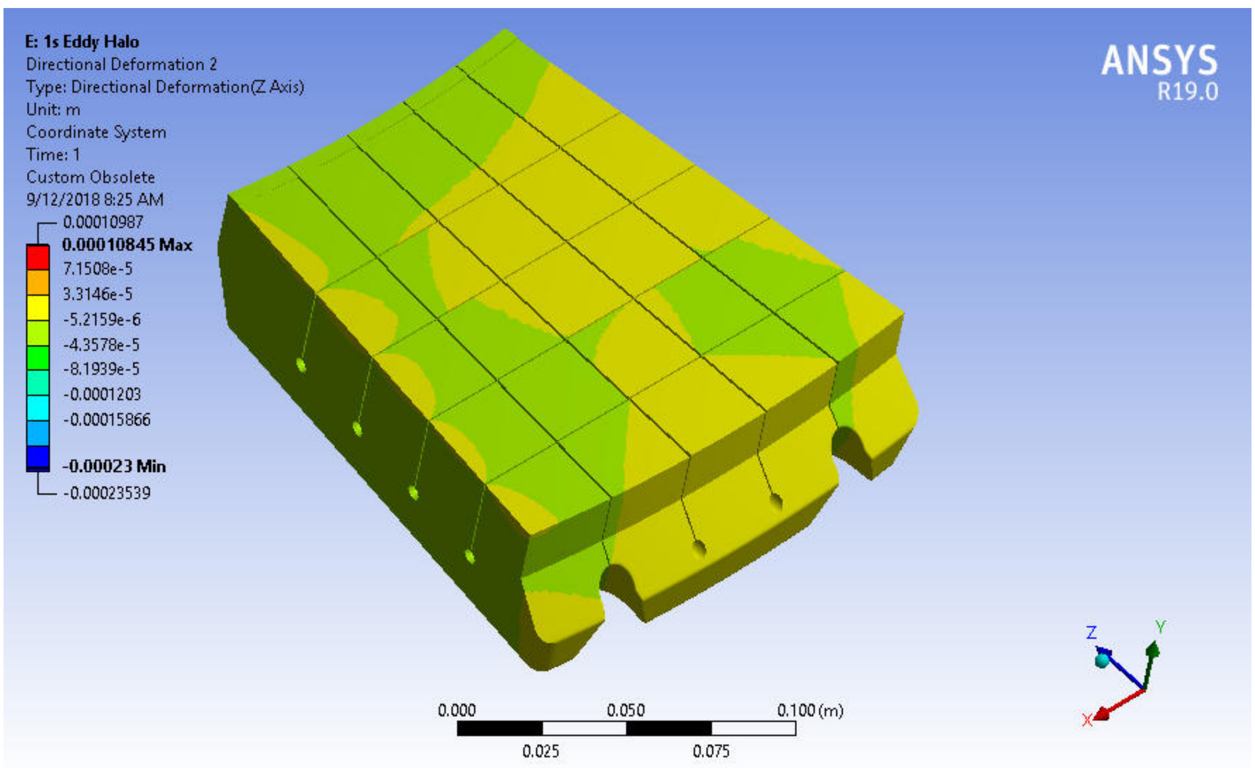


Figure 73. Deformation perpendicular to the tile surface is little affected by the EM loads.

The minimum principal stresses including EM loads in the tile appears in Figure 74. The minimum principal stresses at the rod contact points appears in Figure 75. The minimum principals in the mounting hardware are shown in Figure 76. The maximum principal stresses with EM loads on the tile appears in Figure 77. Likewise, the maximum principal stress in the horizontal mounting rods appears in Figure 78.

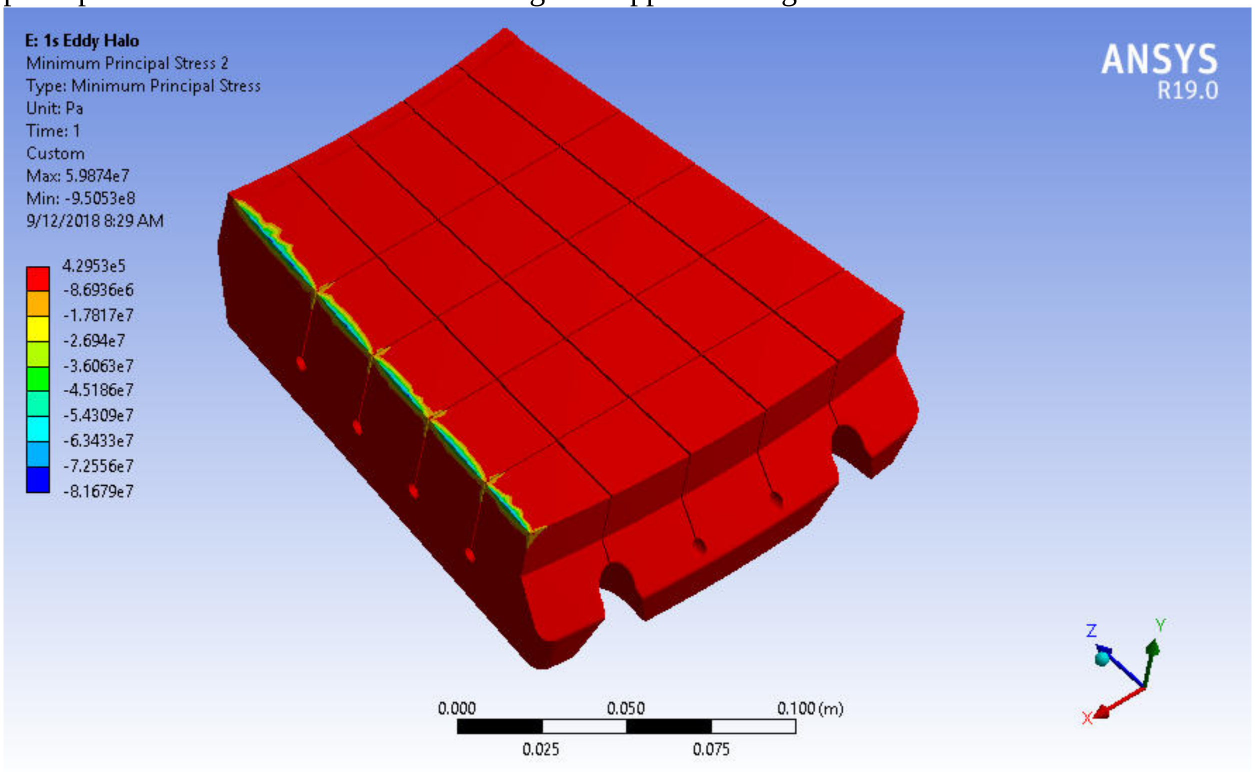


Figure 74. Minimum principal stresses in the tile

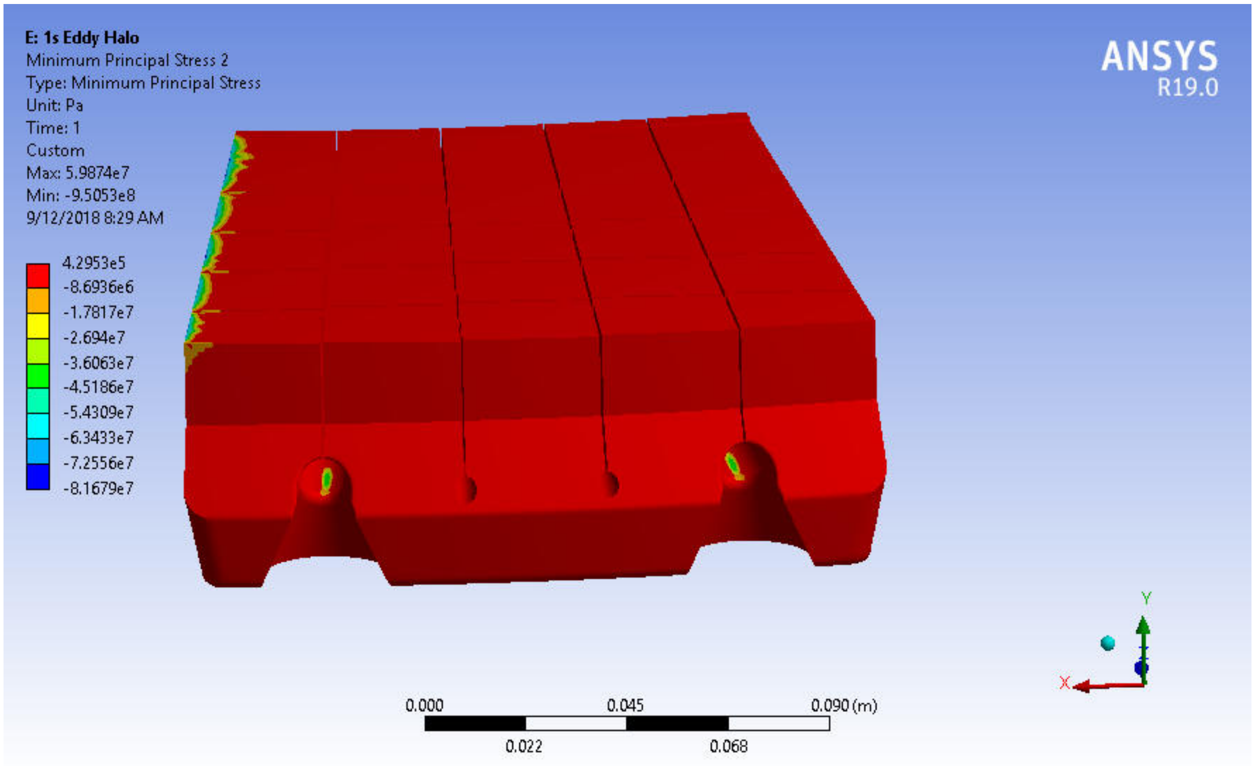


Figure 75. Minimum Principal stress at 1s at rod contact points

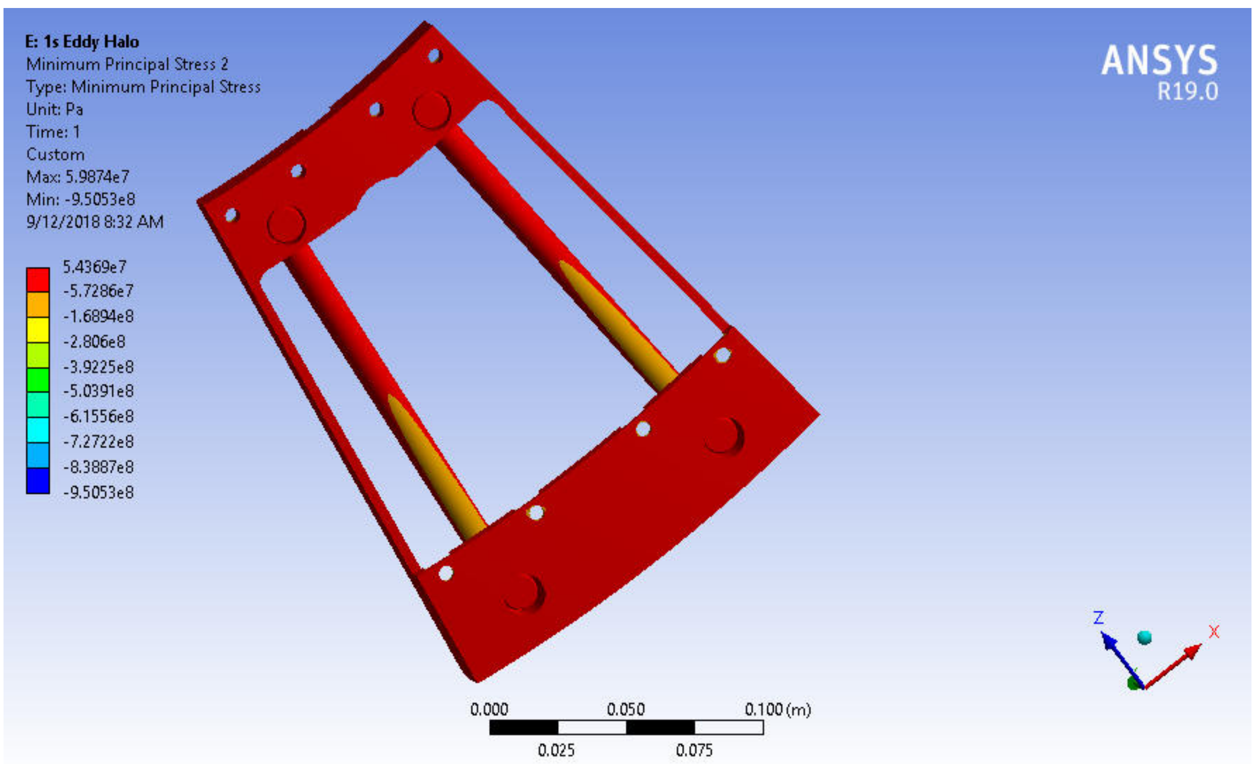


Figure 76. Minimum principal stresses in the mounting hardware.

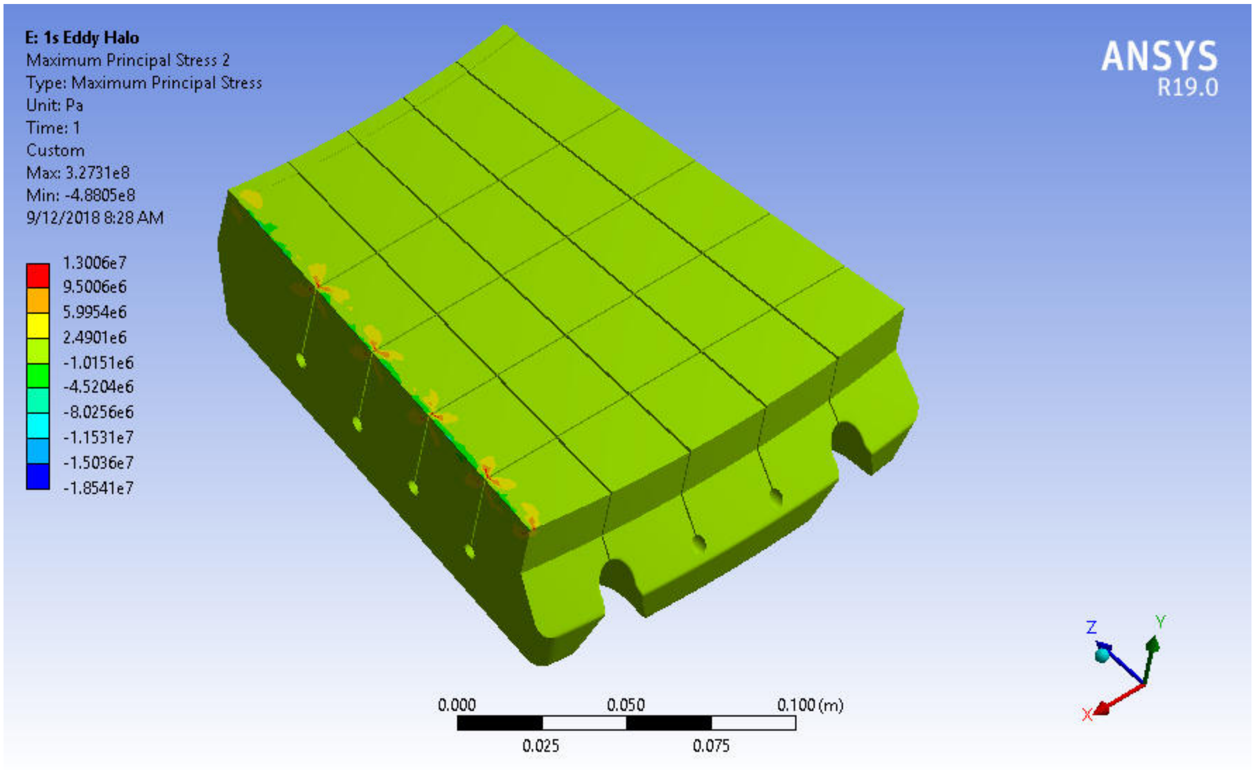


Figure 77. Maximum principal stress at 1s in the tile including EM loads

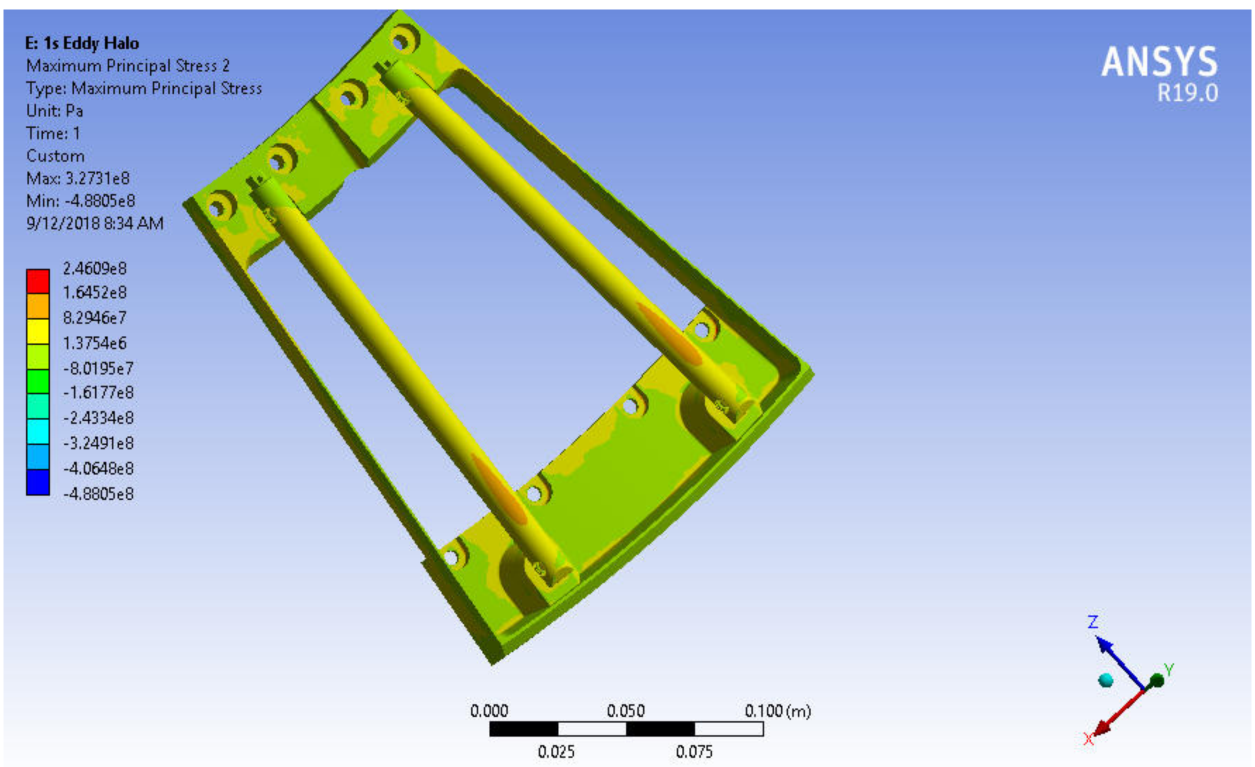


Figure 78. Maximum principal stress in the horizontal mounting rods.

The maximum stress intensity in the horizontal mounting rods is 130 MPa as shown in Figure 79. The reaction force corresponding to the toroidal displacement BC of zero displacement appears in Figure 80; whereas, the reaction force for the baseplate displacement BC is shown in Figure 81.

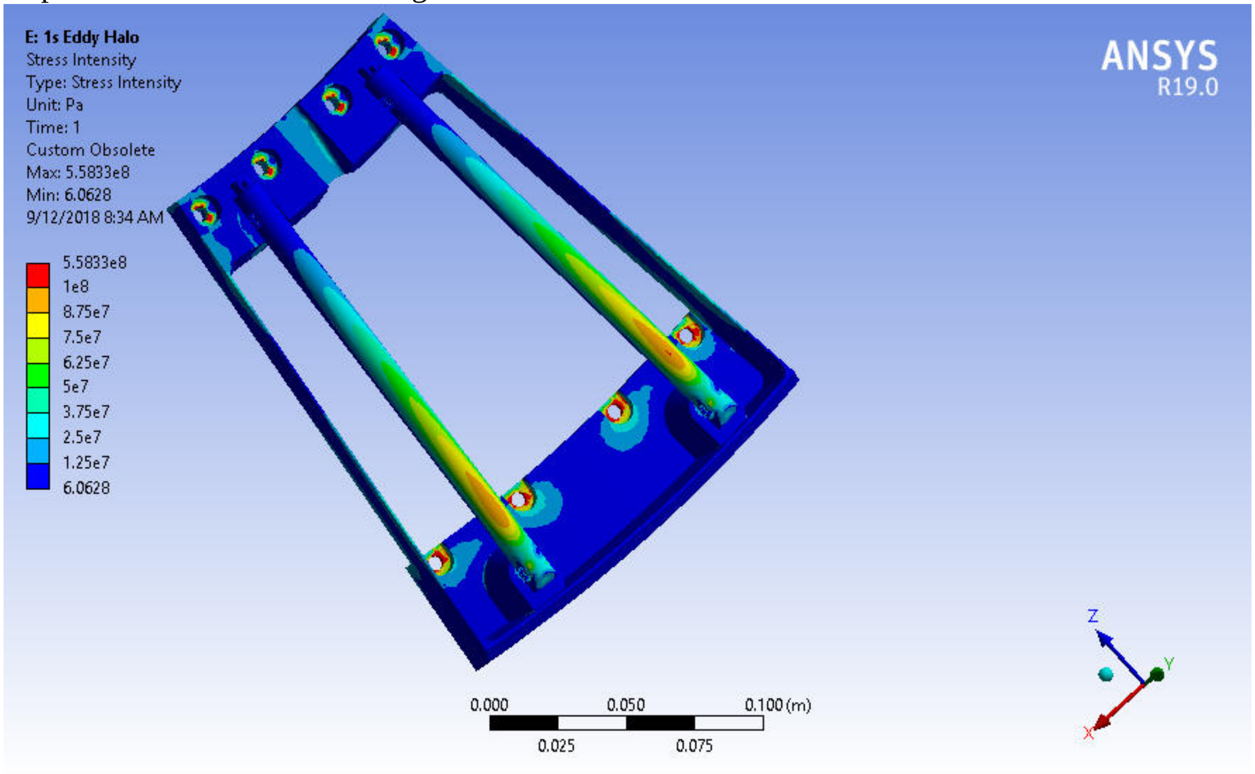


Figure 79. Stress intensity highest in bolt holes.at 1 s including EM loads.

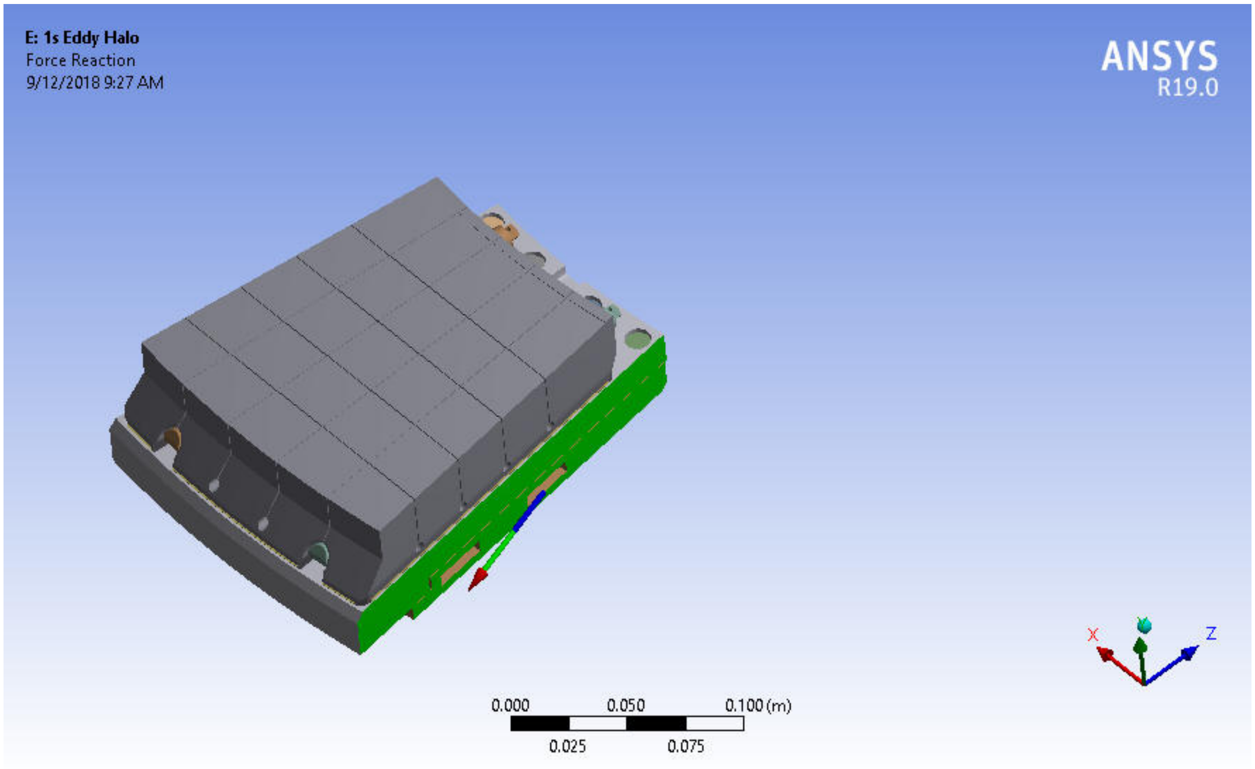


Figure 80. Reaction force provided by limiting displacement.in the toroidal direction.

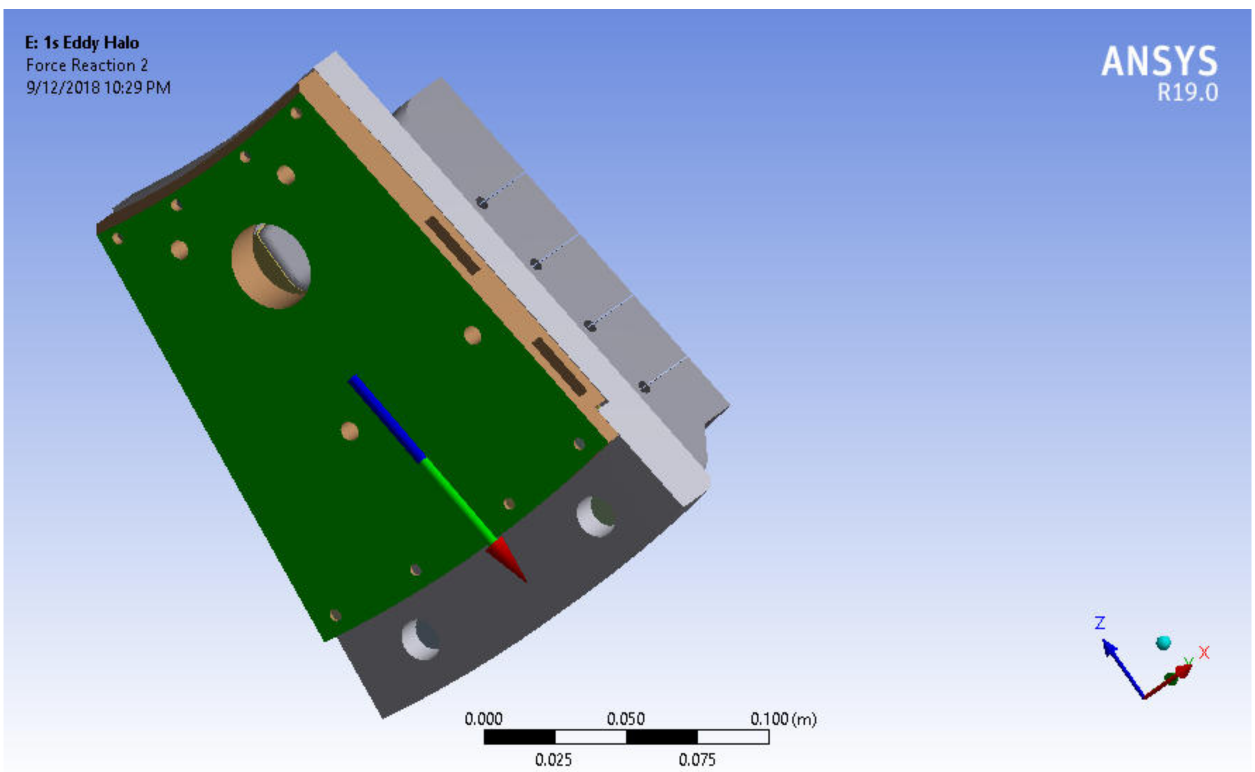


Figure 81. Reaction force provided by displacement2 boundary condition on the bottom of the baseplate at 1s.

Table 7 and Table 8 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite at the end of the 1 s pulse. The bolt holes in the frame exhibit a maximum of 298 MPa equivalent stress in localized areas. Table 9 lists the peak equivalent stress and the corresponding allowable for the components made from Inconel718. Most contact areas in the Inconel parts exceed the allowable slightly. Parts without sharp contacts have a safety factor greater than 3.0. The small bolts in the baseplate have localized equivalent stresses as high as 140 MPa. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced forces.

Table 8: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (jw-ibdh-caslated-tile 1b-c1)	13	30	BPL+Halo+Eddy
Grafoil	1.4	25	BPL+Halo+Eddy

Table 9: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (jw-ibdh-caslated-tile 1b-c1)	-81.7*	-65	BPL+Halo+Eddy
Grafoil	-1.4	-55	BPL+Halo+Eddy

Table 10: Equivalent Stress of Inconel-718 components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	6.3	276	BPL+Halo+Eddy
Frame	132*	276	BPL+Halo+Eddy
Pin	299*	276	BPL+Halo+Eddy
Horizontal Rods	289*	276	BPL+Halo+Eddy

- Highly localized values at contacts. These are not indicative of body values.