Calculation No: NSTXU-CALC-011-21-00 **Revision No: 0**

Calculation of Plasma Facing Components: Center Stack Angular Section (CSA) Tiles Assembly Transient Thermal and Structural Analysis

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

The purpose of this report is to evaluate rows 5 and 6 Center Stack Angular Section (CSA) tile assemblies to ensure each component can withstand total mechanical loads due to halo forces, eddy moments, and thermal stresses during maximum anticipated operating conditions.

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.)

The following references were heavily utilized throughout the calculation

- PFC-180613-AK-01, "PFC thermal and structural analysis procedure" from A.KHODAK to M. Jaworski, R. Ellis, A. Jariwala, B. Linn, J. Klabacha, M. Reinke, P. Titus
- NSTX-CRIT-0001-02, "NSTX (National Spherical Torus Experiment) Structural Design Criteria" dated January 2016
- memo "MODIFICATION OF HEAT FLUX REQUIREMENTS FOR CSAS" from M.L. REINKE to M. JAWORSKI, S. GERHART

Assumptions (Identify all assumptions made as part of this calculation.)
No assumptions were made in this calculation

Calculation (Calculation is either documented here or attached)
Calculation is attached

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

All maximum temperature results fall within the allowable peak temperature of 1600 C. All components in the rows 5 and 6 tile assemblies (tiles, T-bars, shear pins, and bolts) were evaluated under the operating conditions laid out in section 2 and found to be within their mechanical acceptance criteria as laid out in the "NSTX Structural Design Criteria."

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

Preparer's printed name, signature and date Moheb Thomas Digitally signed by Moheb Thomas Date: 2018.09.27 18:10:00 -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 Jiarong Fang Digitally signed by Jiarong Fang Date: 2018.09.27 18:45:22 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

Calculation of Plasma Facing Components: Center Stack Angular Section (CSA) Tiles Assembly Transient Thermal and Structural Analysis

NSTXU-CALC-011-21-00

September 21, 2018

Prepared By:

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Moheb Thomas, Engineering Analyst

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Date: 2018.09.28 23:40:15 -04'00'

Doug Loesser, Head, Mechanical Engineering

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	9/21/18	Initial Release	

Table of Contents

1 Executive Summary

All components in the rows 5 and 6 tile assemblies (tiles, T-bars, shear pins, and bolts) were evaluated under the operating conditions laid out in section 2 and found to be within their mechanical acceptance criteria as laid out in the "NSTX Structural Design Criteria." The Belleville washers are designed for high load functions and are thus deemed acceptable. The margins of safety for other components of interest are summarized in Table 1 for each mechanical loading scenario considered.

	6510 Transient Thermal with Strike Point on Edges [Standard Row 5 + 6]				6510 Transient Thermal with Strike Point over Shear Pin [Standard Row 5 + 6]		6510 Transient Thermal with Strike Point over Shear Pin [Diagnostic Row 5 + 6]		ET-10 Transient Thermal with Strike Point over Shear Pin [Diagnostic Row 5]	6510 [corrected material] Transient Thermal with Strike Point over Shear Pin [Diagnostic Row 5 and 6]
	Row 5 all Mechanical Loads	**Row 6 all Mechanical Loads**	**Row 5 Thermal Stress Only**	**Row 6 Thermal Stress Only**	**Row 5 all Mechanical Loads**	**Row 6 all Mechanical Loads**	**Row 5 (Thermocouple) Thermal Stress Only**	**Row 6 (Thermocouple) Thermal Stress Only**	**Row 5 (Thermocouple) all Mechanical Loads**	**Row 5 (Thermocouple) all Mechanical Loads**
Tile [R6510 Acceptance criteria = 19 MPa in tension and 65 MPa in compression] [ET-10 = 17.15 MPa in tension and 44 MPa in compression]	14.1 MPa max [25.8% margin] -36.3 MPa min [44.2% margin]	10.9 MPa max [42.6% margin] -51.7 MPa min [20.5% margin]	6.1 MPa max [67.9% margin] -35.1 MPa min [46% margin]	9.1 MPa max [52.1% margin] -2.1 MPa min [96.8% margin]	16.6 MPa max [12.6% margin] -58.9 MPa min [9.4% margin]	11.7 MPa max [38.4% margin] -56 MPa min [13.8% margin]	8.0 MPa max [57.9% margin] -67.3 MPa min [exceeds allowable]	10.0 MPa max [47.4% margin] -64.9 MPa min [0.2% margin]	25.6 MPa max [exceeds allowable] -48.2 MPa min [exceeds allowable]	26.8 MPa max [exceeds allowable] -53.4 MPa min [17.8% margin]
T-Bar [Peak allowable stress = 585 MPa]	129.5 MPa intensity [77.9% margin]	119.6 MPa intensity [79.6% margin]	N/A	N/A	135 MPa intensity [76.9% margin]	131 MPa intensity [77.6% margin]	143.2 MPa intensity [75.5% margin]	185.3 MPa intensity [68.3% margin]	168.6 MPa intensity [71.2% margin]	148.2 MPa intensity [74.7% margin]
Shear Pin [Peak allowable stress = 291 MPa]	21.5 MPa intensity [92.6% margin]	17.7 MPa intensity [93.9% margin]	N/A	N/A	25.3 MPa intensity [91.3% margin]	28.7 MPa intensity [90.1% margin]	8.5 MPa intensity [97.1% margin]	53.2 MPa intensity [81.7% margin]	23.0 MPa intensity [92.1% margin]	23.7 MPa intensity [91.9% margin]
Bolt [Peak allowable stress = 585 MPa]	353 MPa intensity [39.7% margin]	361.3 MPa intensity [38.2% margin]	N/A	N/A	357.1 MPa intensity [39% margin]	357.7 MPa intensity [38.9% margin]	386.1 MPa intensity [34% margin]	349 MPa intensity [40.3% margin]	346.6 MPa intensity [40.8% margin]	331.0 MPa intensity [43.4% margin]

Table 1: Tile Assembly Components Results and Margins

The transient thermal analysis results between variations of the row 5 and 6 tiles are compared in Table 2. All maximum temperature results fall within the allowable peak temperature of 1600 C.

Row 5 and 6 Tile Temperatures [C]								
Heat Flux [in 20 minute increments]	1	2	3	4	5	6	7	8
Default 6510 Tiles with Strike Point on Edges	1109.5	1137.8	1149.9	1154.2	1156.9	1157.5	1158.8	1158.4
Default 6510 Tiles with Strike Point above Shear Pin	1139.3	1179.1	1195.1	1202.4	1205.7	1207.3	1209	1208.8
Diagnostic 6510 Tiles with Strike Point above Shear Pin	1196.1	1221.5	1230.4	1234.1	1235.7	1236.4	1237.6	1237.2
6510 Under Tiles with Strike Point above Shear Pin (High flux case)	957.1	974	979.8	982.2	983.1	983.5	984.3	984
6510 Under Tiles with Strike Point above Shear Pin (low flux case)	893.1	908.9	913.4	915.4	916.2	916.6	917.2	916.9
Diagnostic ET-10 Tiles with Strike Point above Shear Pin	709.1	759.3	791.8	811.9	824.1	831.3	836.2	838.4
Diagnostic 6510 (Applicable Material Properties) Tiles with Strike Point above Shear Pin	692.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 2: Row 5 and 6 Tile Variation Temperature Results

2 Purpose

The purpose of this report is to evaluate rows 5 and 6 Center Stack Angular Section (CSA) tile assemblies to ensure each component can withstand total mechanical loads due to halo forces, eddy moments, and thermal stresses during maximum anticipated operating conditions. Thermocouple and gas injection tube tile variations are also assessed to confirm assembly acceptability.

The anticipated thermal conditions are simulated in a transient thermal analysis via ANSYS [ANalysis SYStem] version 19.1 and then input into a static structural analysis to simulate the halo forces and eddy moments. The following models are evaluated within the scope of this calculation.

1. 6510 Transient Thermal with Strike Point on Edges for Standard Row 5 and 6 tiles [CSAS Case 1 of PFC System Requirements]
    a. Row 5 Thermal Stress Only
    b. Row 6 Thermal Stress Only
    c. Row 5 all Mechanical Loads
    d. Row 6 all Mechanical Loads
    e. Preload Only
2. 6510 Transient Thermal with Strike Point over Shear Pin for Standard Row 5 and 6 Tiles [CSAS Case 1 of PFC System Requirements]
    a. Row 5 all Mechanical Loads
    b. Row 6 all Mechanical Loads
3. 6510 Transient Thermal with Strike Point over Shear Pin for Diagnostic Tiles Rows 5 and 6 [CSAS Case 1 of PFC System Requirements]
4. 6510 Transient Thermal With Strike Point over Shear Pin for Under Tiles Rows 5 and 6 [CSAS Case 1 of PFC System Requirements]

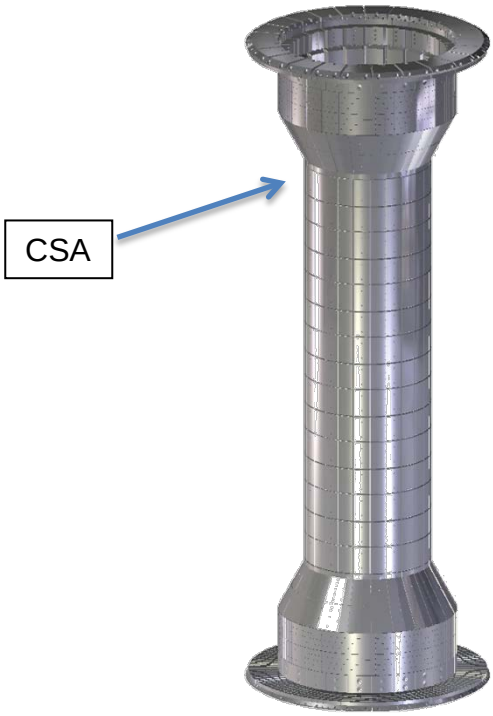


Figure 1: Center Stack Angular Section Tiles Row 5 and 6 Location

3 Assumptions

None. Any assumptions contained within hand calculation are explicitly stated in their respective sections.

4 Inputs

4.1 Material Assignments

- 4.1.1 Casing – Alloy 625
- 4.1.2 Shear Pin – Alloy 625
- 4.1.3 Gaskets – Grafoil
- 4.1.4 Tiles – Graphite 6510
- 4.1.5 T-Bar – Grade 660 SS
- 4.1.6 Bolts – Grade 660 SS
- 4.1.7 Belleville Washers – 316L SS

4.2 Material Data

See appendix 8.3

4.3 Bolt Preload

4.3.1 960 lb = 4270 N per bolt (See sections 4.2 and 4.3 for minimum preload requirements)

4.4 Friction Coefficients

4.4.1 Between Tile [Graphite ET 10] and Gasket [Grafoil] = 0.1 (Table 5.4.3 of Ref.8.2)

4.4.2 Between Tile [Graphite ET 10] and Tee-bar [Grade 660 SS] = 0.1 (Table 5.4.3 of Ref.8.2)

4.4.3 Between Tile [Graphite ET 10] and Sheer Pin [Inconel Alloy 625] = 0.1 (Table 5.4.3 of Ref.8.2)

4.4.4 Between Case [Inconel Nickel-Chromium Alloy 625] and Gasket [Grafoil flexible Graphite] = 0.1 (Table 5.4.3 of Ref.8.2)

4.4.5 Between Case [Inconel Nickel-Chromium Alloy 625] and Tee-Bar [Grade 660 SS] = 0.3

4.5 Thermal

4.5.1 Initial Temperature 25C (Systems Requirements Document)

4.5.2 Surface Fluxes 6.4*10^6 W/m^2 linearly decreasing to 0 over an 8 cm span (Figure 1 of Ref.8.3)

4.5.3 Chamfer Fluxes 3.4*10^7 W/m^2 (Systems Requirements Document)

4.5.4 Radiation Emissivity = 0.7 (Systems Requirements Document)

4.5.5 Ambient Temperature = 110.73C for CSAT1 (Figure 1 of Ref.8.1)

4.5.6 Convection

4.5.6.1 Film Coefficient = 357 W/(m^2*C) (Systems Requirements Document)

4.5.6.2 Ambient Temperature = 22C (Systems Requirements Document)

4.6 Row 5 Mechanical Inputs

4.6.1 Body Force Distribution due to Electromagnetic Forces (Ref. 8.5)

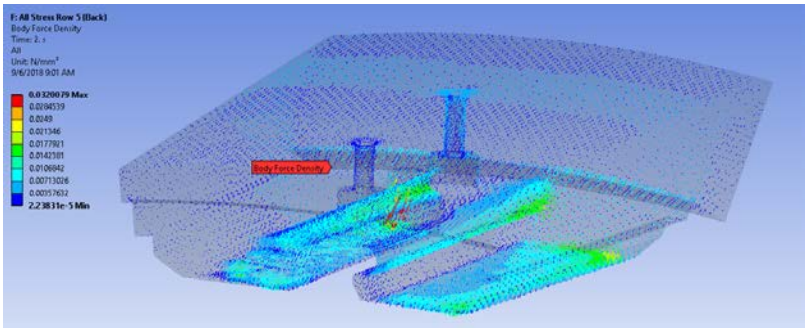


Figure 2: Row 5 Body Force Distribution

4.6.2 Moments (Ref. 8.5)

4.6.2.1 X-direction is -3.03 N*m

4.6.2.2 Y-direction is -25.6 N*m

4.6.2.3 Z-direction is 37.7 N*m

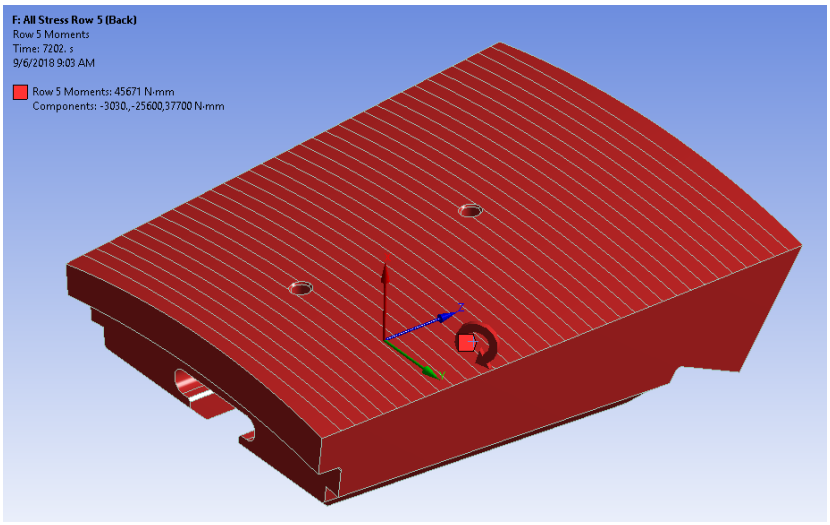


Figure 3: Row 5 Moments

4.7 Row 6 Mechanical Inputs

4.7.1 Body Force Distribution due to Electromagnetic Forces (Ref. 8.5)

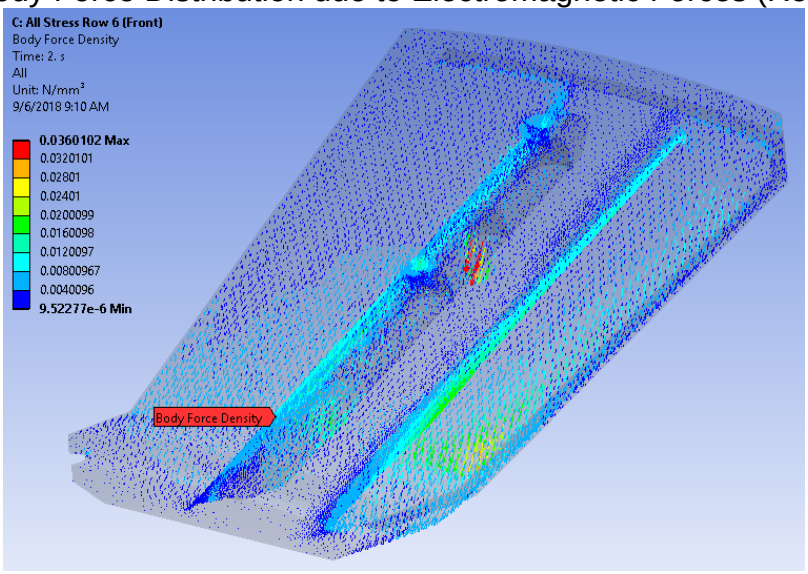


Figure 4: Row 6 Body Force Distribution

4.7.1 Moments (Ref. 8.5)

4.7.1.1 X-direction is -4.52 N*m

4.7.1.2 Y-direction is -19.0 N*m

4.7.1.3 Z-direction is -31.4 N*m

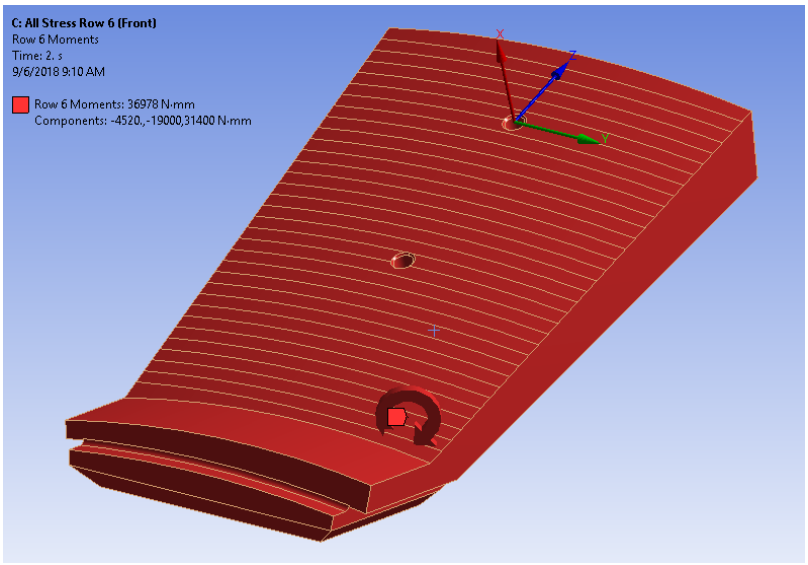


Figure 5: Row 6 Moments

5 ANSYS Results

Thermal inputs for each case are as follows (Figure 5A):

- Radiation
  - Tiles outer surfaces radiating to ambient, 110.73C, 0.7 emissivity
  - Bodies radiating to each other with 0.7 emissivity
- Convection
  - Casing Cooling based on film coefficient of 357 W/m2-C with 22C coolant
- Initial Temperature = 25C
- Fluxes = 6.4*10^6 W/m^2 linearly decreasing to 0 over an 8 cm span
- Chamfer flux is 3.4*10^7 W/m^2 (Figure 5B)
- Strike points are located on the top-most edge or directly above the shear pin depending on the scenario being evaluated.

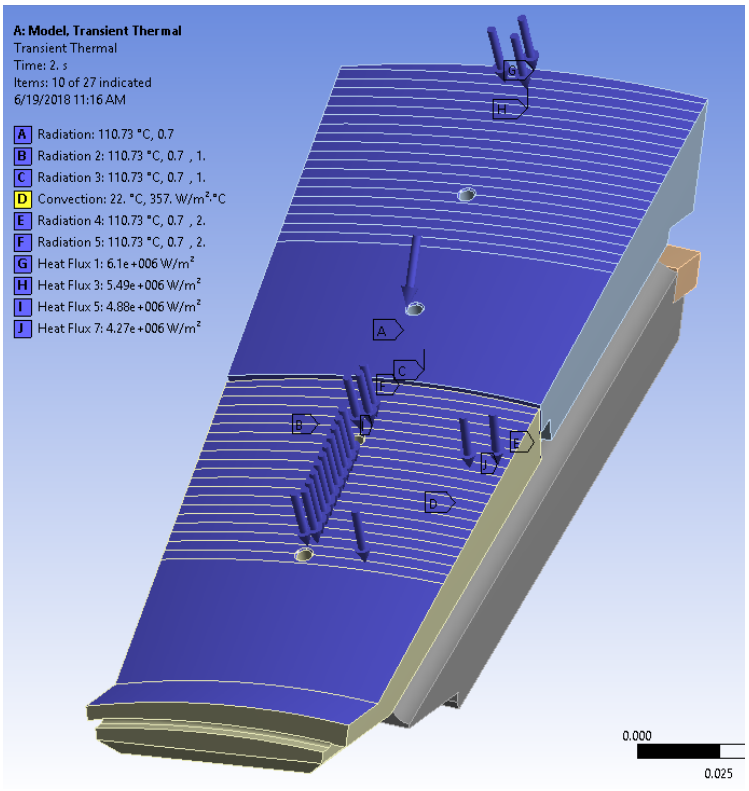


Figure 5A: General Thermal Model

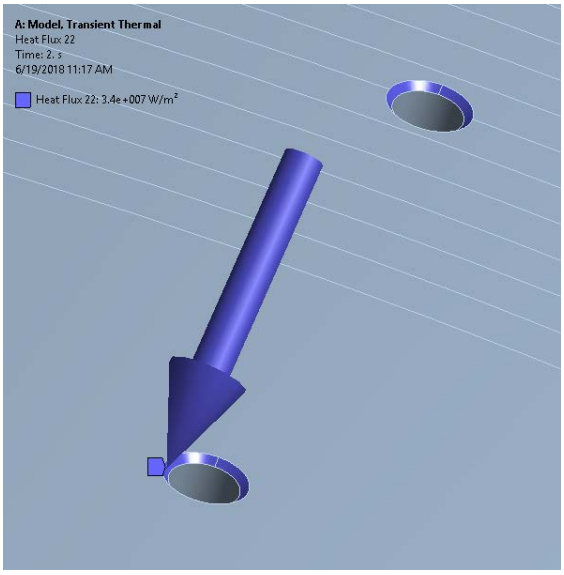


Figure 5B: Chamfer Heat Flux

5.1 6510 Transient Thermal with Max Flux on Edges [Standard Row 5 and 6]

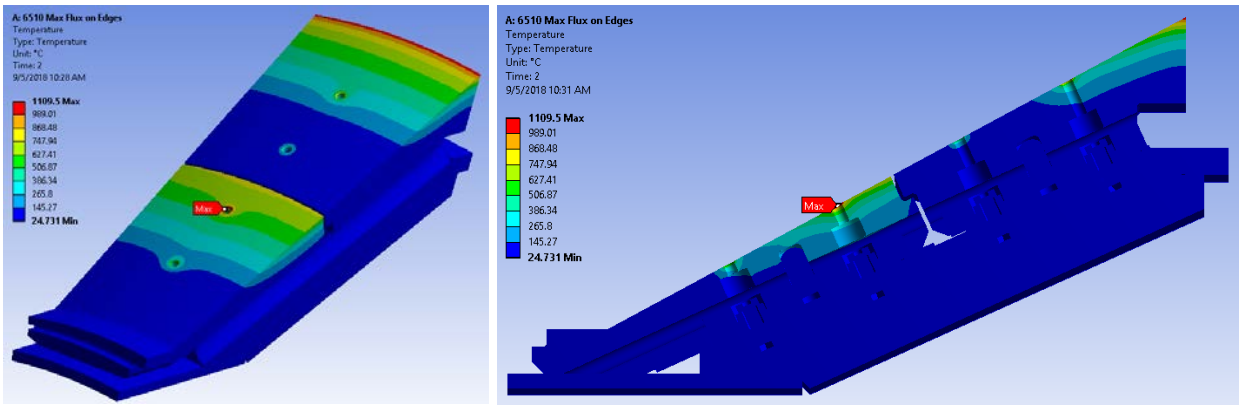


Figure 6: End of First Flux Shot for Standard Tiles with Strike Point on Edges

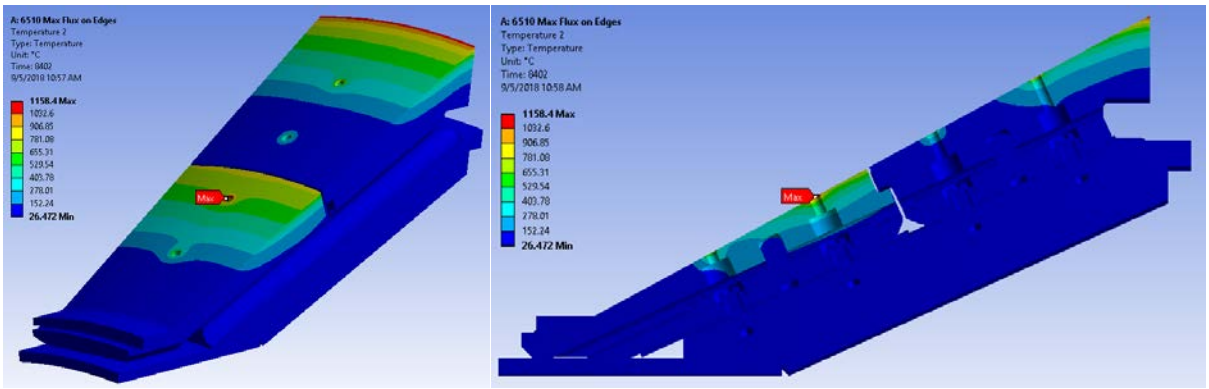


Figure 7: End of Eighth Flux Shot for Standard Tiles with Strike Point on Edges

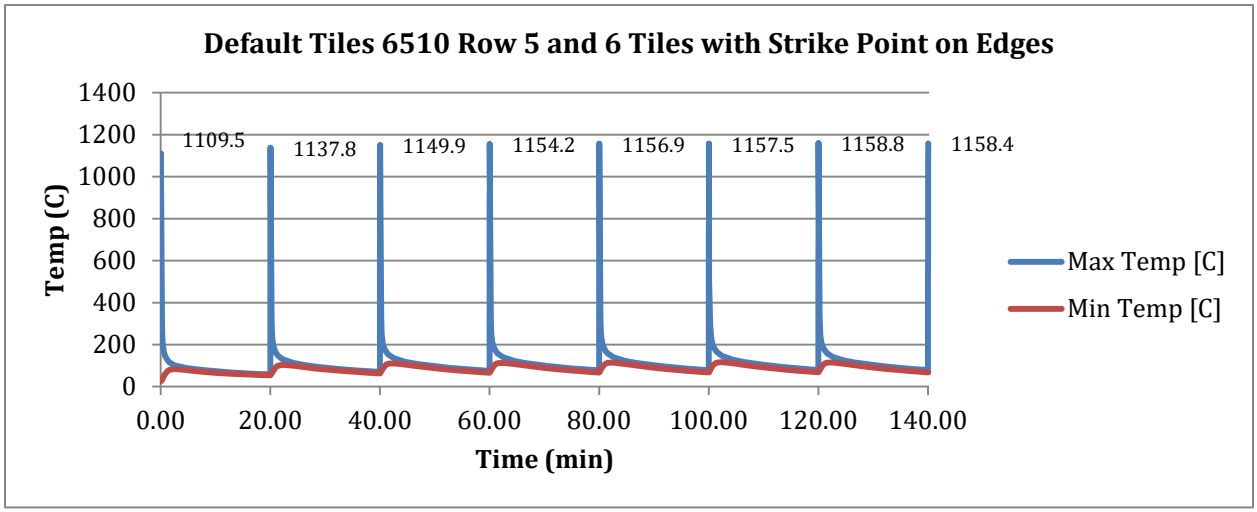


Figure 8: Transient Thermal Results for Default Tiles with Strike Point on Edges

5.1.1 Row 5 Thermal Stress Only

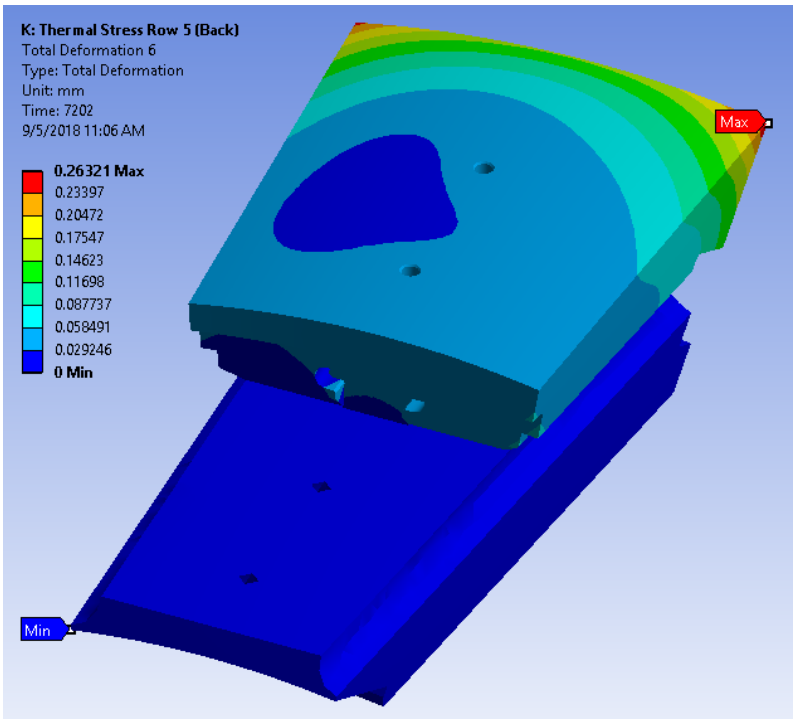


Figure 10: Default Row 5 Tile, Strike Point on Edge, Thermal Stress Only Deformation

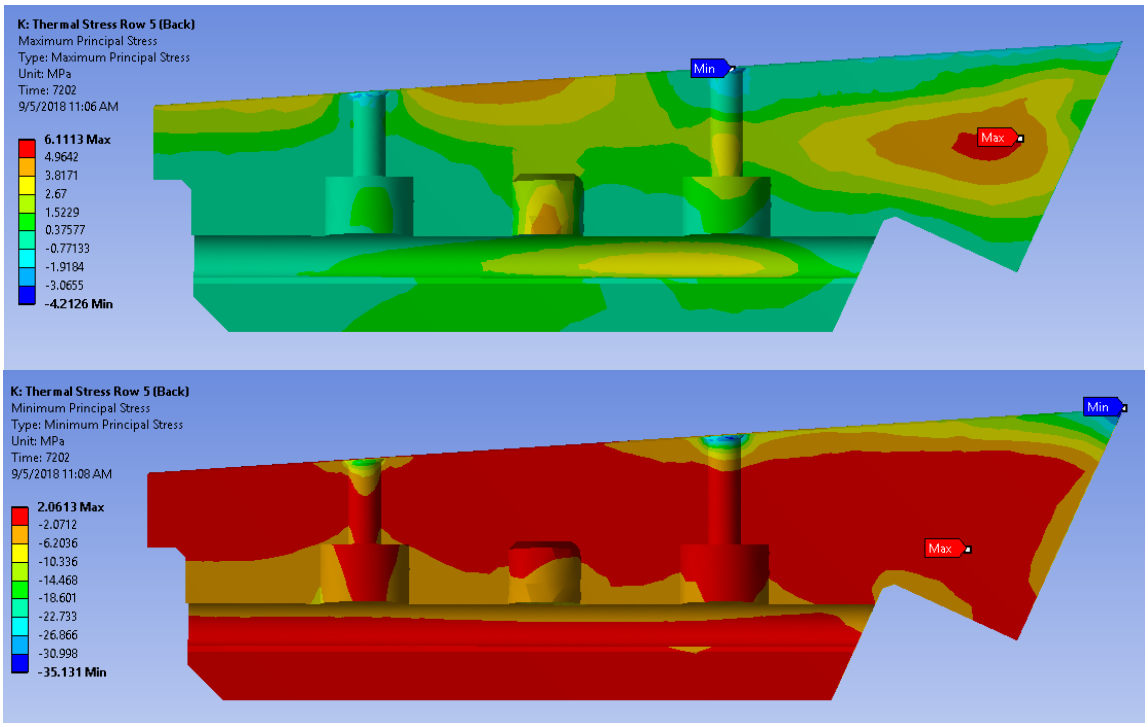


Figure 11: Default Row 5 Tile, Strike Point on Edge, Thermal Stress Only Stresses

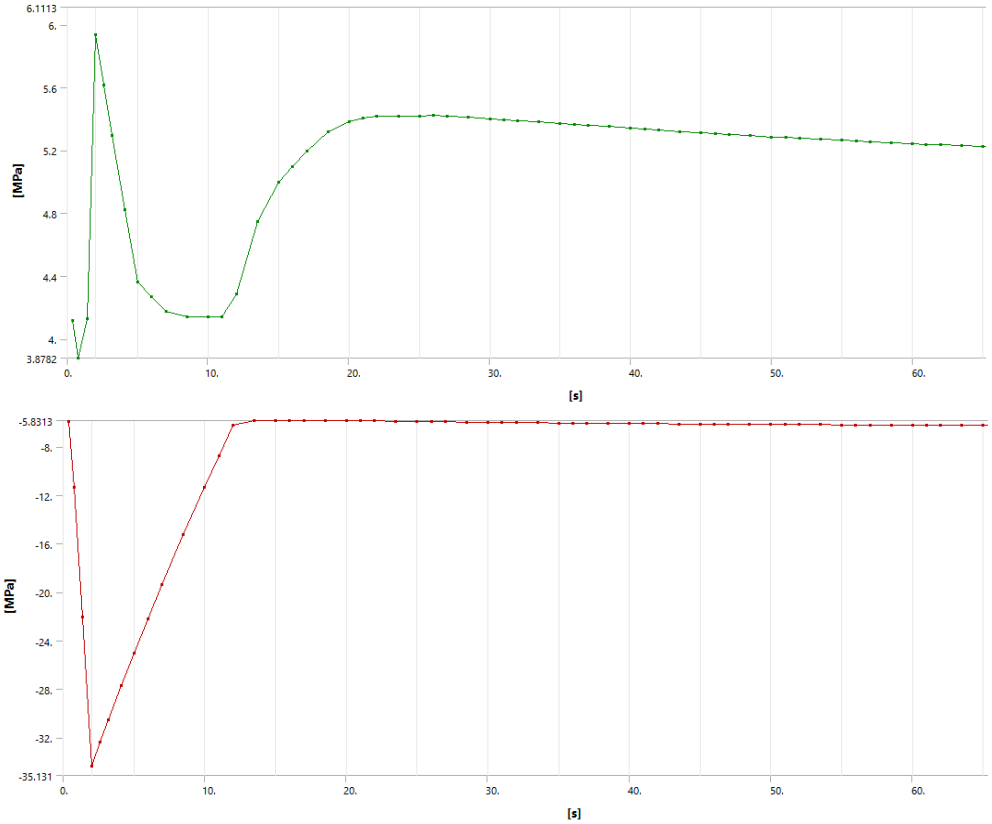


Figure 11: Default Row 5 Tile, Strike Point on Edge, Thermal Stress Only Stress Plots

5.1.2 Row 6 Thermal Stress Only

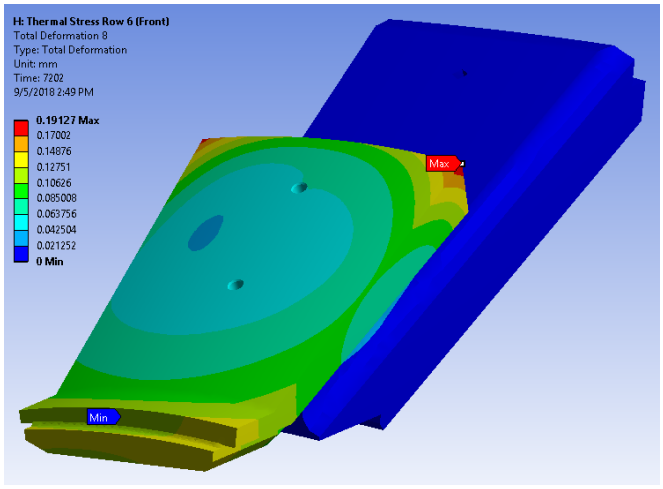


Figure 12: Default Row 6 Tile, Strike Point on Edge, Thermal Stress Only Deformation

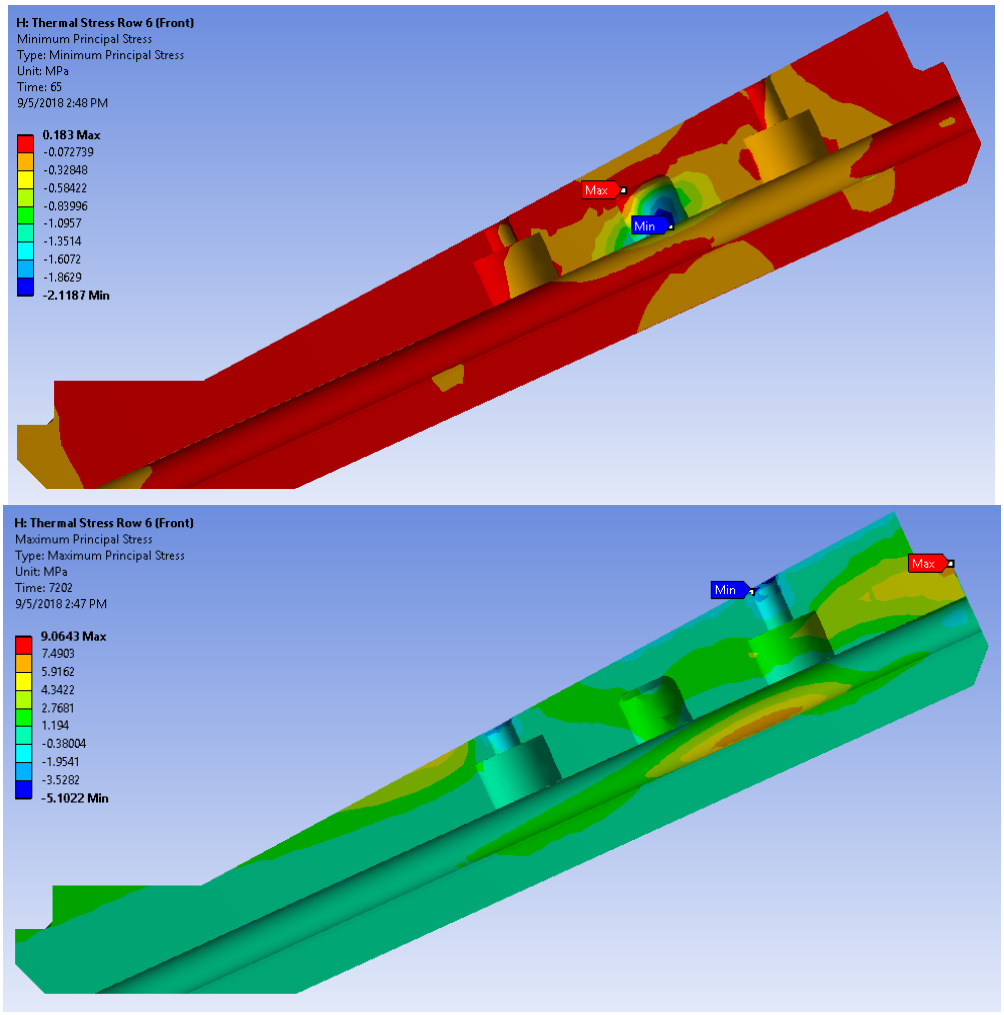
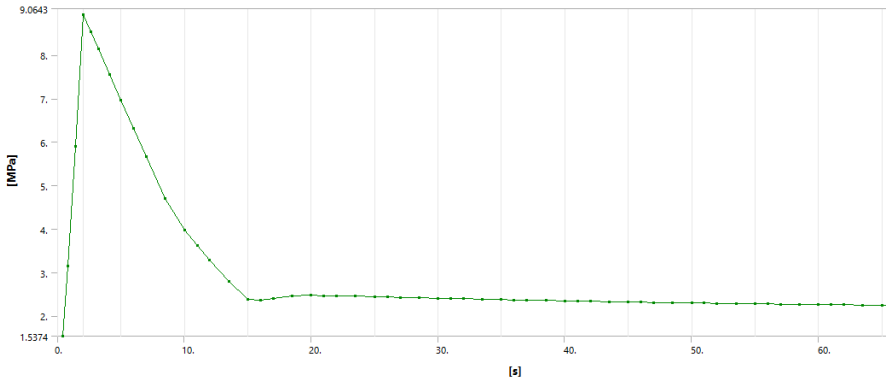


Figure 13: Default Row 6 Tile, Strike Point on Edge, Thermal Stress Only Stresses



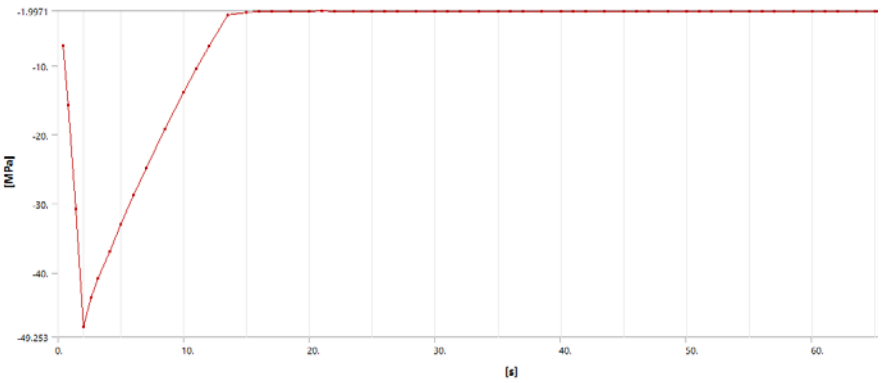


Figure 14: Default Row 6 Tile, Strike Point on Edge, Thermal Stress Only Stress Plots

5.1.3 Row 5 All Mechanical Loads

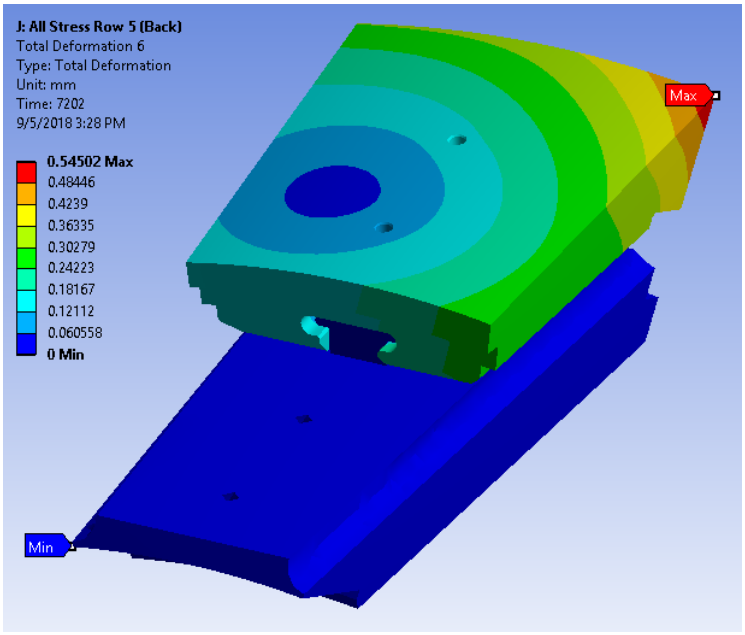
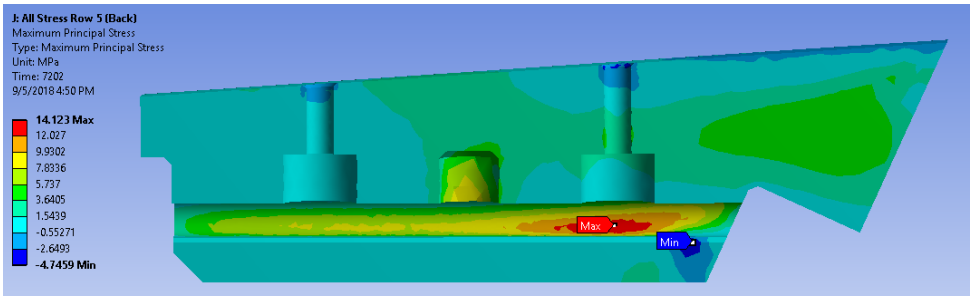


Figure 15: Default Row 5 Tile, Strike Point on Edge, All Mechanical Stress Deformation



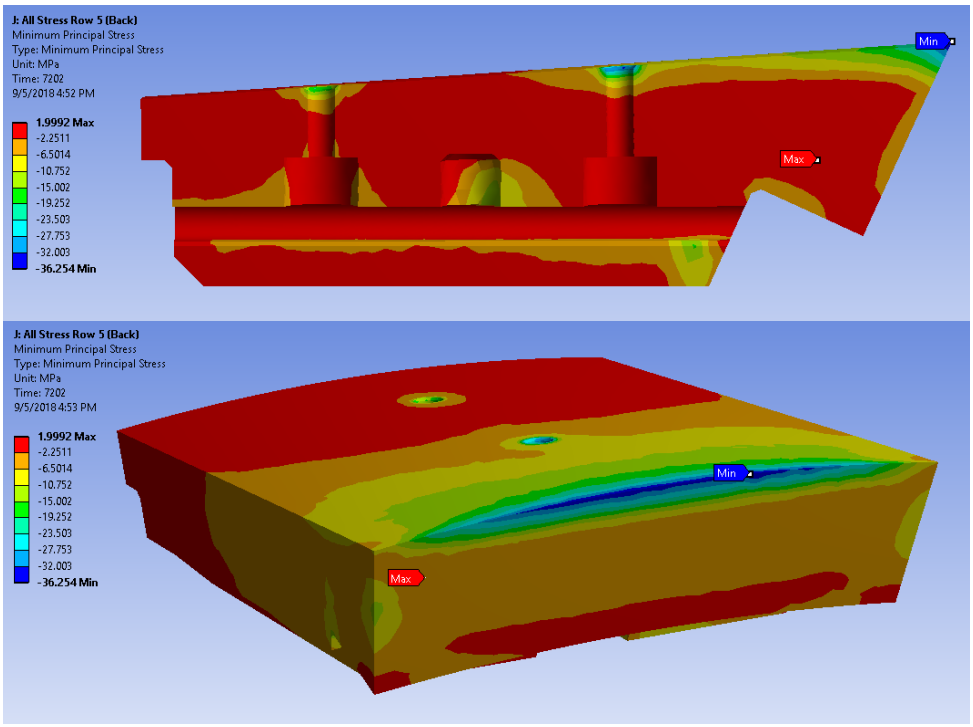


Figure 16: Default Row 5 Tile, Strike Point on Edge, All Mechanical Stresses

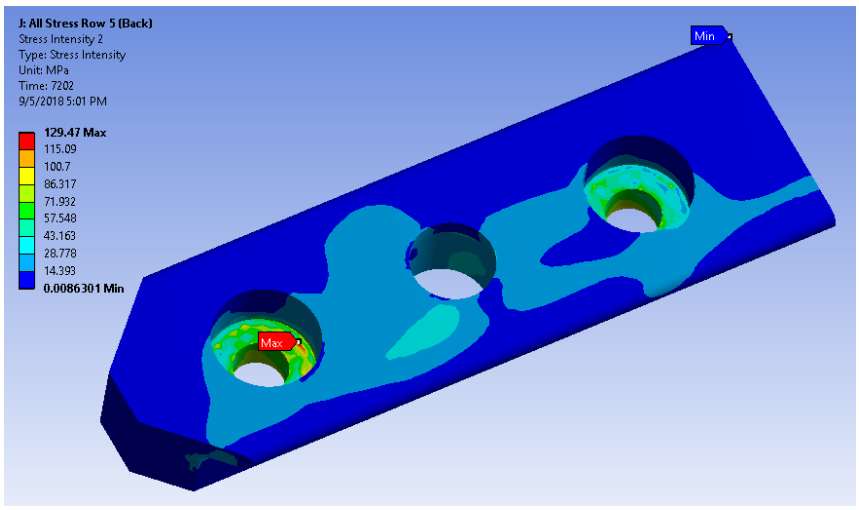


Figure 17: Default Row 5, Strike Point on Edges, All Mechanical Loads, Stress on T-Bar

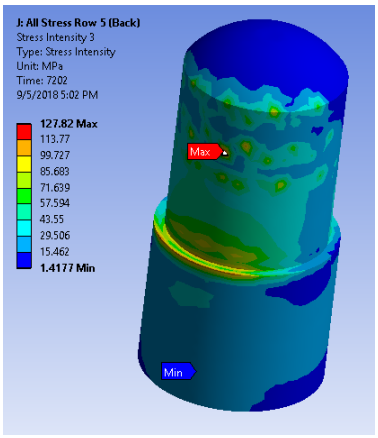


Figure 18: Default Row 5, Strike Point on Edges, All Mechanical Loads, Stress on Shear Pin

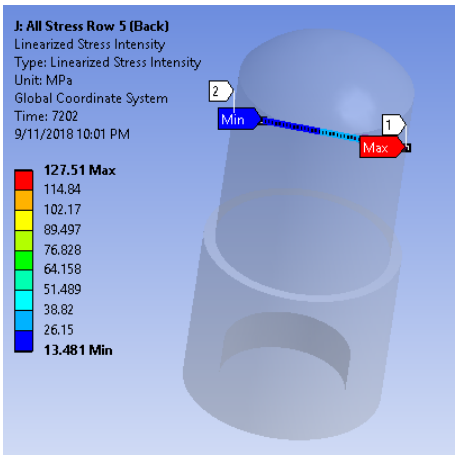


Figure 19: Shear Pin Linearized Stress for Default Row 5, Strike Point on Edges, All Mechanical Loads

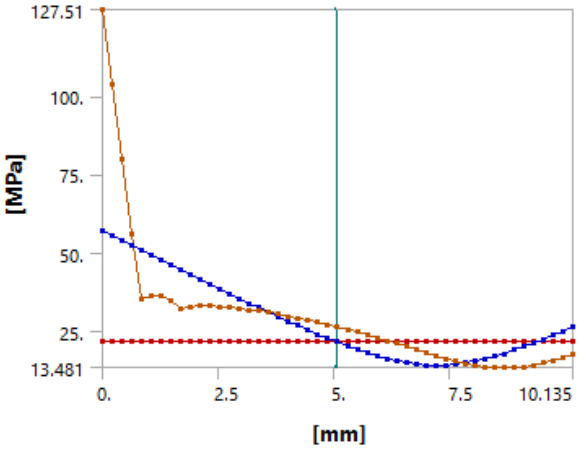


Figure 20: Shear Pin Linearized Stress Graphs for Default Row 5, Strike Point on Edges, All Mechanical Loads

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	21.537	38.958	57.018	81.228	127.51
2	0.21114	21.537	37.335	55.446	57.468	103.81
3	0.42229	21.537	35.712	53.877	33.727	79.889
4	0.63343	21.537	34.088	52.311	13.053	56.204
5	0.84457	21.537	32.465	50.749	18.079	35.071
6	1.0557	21.537	30.842	49.19	16.53	36.503
7	1.2669	21.537	29.219	47.637	15.059	36.474
8	1.478	21.537	27.595	46.088	13.524	34.496
9	1.6891	21.537	25.972	44.544	14.78	32.262
10	1.9003	21.537	24.349	43.006	13.748	32.699
11	2.1114	21.537	22.726	41.475	12.72	33.159
12	2.3226	21.537	21.102	39.951	11.962	32.968
13	2.5337	21.537	19.479	38.436	11.274	32.808
14	2.7449	21.537	17.856	36.929	10.667	32.566
15	2.956	21.537	16.233	35.434	10.145	32.25
16	3.1672	21.537	14.609	33.95	9.7116	31.868
17	3.3783	21.537	12.986	32.479	9.4045	31.525
18	3.5894	21.537	11.363	31.024	9.1583	30.971
19	3.8006	21.537	9.7396	29.587	9.0353	30.332
20	4.0117	21.537	8.1163	28.171	9.0725	29.713
21	4.2229	21.537	6.493	26.778	9.1634	29.137
22	4.434	21.537	4.8698	25.413	9.0616	28.544
23	4.6452	21.537	3.2465	24.08	8.9523	27.861
24	4.8563	21.537	1.6233	22.786	8.826	27.099
25	5.0674	21.537	6.731e-014	21.537	8.7153	26.328
26	5.2786	21.537	1.6233	20.341	8.4245	25.479
27	5.4897	21.537	3.2465	19.209	8.1237	24.688
28	5.7009	21.537	4.8698	18.152	7.6838	23.79
29	5.912	21.537	6.493	17.183	7.1638	22.846
30	6.1232	21.537	8.1163	16.319	6.6567	21.955
31	6.3343	21.537	9.7396	15.574	6.0779	21.023
32	6.5454	21.537	11.363	14.966	5.3025	20.005
33	6.7566	21.537	12.986	14.511	4.5777	18.998
34	6.9677	21.537	14.609	14.221	4.3996	18.081
35	7.1789	21.537	16.233	14.104	4.199	17.162
36	7.39	21.537	17.856	14.166	3.877	16.229
37	7.6012	21.537	19.479	14.403	3.7931	15.415
38	7.8123	21.537	21.102	14.81	4.0596	14.658
39	8.0234	21.537	22.726	15.376	4.5725	14.097
40	8.2346	21.537	24.349	16.088	4.8969	13.673
41	8.4457	21.537	25.972	16.928	5.2984	13.481
42	8.6569	21.537	27.595	17.88	6.4205	13.631
43	8.868	21.537	29.219	18.928	7.2188	13.603
44	9.0792	21.537	30.842	20.055	7.9151	13.712
45	9.2903	21.537	32.465	21.25	8.6656	14.173
46	9.5015	21.537	34.088	22.501	9.7163	14.836
47	9.7126	21.537	35.712	23.798	10.808	15.621
48	9.9237	21.537	37.335	25.134	11.924	16.511
49	10.135	21.537	38.958	26.503	13.037	17.484

Table 3: Shear Pin Linearized Stress Table for Default Row 5, Strike Point on Edges, All Mechanical Loads

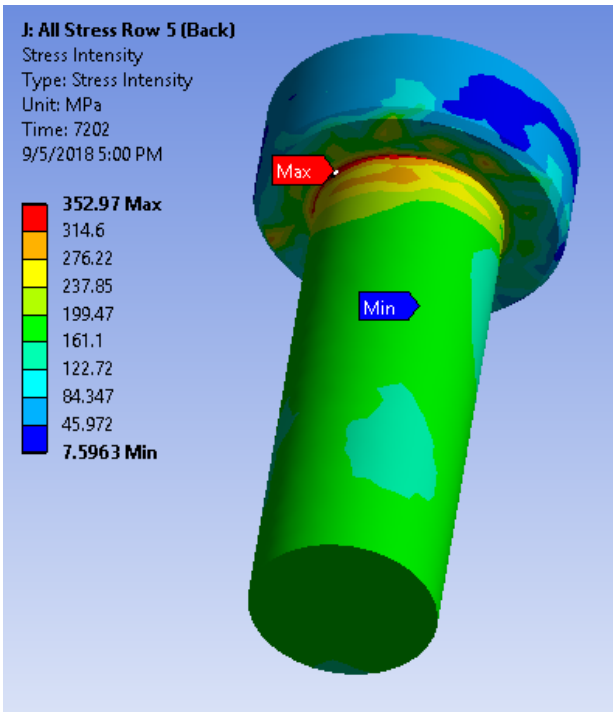


Figure 21: Default Row 5, Strike Point on Edges, All Mechanical Loads, Stress on Bolt

5.1.4 Row 6 All Mechanical Loads

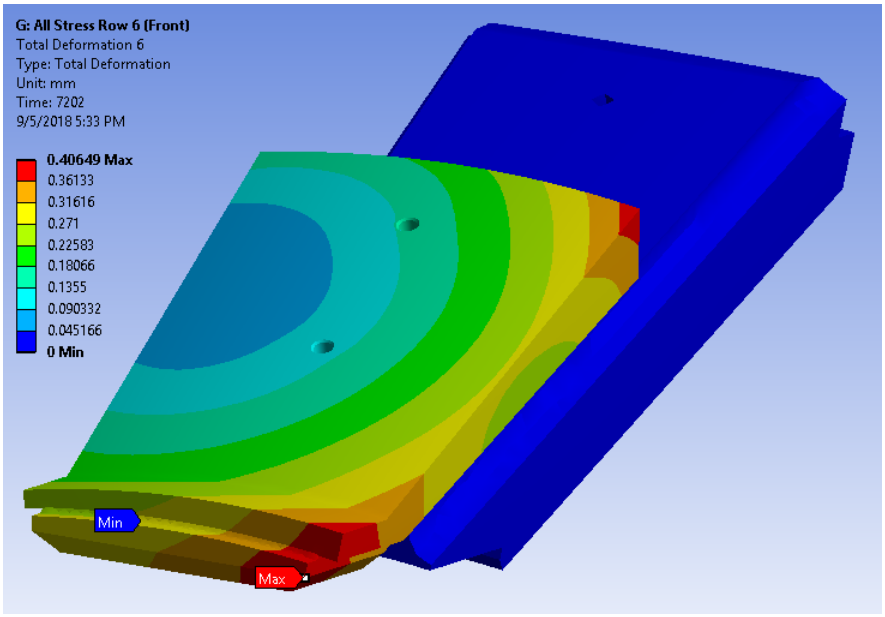


Figure 22: Default Row 6 Tile, Strike Point on Edge, All Mechanical Stress Deformation

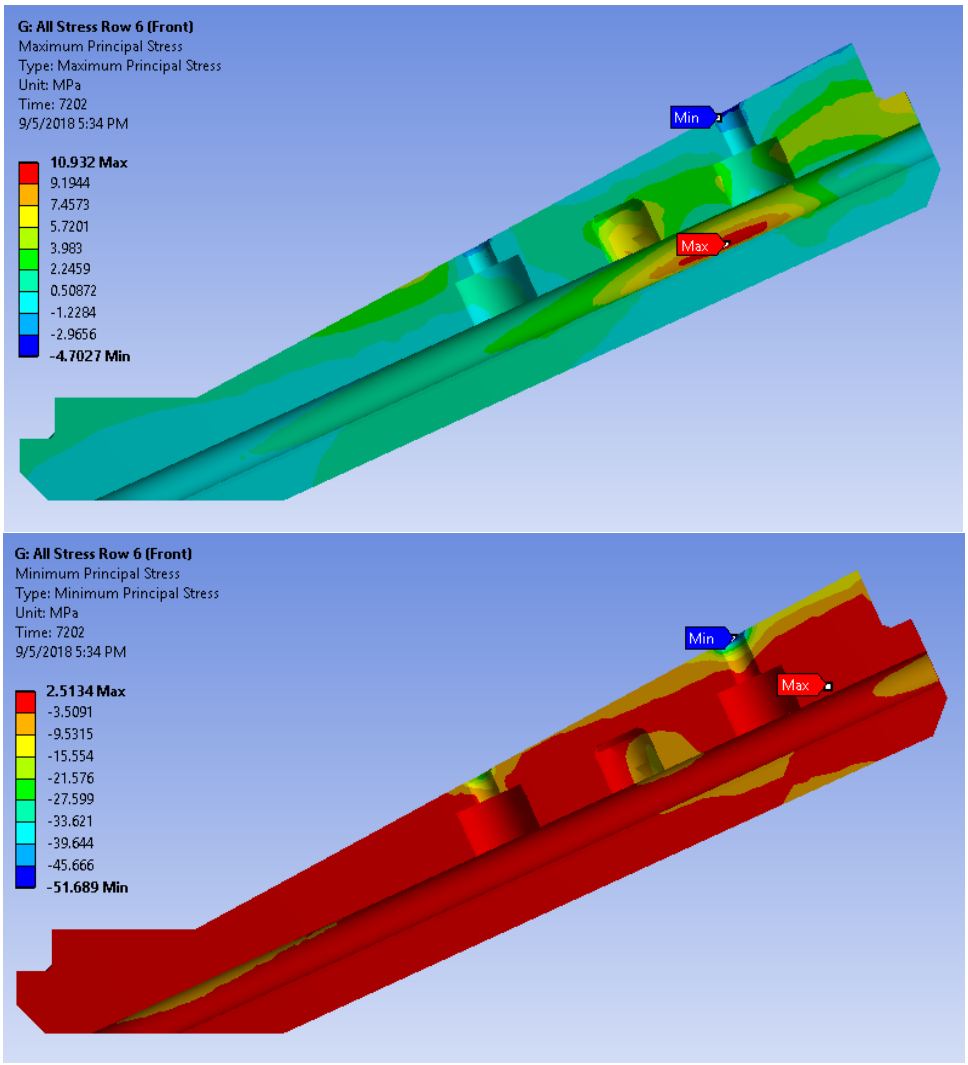


Figure 23: Default Row 6 Tile, Strike Point on Edge, All Mechanical Stresses

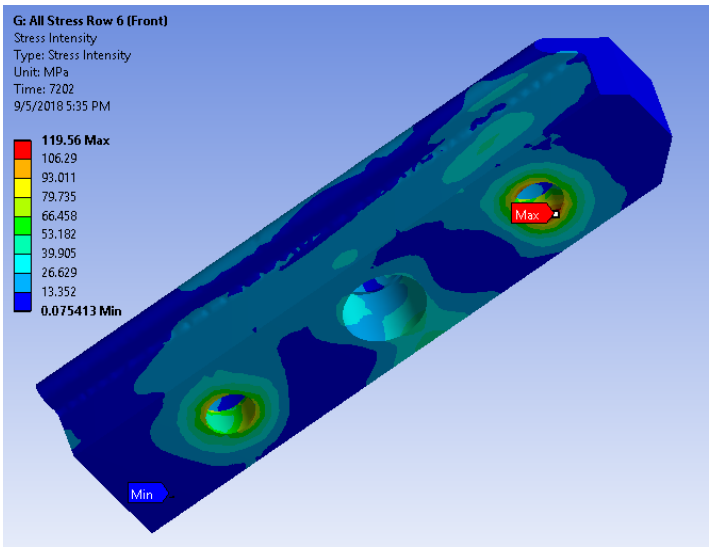


Figure 24: Default Row 6, Strike Point on Edges, All Mechanical Loads, Stress on T-Bar

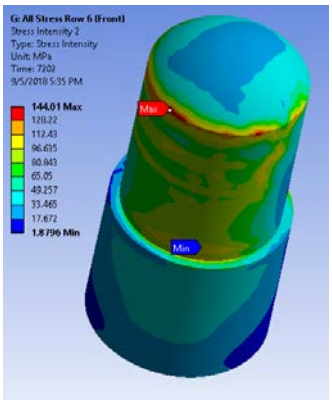


Figure 25: Default Row 6, Strike Point on Edges, All Mechanical Loads, Stress on Shear Pin

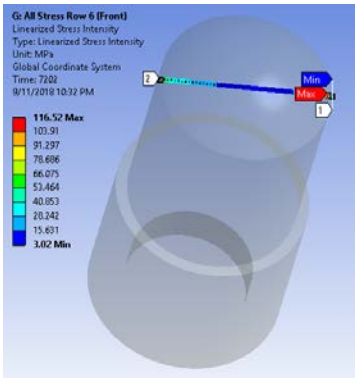


Figure 26: Shear Pin Linearized Stress for Default Row 6, Strike Point on Edges, All Mechanical Loads

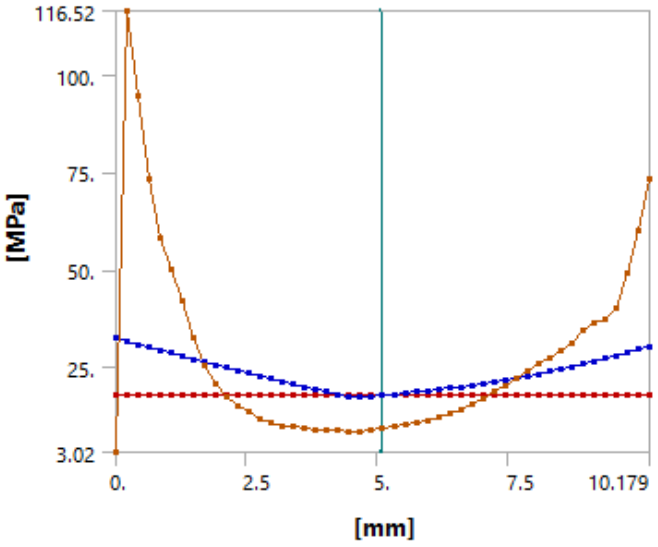


Figure 27: Shear Pin Linearized Stress Graph for Default Row 6, Strike Point on Edges, All Mechanical Loads

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	17.698	23.724	32.314	33.651	3.02
2	0.21207	17.698	22.735	31.538	102.34	116.52
3	0.42414	17.698	21.747	30.765	71.193	94.556
4	0.63621	17.698	20.758	29.997	43.533	73.201
5	0.84828	17.698	19.77	29.232	28.969	58.061
6	1.0604	17.698	18.781	28.472	21.594	49.903
7	1.2724	17.698	17.793	27.715	14.383	41.751
8	1.4845	17.698	16.804	26.964	8.2991	32.642
9	1.6966	17.698	15.816	26.218	8.6785	25.414
10	1.9086	17.698	14.827	25.476	11.308	20.727
11	2.1207	17.698	13.839	24.741	14.317	17.314
12	2.3328	17.698	12.85	24.011	17.006	14.98
13	2.5448	17.698	11.862	23.288	18.884	13.247
14	2.7569	17.698	10.873	22.573	20.768	11.745
15	2.969	17.698	9.885	21.865	22.315	10.5
16	3.1811	17.698	8.8965	21.167	23.31	9.6656
17	3.3931	17.698	7.908	20.479	23.612	9.4607
18	3.6052	17.698	6.9195	19.804	23.354	9.1412
19	3.8173	17.698	5.931	19.147	23.319	8.8914
20	4.0293	17.698	4.9425	18.517	23.633	8.7444
21	4.2414	17.698	3.954	17.938	23.589	8.5536
22	4.4535	17.698	2.9655	17.501	22.828	8.2552
23	4.6655	17.698	1.977	17.374	22.082	8.4417
24	4.8776	17.698	0.9885	17.491	21.355	8.7795
25	5.0897	17.698	4.6566e-016	17.698	20.642	9.2449
26	5.3018	17.698	0.9885	17.944	19.71	9.8032
27	5.5138	17.698	1.977	18.214	18.235	10.142
28	5.7259	17.698	2.9655	18.503	16.744	10.68
29	5.938	17.698	3.954	18.809	15.227	11.323
30	6.15	17.698	4.9425	19.135	13.699	12.12
31	6.3621	17.698	5.931	19.479	12.32	13.037
32	6.5742	17.698	6.9195	19.845	10.775	14.16
33	6.7863	17.698	7.908	20.232	9.2024	15.441
34	6.9983	17.698	8.8965	20.644	7.8971	16.959
35	7.2104	17.698	9.885	21.082	7.1099	18.62
36	7.4225	17.698	10.873	21.547	6.9607	20.348
37	7.6345	17.698	11.862	22.041	7.3901	22.127
38	7.8466	17.698	12.85	22.565	8.2636	23.684
39	8.0587	17.698	13.839	23.12	9.5395	25.602
40	8.2707	17.698	14.827	23.705	10.781	27.299
41	8.4828	17.698	15.816	24.321	12.158	29.001
42	8.6949	17.698	16.804	24.967	13.495	30.987
43	8.907	17.698	17.793	25.641	14.948	34.599
44	9.119	17.698	18.781	26.342	17.879	36.438
45	9.3311	17.698	19.77	27.069	21.236	37.009
46	9.5432	17.698	20.758	27.818	24.044	40.226
47	9.7552	17.698	21.747	28.588	33.795	49.118
48	9.9673	17.698	22.735	29.378	48.077	60.054
49	10.179	17.698	23.724	30.185	64.096	73.116

Table 4: Figure 27: Shear Pin Linearized Stress Table for Default Row 6, Strike Point on Edges, All Mechanical Loads

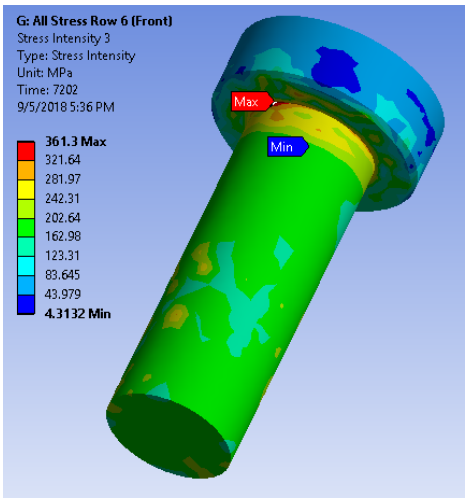


Figure 28: Default Row 6, Strike Point on Edges, All Mechanical Loads, Stress on Bolt

5.1.5 Preload Only [No Thermal inputs]

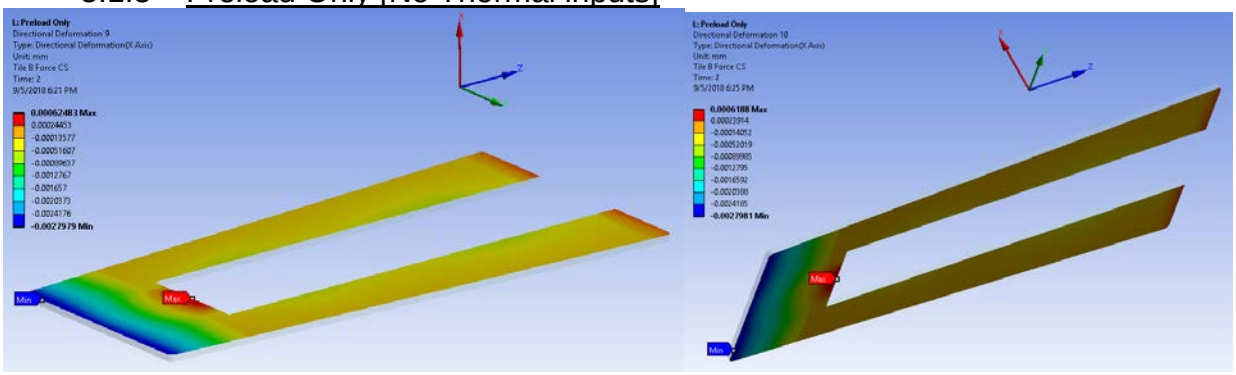


Figure 29: Top and Bottom Surface Deformation of Row 6 Grafoil

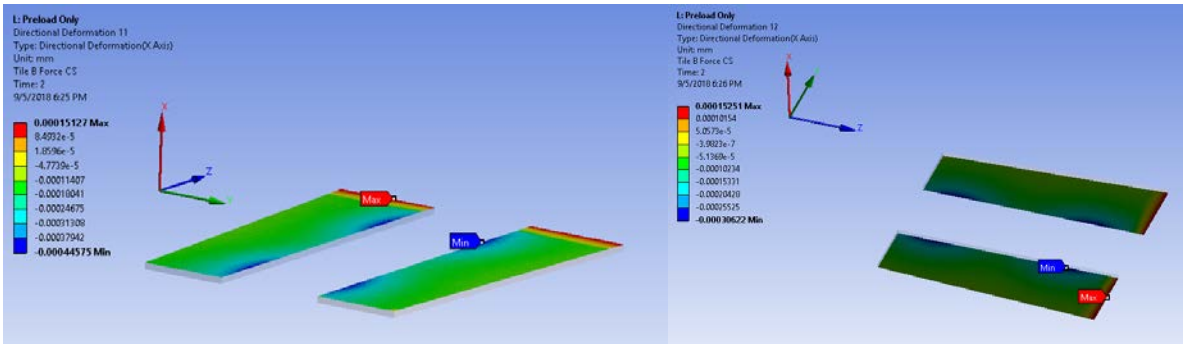


Figure 30: Top and Bottom Surface Deformation of Row 5 Grafoil

Row 5 Compression						Row 6 Compression					
Top Surface		Bottom Surface		Change in gasket thickness [mm]		Top Surface		Bottom Surface		Change in gasket thickness [mm]	
Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1.51E-04	-4.46E-04	1.53E-04	-3.06E-04	1.24E-06	1.40E-04	6.25E-04	-2.80E-03	6.19E-04	-2.80E-03	6.03E-06	2.00E-07

	Overall Max	Overall Min
mm	1.24E-06	1.40E-04
in	4.88E-08	5.49E-06
% deformation	0.000081	9.16E-03

	Overall Max	Overall Min
mm	6.03E-06	2E-07
in	2.37402E-07	7.87402E-09
% deformation	0.000396	1.31234E-05

Table 5: Grafoil Deformation Calculation

5.2 6510 Transient Thermal with Max Flux over Shear Pin [Standard Row 5 and 6 Tiles]

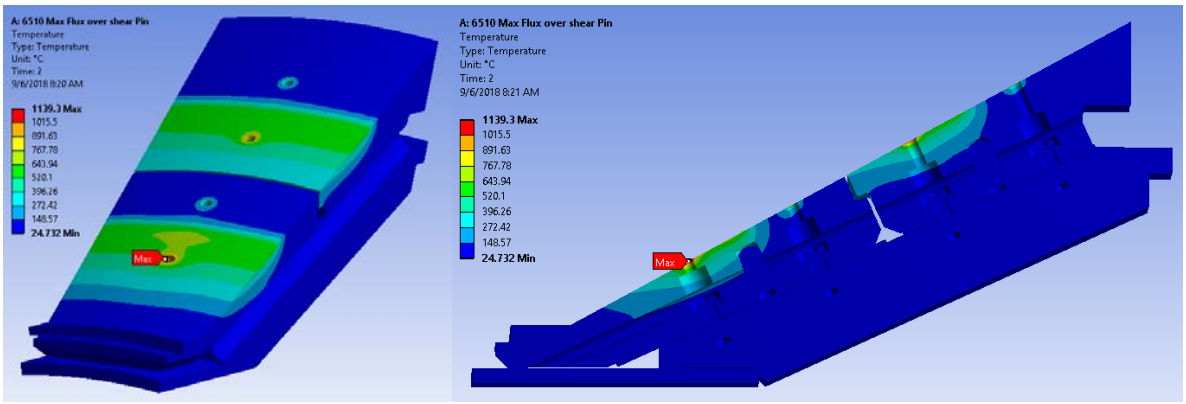


Figure 31: Standard Tiles With Strike Point over Shear Pins Temperature After First Flux Shot

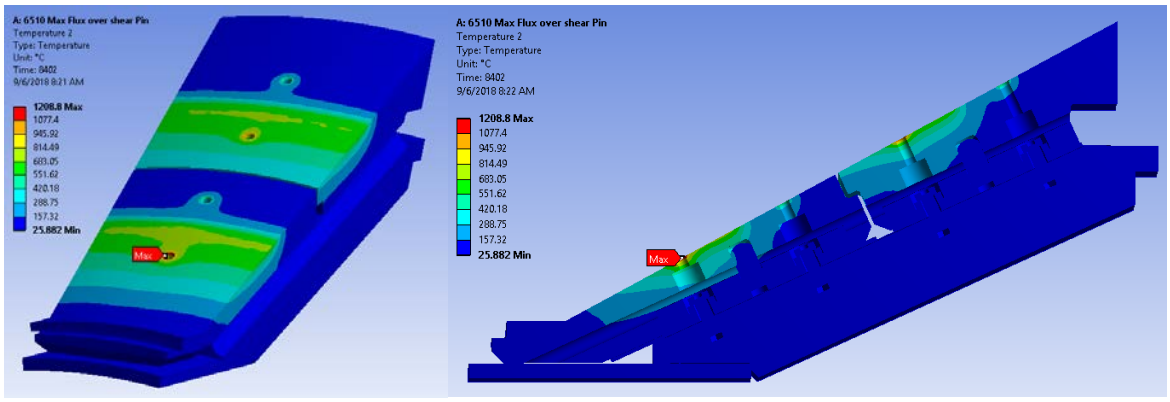


Figure 32: Standard Tiles With Strike Point over Shear Pins Temperature After Eighth Flux Shot

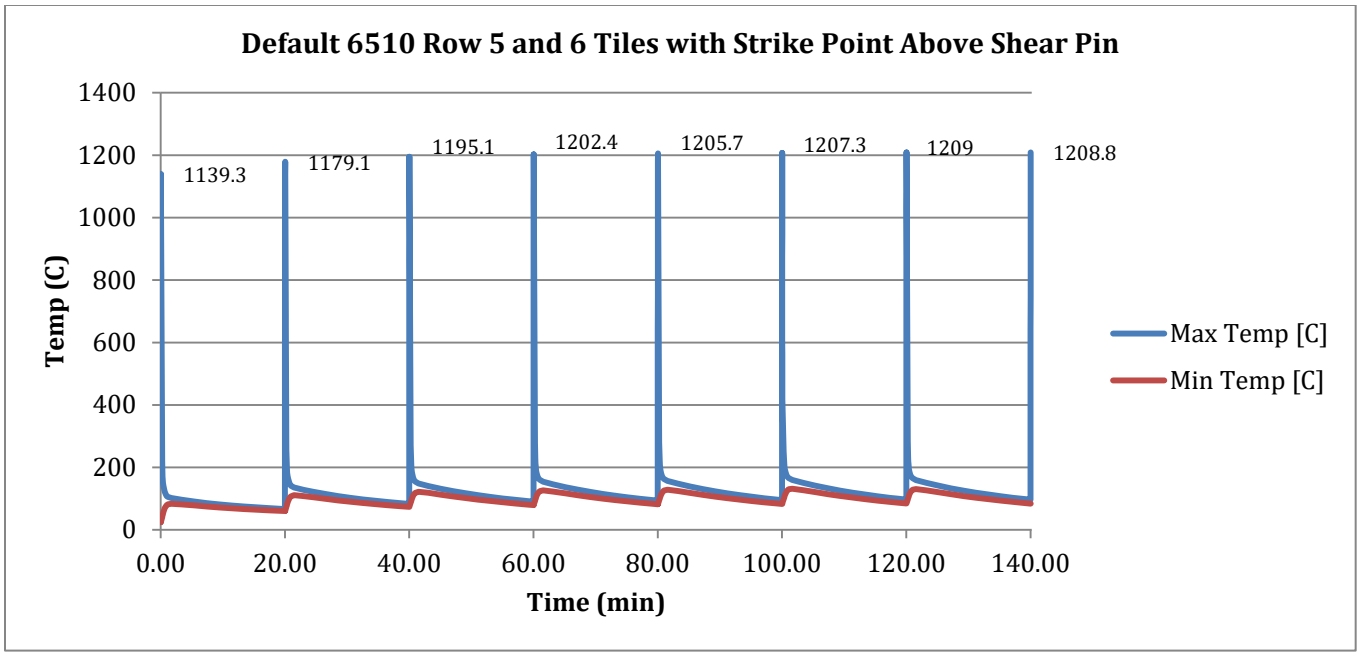


Figure 33: Transient Thermal Results for Default Tiles with Strike Point over Shear Pins

5.2.1 Row 5 All Mechanical Loads

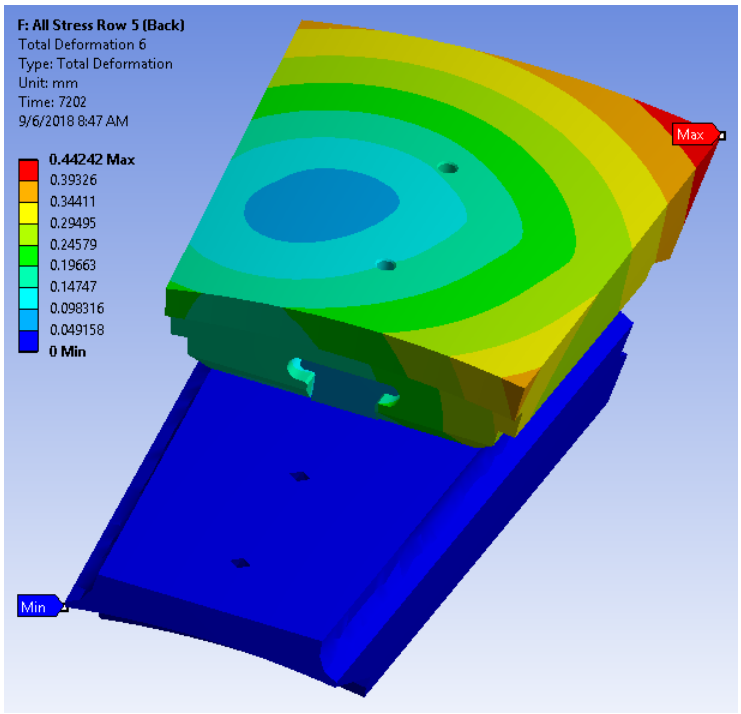


Figure 34: Default Row 5 Tile, Strike Point over shear Pin, All Mechanical Stress Deformation

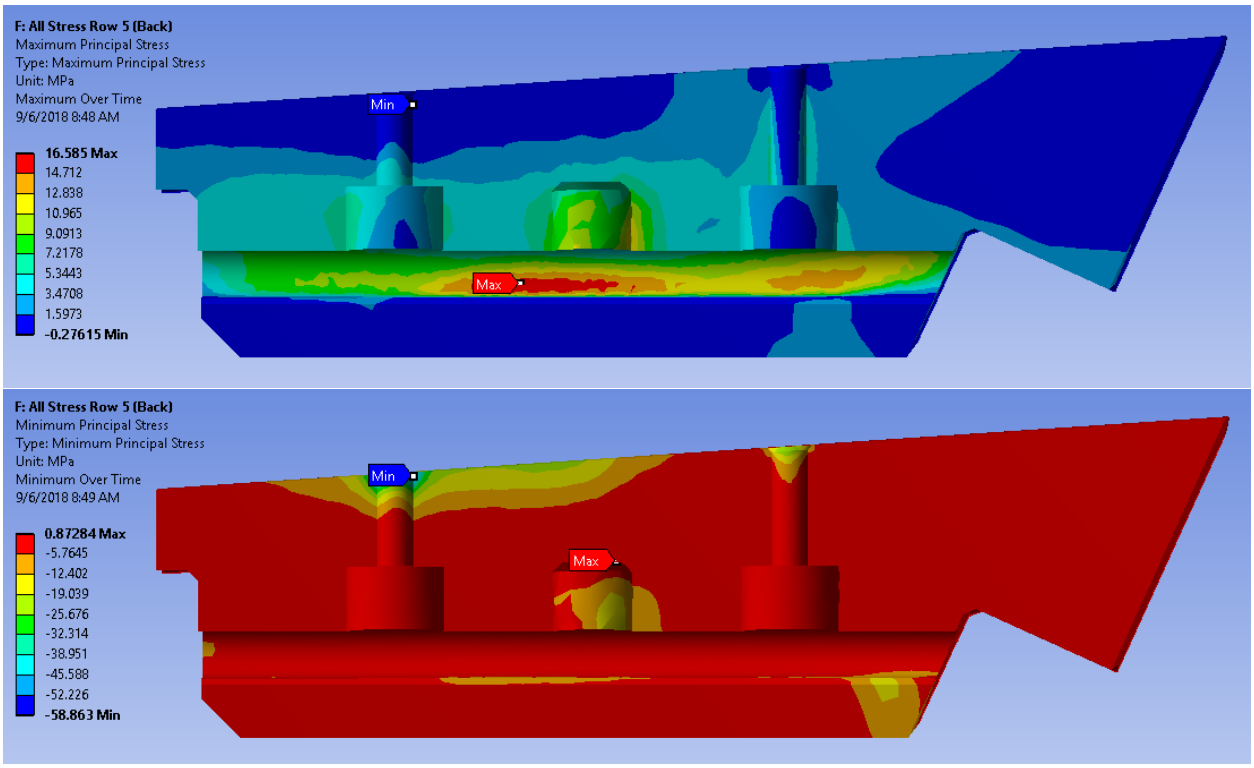


Figure 35: Default Row 5 Tile, Strike Point on Edge, All Mechanical Stresses

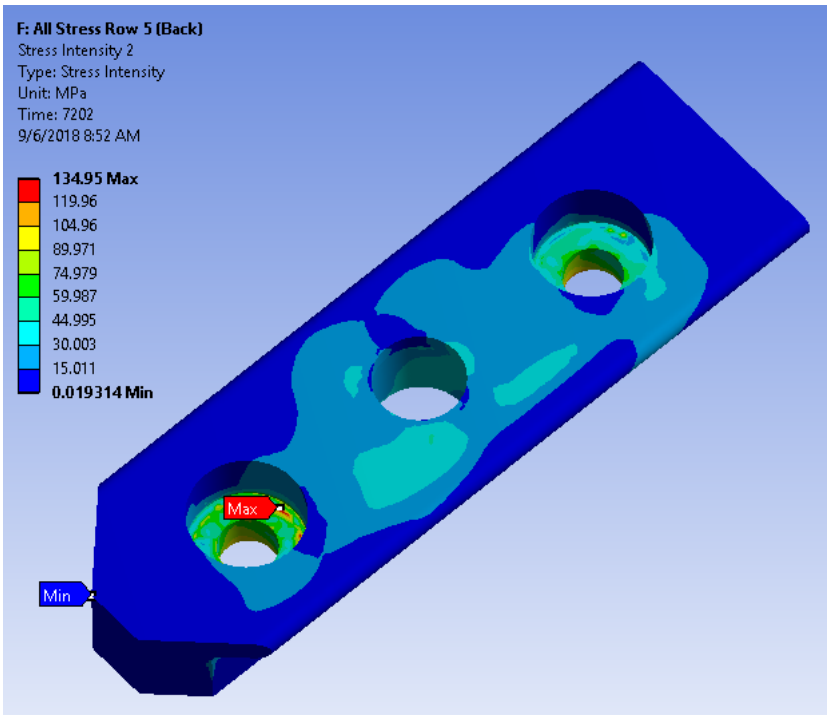


Figure 36: Default Row 65, Strike Point Over Shear Pins, All Mechanical Loads, Stress on T-Bar

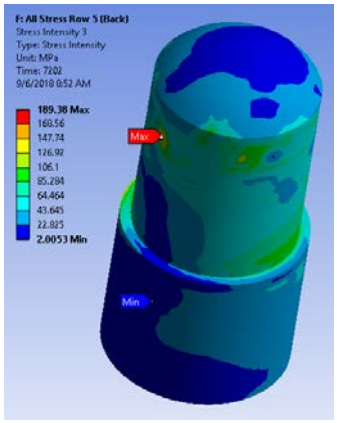


Figure 37: Default Row 5, Strike Point Over Shear Pins, All Mechanical Loads, Stress on Shear Pin

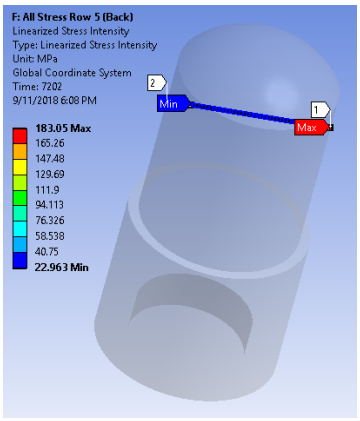


Figure 38: Shear Pin Linearized Stress for Default Row 5, Strike Point over shear Pin, All Mechanical Loads

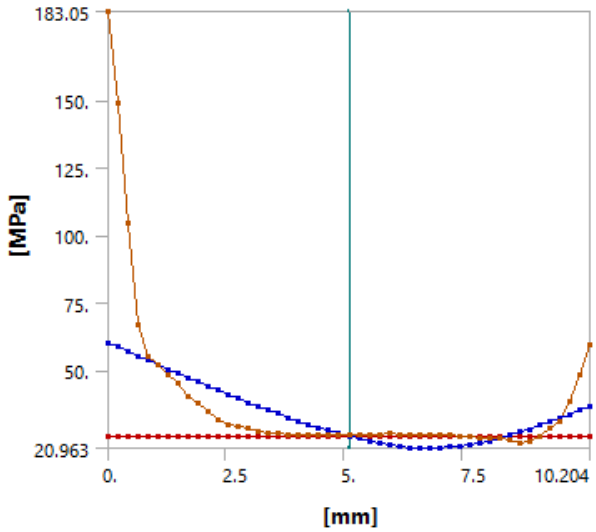


Figure 39: Shear Pin Linearized Stress Graph for Default Row 5, Strike Point over Shear Pin, All Mechanical Loads

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	25.344	43.371	60.084	145.23	183.05
2	0.21258	25.344	41.564	58.417	111.19	148.92
3	0.42516	25.344	39.757	56.76	65.67	104.36
4	0.63774	25.344	37.949	55.112	22.733	66.852
5	0.85032	25.344	36.142	53.475	24.686	55.254
6	1.0629	25.344	34.335	51.849	22.432	51.764
7	1.2755	25.344	32.528	50.236	20.532	48.3
8	1.4881	25.344	30.721	48.636	19.094	44.874
9	1.7006	25.344	28.914	47.051	17.446	40.039
10	1.9132	25.344	27.107	45.483	17.859	37.403
11	2.1258	25.344	25.3	43.932	18.475	34.504
12	2.3384	25.344	23.493	42.4	19.203	31.712
13	2.551	25.344	21.685	40.889	19.737	29.413
14	2.7635	25.344	19.878	39.4	18.765	29.113
15	2.9761	25.344	18.071	37.937	18.332	28.214
16	3.1887	25.344	16.264	36.5	18.444	27.252
17	3.4013	25.344	14.457	35.093	18.217	26.602
18	3.6138	25.344	12.65	33.719	17.447	26.357
19	3.8264	25.344	10.843	32.38	16.795	26.205
20	4.039	25.344	9.0356	31.08	16.482	26.138
21	4.2516	25.344	7.2285	29.824	16.269	26.039
22	4.4642	25.344	5.4214	28.615	15.666	26.016
23	4.6767	25.344	3.6142	27.461	15.067	25.924
24	4.8893	25.344	1.8071	26.368	14.505	25.868
25	5.1019	25.344	1.5636e-014	25.344	13.985	25.845
26	5.3145	25.344	1.8071	24.398	13.185	25.892
27	5.5271	25.344	3.6142	23.542	12.561	25.954
28	5.7396	25.344	5.4214	22.787	12.143	26.076
29	5.9522	25.344	7.2285	22.147	11.918	26.256
30	6.1648	25.344	9.0356	21.634	11.31	26.11
31	6.3774	25.344	10.843	21.26	10.756	25.985
32	6.59	25.344	12.65	21.034	10.404	25.878
33	6.8025	25.344	14.457	20.963	10.13	25.767
34	7.0151	25.344	16.264	21.05	9.9438	25.804
35	7.2277	25.344	18.071	21.295	9.79	25.621
36	7.4403	25.344	19.878	21.693	9.8153	25.335
37	7.6529	25.344	21.685	22.24	10.186	25.045
38	7.8654	25.344	23.493	22.927	10.012	24.707
39	8.078	25.344	25.3	23.745	9.8653	24.466
40	8.2906	25.344	27.107	24.68	10.926	24.512
41	8.5032	25.344	28.914	25.721	11.943	24.239
42	8.7157	25.344	30.721	26.854	12.436	22.963
43	8.9283	25.344	32.528	28.068	15.162	23.305
44	9.1409	25.344	34.335	29.352	18.461	25.194
45	9.3535	25.344	36.142	30.695	23.052	28.581
46	9.5661	25.344	37.949	32.089	23.52	30.612
47	9.7786	25.344	39.757	33.526	25.984	38.571
48	9.9912	25.344	41.564	35.002	30.878	48.282
49	10.204	25.344	43.371	36.509	37.899	59.084

Table 6: Shear Pin Linearized Stress Table for Default Row 5, Strike Point over Shear Pin, All Mechanical Loads

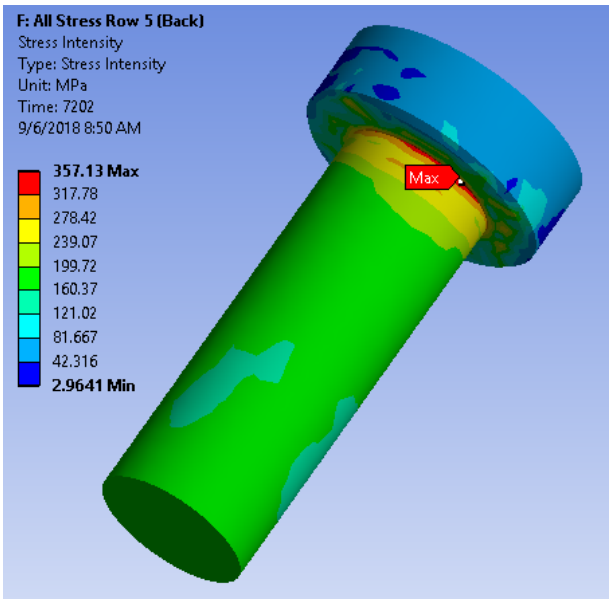


Figure 40: Default Row 5, Strike Point Over Shear Pins, All Mechanical Loads, Stress on Bolt

5.2.2 Row 6 All Mechanical Loads

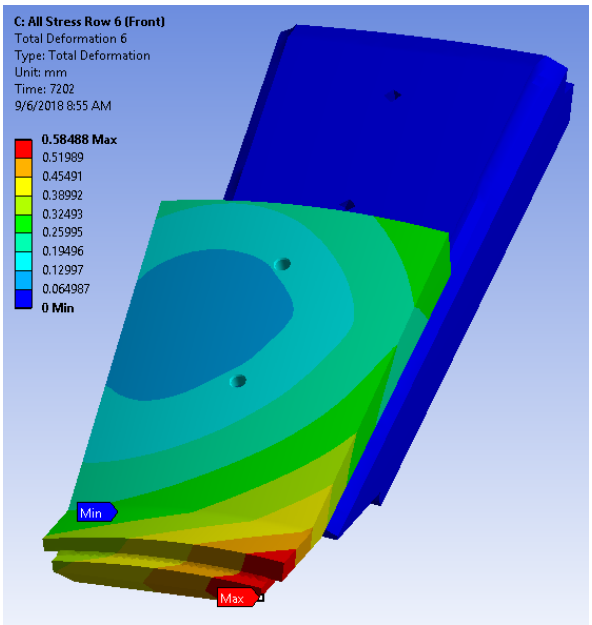


Figure 41: Default Row 6 Tile, Strike Point over shear Pin, All Mechanical Stress Deformation

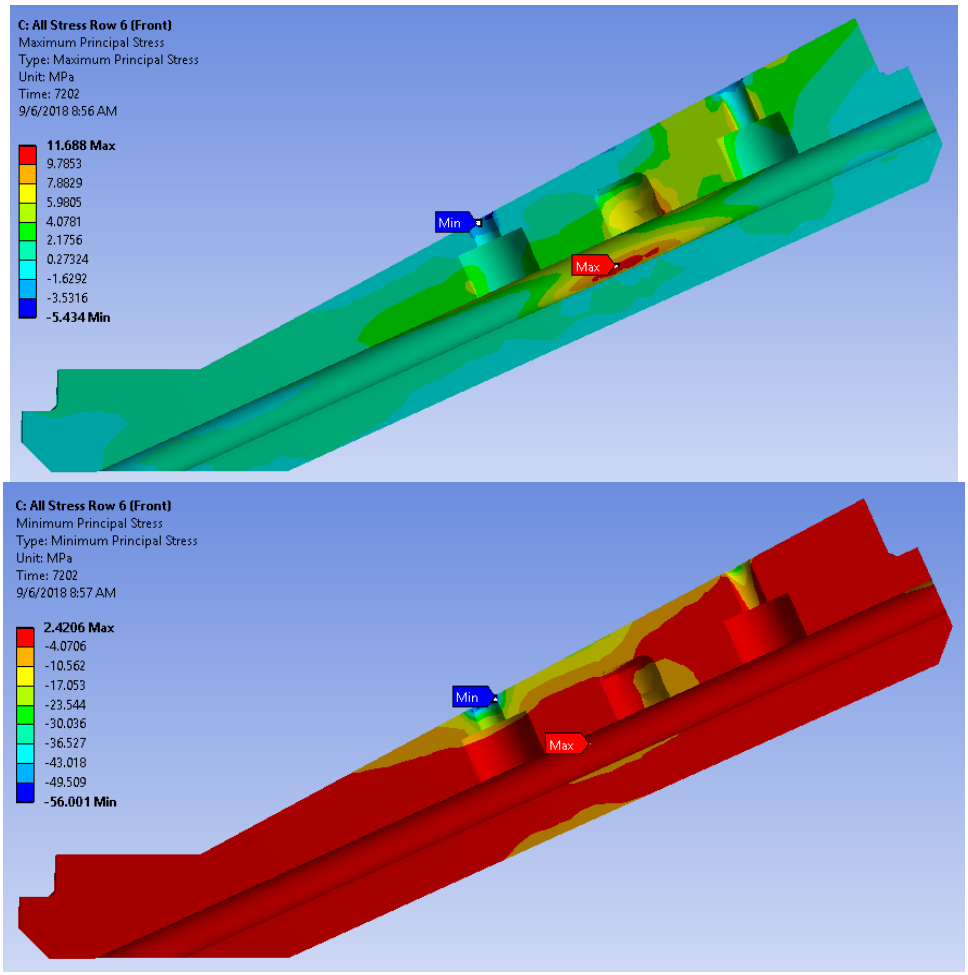


Figure 42: Default Row 6 Tile, Strike Point on Edge, All Mechanical Stresses

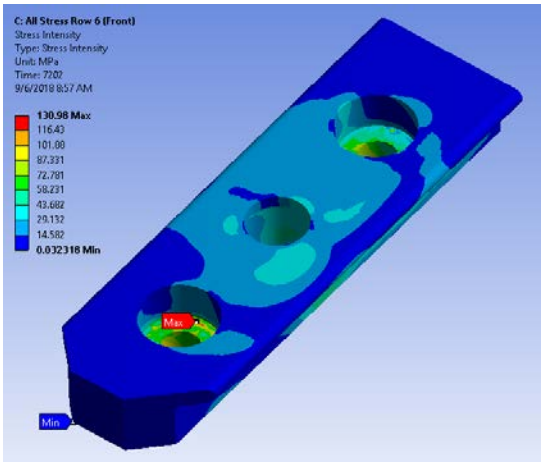


Figure 43: Default Row 6, Strike Point Over Shear Pins, All Mechanical Loads, Stress on T-Bar

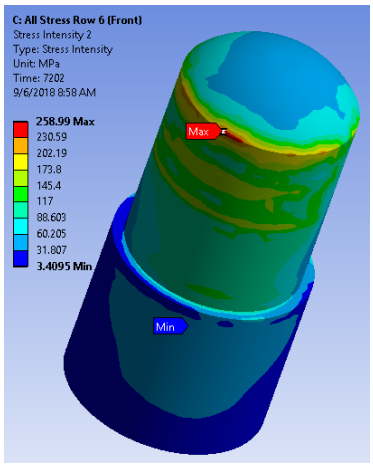


Figure 44: Default Row 6, Strike Point Over Shear Pins, All Mechanical Loads, Stress on Shear Pin

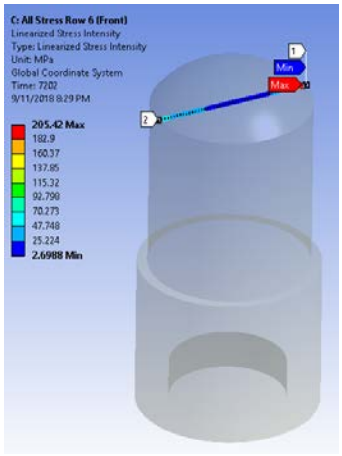


Figure 45: Shear Pin Linearized Stress for Default Row 6, Strike Point over Shear Pin, All Mechanical Loads

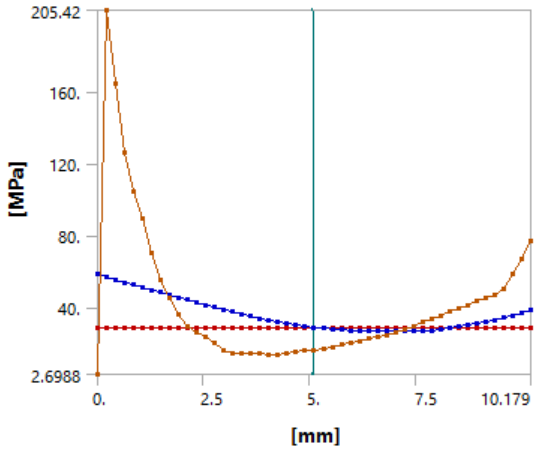


Figure 46: Shear Pin Linearized Stress Graph for Default Row 6, Strike Point over Shear Pin, All Mechanical Loads

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	28.676	37.143	58.285	59.106	2.6988
2	0.21207	28.676	35.595	56.845	177.77	205.42
3	0.42414	28.676	34.048	55.41	118.84	164.88
4	0.63621	28.676	32.5	53.979	72.549	126.51
5	0.84828	28.676	30.952	52.552	52.105	104.62
6	1.0604	28.676	29.405	51.132	38.302	89.331
7	1.2724	28.676	27.857	49.717	20.489	70.092
8	1.4845	28.676	26.31	48.309	15.42	55.305
9	1.6966	28.676	24.762	46.909	15.452	45.458
10	1.9086	28.676	23.214	45.518	21.608	35.966
11	2.1207	28.676	21.667	44.137	26.722	29.717
12	2.3328	28.676	20.119	42.769	31.645	26.405
13	2.5448	28.676	18.571	41.416	34.856	23.25
14	2.7569	28.676	17.024	40.081	36.915	20.022
15	2.969	28.676	15.476	38.767	38.175	16.424
16	3.1811	28.676	13.929	37.48	39.375	14.587
17	3.3931	28.676	12.381	36.225	40.334	14.694
18	3.6052	28.676	10.833	35.012	40.503	14.456
19	3.8173	28.676	9.2857	33.85	40.701	14.312
20	4.0293	28.676	7.7381	32.752	39.774	13.69
21	4.2414	28.676	6.1905	31.733	38.752	13.766
22	4.4535	28.676	4.6429	30.806	37.886	14.387
23	4.6655	28.676	3.0952	29.984	37.02	14.972
24	4.8776	28.676	1.5476	29.274	36.049	15.865
25	5.0897	28.676	8.2057e-013	28.676	33.841	16.084
26	5.3018	28.676	1.5476	28.183	31.677	16.77
27	5.5138	28.676	3.0952	27.781	29.527	17.843
28	5.7259	28.676	4.6429	27.459	27.115	19.059
29	5.938	28.676	6.1905	27.203	24.481	20.114
30	6.15	28.676	7.7381	27.004	21.865	21.261
31	6.3621	28.676	9.2857	26.855	19.004	22.449
32	6.5742	28.676	10.833	26.751	15.983	23.442
33	6.7863	28.676	12.381	26.691	13.035	24.516
34	6.9983	28.676	13.929	26.678	10.351	25.825
35	7.2104	28.676	15.476	26.717	8.9801	27.493
36	7.4225	28.676	17.024	26.819	8.5886	29.631
37	7.6345	28.676	18.571	27.002	8.9427	31.676
38	7.8466	28.676	20.119	27.289	10.177	33.651
39	8.0587	28.676	21.667	27.707	12.053	35.638
40	8.2707	28.676	23.214	28.278	13.946	37.39
41	8.4828	28.676	24.762	29.011	15.879	39.111

Table 7: Shear Pin Linearized Stress Table for Default Row 6, Strike Point over Shear Pin, All Mechanical Loads

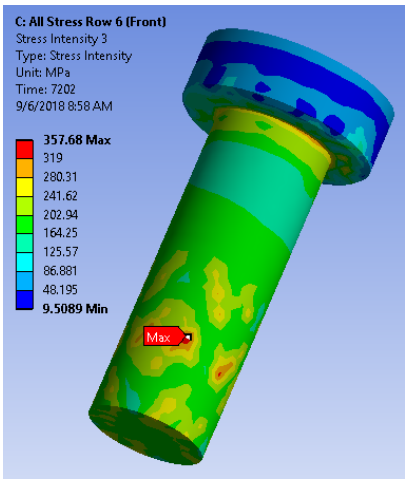


Figure 47: Default Row 5, Strike Point Over Shear Pins, All Mechanical Loads, Stress on Bolt

5.3 6510 Transient Thermal with Max Flux Over Shear Pin [Diagnostic Tiles Row 5 and 6]

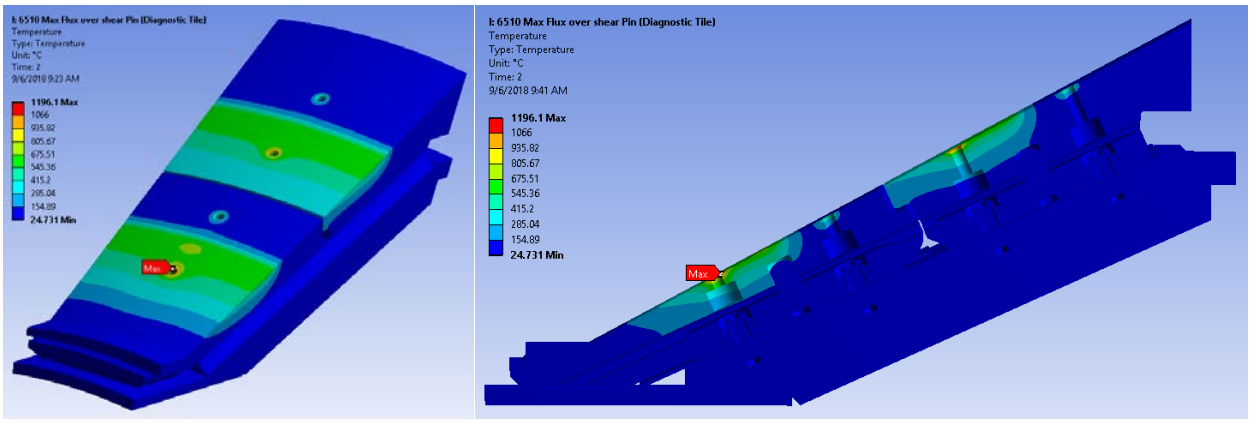


Figure 48: Diagnostic Tiles With Strike Point over Shear Pins Temperature After First Flux Shot

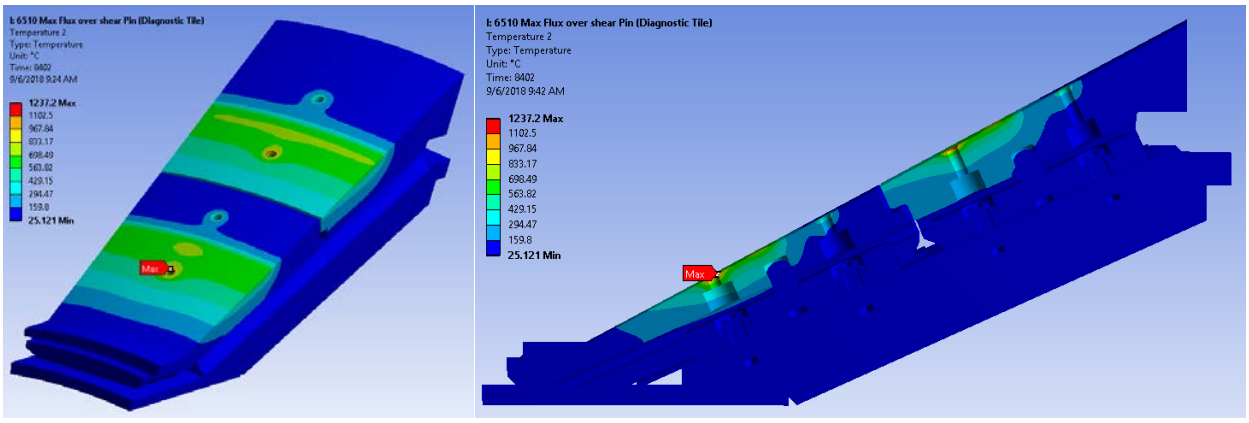


Figure 49: Diagnostic Tiles With Strike Point over Shear Pins Temperature After Eighth Flux Shot

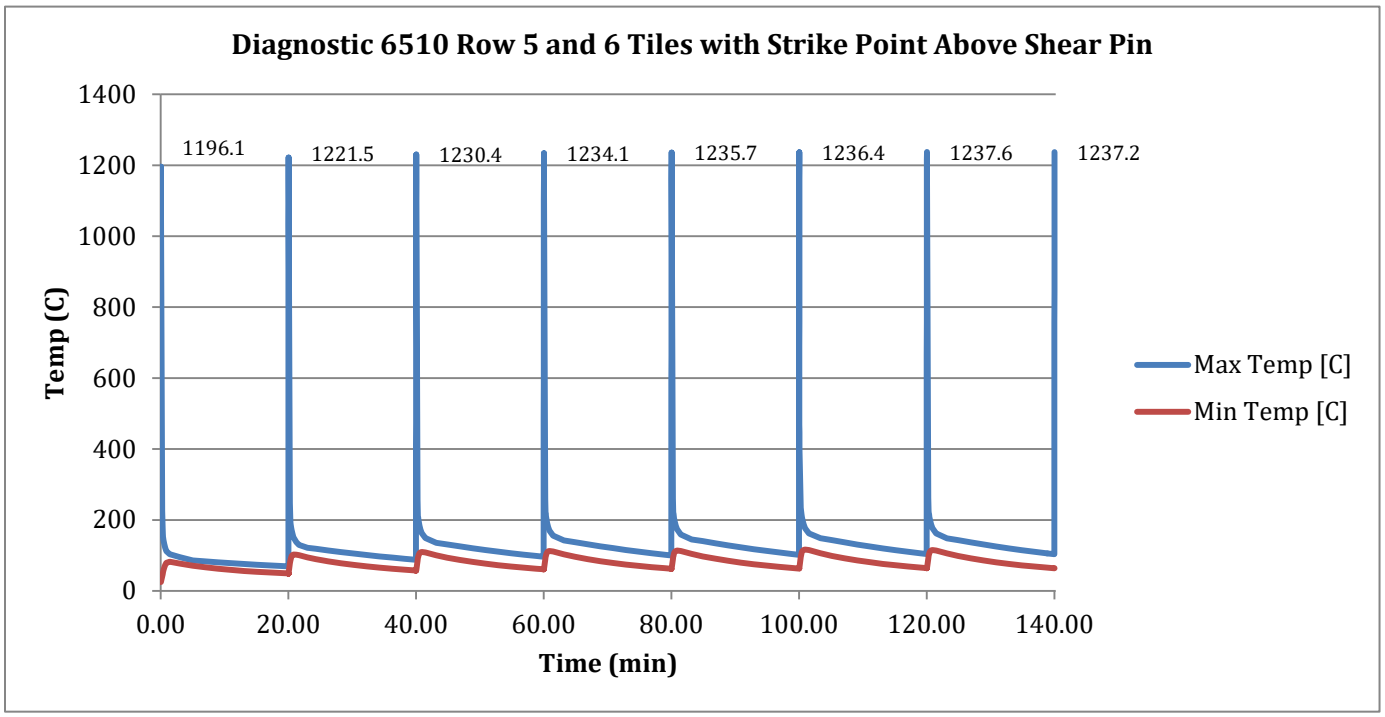


Figure 50: Transient Thermal Results for Diagnostic Tiles with Strike Point over Shear Pins

5.3.1 Row 5 Diagnostic Tile [Thermocouple], Thermal Stress

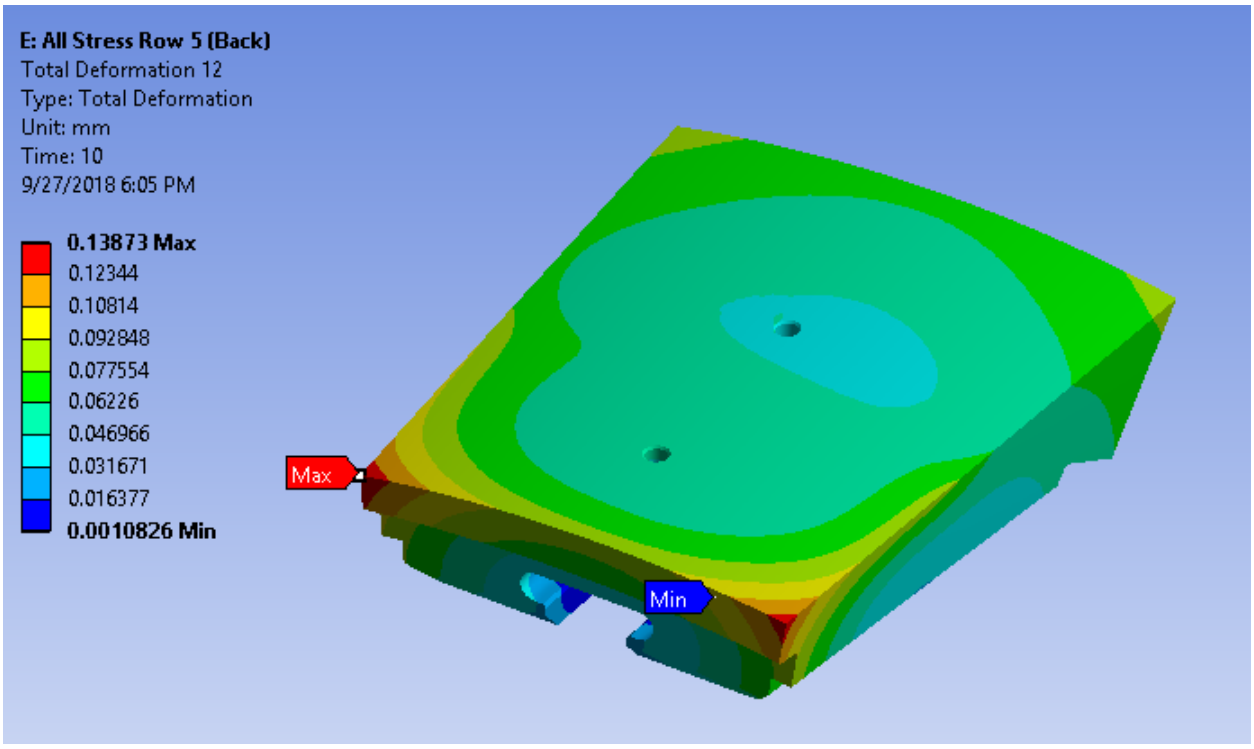
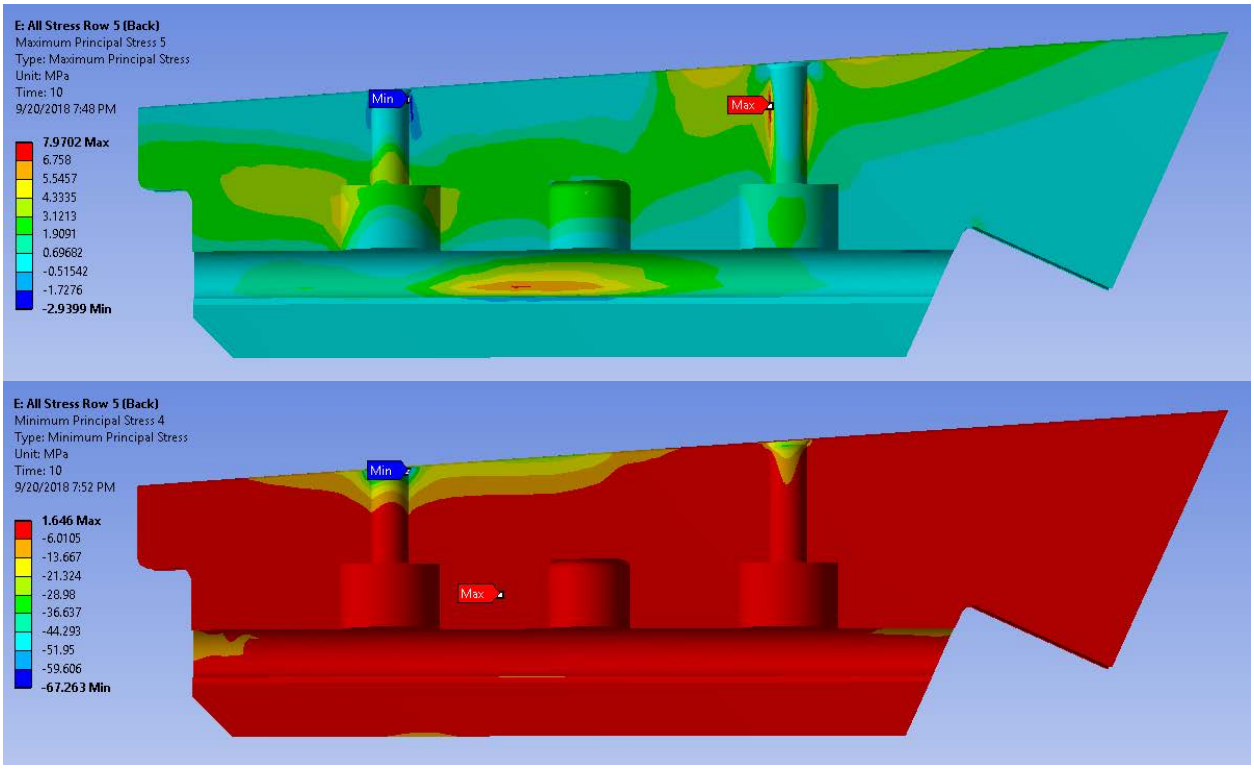


Figure 51: Row 5 (Thermocouple) 6510 Thermal Stress Deformation



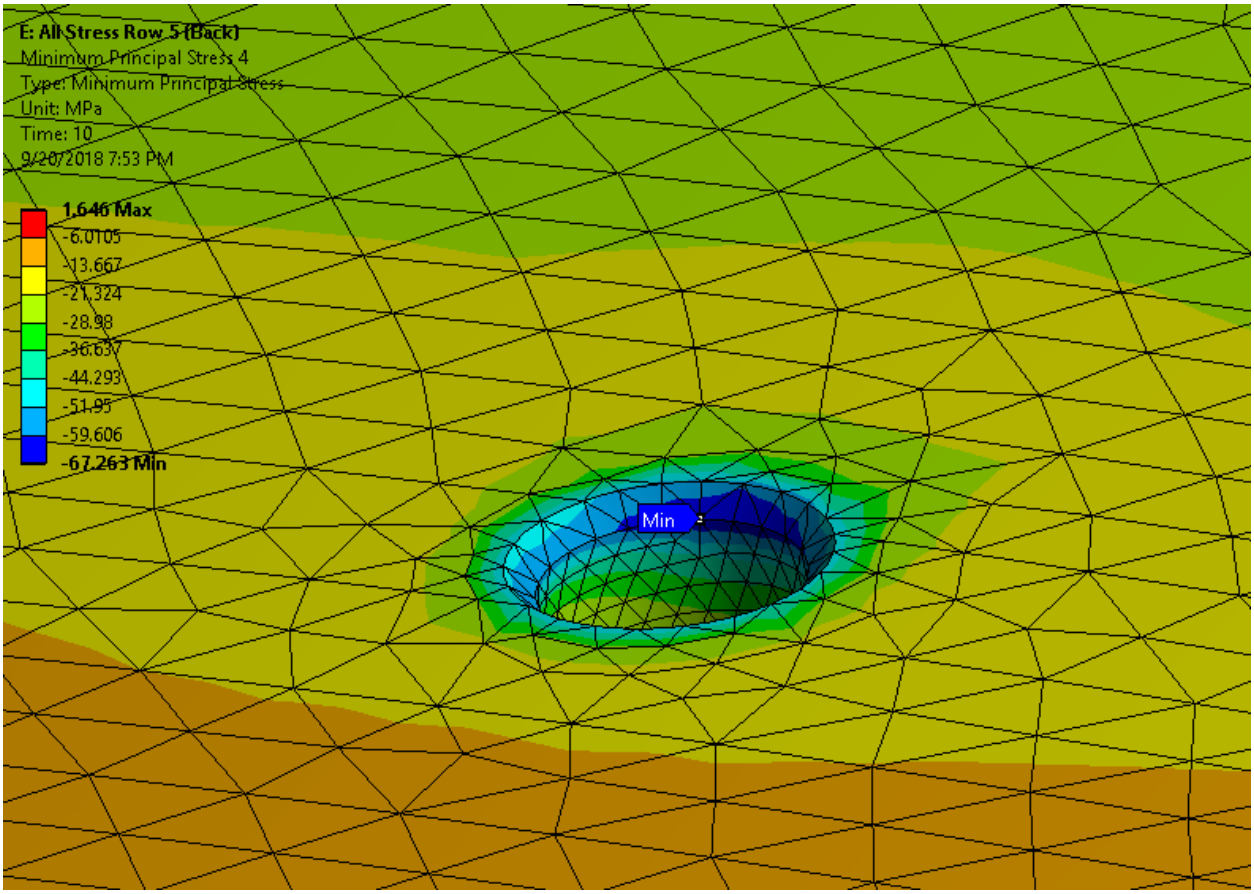


Figure 52: Row 5 (Thermocouple) 6510 Thermal Stresses

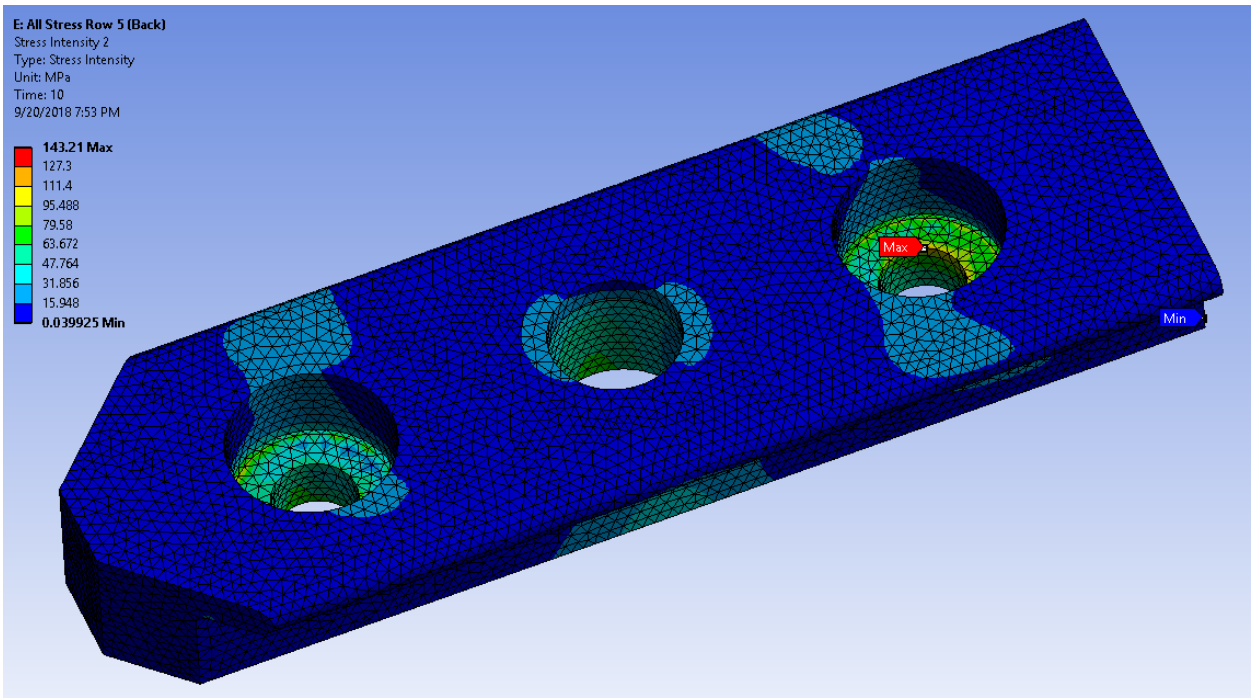


Figure 53: Row 5 (Thermocouple) 6510 Thermal Stress on T-Bar

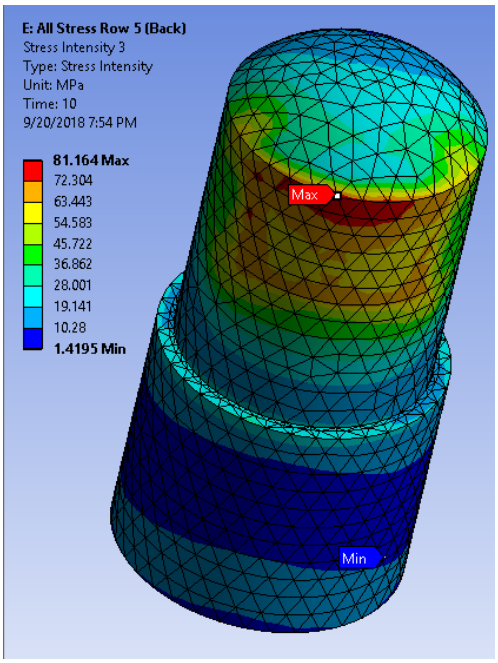


Figure 54: Row 5 (Thermocouple) 6510 Thermal Stress on Shear Pin

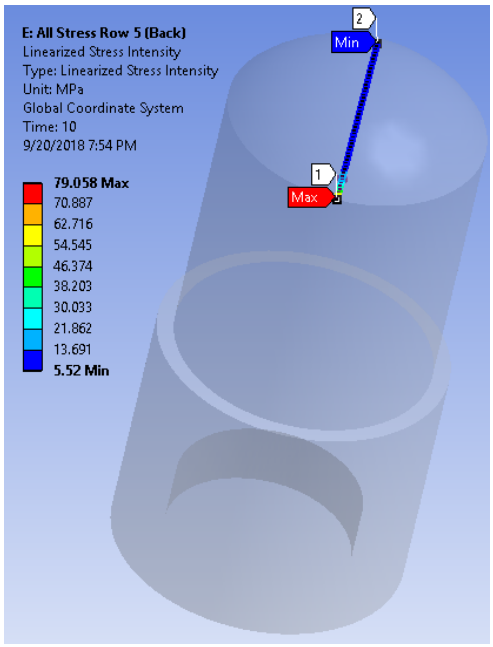


Figure 55: Shear Pin Linearized Stress for Row 5 (Thermocouple) 6510 with All Thermal Stress Loads

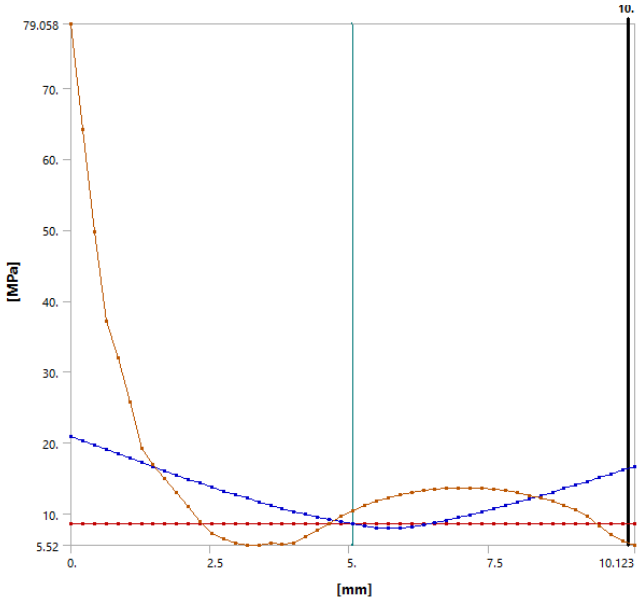


Figure 56: Shear Pin Linearized Stress Graph for Row 5 (Thermocouple) 6510 with Thermal Stress Loads

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	8.4941	15.775	20.824	62.887	79.058
2	0.21089	8.4941	15.118	20.206	44.762	64.099
3	0.42179	8.4941	14.46	19.591	30.247	49.808
4	0.63268	8.4941	13.803	18.98	18.352	37.18
5	0.84357	8.4941	13.146	18.373	13.73	32.028
6	1.0545	8.4941	12.488	17.769	9.4304	25.717
7	1.2654	8.4941	11.831	17.171	8.3032	19.145
8	1.4763	8.4941	11.174	16.578	9.6245	16.865
9	1.6871	8.4941	10.517	15.992	10.986	14.971
10	1.898	8.4941	9.8593	15.412	12.284	12.987
11	2.1089	8.4941	9.202	14.84	12.586	10.925
12	2.3198	8.4941	8.5447	14.277	13.243	8.8273
13	2.5307	8.4941	7.8874	13.725	13.681	7.1904
14	2.7416	8.4941	7.2302	13.184	14.419	6.3848
15	2.9525	8.4941	6.5729	12.656	14.579	5.8535
16	3.1634	8.4941	5.9156	12.143	14.275	5.521
17	3.3743	8.4941	5.2583	11.647	14.036	5.5366
18	3.5852	8.4941	4.601	11.17	13.86	5.8186
19	3.7961	8.4941	3.9437	10.713	13.296	5.7464
20	4.007	8.4941	3.2864	10.278	12.644	5.8558
21	4.2179	8.4941	2.6291	9.8675	11.933	6.6909
22	4.4288	8.4941	1.9719	9.4824	11.108	7.6399
23	4.6397	8.4941	1.3146	9.1241	10.302	8.6021
24	4.8505	8.4941	0.65729	8.7939	9.6491	9.6329
25	5.0614	8.4941	2.7033e-015	8.4941	8.8432	10.453
26	5.2723	8.4941	0.65729	8.2294	8.0384	11.128
27	5.4832	8.4941	1.3146	8.013	7.4256	11.743
28	5.6941	8.4941	1.9719	7.8822	7.075	12.245
29	5.905	8.4941	2.6291	7.9029	6.7269	12.602
30	6.1159	8.4941	3.2864	8.0793	6.3919	12.949
31	6.3268	8.4941	3.9437	8.3478	6.0403	13.277
32	6.5377	8.4941	4.601	8.6684	5.57	13.443
33	6.7486	8.4941	5.2583	9.0238	5.0896	13.593
34	6.9595	8.4941	5.9156	9.4057	4.5006	13.63
35	7.1704	8.4941	6.5729	9.8091	3.888	13.58
36	7.3813	8.4941	7.2302	10.231	3.7332	13.531
37	7.5922	8.4941	7.8874	10.667	3.9401	13.484
38	7.8031	8.4941	8.5447	11.118	4.1068	13.299
39	8.0139	8.4941	9.202	11.58	4.3483	12.949
40	8.2248	8.4941	9.8593	12.052	4.8035	12.574
41	8.4357	8.4941	10.517	12.533	5.383	12.156
42	8.6466	8.4941	11.174	13.023	6.117	11.705
43	8.8575	8.4941	11.831	13.52	7.0087	11.116
44	9.0684	8.4941	12.488	14.023	7.9311	10.489
45	9.2793	8.4941	13.146	14.532	8.9277	9.6402
46	9.4902	8.4941	13.803	15.046	10.372	8.2115
47	9.7011	8.4941	14.46	15.566	12.053	6.9642
48	9.912	8.4941	15.118	16.089	13.807	6.1715
49	10.123	8.4941	15.775	16.617	15.658	5.52

Table 8: Shear Pin Linearized Stress Table for Row 5 (Thermocouple) 6510 with Thermal Stress Loads

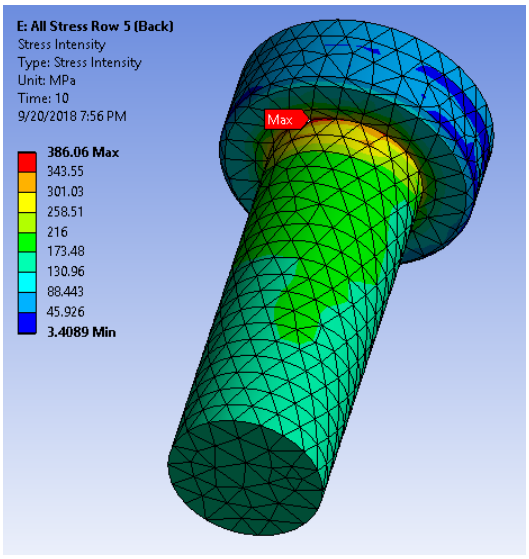


Figure 57: Row 5 (Thermocouple) 6510 with Thermal Stress Loads on Bolt

5.3.2 Row 6 Diagnostic Tile [Gas Injection] Thermal Stress

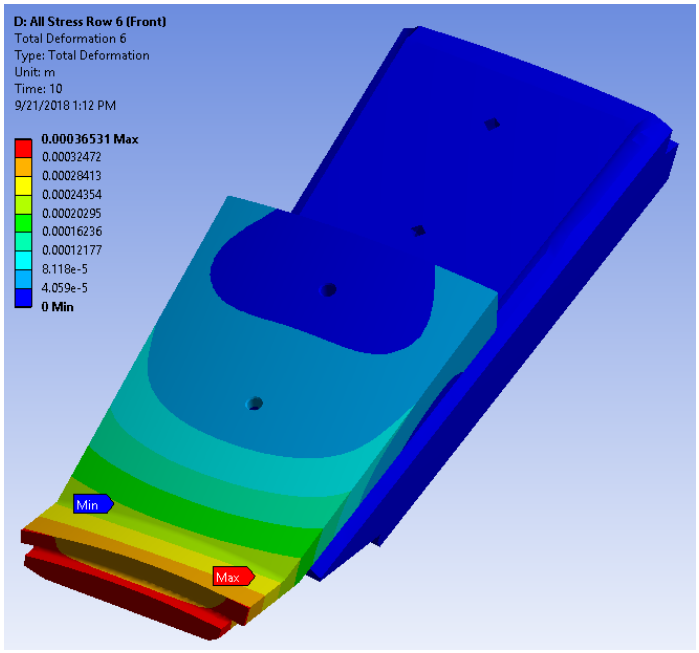
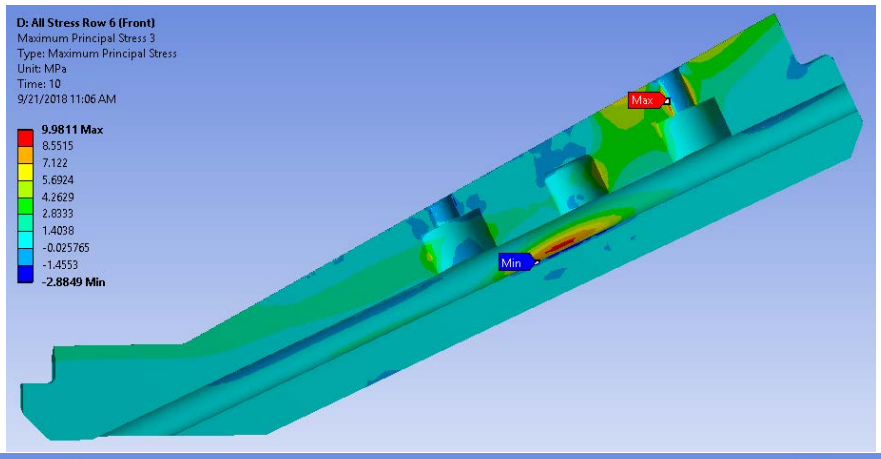
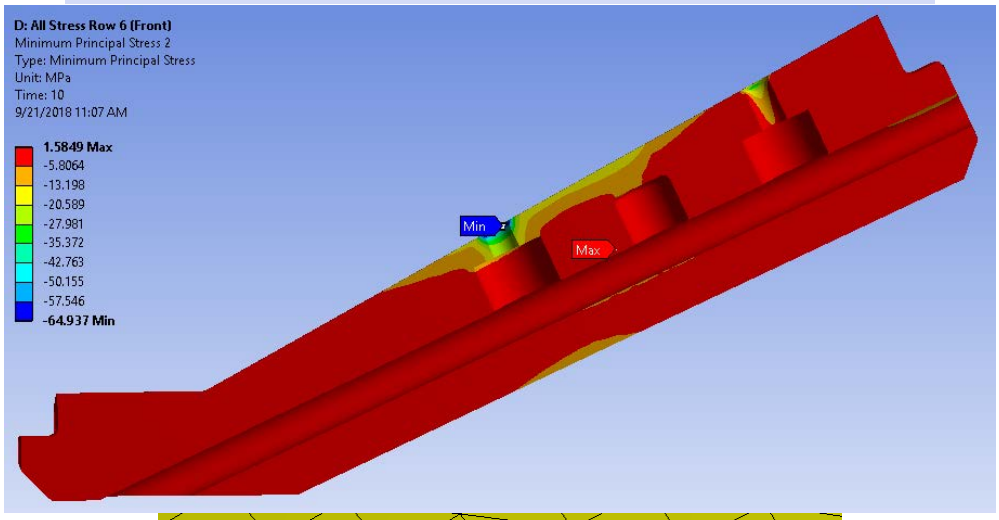


Figure 58: Row 6 (Gas Injection) 6510 Thermal Stress Deformation





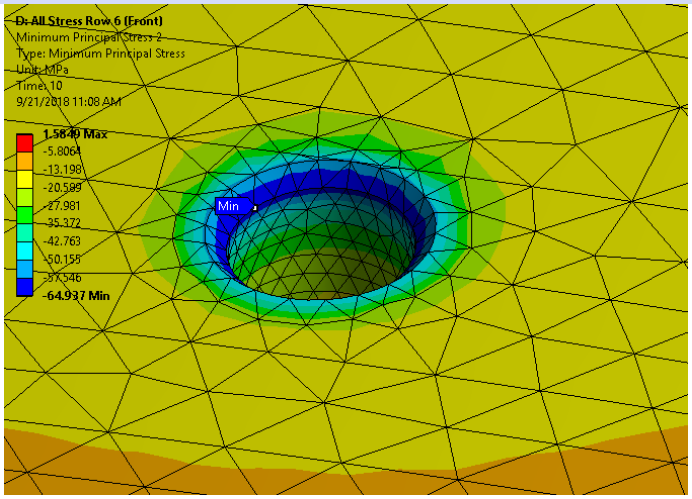


Figure 59: Row 6 (Gas Injection) 6510 Thermal Stresses

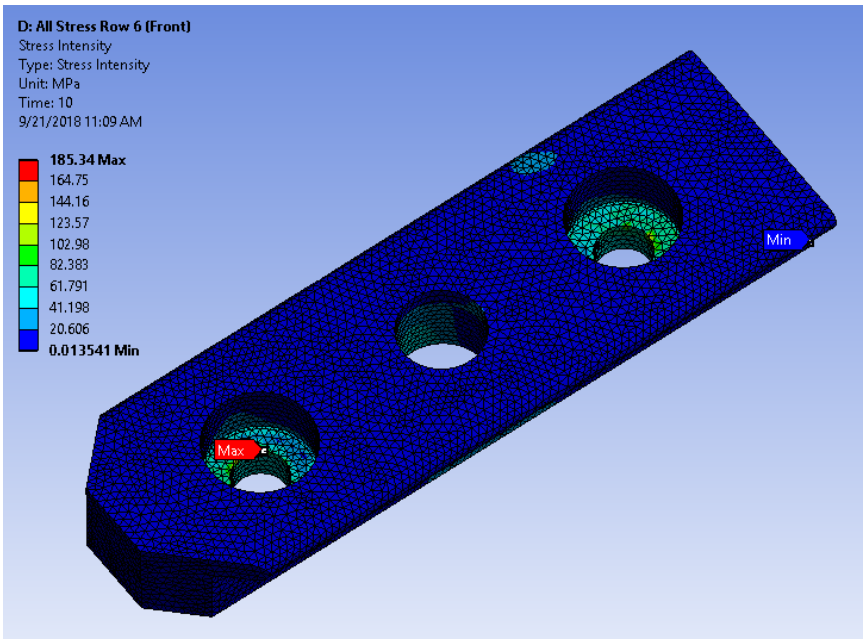


Figure 60: Row 6 (Gas Injection) 6510 Thermal Stress on T-Bar

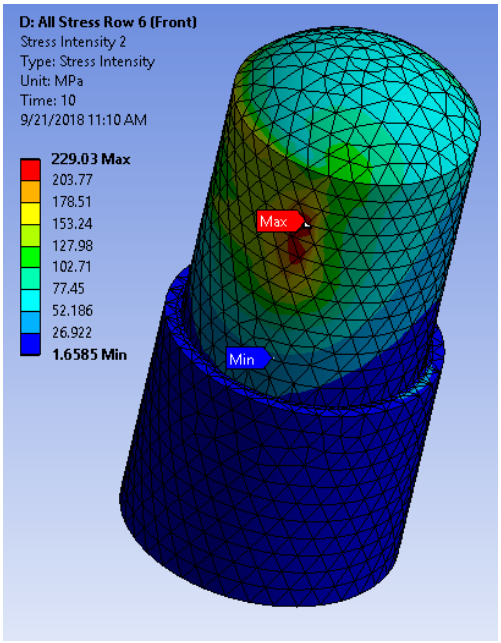


Figure 61: Row 6 (Gas Injection) 6510 Thermal Stress on Shear Pin

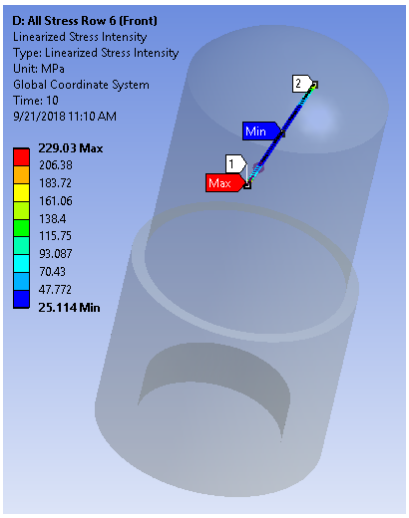


Figure 62: Shear Pin Linearized Stress for Row 6 (Gas Injection) 6510 with All Thermal Stress Loads

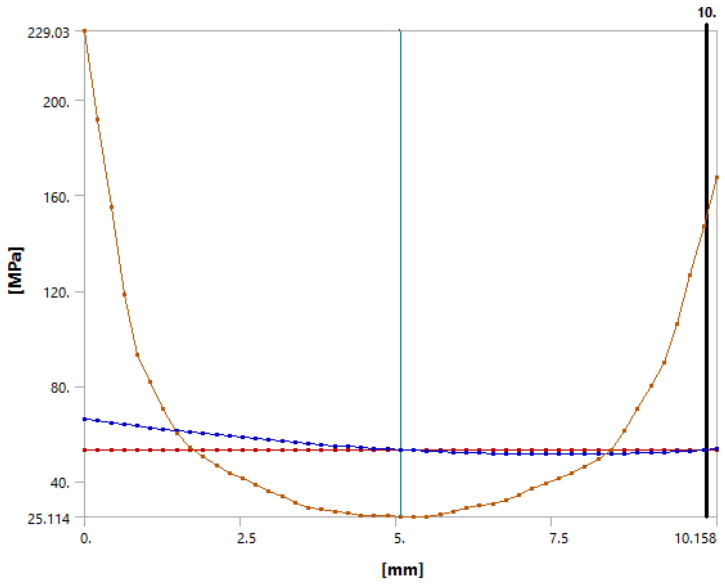


Figure 63: Shear Pin Linearized Stress Graph for Row 6 (Gas Injection) 6510 with Thermal Stress Loads

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	53.234	28.882	66.107	169.55	229.03
2	0.21163	53.234	27.679	65.375	132.4	191.92
3	0.42325	53.234	26.476	64.656	95.294	154.94
4	0.63488	53.234	25.272	63.952	58.443	118.21
5	0.8465	53.234	24.069	63.263	34.534	93.357
6	1.0581	53.234	22.865	62.588	24.414	81.817
7	1.2698	53.234	21.662	61.929	16.538	70.611
8	1.4814	53.234	20.458	61.286	13.666	59.936
9	1.693	53.234	19.255	60.659	14.771	54.459
10	1.9046	53.234	18.052	60.049	16.392	50.687
11	2.1163	53.234	16.848	59.456	20.806	46.927
12	2.3279	53.234	15.645	58.881	25.796	43.328
13	2.5395	53.234	14.441	58.325	27.247	41.226
14	2.7511	53.234	13.238	57.787	28.766	38.631
15	2.9628	53.234	12.034	57.269	30.322	36.051
16	3.1744	53.234	10.831	56.77	31.91	33.487
17	3.386	53.234	9.6275	56.291	32.727	31.156
18	3.5976	53.234	8.4241	55.833	33.025	28.968
19	3.8093	53.234	7.2206	55.395	32.651	28.086
20	4.0209	53.234	6.0172	54.979	32.305	27.324
21	4.2325	53.234	4.8137	54.585	32.244	26.539
22	4.4441	53.234	3.6103	54.213	32.292	25.797
23	4.6558	53.234	2.4069	53.864	31.958	25.425
24	4.8674	53.234	1.2034	53.537	31.454	25.508
25	5.079	53.234	7.823e-014	53.234	31.45	25.213
26	5.2906	53.234	1.2034	52.954	31.496	25.114
27	5.5023	53.234	2.4069	52.698	31.376	25.375
28	5.7139	53.234	3.6103	52.465	30.916	26.207
29	5.9255	53.234	4.8137	52.257	30.403	27.487
30	6.1371	53.234	6.0172	52.073	29.933	28.782
31	6.3488	53.234	7.2206	51.913	29.433	29.749
32	6.5604	53.234	8.4241	51.777	29.02	30.764
33	6.772	53.234	9.6275	51.666	28.772	32.125
34	6.9836	53.234	10.831	51.579	27.275	34.391
35	7.1953	53.234	12.034	51.516	25.3	37.012
36	7.4069	53.234	13.238	51.478	23.559	39.081
37	7.6185	53.234	14.441	51.465	21.737	41.046
38	7.8301	53.234	15.645	51.475	17.801	43.542
39	8.0418	53.234	16.848	51.51	13.79	46.156
40	8.2534	53.234	18.052	51.57	10.276	49.371
41	8.465	53.234	19.255	51.655	7.7497	53.077
42	8.6767	53.234	20.458	51.765	10.002	61.154
43	8.8883	53.234	21.662	51.903	19.421	70.433
44	9.0999	53.234	22.865	52.071	29.998	80.022
45	9.3115	53.234	24.069	52.276	40.873	89.829
46	9.5232	53.234	25.272	52.529	58.982	106.24
47	9.7348	53.234	26.476	52.841	80.688	126.32
48	9.9464	53.234	27.679	53.219	102.51	146.8
49	10.158	53.234	28.882	53.65	124.39	167.52

Table 9: Shear Pin Linearized Stress Table for Row 6 (Gas Injection) 6510 with Thermal Stress Loads

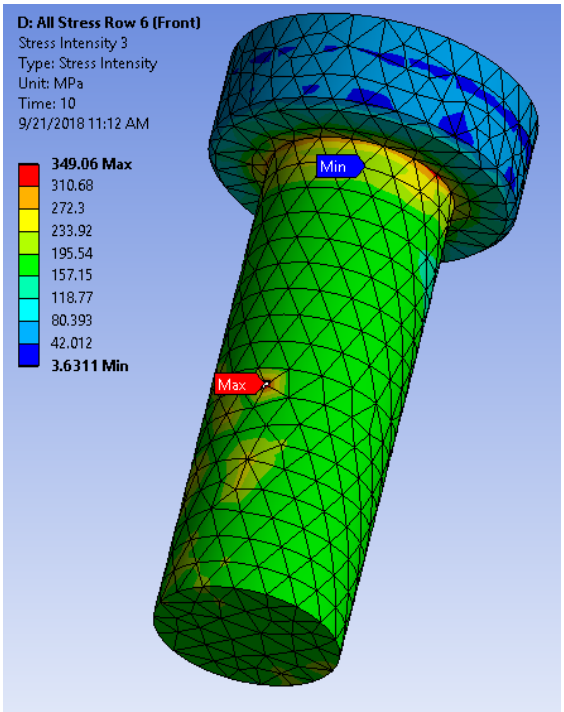


Figure 64: Row 6 (Gas Injection) 6510 with Thermal Stress Loads on Bolt

5.4 6510 Transient Thermal with Max Flux over Shear Pin [Under Tiles – Rows 5 and 6] High Heat Flux Case

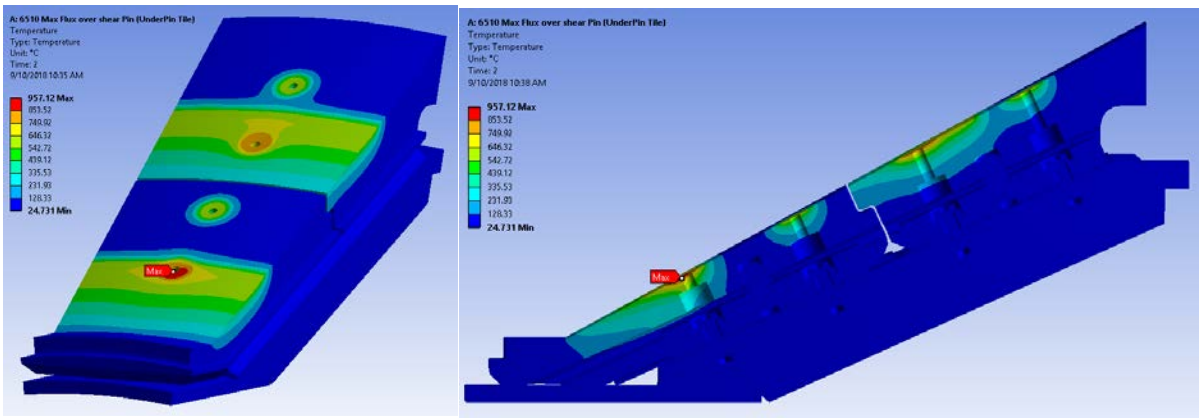


Figure 65: Under Tiles High Heat Flux Case With Strike Point over Shear Pins Temperature After First Flux Shot

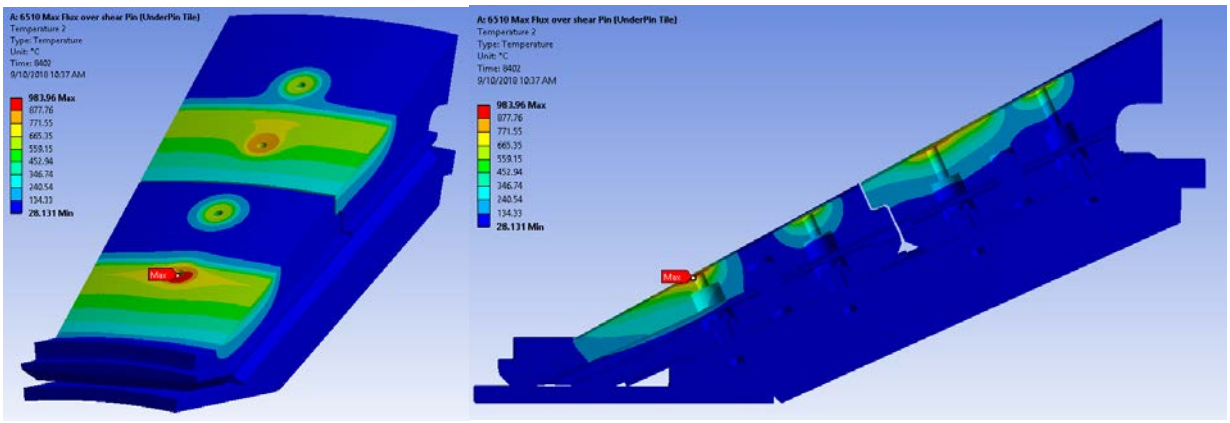


Figure 66: Under Tiles High Heat Flux Case With Strike Point over Shear Pins Temperature After Eighth Flux Shot

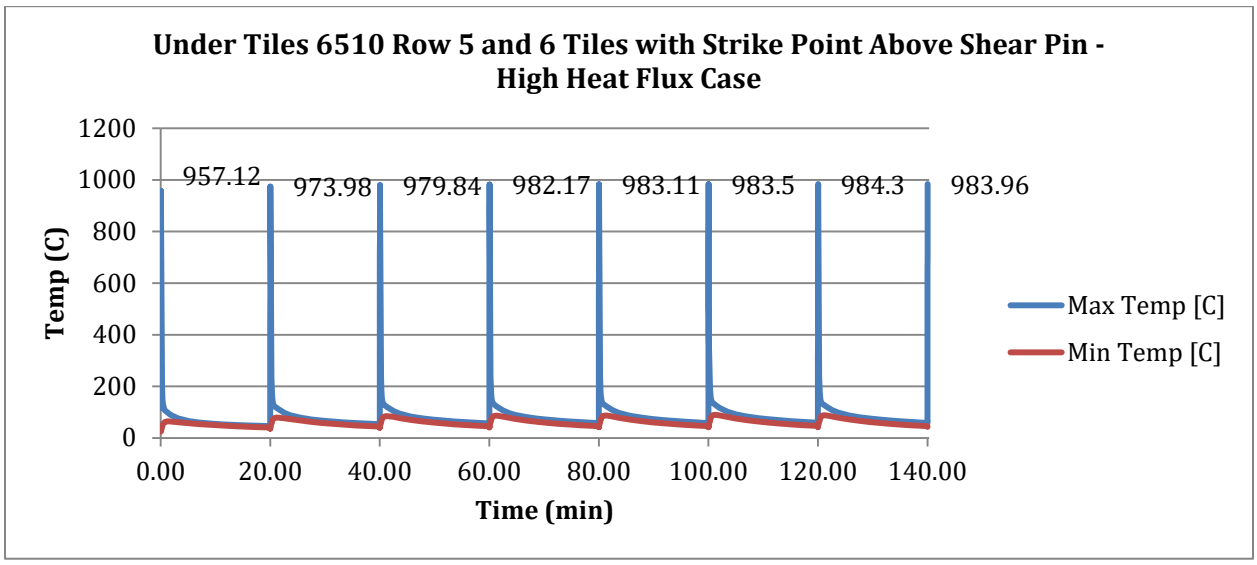


Figure 67: Transient Thermal Results for Under Tiles High Heat Flux Case with Strike Point over Shear Pins

5.5 6510 Transient Thermal with Max Flux over Shear Pin [Under Tiles – Row 5 and 6] Low Heat Flux Case

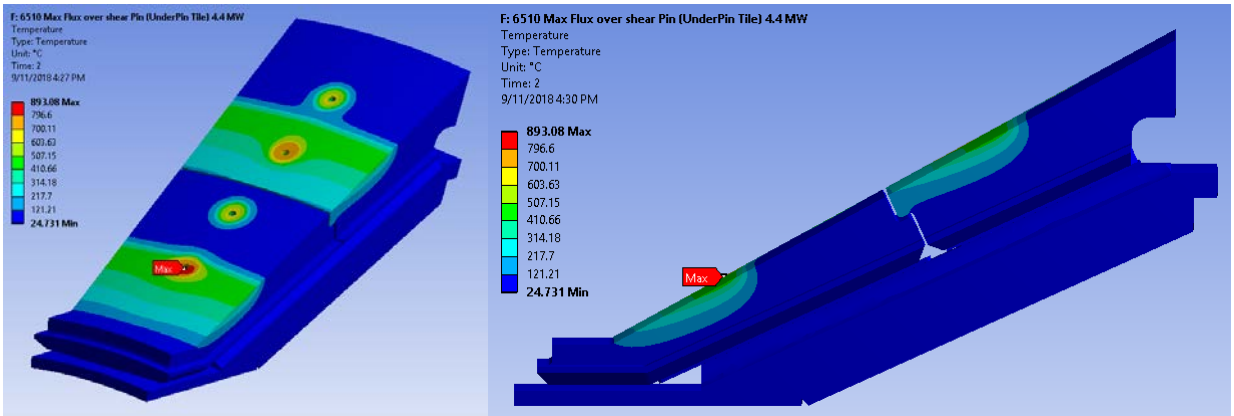


Figure 68: Under Tiles High Heat Flux Case With Strike Point over Shear Pins Temperature After First Flux Shot

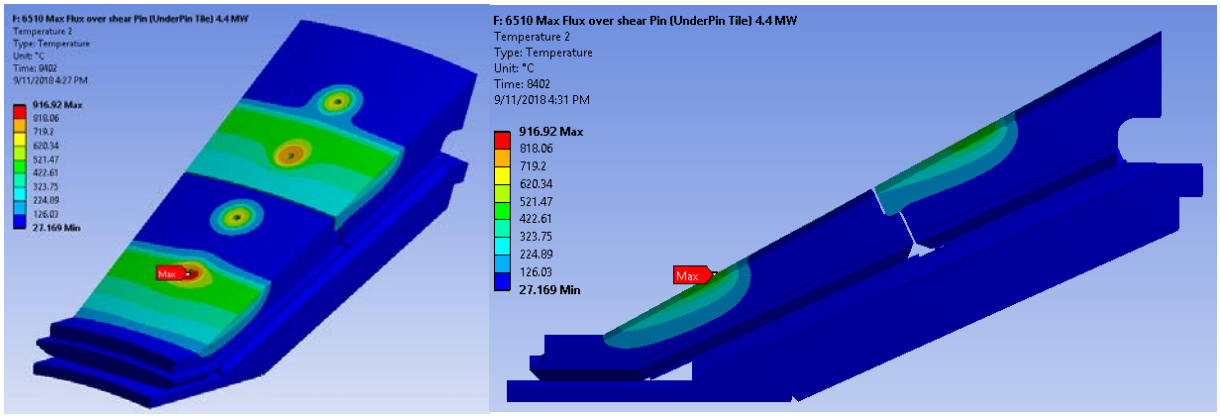


Figure 69: Under Tiles High Heat Flux Case With Strike Point over Shear Pins Temperature After Eighth Flux Shot

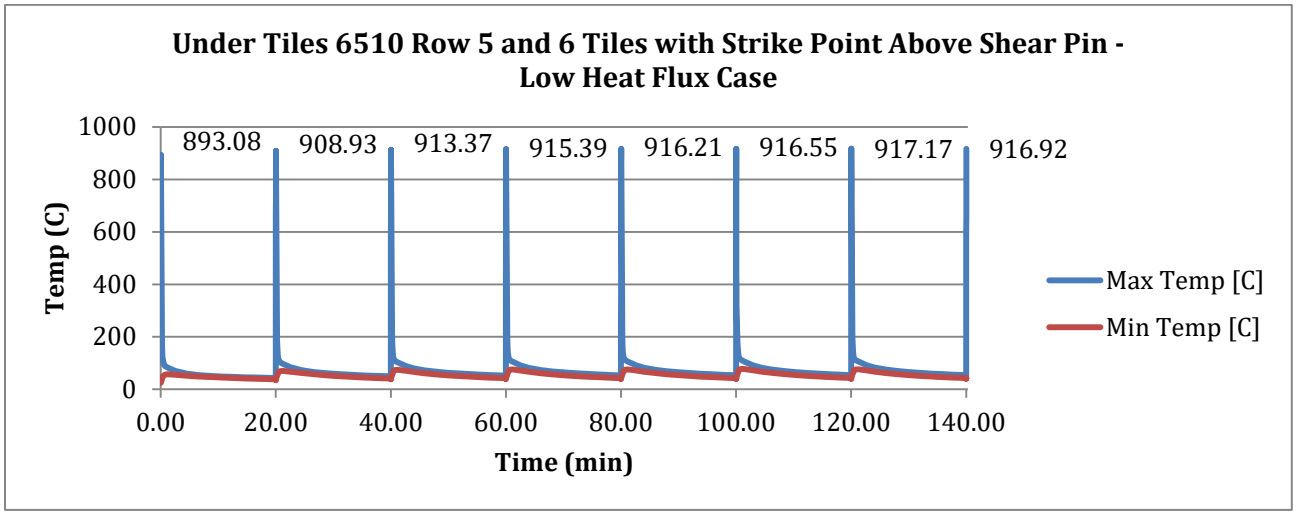


Figure 70: Transient Thermal Results for Under Tiles High Heat Flux Case with Strike Point over Shear Pins

5.6 Diagnostic ET-10 Tiles with Strike Point above Shear Pin

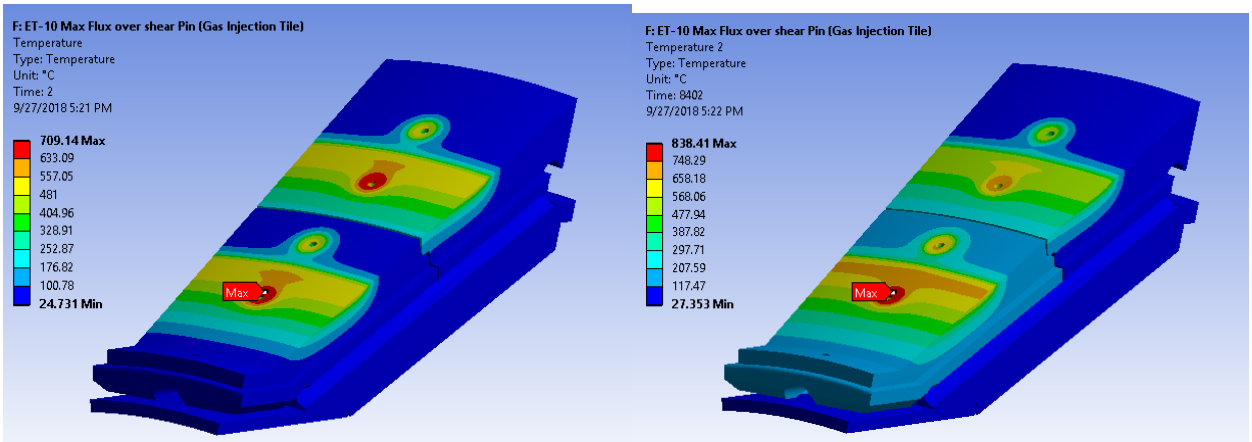


Figure 71: Temperatures after First and Eighth Flux Shot

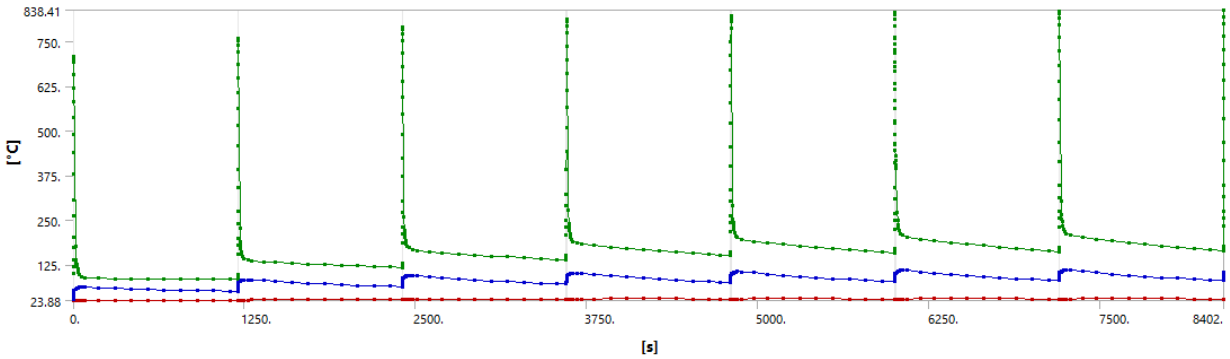


Figure 72: Transient Thermal Results for Eight Flux Shots

5.6.1 Diagnostic ET-10 Tiles with Strike Point above Shear Pin Row 5 All Mechanical Loads

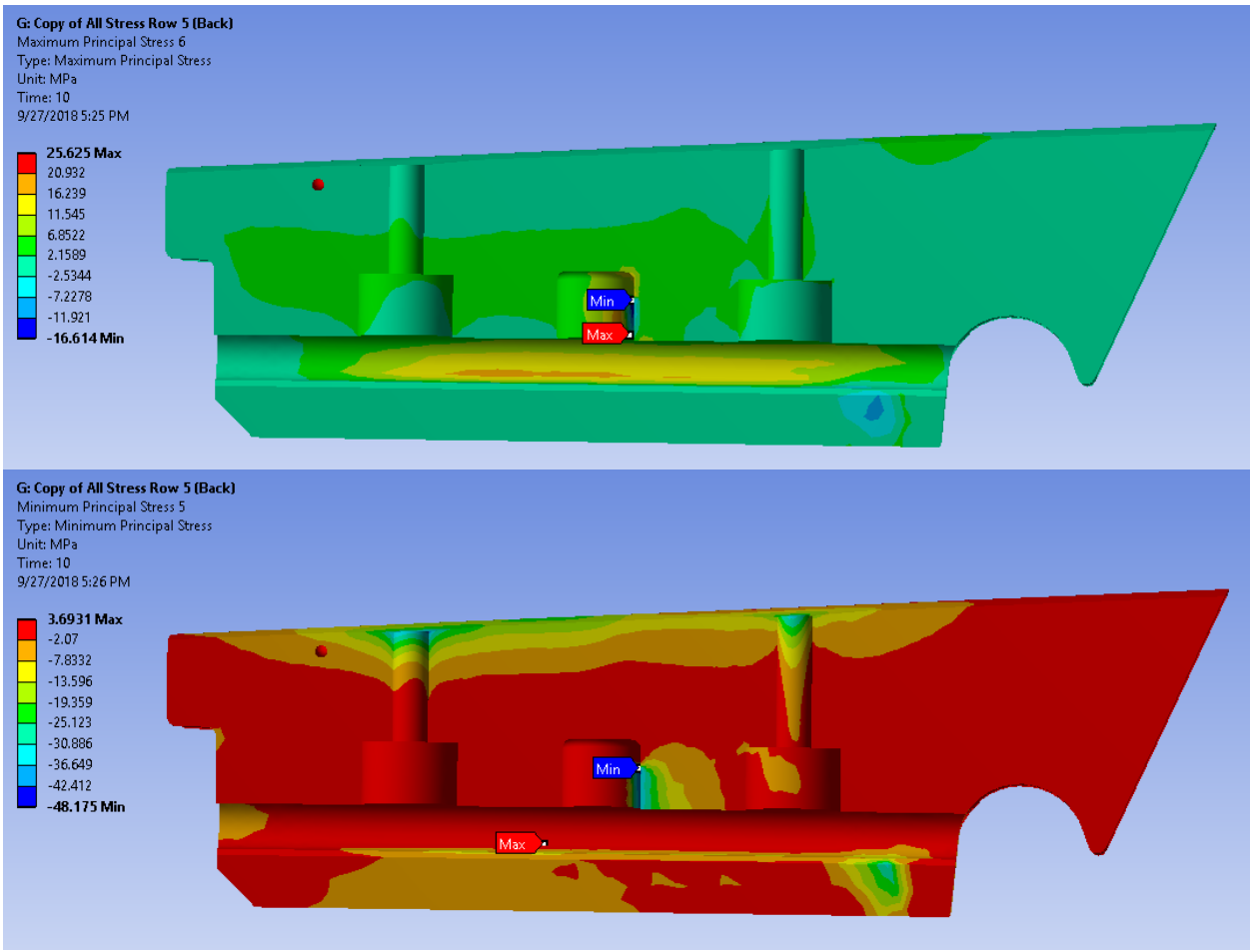


Figure 73: Maximum and Minimum Tile Stresses

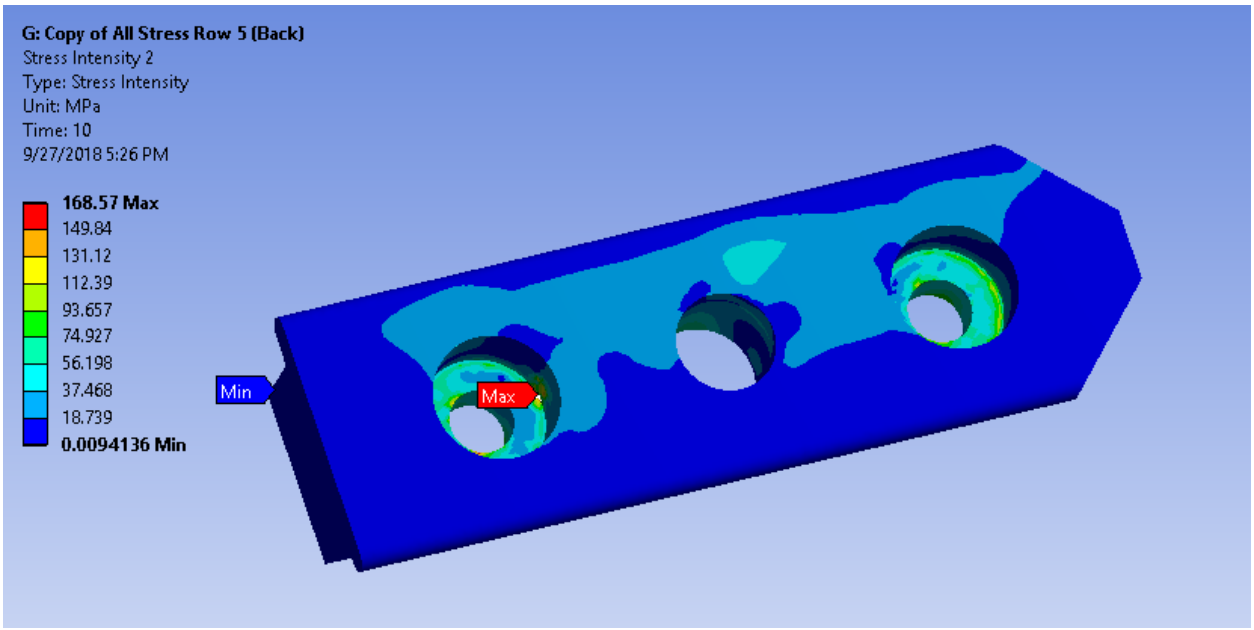


Figure 74: T-Bar Stress Intensity

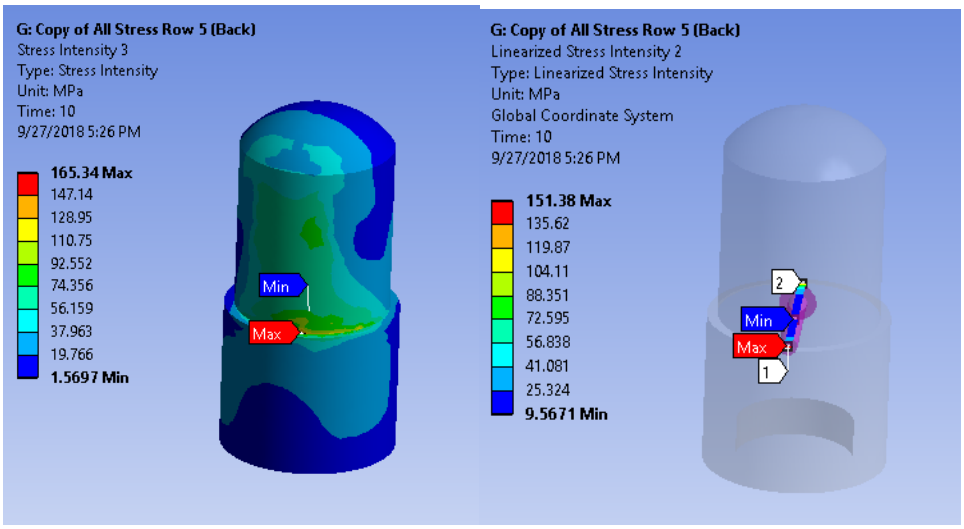


Figure 75: Shear Pin Stress Intensity

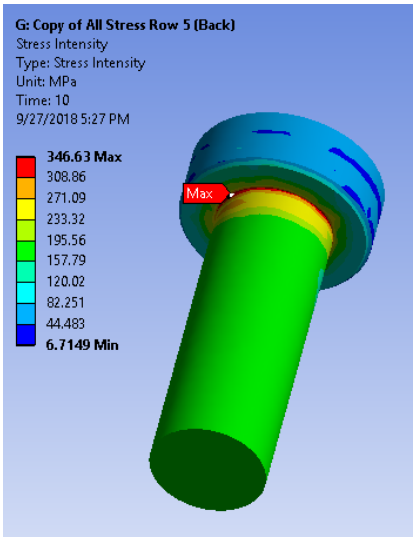


Figure 76: Bolt Stress Intensity

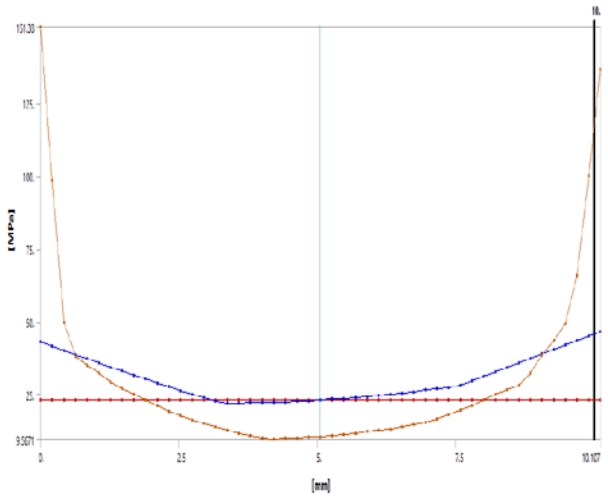


Figure 77: Shear Pin Linearized Stress Intensity

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
4	0.63167	23.012	34.871	38.59	6.8396	38.21
5	0.84223	23.012	33.211	37.166	5.3015	35.129
6	1.0528	23.012	31.55	35.755	4.5555	32.23
7	1.2633	23.012	29.89	34.357	5.1524	29.37
8	1.4739	23.012	28.229	32.973	6.2539	26.882
9	1.6845	23.012	26.569	31.604	6.6941	25.03
10	1.895	23.012	24.908	30.249	7.3285	23.03
11	2.1056	23.012	23.248	28.91	8.0497	20.97
12	2.3161	23.012	21.587	27.587	8.8719	19.187
13	2.5267	23.012	19.926	26.28	9.8933	17.63
14	2.7372	23.012	18.266	24.992	10.591	16.235
15	2.9478	23.012	16.605	23.723	11.194	14.953
16	3.1583	23.012	14.945	22.498	11.633	13.823
17	3.3689	23.012	13.284	22.082	12.054	12.684
18	3.5795	23.012	11.624	22.069	12.327	11.632
19	3.79	23.012	9.9632	22.099	12.478	10.766
20	4.0006	23.012	8.3027	22.165	12.638	9.929
21	4.2111	23.012	6.6422	22.267	12.747	9.5671
22	4.4217	23.012	4.9816	22.403	12.638	9.8093
23	4.6322	23.012	3.3211	22.573	12.546	10.085
24	4.8428	23.012	1.6605	22.776	12.57	10.268
25	5.0534	23.012	2.0521e-014	23.012	12.611	10.465
26	5.2639	23.012	1.6605	23.278	12.504	10.828
27	5.4745	23.012	3.3211	23.574	12.398	11.219
28	5.685	23.012	4.9816	23.9	12.314	11.617
29	5.8956	23.012	6.6422	24.253	12.211	12.076
30	6.1061	23.012	8.3027	24.633	12.012	12.645
31	6.3167	23.012	9.9632	25.038	11.829	13.224
32	6.5272	23.012	11.624	25.468	11.671	13.808
33	6.7378	23.012	13.284	25.921	11.507	14.425
34	6.9484	23.012	14.945	26.397	11.004	15.395
35	7.1589	23.012	16.605	26.896	10.481	16.432
36	7.3695	23.012	18.266	27.429	10.004	17.893
37	7.58	23.012	19.926	28.252	9.5792	19.463
38	7.7906	23.012	21.587	29.689	9.2339	20.98
39	8.0011	23.012	23.248	31.183	8.1446	23.146
40	8.2117	23.012	24.908	32.689	7.6908	25.115
41	8.4223	23.012	26.569	34.205	7.6386	26.635
42	8.6328	23.012	28.229	35.728	7.6813	28.207
43	8.8434	23.012	29.89	37.258	5.4477	32.254
44	9.0539	23.012	31.55	38.794	5.1715	38.528
45	9.2645	23.012	33.211	40.337	8.8692	43.448
46	9.475	23.012	34.871	41.884	14.83	49.256
47	9.6856	23.012	36.532	43.437	32.17	65.843
48	9.8961	23.012	38.192	44.995	68.795	100.29
49	10.107	23.012	39.853	46.557	106.47	136.84

Table 9A: Shear Pin Stress Intensity

5.7 Diagnostic 6510 (Applicable Material Data) Tiles with Strike Point Above Shear Pin Row 5 All Mechanical Loads

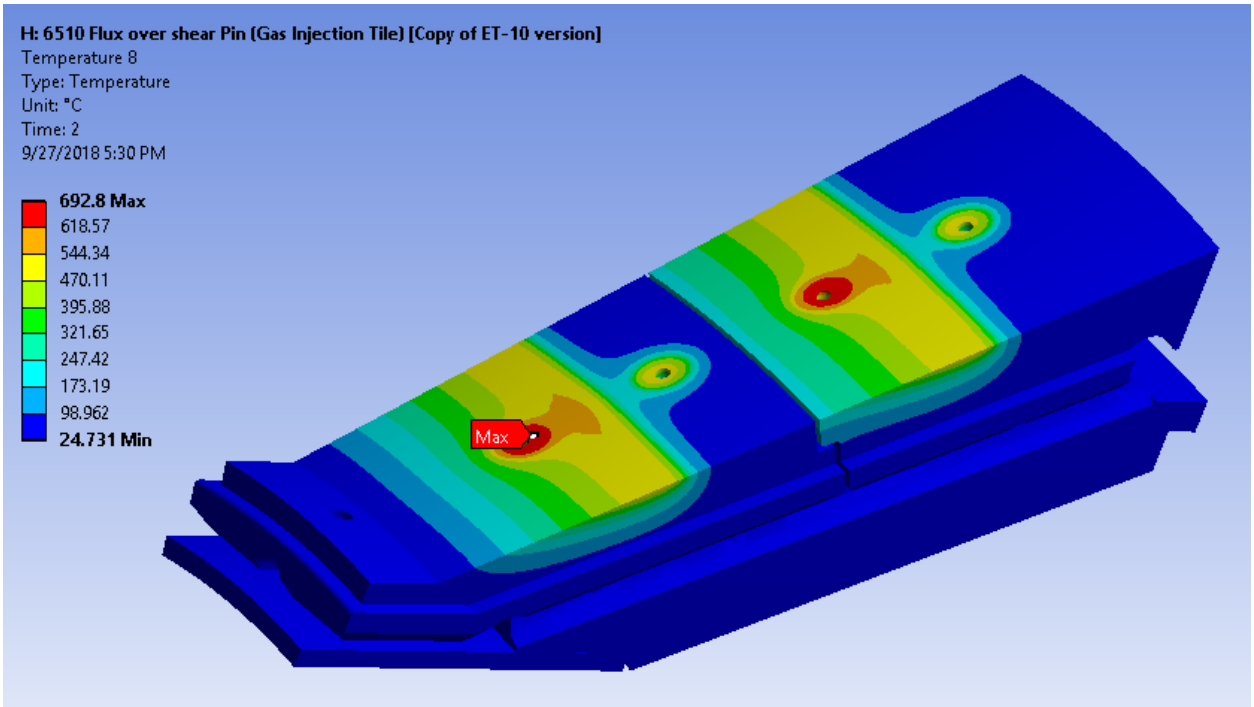


Figure 78: Temperature at End of First Flux Shot

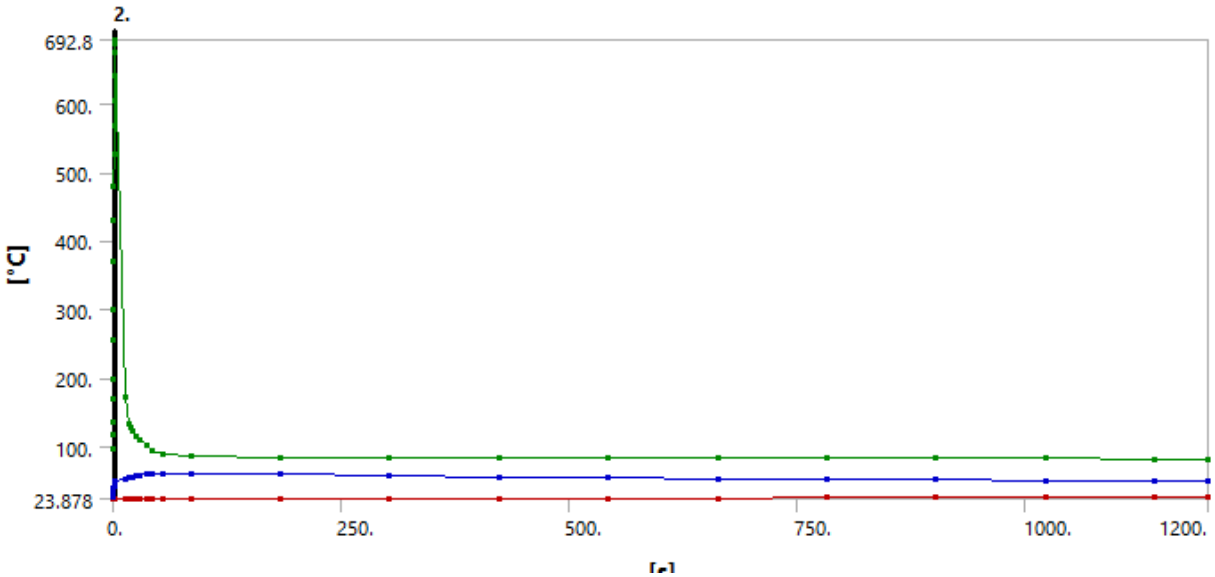


Figure 79: Temperature at End of First Flux Shot

5.7.1 Diagnostic 6510 (Applicable Material Data) Tiles with Strike Point Above Shear Pin Row 5 All Mechanical Loads

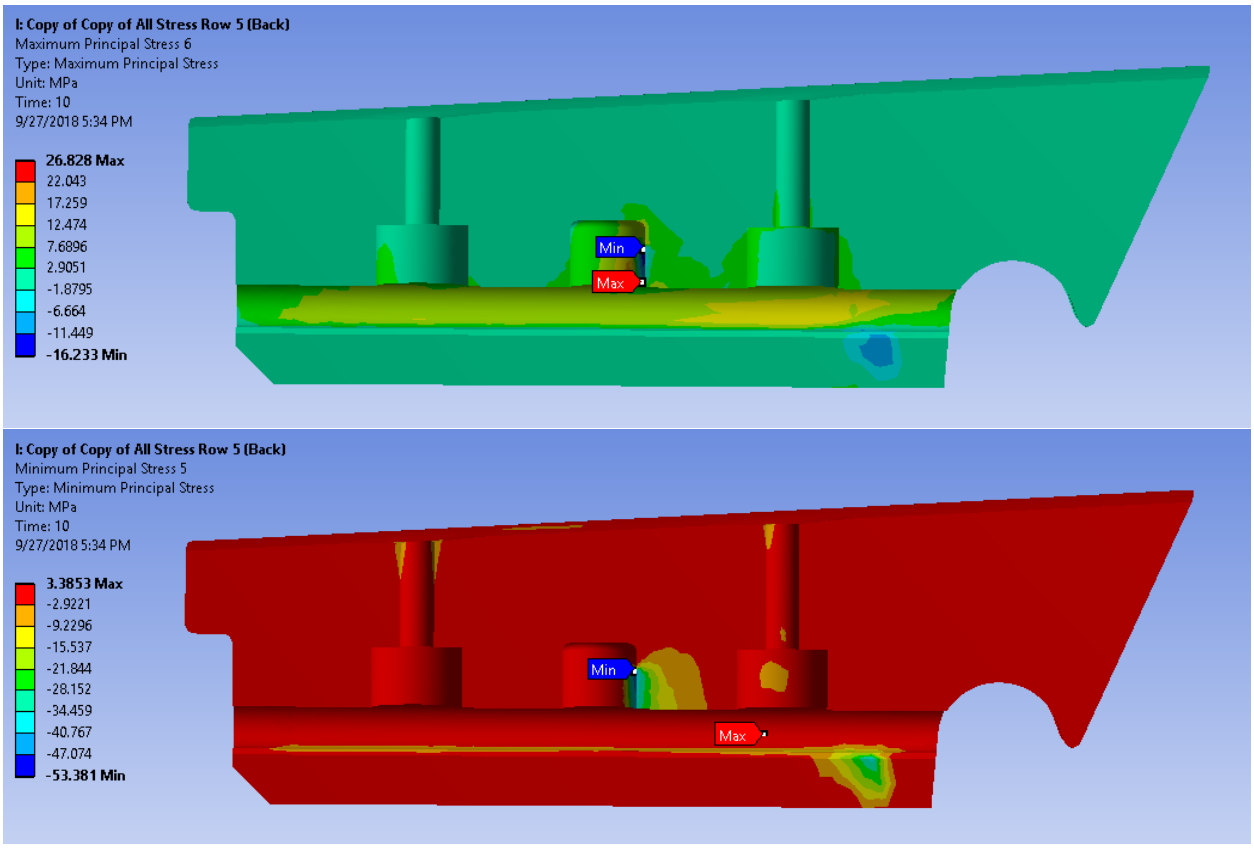


Figure 80: Tile Max and Min Stresses

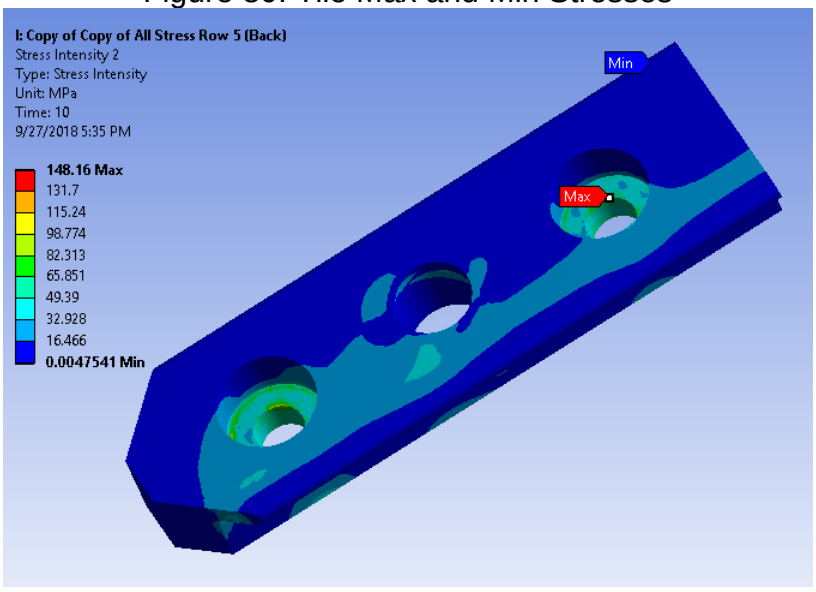


Figure 81: T-Bar Stress Intensity

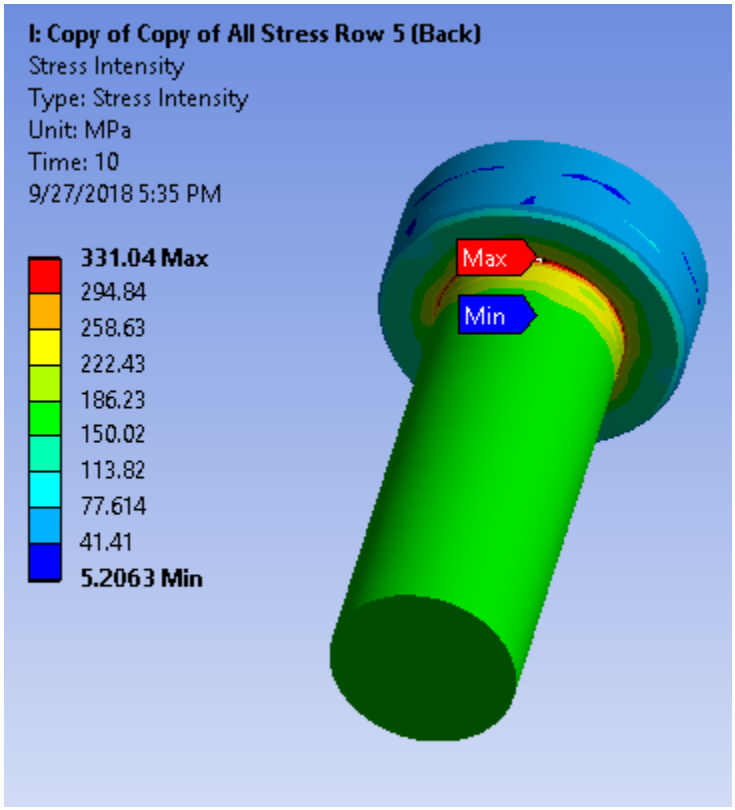


Figure 82: Bolt Stress Intensity

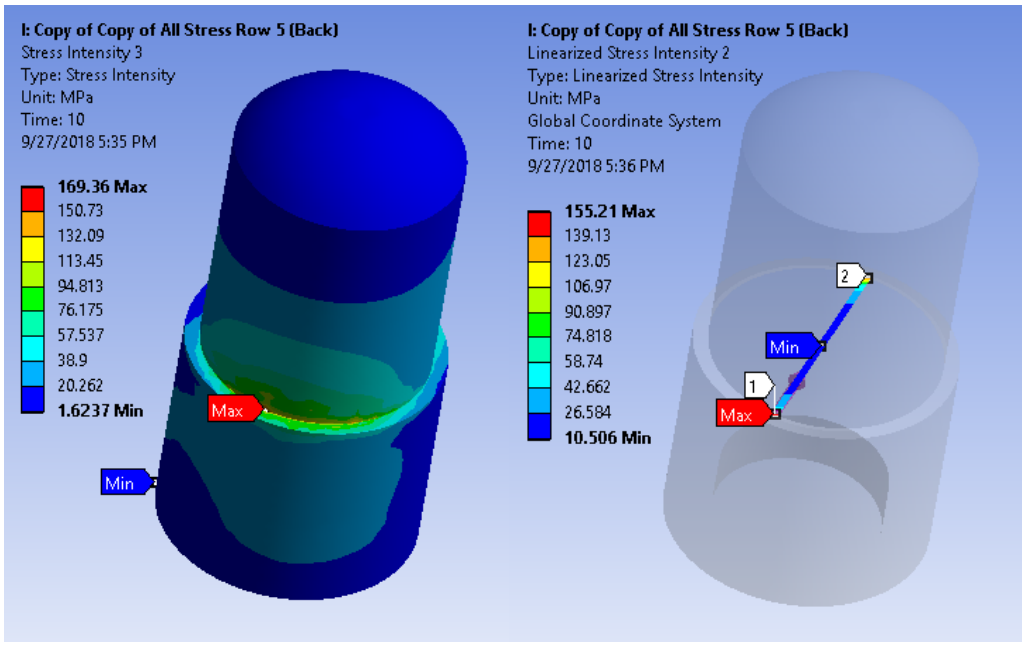


Figure 83: Shear Pin Stress and Linearized Stress

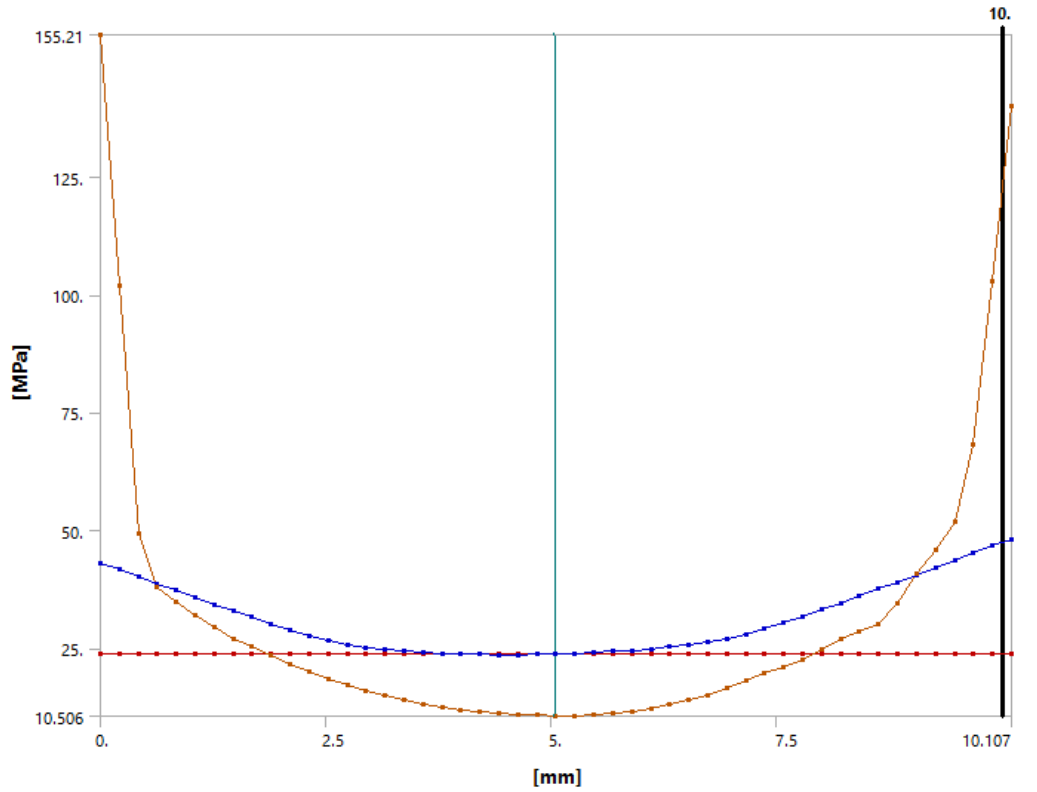


Figure 84: Shear Pin Linearized Stress Plot

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	23.706	40.515	43.123	131.03	155.21
2	0.21056	23.706	38.827	41.617	77.29	101.86
3	0.42111	23.706	37.139	40.123	18.495	49.417
4	0.63167	23.706	35.451	38.641	7.7404	37.816
5	0.84223	23.706	33.762	37.173	5.7576	34.833
6	1.0528	23.706	32.074	35.721	5.2869	32.043
7	1.2633	23.706	30.386	34.286	5.3273	29.338
8	1.4739	23.706	28.698	32.874	6.1799	27.051
9	1.6845	23.706	27.01	31.489	6.5434	25.305
10	1.895	23.706	25.322	30.142	7.1043	23.411
11	2.1056	23.706	23.634	28.849	7.7688	21.458
12	2.3161	23.706	21.946	27.643	8.2191	19.808
13	2.5267	23.706	20.257	26.58	8.6673	18.392
14	2.7372	23.706	18.569	25.722	9.4724	17.082
15	2.9478	23.706	16.881	25.086	10.208	15.914
16	3.1583	23.706	15.193	24.626	10.783	14.949
17	3.3689	23.706	13.505	24.284	11.383	13.978
18	3.5795	23.706	11.817	24.026	11.905	13.077
19	3.79	23.706	10.129	23.832	12.293	12.458
20	4.0006	23.706	8.4406	23.694	12.695	11.878
21	4.2111	23.706	6.7525	23.605	13.042	11.377
22	4.4217	23.706	5.0644	23.564	13.14	11.094
23	4.6322	23.706	3.3762	23.567	13.25	10.874
24	4.8428	23.706	1.6881	23.615	13.473	10.667
25	5.0534	23.706	2.0862e-014	23.706	13.709	10.506
26	5.2639	23.706	1.6881	23.84	13.751	10.596
27	5.4745	23.706	3.3762	24.018	13.778	10.786
28	5.685	23.706	5.0644	24.24	13.816	11.07
29	5.8956	23.706	6.7525	24.508	13.809	11.48
30	6.1061	23.706	8.4406	24.828	13.607	12.22
31	6.3167	23.706	10.129	25.207	13.403	13.083
32	6.5272	23.706	11.817	25.663	13.21	14.031
33	6.7378	23.706	13.505	26.234	12.992	15.067
34	6.9484	23.706	15.193	26.976	12.367	16.481
35	7.1589	23.706	16.881	27.936	11.674	17.986
36	7.3695	23.706	18.569	29.09	11.006	19.508
37	7.58	23.706	20.257	30.372	10.368	21.041
38	7.7906	23.706	21.946	31.73	9.8075	22.542
39	8.0011	23.706	23.634	33.134	8.4251	24.744
40	8.2117	23.706	25.322	34.57	7.867	26.742
41	8.4223	23.706	27.01	36.029	7.774	28.327
42	8.6328	23.706	28.698	37.506	7.8731	30.098
43	8.8434	23.706	30.386	38.998	5.8013	34.344
44	9.0539	23.706	32.074	40.503	6.2544	40.783
45	9.2645	23.706	33.762	42.019	10.276	45.732
46	9.475	23.706	35.451	43.545	16.928	51.871
47	9.6856	23.706	37.139	45.08	35.006	68.352
48	9.8961	23.706	38.827	46.624	72.558	102.89
49	10.107	23.706	40.515	48.175	111.36	140.18

Table 9B: Shear Pin Linearized Stress Table

6 Hand Calculations

6.1 Gasket Compression

6.1.1 Normal Stress

Compressive stress is calculated as follows:

$$\sigma_{\text{row 6}} = \frac{F_n}{A} = \frac{1920\ \text{lbf}}{6.37\ \text{in}^2} = 301.4\text{psi}$$

$$\sigma_{\text{row 5}} = \frac{F_n}{A} = \frac{1920\ \text{lbf}}{5.52\ \text{in}^2} = 347.8\text{psi}$$

Where

σ = normal stress in psi (lbf/in2)

F_n = normal force acting perpendicular to the area (lbf) =960*2=1920 lb

A = area (in^2) = 4107.0 mm^2 = 6.37 in^2 for row 6; and 3558.8 mm^2 = 5.52 in^2 for row 5.

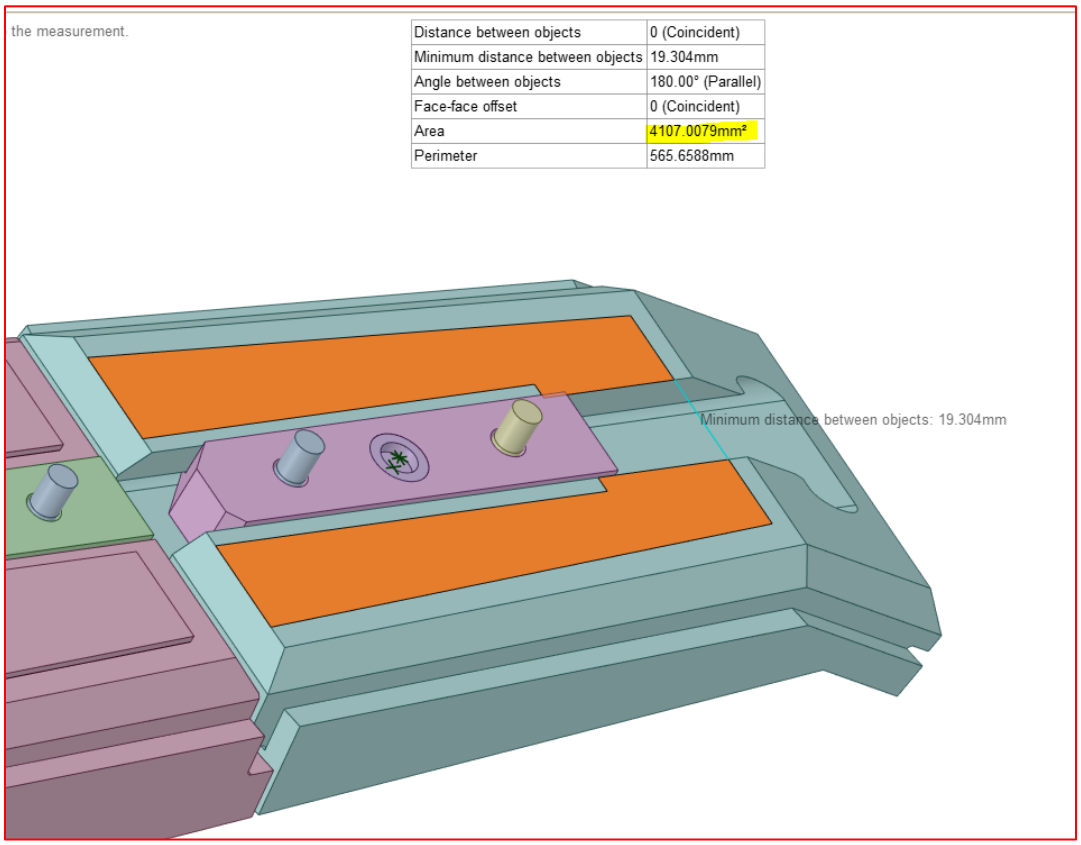


Figure 85: Row 6 Gasket Compressibility Area

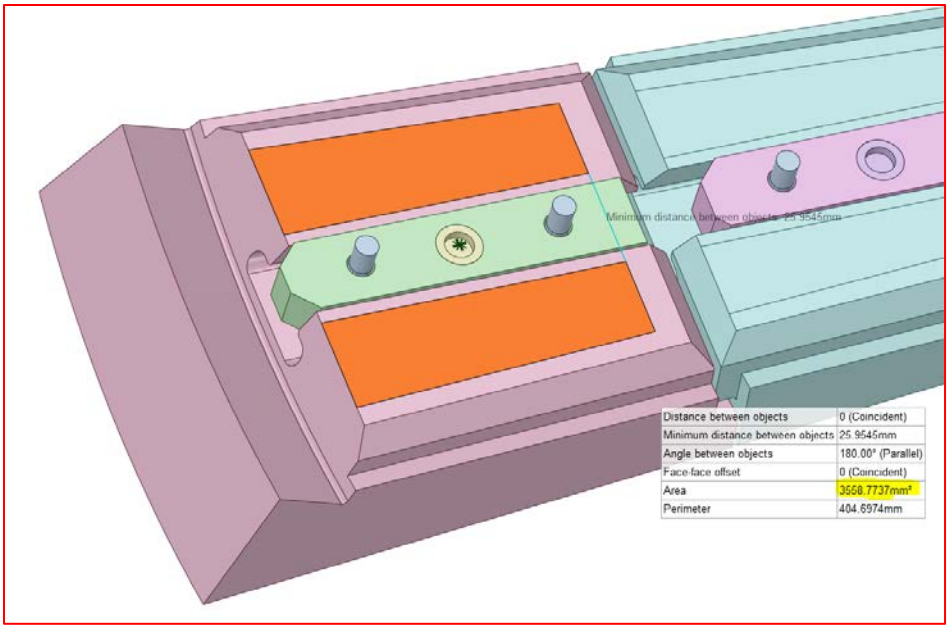


Figure 86: Row 5 Gasket Compressibility Area

6.1.2 Change in Gasket Thickness

$$dl_{row\ 6} = \frac{(\sigma)(l_0)}{E} = \frac{(301.4psi)(0.06\ in)}{27{,}557.2\ psi} = 0.00066\ in$$

$$dl_{row\ 5} = \frac{(\sigma)(l_0)}{E} = \frac{(347.8psi)(0.06\ in)}{27{,}557.2\ psi} = 0.00076\ in$$

Where
dl= change of length (in)
l_0= initial thickness of gasket = 1.524 mm = 0.06 in
E = Young's Modulus of Elasticity (psi) = 1.9*10^8 Pa = 27,557.2 Psi [per engineering data Appendix 8.3]

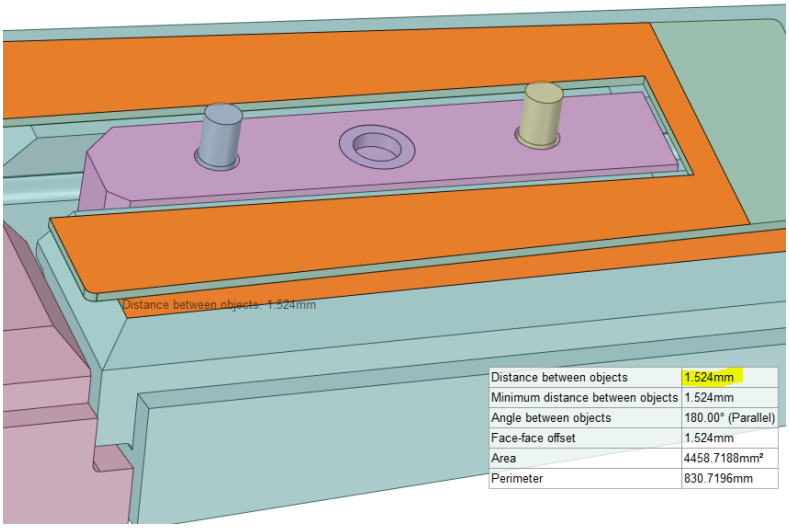


Figure 87: Gasket Thickness

6.1.3 Percent Deformation

$$\%\ \text{deformation}_{\text{row 6}} = \left(\frac{0.00066\ \text{in}}{0.06\ \text{in}}\right) 100 = 1.1\%$$

$$\%\ \text{deformation}_{\text{row 6}} = \left(\frac{0.00076\ \text{in}}{0.06\ \text{in}}\right) 100 = 1.27\%$$

6.2 Minimum Pretension Requirements to Prevent Sliding Due to Halo Forces

Figure 52 displays a free-body diagram containing all the planar forces acting on tile 5 parallel to the casing. The total resistive force resulting from the bolts normal force (N* μ) must be greater than 1376 N. Therefore, the minimum total normal force must be at least (0.3)(1376N)=4587 N=1031 lbf. Therefore, the minimum pretension on each bolt is 516 lbs.

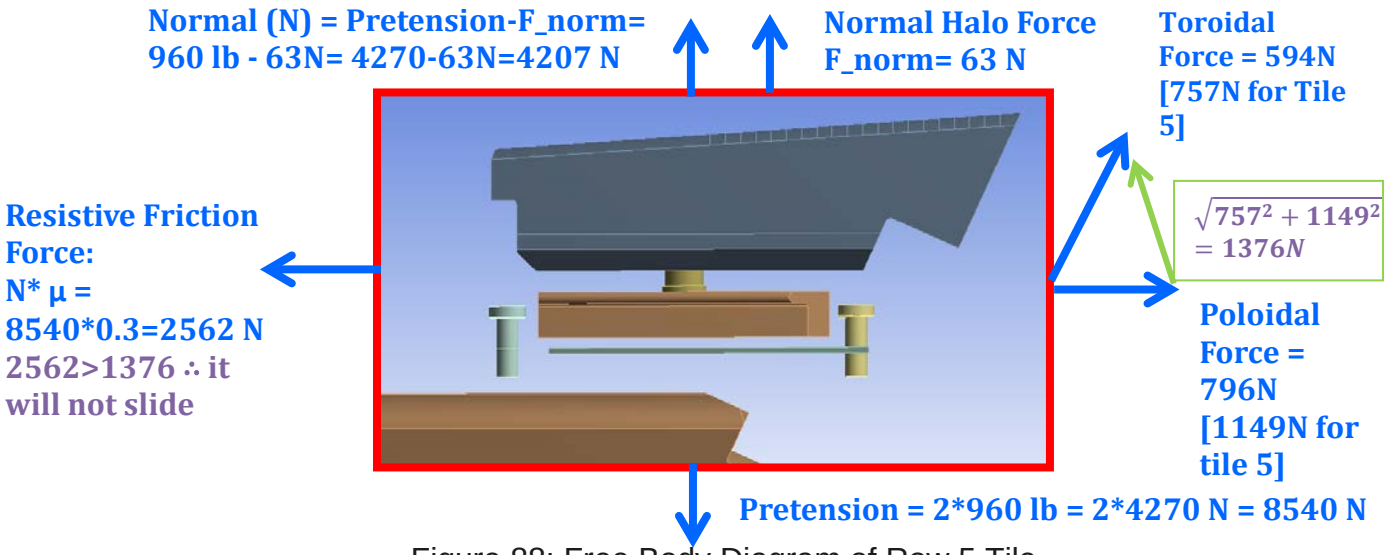


Figure 88: Free Body Diagram of Row 5 Tile

Figure 53 displays a free-body diagram containing all the planar forces acting on tile 6 parallel to the casing. The total resistive force resulting from the bolts normal force (N* μ) must be greater than 993 N. Therefore, the minimum total normal force must be at least (0.3)(993N)=3310 N=744 lbf. Therefore, the minimum pretension on each bolt is 372 lbs.

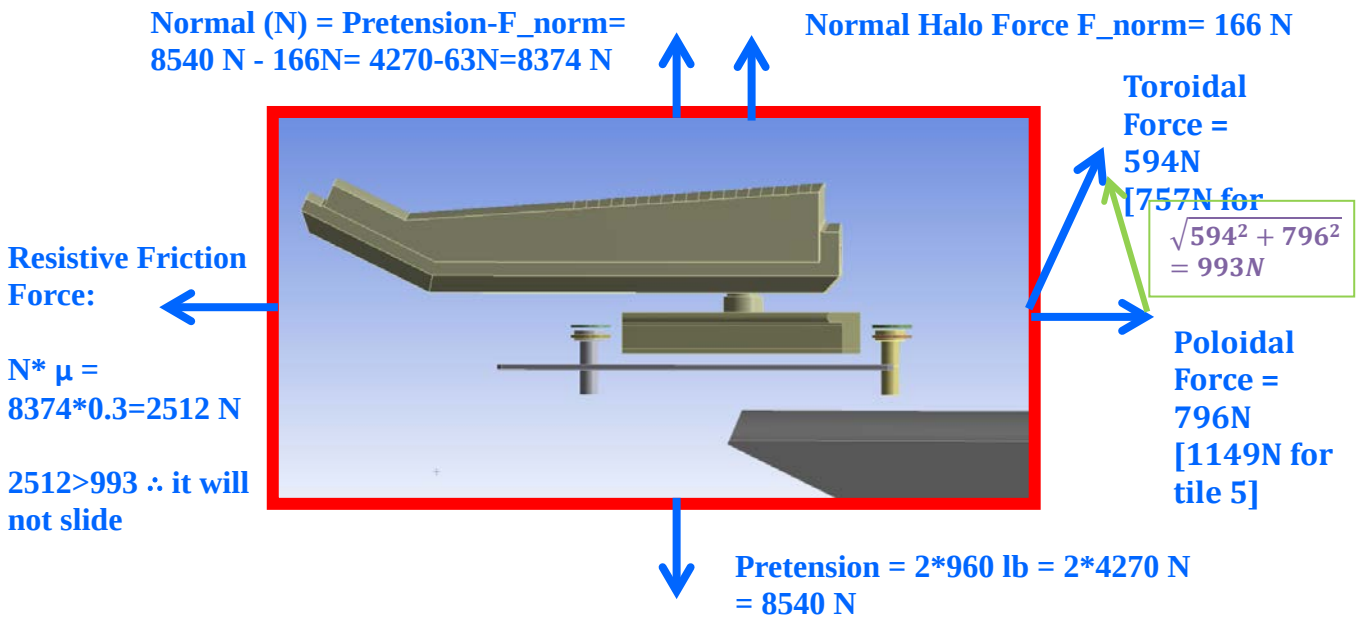


Figure 89: Free Body Diagram of Row 6 Tile

6.3 Heat Flux Conservatism

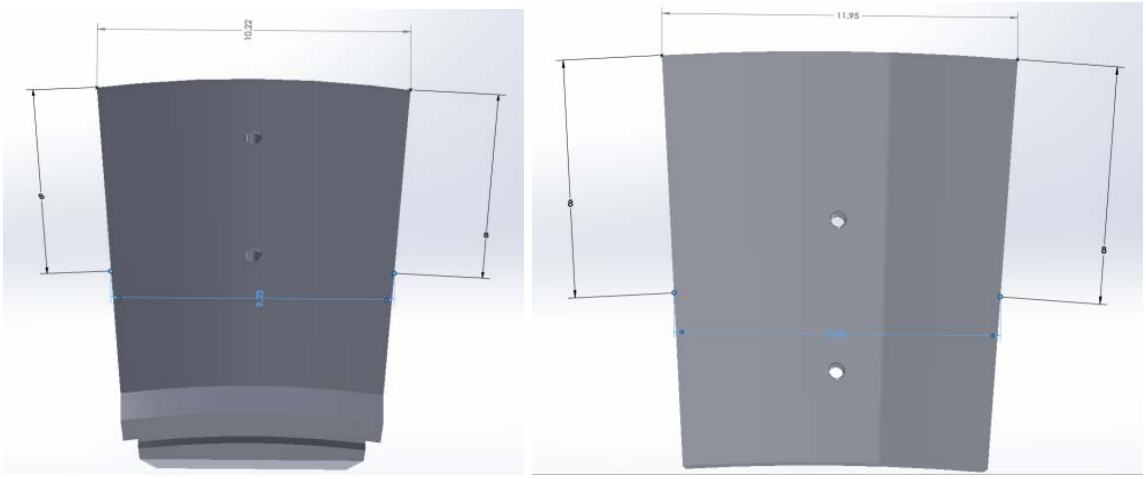


Figure 90: Tile Surface Area Dimensions

- $Tile\ 6\ Average\ Section\ Width = \frac{10.22cm+9.23cm}{2} = 9.725\ cm$
- $Tile\ 5\ Average\ Section\ Width = \frac{11.95cm+10.96cm}{2} = 11.455\ cm$
- Section length for both tiles is $\frac{8cm}{20} = 0.4\ cm$

- Average section heat flux is: $\frac{6.4*10^6 \frac{W}{m^2}}{2}$
- Upper Rieman Sum of a linear function
- Equation for Extra Power (W) Applied to a Tile can be expresses as:
- $n * w * l * \left(Q_i - Q_{max}\left(\frac{2i-1}{2n}\right)\right)$ *where* $\lim_{n\to\infty} \sum_{i=1}^{n} w * l * \left(Q_i - Q_{max}\left(\frac{2i-1}{2n}\right)\right) = 0$

  where,
  - The highest value of I is applied to the segment with the largest heat flux
  - n= Total number of length increments = 20
  - w = width of the increment
    - (Conservatively assumed as constant for each tile – in reality a greater flux is applied to the wider segments towards the top of the tiles)
  - l = length of the increment (constant for each tile at 8cm/n)
  - Qmax =6.4*10^6 W/m^2 (See bar graph below)
  - Qi = flux applied to increment i

Number of Increments	Extra Power Applied to Tile 5 [kW]	Extra Power Applied to Tile 6 [kW]
1	29.3	24.9
10	2.9	2.5
20	1.5	1.2
40	0.7	0.6
80	0.4	0.3

Table 11: Conservatism in Tile Surface Heat Flux Increment Numbers

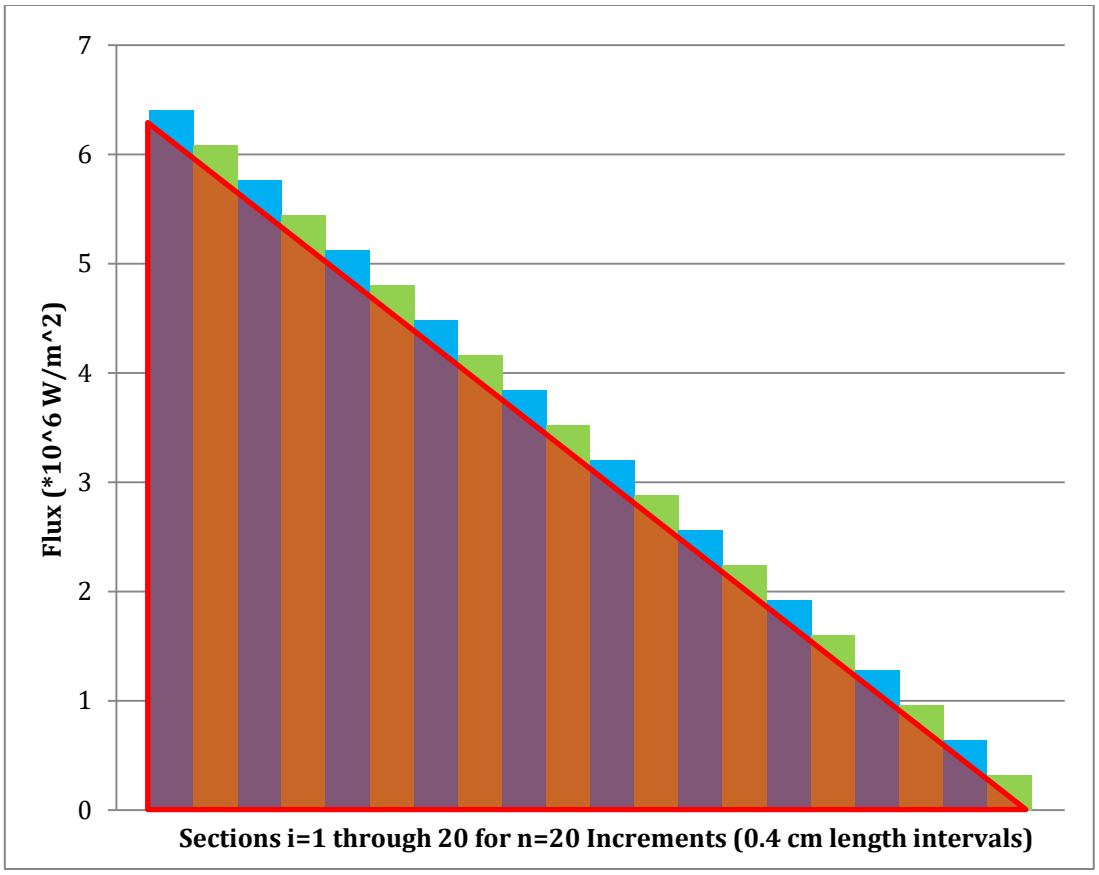


Figure 91: Conceptual Illustration of Conservatism in Tile Heat Flux

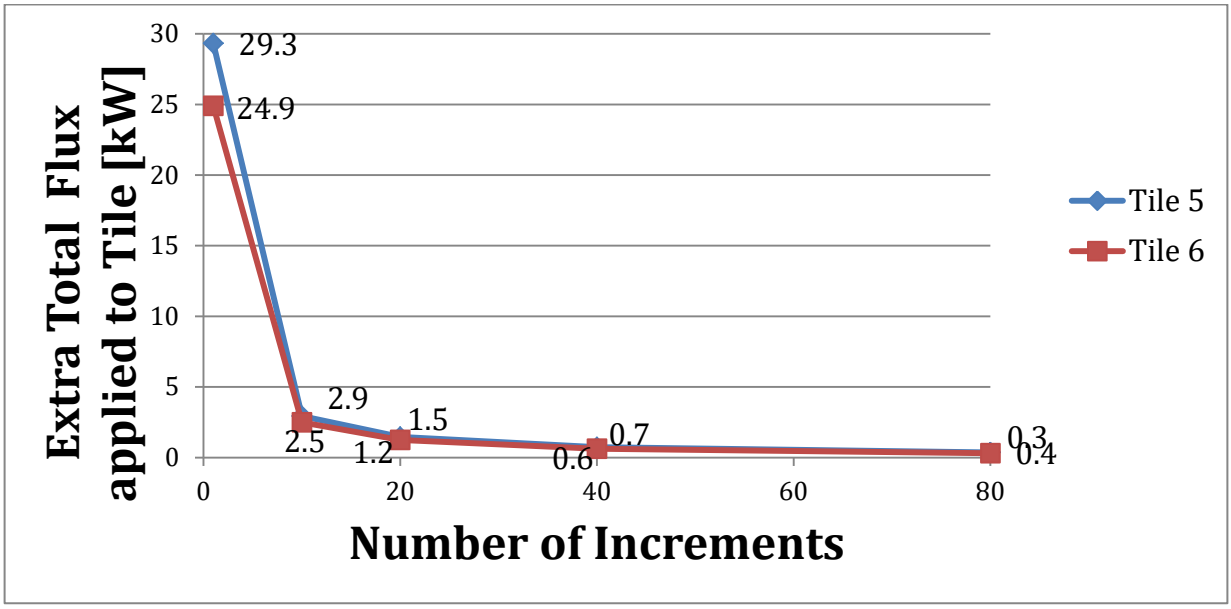


Figure 92: Conservatism in Tile Heat Flux

7 Conclusion

The following results are summarized in section 1.

7.1 Tiles

The primary tile material evaluated is Graphite 6510. Graphite 6510 has a tensile strength of 38 MPa and compressive strength of 130 MPa (Appendix. 8.2). Per section 2.5.2.4 of Ref. 8.4, the allowable stress for carbon tiles is ½ of the ultimate tensile and compressive stresses. Thus, the acceptance criterion for the 6510 tiles is 19 MPa in tension and 65 MPa in compression.

The maximum stress from row 5 and 6 analysis from all the 6510 scenarios evaluated is 16.6 Mpa in tension (Section 5) and 67.3 Mpa in compression (Section 5). The maximum tension value fall within the acceptance criterion of 19 MPa with a margin of 12.6%. The maximum compression value of 67.3 MPA exceeds the 65 MPa criterion.

ET-10 has a tensile strength of 34.3 MPa and compressive strength of 98 MPa (Appendix. 8.2). Per section 2.5.2.4 of Ref. 8.4, the allowable stress for carbon tiles is ½ of the ultimate tensile and compressive stresses. Thus, the acceptance criterion for the ET-10 tiles is 17.15 MPa in tension and 44 MPa in compression.

The maximum stress for the ET-10 scenarios evaluated is 25.6 Mpa in tension (Section 5) and 48.2 Mpa in compression (Section 5). The maximum tension and compression values exceed the acceptance criterion of 17.15 MPa and 44 MPa.

7.2 T-Bar

The T-Bar material is Grade 660 SS (Section 3.2.6). Grade 660 SS has a yield stress of 585-725 Mpa (Appendix 8.1). Conservatively taking the lower value of 585 MPa (for class A, B, or C grade 660 SS) to calculate the design tresca stress (S_m) value as 2/3 of the material yield stress (Guidance per section 2.4.1.1 of Ref. 8.4) results in an S_m value of 390 MPa. The peak allowable stress for the bolts is calculated (per guidance of section 2.4.1.4.1 and 2.4.1.4.2 of Ref. 8.4) as follows: $1.5(K)(S_m)=1.5(1)(390\ MPa)=585\ MPa$. The multiplier “K” is conservatively assigned a value of 1.0 to reflect normal operating conditions per section 2.4.1.5 of Ref. 8.4.

The maximum T-bar stress from row 5 and 6 analysis from all the scenarios evaluated is 185.3 Mpa (Section 5) which is less than the peak allowable stress of 585 MPa. Thus, the T-bars satisfy the stress acceptance criteria with an 68.3% margin.

7.3 Shear Pin

The shear pin material is Alloy 625 (Section 3.2.2). The bending stress is calculated as follows: Mc/I= 73 MPa which is multiplied by Kt=1.8 to account for fillet stress concentration to allow peak stress value of 131 Mpa. However, the primary allowable is 291 with the new factor for the fillet. The highest linearized stress concentration on the shear pin is 28.7 MPa. This maximum stress provides a 90.1% margin.

7.4 Bolts

7.4.1 Basic Stress Limits

The bolt material is Grade 660 SS (Section 3.2.6). Grade 660 SS has a yield stress of 585-725 Mpa (Appendix 8.1). Conservatively taking the lower value of 585 MPa (for class A, B, or C grade 660 SS) to calculate the design tresca stress (S_m) value as 2/3 of the material yield stress (Guidance per section 2.4.1.1 of Ref. 8.4) results in an S_m value of 390 MPa. The peak allowable stress for the bolts is calculated (per guidance of section 2.4.1.4.1 and 2.4.1.4.2 of Ref. 8.4) as follows: 1.5(K)(S_m)=1.5(1)(390 MPa)=585 MPa. The multiplier "K" is conservatively assigned a value of 1.0 to reflect normal operating conditions per section 2.4.1.5 of Ref. 8.4.

The maximum bolt stress from row 5 and 6 analysis from all the scenarios evaluated is 361.3 Mpa (Section 5) which is less than the peak allowable stress of 585 MPa. Thus, the bolts satisfy the stress acceptance criteria with a 38.2% margin.

7.4.2 Preload Stress Limits

Per section 2.4.1.4.3 of Ref. 8.4, the bolt preload stress is not to exceed 0.75 of the yield stress (S_y). Using the yield stress of 585 MPa results in a maximum preload stress acceptance criterion of 439 MPa.

The bolt shank has a diameter of 5.766 mm (0.005766 m). Thus, the shank cross sectional area is $\pi r^2=\pi*(0.005766\ m)^2=1.044E\text{-}4\ m^2$. The bolt preload of 4270 N (Section 3.3) results in a bolt shank preload stress of $(4270N/1.044E\text{-}4\ m^2)*10^{-6}$ = 40.9 MPa. The preload stress of = 40.9 MPa is less than the peak allowable preload stress. Thus, the bolts satisfy the preload stress acceptance criteria.

8 References

8.1 PFC-180613-AK-01, "PFC thermal and structural analysis procedure" from A.KHODAK to M. Jaworski, R. Ellis, A. Jariwala, B. Linn, J. Klabacha, M. Reinke, P. Titus

8.2 "Introduction to Tribology" Second Edition by Bharat Bhushan

8.3 memo "MODIFICATION OF HEAT FLUX REQUIREMENTS FOR CSAS" from M.L. REINKE to M. JAWORSKI, S. GERHART

8.4 NSTX-CRIT-0001-02, “NSTX (National Spherical Torus Experiment) Structural Design Criteria” dated January 2016

8.5 NSTXU-CALC-11-1100, “EM Loads on Center Stack Angular (CSA) Section Tiles”

9 Appendices

9.1 Grade 660 SS Properties

9.2 Graphite R6510 Properties

9.3 Material Data

9.4 Minimum Pretension Requirements to Prevent Sliding Due to Halo Forces and Toroidal Eddy Moment