Calculation No: NSTXU-CALC-011-20-00 **Revision No: 0**

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

The purpose of this report is to evaluate IBDV 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.)

See attached report section “References”

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

See attached report section “Assumptions”

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.)

All maximum temperature results fall within the allowable peak temperature of 1600 C. All components in the IBDV LHF 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 18:13:16 -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

Han Zhang
Digitally signed by Han Zhang
Date: 2018.09.28 10:16:17 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

Calculation of Plasma Facing Components: IBDV LHF Tile and Variants Transient Thermal and Structural Analysis

NSTXU-CALC-011-20-00

September 21, 2018

Prepared By:

Moheb Thomas Digitally signed by Moheb Thomas Date: 2018.09.27 18:13:29 -04'00'

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Michael Jaworski Digitally signed by Michael Jaworski Date: 2018.09.28 23:37:04 -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 IBDV (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.

	Default tile [POCO TM]	Langmuir and Mirnov Cutout Tile [POTO TM]	Langmuir and Mirnov Cutout Tile [6510]
Tile [POCO TM Acceptance criteria = 20.5 MPa in tension and 55 MPa in compression] [R6510 Acceptance criteria = 19 MPa in tension and 65 MPa in compression]	15.3 MPa max [25.4% margin] -54.9 MPa min [0.2% margin]	21.3 MPa max [Exceeds allowable] -53.5 MPa min [2.7% margin]	16.3 MPa max [14.2% margin] -44.8 MPa min [31.1% margin]
T-Bar [Peak allowable stress = 1,034 MPa]	72.3 MPa intensity [93.0% margin]	69.5 MPa intensity [93.3% margin]	N/A
Shear Pin [Peak allowable stress = 291 MPa]	13.9 MPa intensity [95.2% margin]	12.8 MPa intensity [95.6% margin]	N/A
Bolt [Peak allowable stress = 1,034 MPa]	115.2 MPa intensity [88.9% margin]	103.0 MPa intensity [90.0% margin]	N/A

Table 1: Tile Assembly Components Results and Margins

The transient thermal analysis results are compared in Table 2. All maximum temperature results fall within the allowable peak temperature of 1600 C.

Temperature in C after first flux shot	
Default tile	925.99
Langmuir and Mirnov Cutout Tile	919.14

Table 2: IBDV Temperature Results

2 Purpose

The purpose of this report is to evaluate IBDF LHF 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.

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 – 718
4.1.2 Shear Pin – 718
4.1.3 Gaskets – GTA
4.1.4 Tiles – POCO
4.1.5 T-Bar – 718
4.1.6 Bolts – 718
4.1.7 Belleville Washers – 718

4.2 Bolt Preload

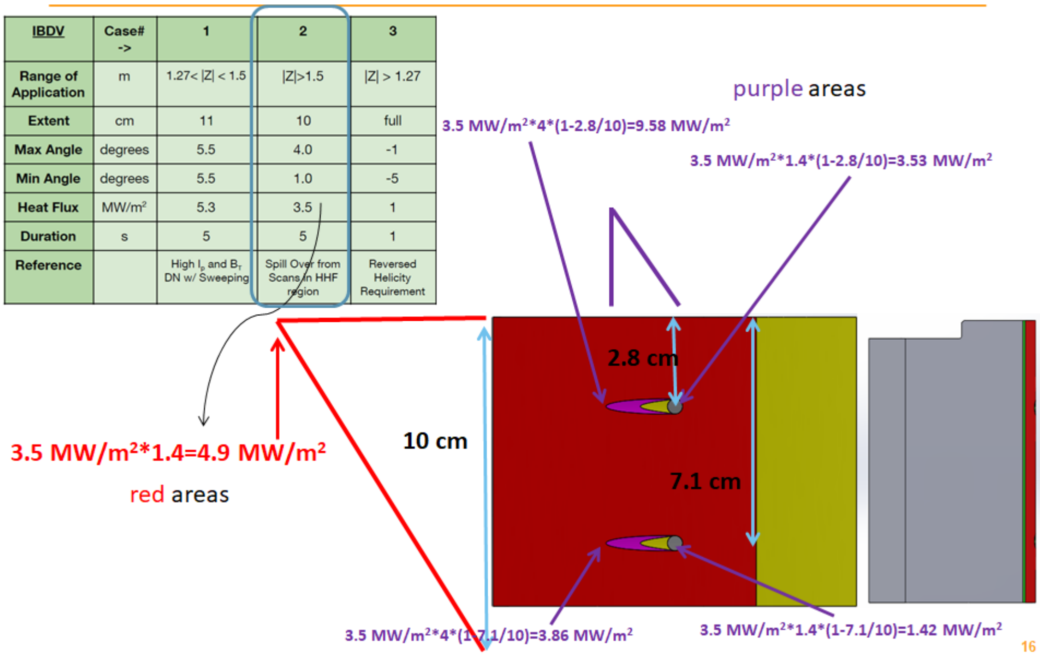
4.2.1 750 N per bolt = 168.6 lbf

4.3 Friction Coefficients

4.3.1 Between Belleville washer and Tee-bar = 0.3
4.3.2 Between Tile and Gasket = 0.1
4.3.3 Between Tile and Tee-bar = 0.1
4.3.4 Between Tile and Sheer Pin = 0.1
4.3.5 Between Case and Gasket = 0.1

4.4 Thermal

4.4.1 Initial Temperature 41C
4.4.2 Surface Fluxes – see figure 2
4.4.3 Radiation Emissivity = 0.7 (Systems Requirements Document)
4.4.4 Ambient Temperature = 126C (Ref.7.1)
4.4.5 Convection
4.4.5.1 Film Coefficient = 288 W/(m^2*C) (Systems Requirements Document)
4.4.5.2 Ambient Temperature = 22C (Systems Requirements Document)



IBDV	Case# ->	1	2	3
Range of Application	m	1.27< |Z| < 1.5	|Z|>1.5	|Z| > 1.27
Extent	cm	11	10	full
Max Angle	degrees	5.5	4.0	-1
Min Angle	degrees	5.5	1.0	-5
Heat Flux	MW/m^2	5.3	3.5	1
Duration	s	5	5	1
Reference		High I_p and B_T DN w/ Sweeping	Spill Over from Scans in HHF region	Reversed Helicity Requirement

Figure 2: Thermal Fluxes on Surface

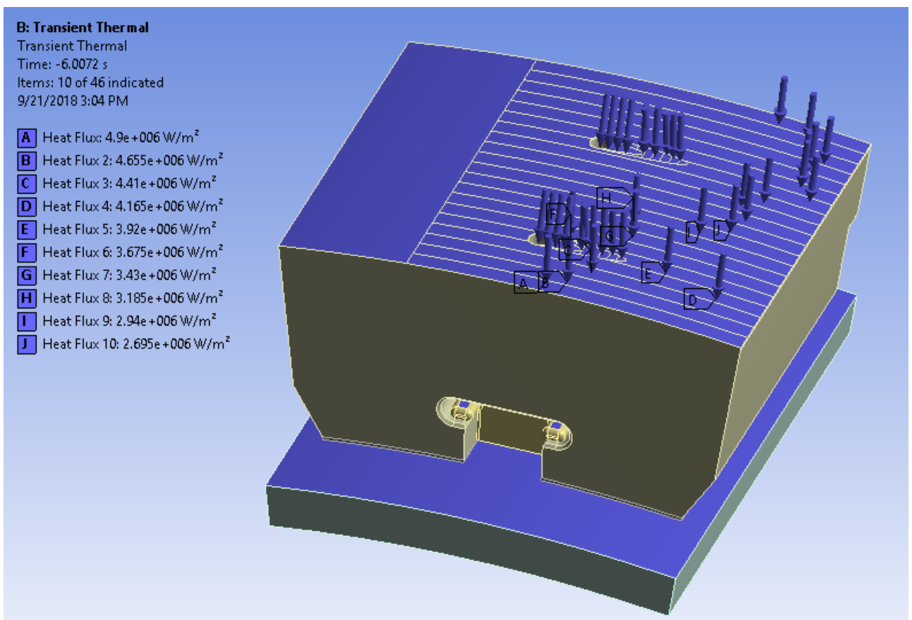


Figure 3: General Thermal Model

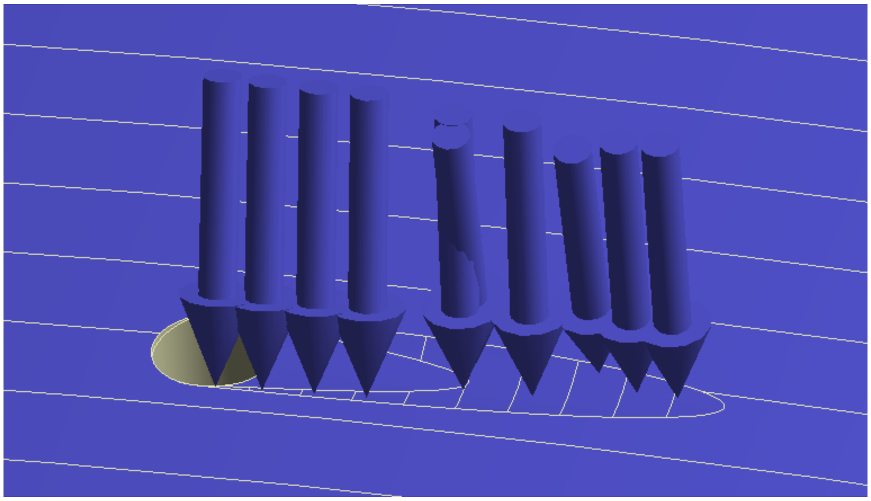


Figure 4: Chamfer Heat Flux

4.5 Mechanical Inputs

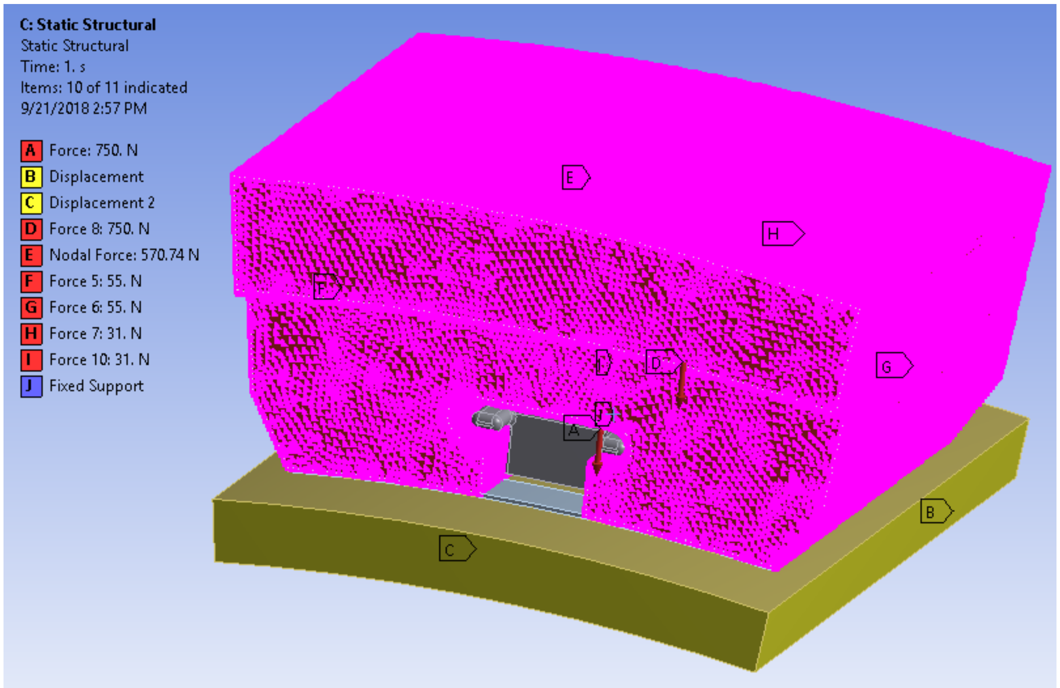


Figure 5: Tile forces and moments

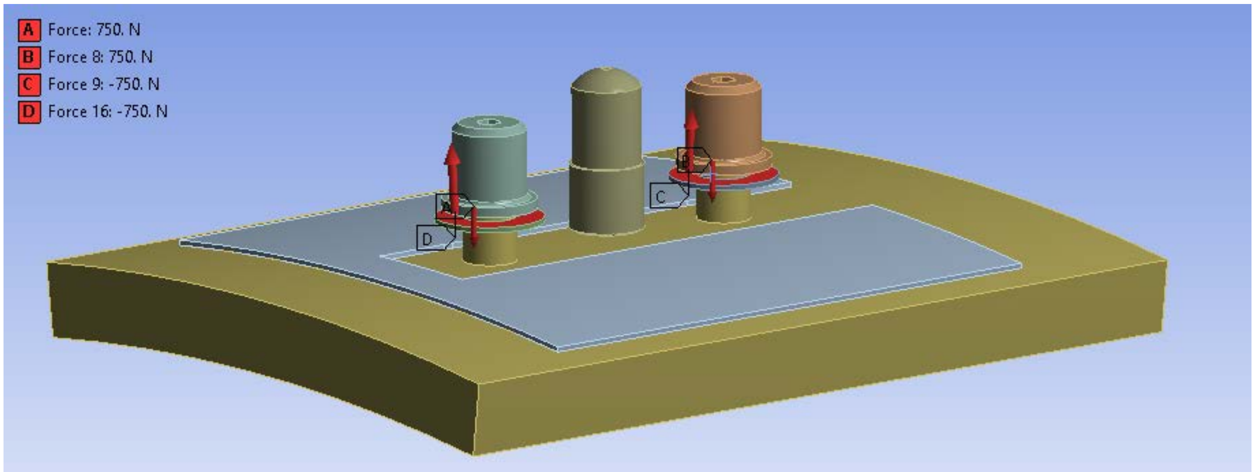


Figure 6: Preload Forces

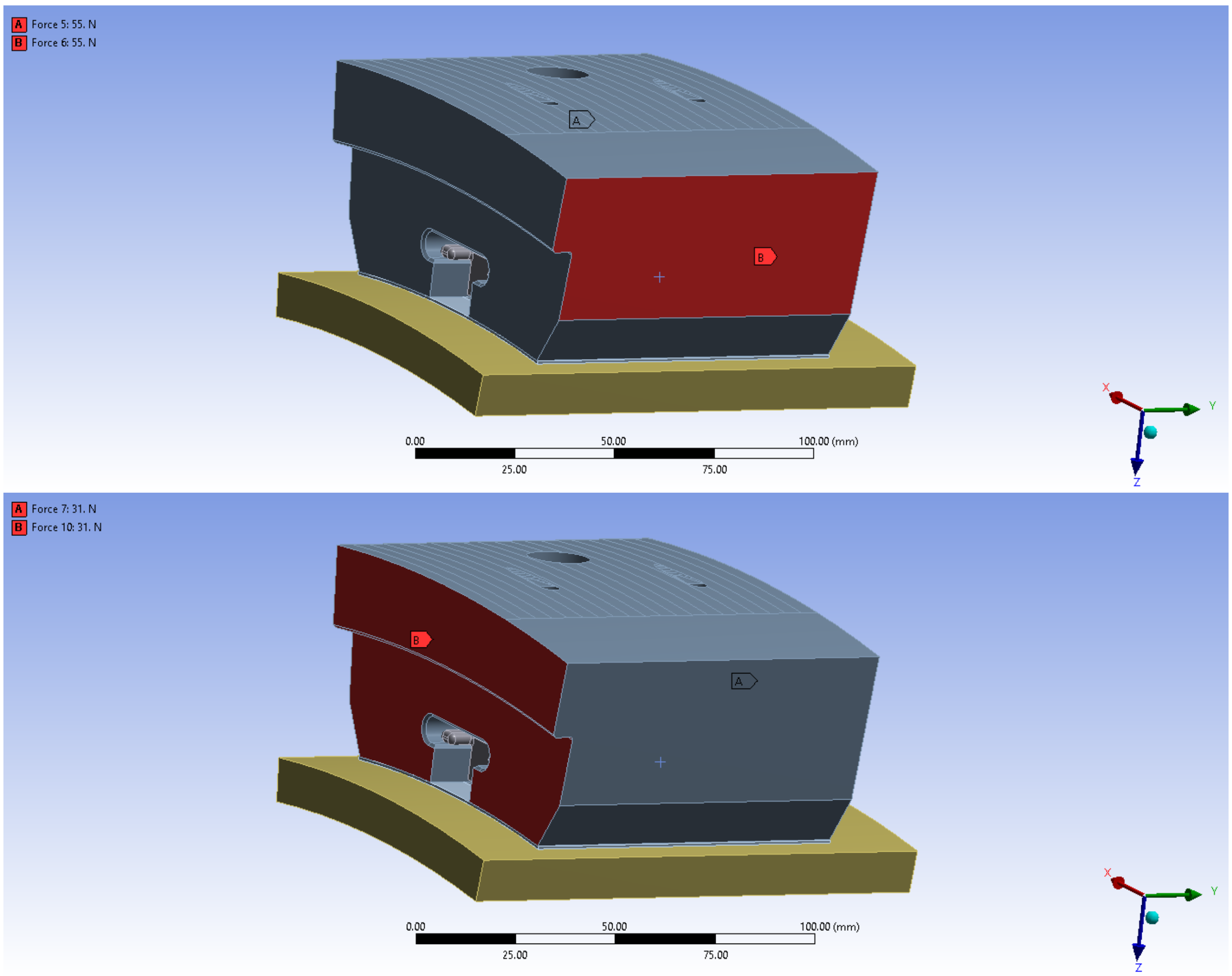


Figure 7: Body Moments

5 ANSYS Results

5.1 Thermal Results

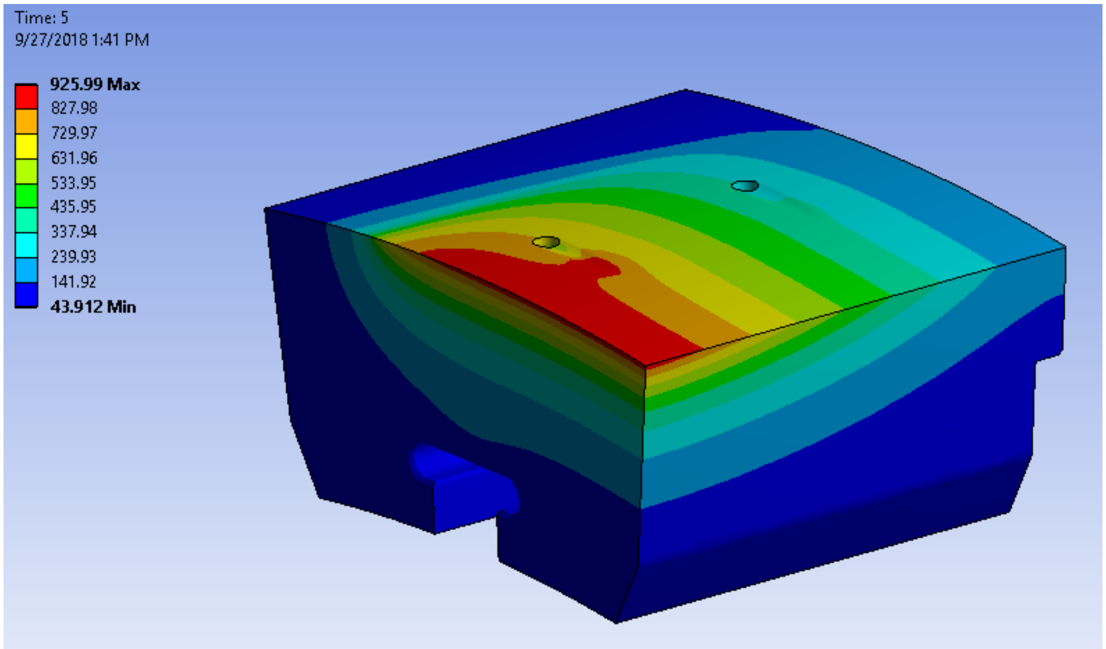


Figure 8: Default Tile Thermal Results at End of 5 Seconds Flux Shot

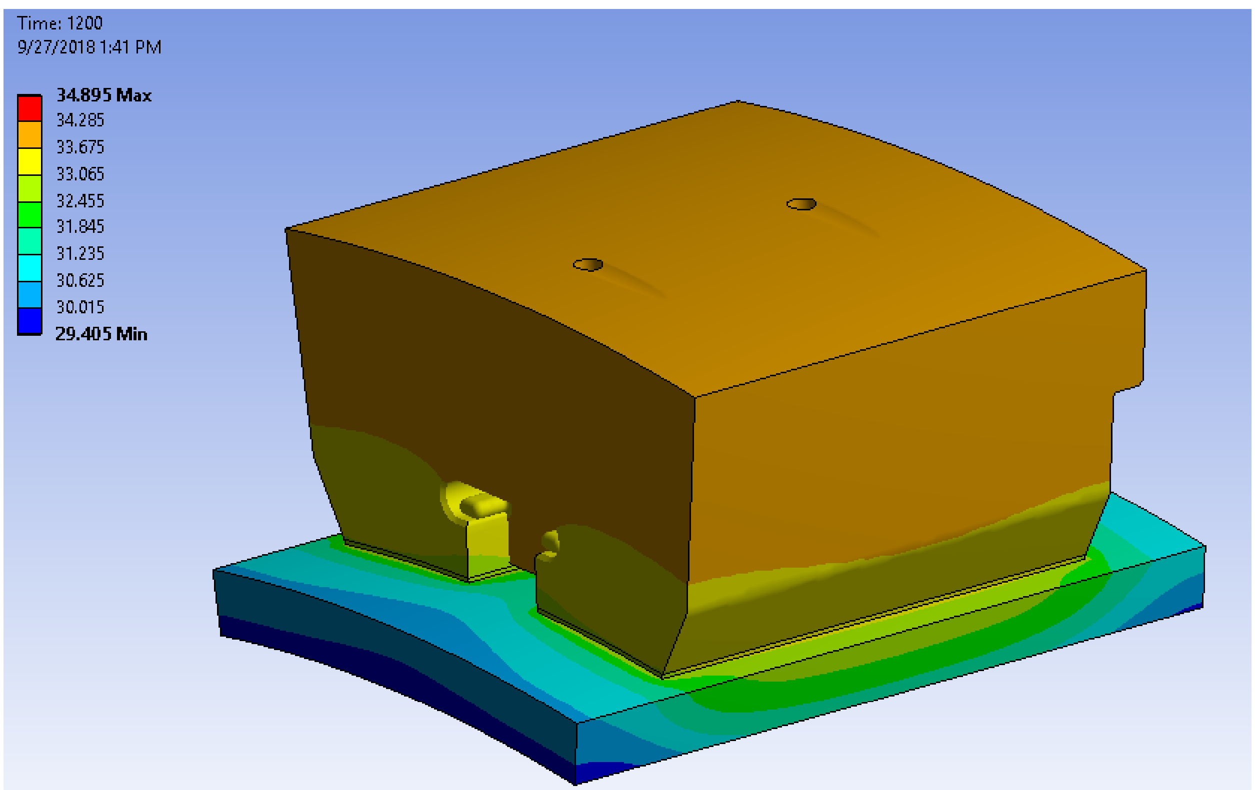


Figure 9: Temperature Immediately Preceding Second Flux Shot

	Time [s]	Minimum [°C]	Maximum [°C]
1	1.e-002	40.932	104.66
2	1.5533e-002	40.905	122.49
3	2.1067e-002	40.883	135.34
4	3.7666e-002	40.842	161.39
5	8.7466e-002	40.766	206.99
6	0.13727	40.711	239.9
7	0.23727	40.629	286.24
8	0.33727	40.557	322.93
9	0.43727	40.498	353.9
10	0.53727	40.446	381.08
11	0.63727	40.4	405.55
12	0.73727	40.357	428.02
13	0.83727	40.317	448.84
14	0.93727	40.278	468.34
15	1.	40.255	480.13
16	1.04	40.241	487.46
17	1.08	40.227	494.65
18	1.2	40.187	515.01
19	1.32	40.15	534.35
20	1.68	40.051	585.81
21	2.08	39.953	637.47
22	2.48	39.864	684.74
23	2.88	39.782	728.63
24	3.28	39.706	769.86
25	3.68	39.635	808.93
26	4.08	39.568	846.1
27	4.48	39.505	881.59
28	4.74	39.466	904.08
29	5.	39.429	925.99
30	16.95	39.149	322.5
31	20.933	39.215	259.8
32	23.484	39.326	233.86
33	26.035	39.51	214.96
34	31.094	40.161	190.18
35	37.745	41.43	168.9
36	46.046	43.399	151.78
37	56.28	46.053	138.29
38	69.26	49.271	127.39
39	86.725	52.795	118.01
40	112.34	56.131	109.08
41	155.	58.092	99.384
42	239.2	56.212	87.483
43	358.7	50.877	76.458
44	478.2	45.652	66.208
45	597.7	41.221	57.656
46	717.2	37.645	50.779
47	836.7	34.815	45.335
48	956.2	32.597	41.061
49	1075.7	30.868	37.724
50	1137.8	30.085	36.211
51	1200.	29.405	34.895

Table 3: Temperature for Default Tile with Respect to Time

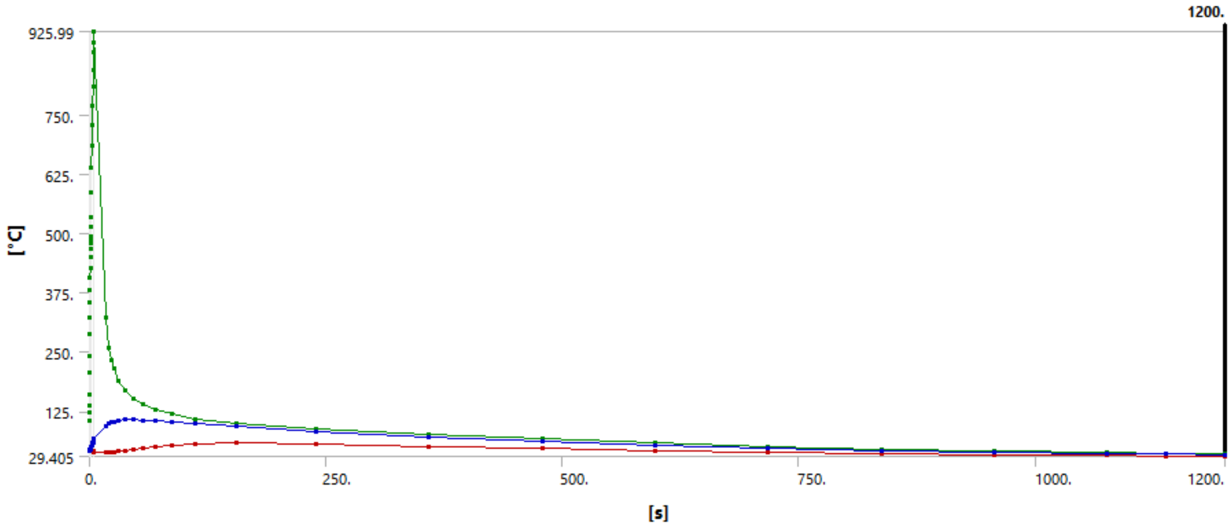


Figure 10: Transient Thermal Results for Default Tile

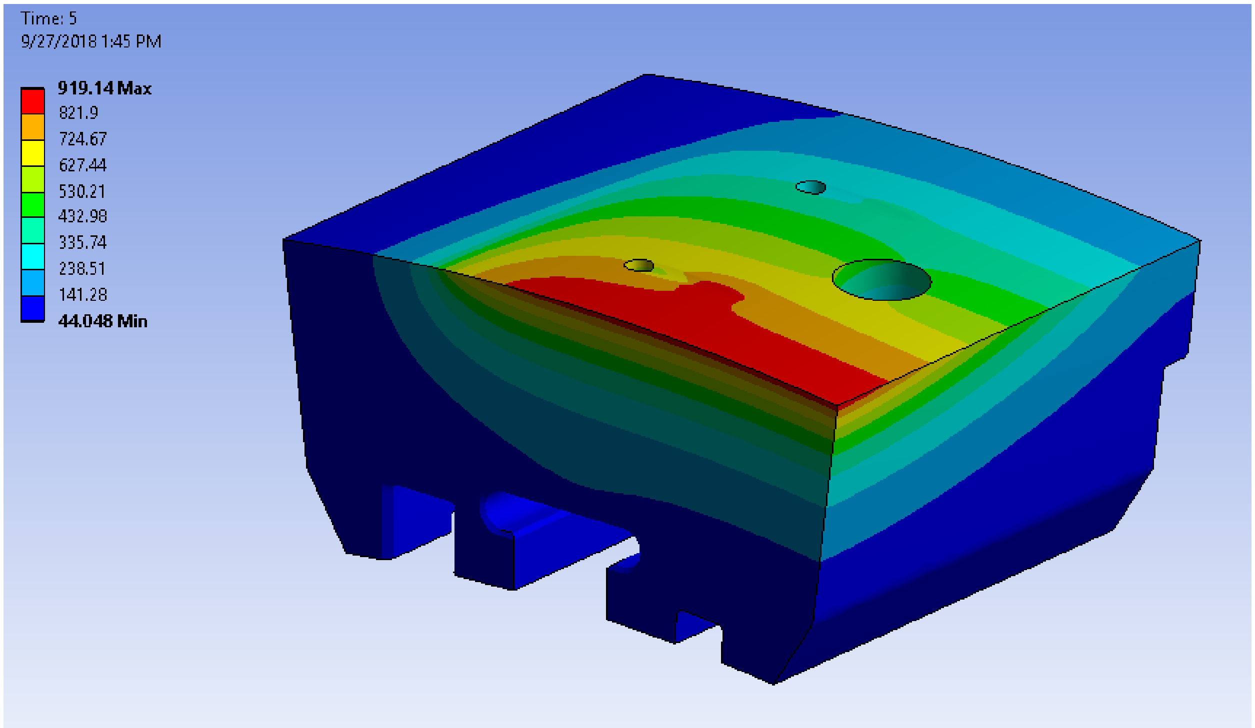


Figure 11: Variant Tile Thermal Results at End of 5 Seconds Flux Shot

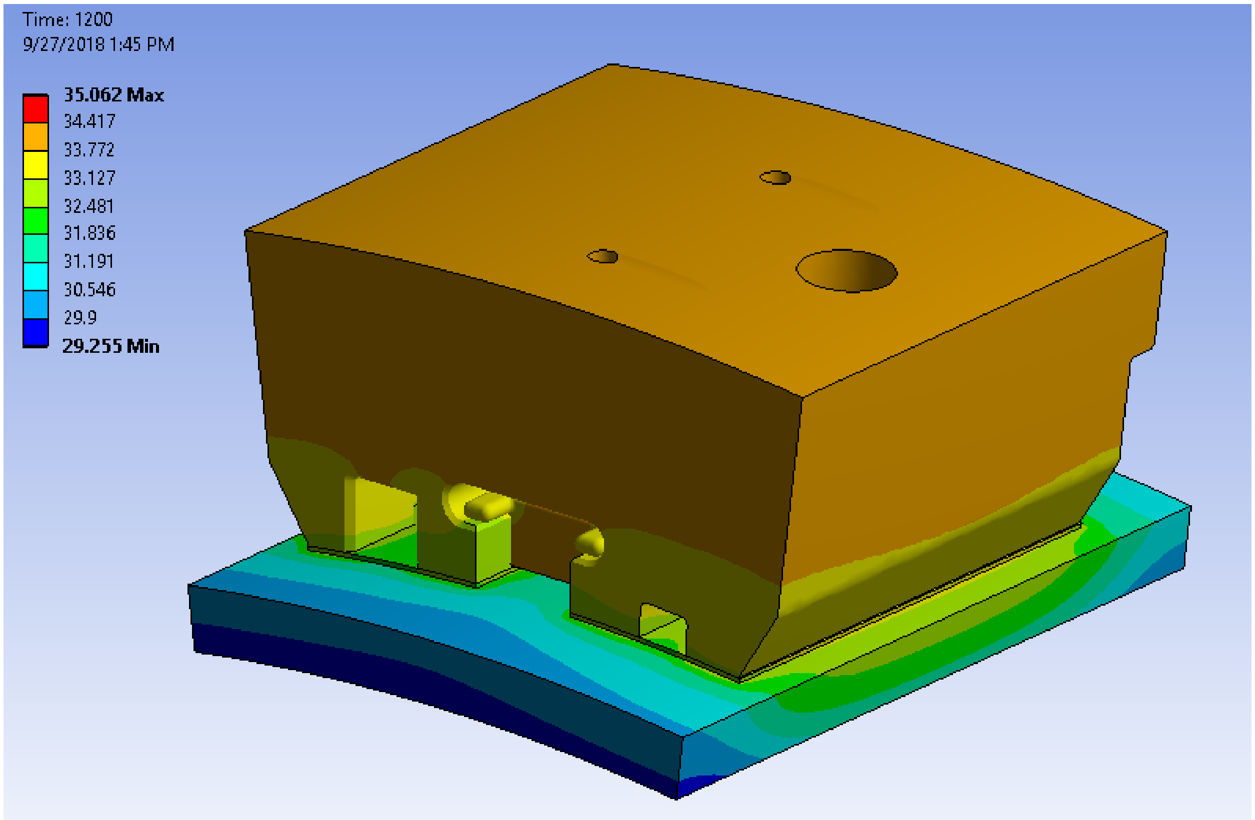


Figure 12: Variant Tile Temperature Immediately Preceding Second Flux Shot

	Time [s]	Minimum [°C]	Maximum [°C]
1	1.e-002	40.939	103.79
2	1.5559e-002	40.912	121.59
3	2.1117e-002	40.889	134.78
4	3.7793e-002	40.845	160.59
5	8.7821e-002	40.767	205.65
6	0.13785	40.709	238.21
7	0.23785	40.627	284.06
8	0.33785	40.557	320.41
9	0.43785	40.498	351.15
10	0.53785	40.446	378.15
11	0.63785	40.399	402.47
12	0.73785	40.356	424.75
13	0.83785	40.316	445.41
14	0.93785	40.279	464.77
15	1.	40.256	476.37
16	1.04	40.242	483.65
17	1.08	40.228	490.79
18	1.2	40.189	511.02
19	1.32	40.151	530.23
20	1.68	40.052	581.39
21	2.08	39.954	632.69
22	2.48	39.865	679.61
23	2.88	39.782	723.18
24	3.28	39.705	764.09
25	3.68	39.633	802.87
26	4.08	39.565	839.8
27	4.48	39.501	875.04
28	4.74	39.461	897.37
29	5.	39.423	919.14
30	16.95	39.068	323.96
31	20.933	39.094	261.82
32	23.382	39.169	237.01
33	25.83	39.303	218.84
34	30.784	39.824	194.48
35	37.535	40.916	172.74
36	46.166	42.706	154.85
37	56.994	45.173	140.61
38	71.022	48.211	129.01
39	90.239	51.563	118.98
40	118.33	54.642	109.47
41	163.86	56.327	99.207
42	250.43	54.509	86.127
43	369.93	49.487	75.663
44	489.43	44.537	65.681
45	608.93	40.324	57.254
46	728.43	36.916	50.445
47	847.93	34.221	45.049
48	967.43	32.113	40.816
49	1086.9	30.472	37.516
50	1200.	29.255	35.062

Table 4: Temperature for Variant Tile with Respect to Time

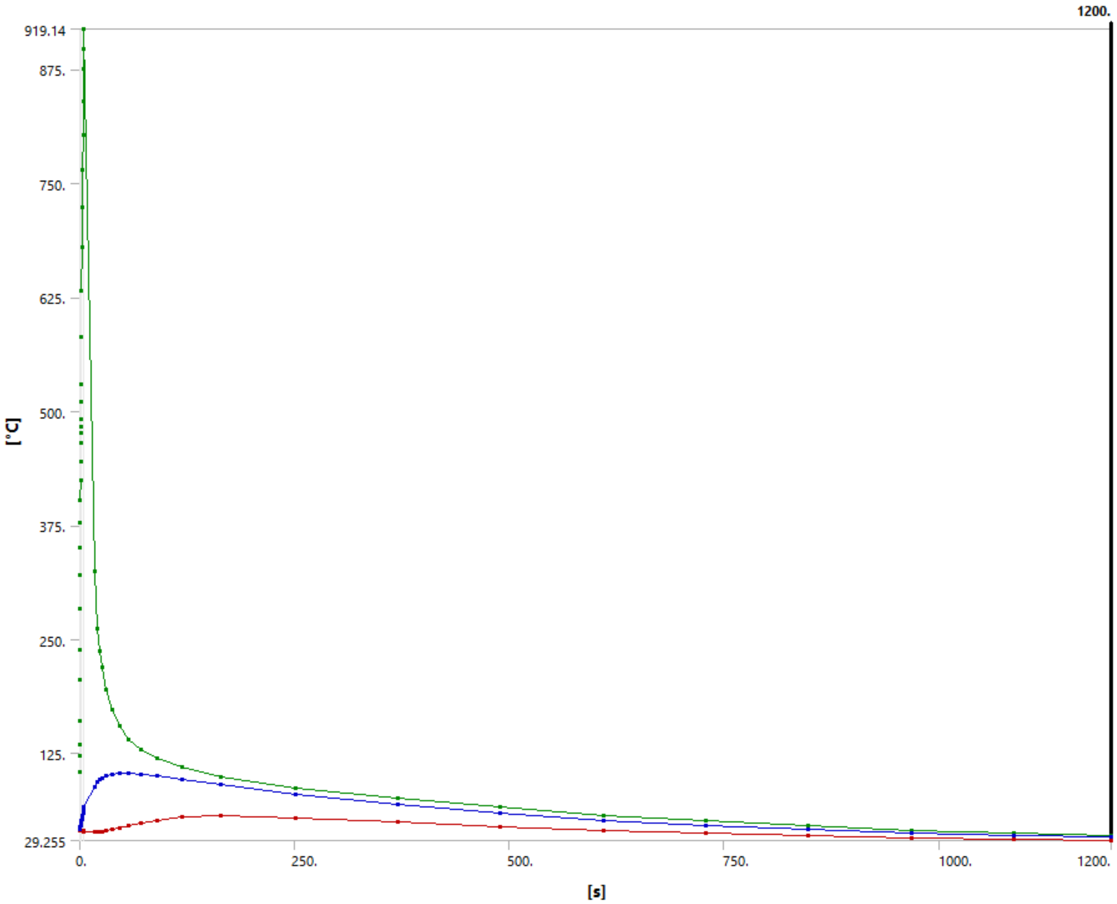


Figure 13: Transient Thermal Results for Variant Tile

5.2 Mechanical Results

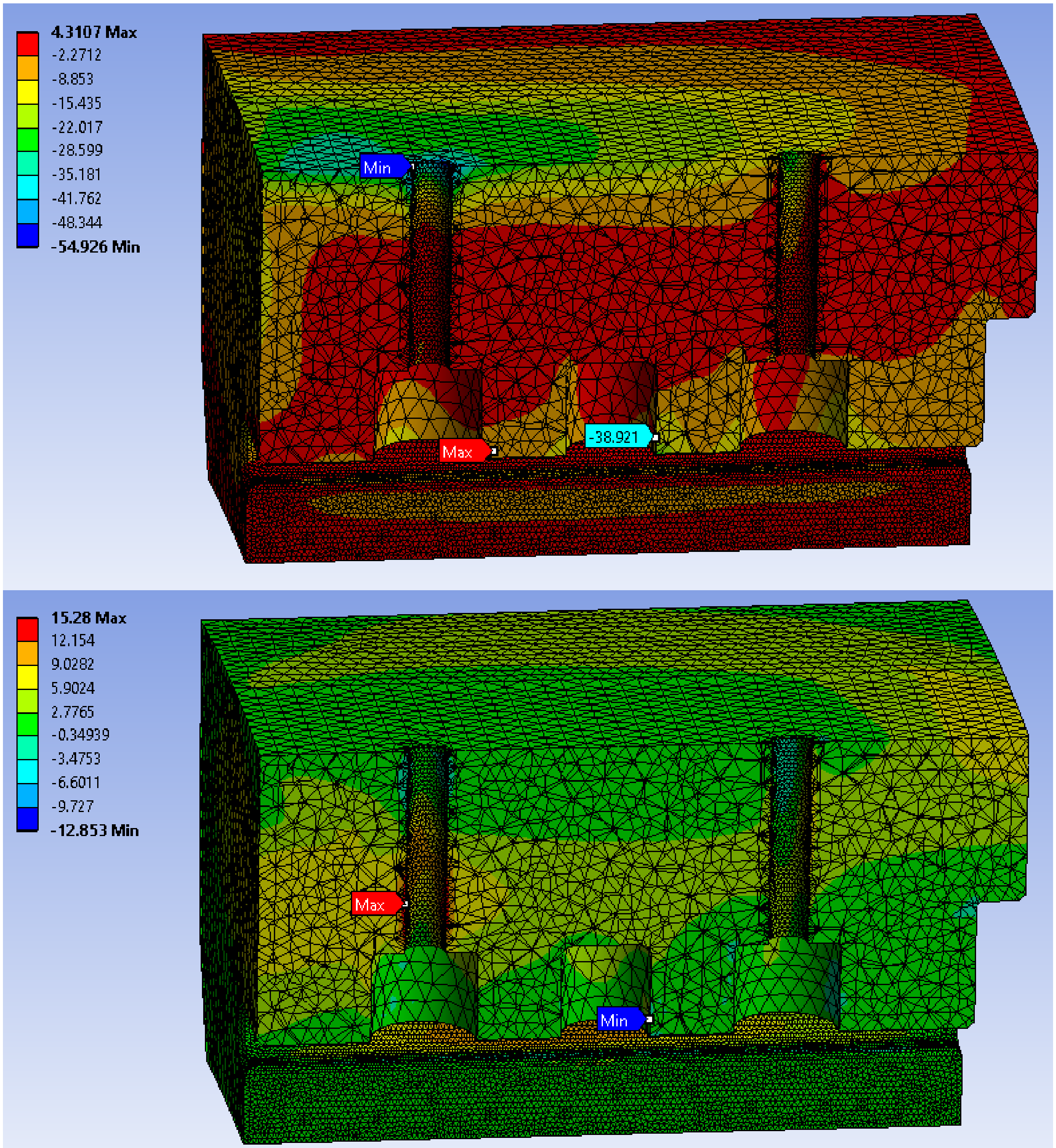


Figure 14: Default Tile Stresses

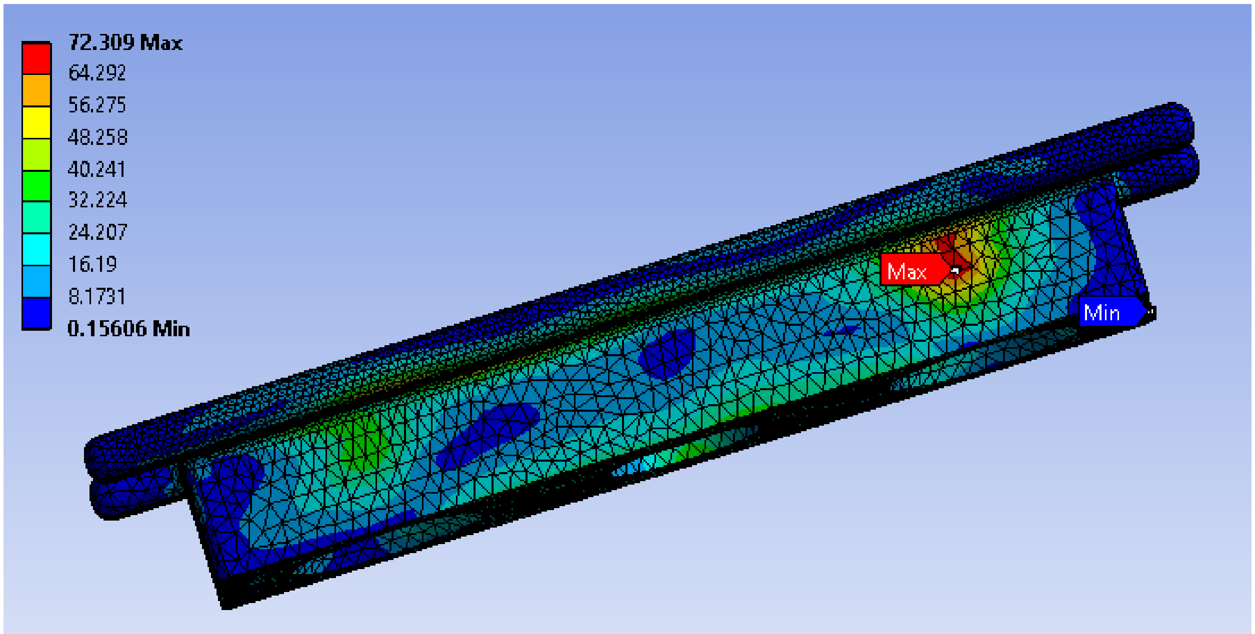


Figure 15: Default Tile T-Bar

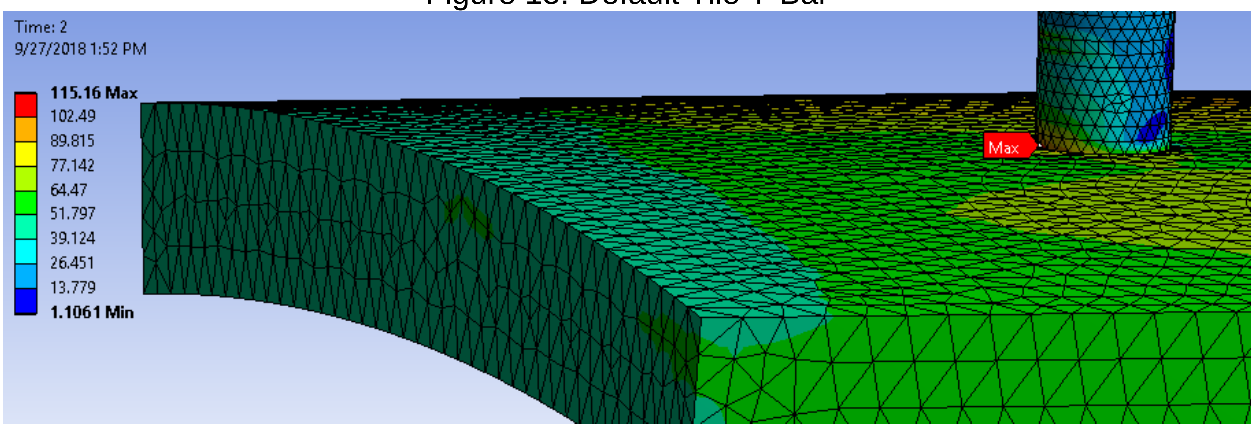


Figure 16: Default Tile Bolt Stress

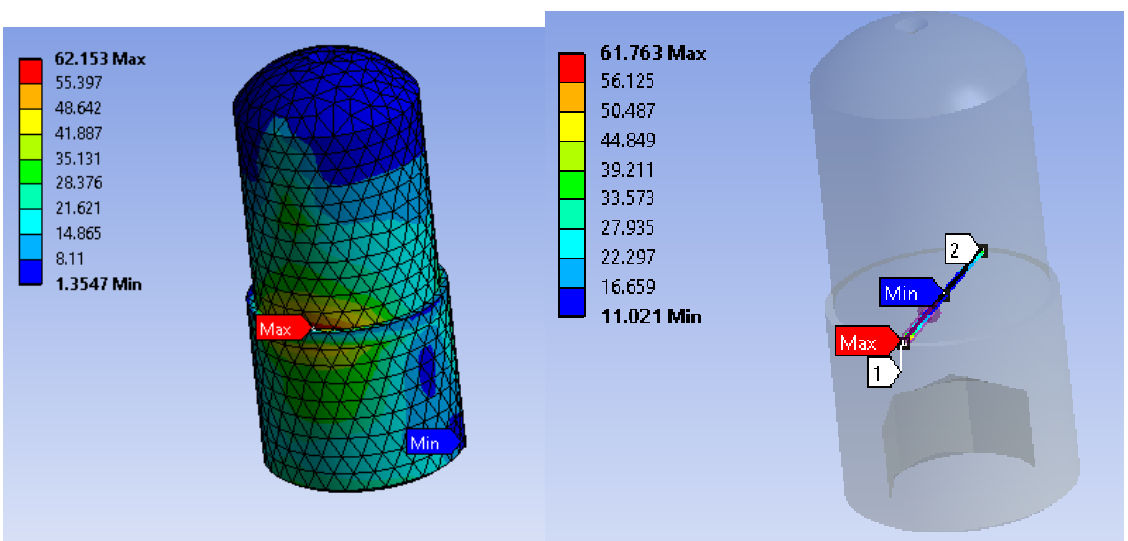


Figure 17: Default Tile Shear Pin Stresses

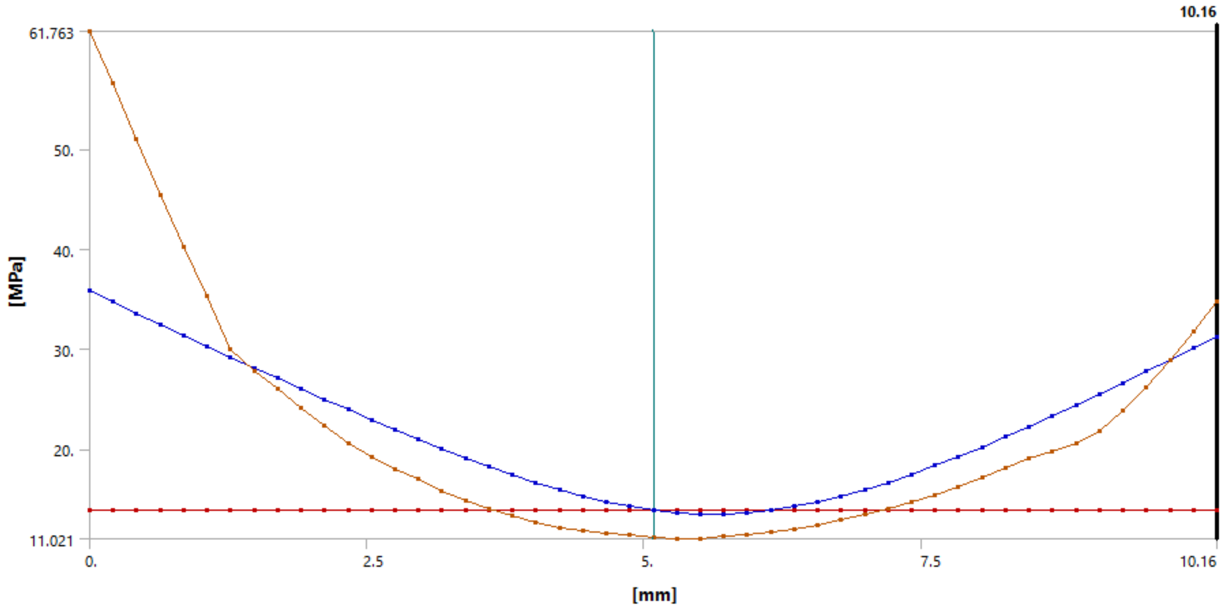


Figure 18: Default Tile Shear Pin Linearized Stress

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	13.904	31.092	35.847	27.043	61.763
2	0.21167	13.904	29.796	34.716	22.807	56.522
3	0.42333	13.904	28.501	33.595	18.191	50.942
4	0.635	13.904	27.205	32.483	13.607	45.452
5	0.84666	13.904	25.91	31.379	9.354	40.261
6	1.0583	13.904	24.614	30.283	5.4176	35.343
7	1.27	13.904	23.319	29.195	1.2926	29.987
8	1.4817	13.904	22.023	28.117	2.2344	27.823
9	1.6933	13.904	20.728	27.05	3.7188	26.019
10	1.905	13.904	19.432	25.995	4.503	24.173
11	2.1167	13.904	18.137	24.953	5.5388	22.296
12	2.3283	13.904	16.841	23.926	6.6682	20.522
13	2.54	13.904	15.546	22.917	7.7024	19.174
14	2.7517	13.904	14.25	21.929	7.9824	17.985
15	2.9633	13.904	12.955	20.964	8.1648	16.959
16	3.175	13.904	11.659	20.026	8.388	15.856
17	3.3867	13.904	10.364	19.121	8.6459	14.83
18	3.5983	13.904	9.0684	18.253	8.5727	13.993
19	3.81	13.904	7.7729	17.429	8.2407	13.284
20	4.0217	13.904	6.4775	16.656	7.9611	12.666
21	4.2333	13.904	5.182	15.944	7.8397	12.164
22	4.445	13.904	3.8865	15.302	7.6966	11.78
23	4.6567	13.904	2.591	14.74	7.181	11.635
24	4.8683	13.904	1.2955	14.271	6.6293	11.46
25	5.08	13.904	5.3086e-015	13.904	6.0573	11.219
26	5.2916	13.904	1.2955	13.65	5.5767	11.021
27	5.5033	13.904	2.591	13.516	5.1505	11.026
28	5.715	13.904	3.8865	13.508	4.6696	11.226
29	5.9266	13.904	5.182	13.627	4.2444	11.464
30	6.1383	13.904	6.4775	13.871	3.8921	11.745
31	6.35	13.904	7.7729	14.233	3.5799	11.972
32	6.5616	13.904	9.0684	14.705	3.2991	12.414
33	6.7733	13.904	10.364	15.277	3.0843	12.962
34	6.985	13.904	11.659	15.938	2.9826	13.529
35	7.1966	13.904	12.955	16.677	3.0211	14.087
36	7.4083	13.904	14.25	17.484	3.1736	14.664
37	7.62	13.904	15.546	18.351	3.3406	15.323
38	7.8316	13.904	16.841	19.268	3.369	16.212
39	8.0433	13.904	18.137	20.228	3.428	17.143
40	8.255	13.904	19.432	21.226	3.5377	18.089
41	8.4666	13.904	20.728	22.256	3.6943	19.045
42	8.6783	13.904	22.023	23.314	4.001	19.806
43	8.89	13.904	23.319	24.397	4.4077	20.573
44	9.1016	13.904	24.614	25.5	4.514	21.761
45	9.3133	13.904	25.91	26.621	4.1205	23.88
46	9.525	13.904	27.205	27.758	5.7877	26.18
47	9.7366	13.904	28.501	28.909	9.3866	28.839
48	9.9483	13.904	29.796	30.073	13.209	31.739
49	10.16	13.904	31.092	31.247	17.106	34.821

Table 5: Default Tile Shear Pin Linearized Stress

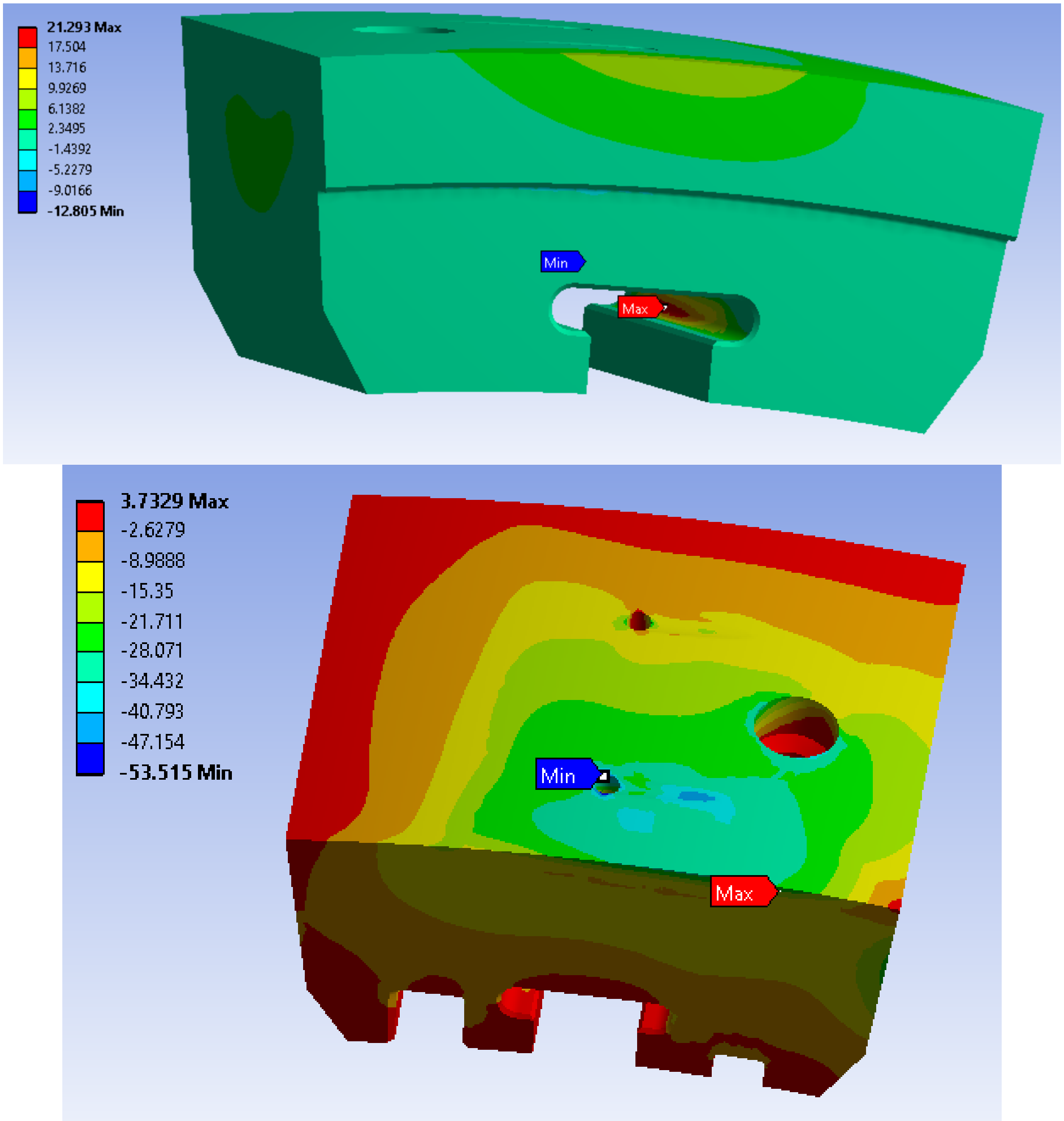


Figure 19: Variant Tile Stresses

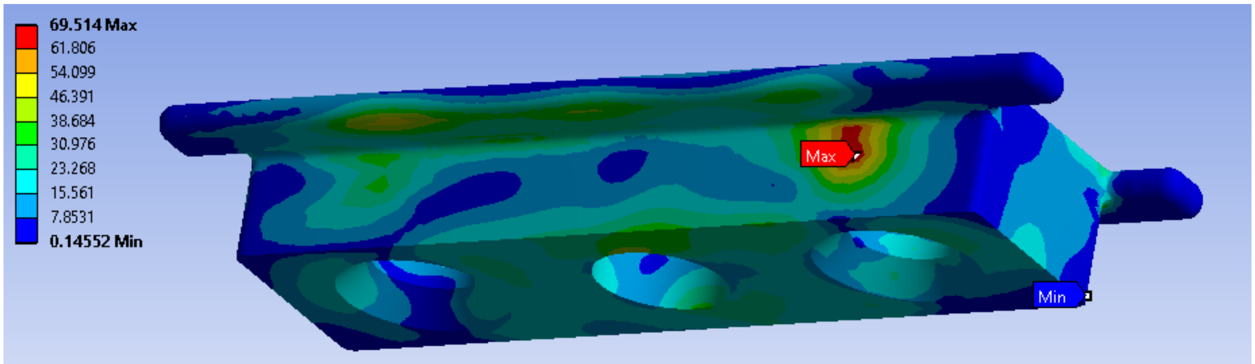


Figure 20: Variant Tile T-Bar

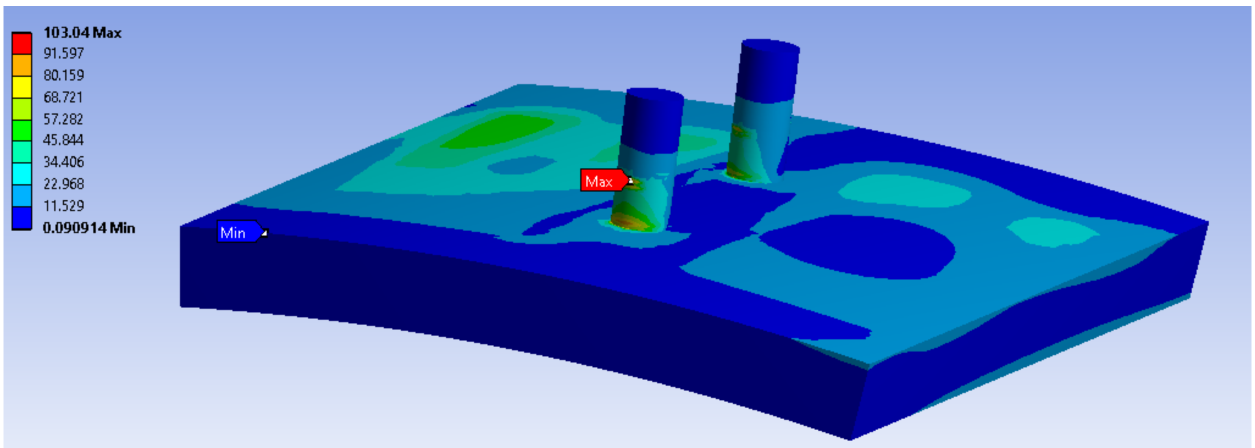


Figure 21: Variant Tile Bolt Stress

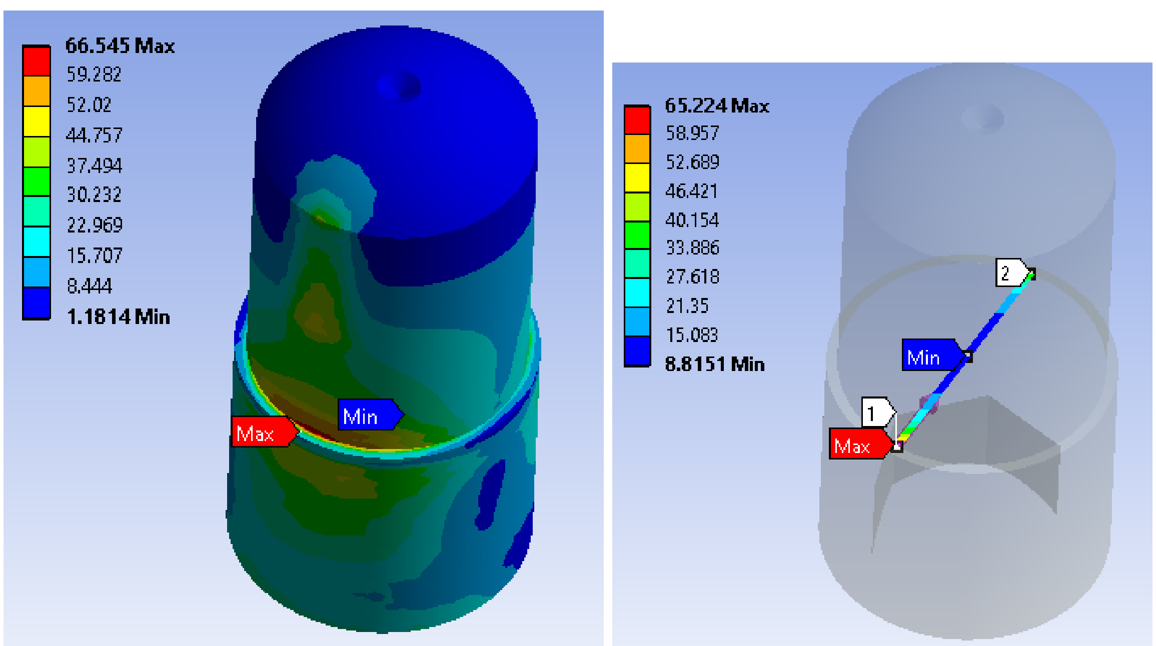


Figure 22: Variant Tile Shear Pin Stresses

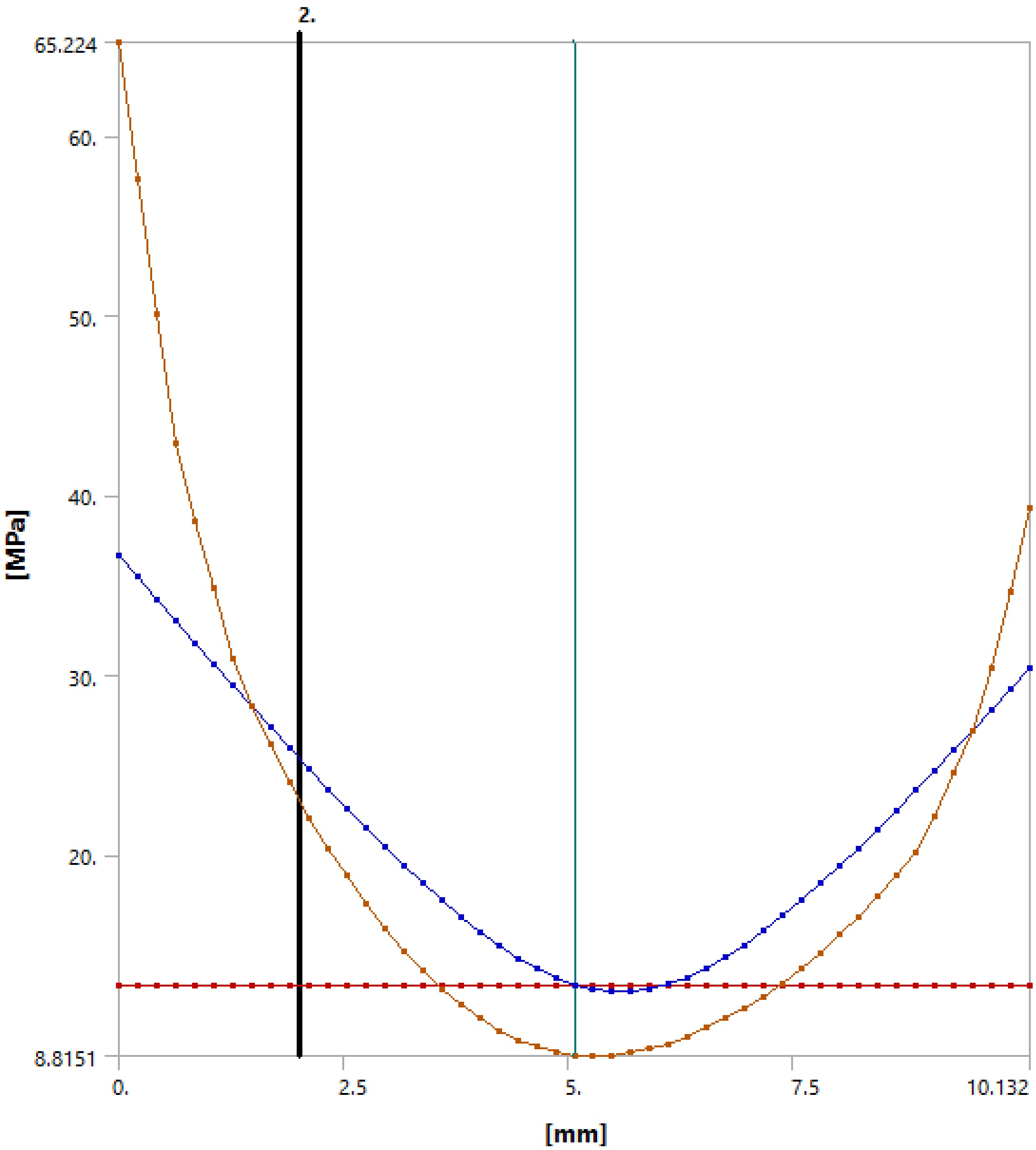


Figure 23: Variant Tile Shear Pin Linearized Stress

	Length [mm]	Membrane [MPa]	Bending [MPa]	Membrane+Bending [MPa]	Peak [MPa]	Total [MPa]
1	0.	12.754	30.895	36.65	29.993	65.224
2	0.21107	12.754	29.607	35.434	23.562	57.617
3	0.42215	12.754	28.32	34.223	17.464	50.12
4	0.63322	12.754	27.033	33.017	11.978	42.935
5	0.8443	12.754	25.745	31.817	8.419	38.521
6	1.0554	12.754	24.458	30.625	5.3269	34.848
7	1.2664	12.754	23.171	29.44	2.833	30.962
8	1.4775	12.754	21.884	28.264	3.1504	28.299
9	1.6886	12.754	20.596	27.099	3.8633	26.134
10	1.8997	12.754	19.309	25.945	4.9253	24.063
11	2.1107	12.754	18.022	24.804	6.0432	22.064
12	2.3218	12.754	16.735	23.68	6.6601	20.308
13	2.5329	12.754	15.447	22.574	7.0127	18.846
14	2.744	12.754	14.16	21.489	7.5457	17.326
15	2.955	12.754	12.873	20.43	8.1308	15.861
16	3.1661	12.754	11.585	19.401	8.5101	14.626
17	3.3772	12.754	10.298	18.408	8.5014	13.566
18	3.5883	12.754	9.0109	17.457	8.4805	12.566
19	3.7993	12.754	7.7236	16.555	8.3789	11.695
20	4.0104	12.754	6.4364	15.712	8.1459	10.927
21	4.2215	12.754	5.1491	14.937	7.9921	10.188
22	4.4326	12.754	3.8618	14.242	7.8333	9.6441
23	4.6436	12.754	2.5745	13.639	7.449	9.3443
24	4.8547	12.754	1.2873	13.139	7.0959	8.9895
25	5.0658	12.754	5.2898e-015	12.754	6.7073	8.8492
26	5.2768	12.754	1.2873	12.495	6.32	8.8151
27	5.4879	12.754	2.5745	12.369	5.9465	8.8345
28	5.699	12.754	3.8618	12.378	5.5024	9.0279
29	5.9101	12.754	5.1491	12.523	5.1405	9.2481
30	6.1211	12.754	6.4364	12.798	4.8996	9.4854
31	6.3322	12.754	7.7236	13.195	4.5987	9.9098
32	6.5433	12.754	9.0109	13.702	4.3836	10.369
33	6.7544	12.754	10.298	14.308	4.1893	10.9
34	6.9654	12.754	11.585	15.	4.0617	11.495
35	7.1765	12.754	12.873	15.767	4.071	12.091
36	7.3876	12.754	14.16	16.598	4.0155	12.87
38	7.8097	12.754	16.735	18.418	4.0551	14.565
39	8.0208	12.754	18.022	19.392	4.0369	15.57
40	8.2319	12.754	19.309	20.4	4.1062	16.589
41	8.443	12.754	20.596	21.438	4.1613	17.718
42	8.654	12.754	21.884	22.501	4.2874	18.875
43	8.8651	12.754	23.171	23.585	4.4357	20.106
44	9.0762	12.754	24.458	24.689	4.2694	22.171
45	9.2872	12.754	25.745	25.81	4.5002	24.56
46	9.4983	12.754	27.033	26.945	5.3019	26.941
47	9.7094	12.754	28.32	28.093	10.293	30.39
48	9.9205	12.754	29.607	29.252	16.256	34.623
49	10.132	12.754	30.895	30.421	22.246	39.273

Table 6: Variant Tile Shear Pin Linearized Stress

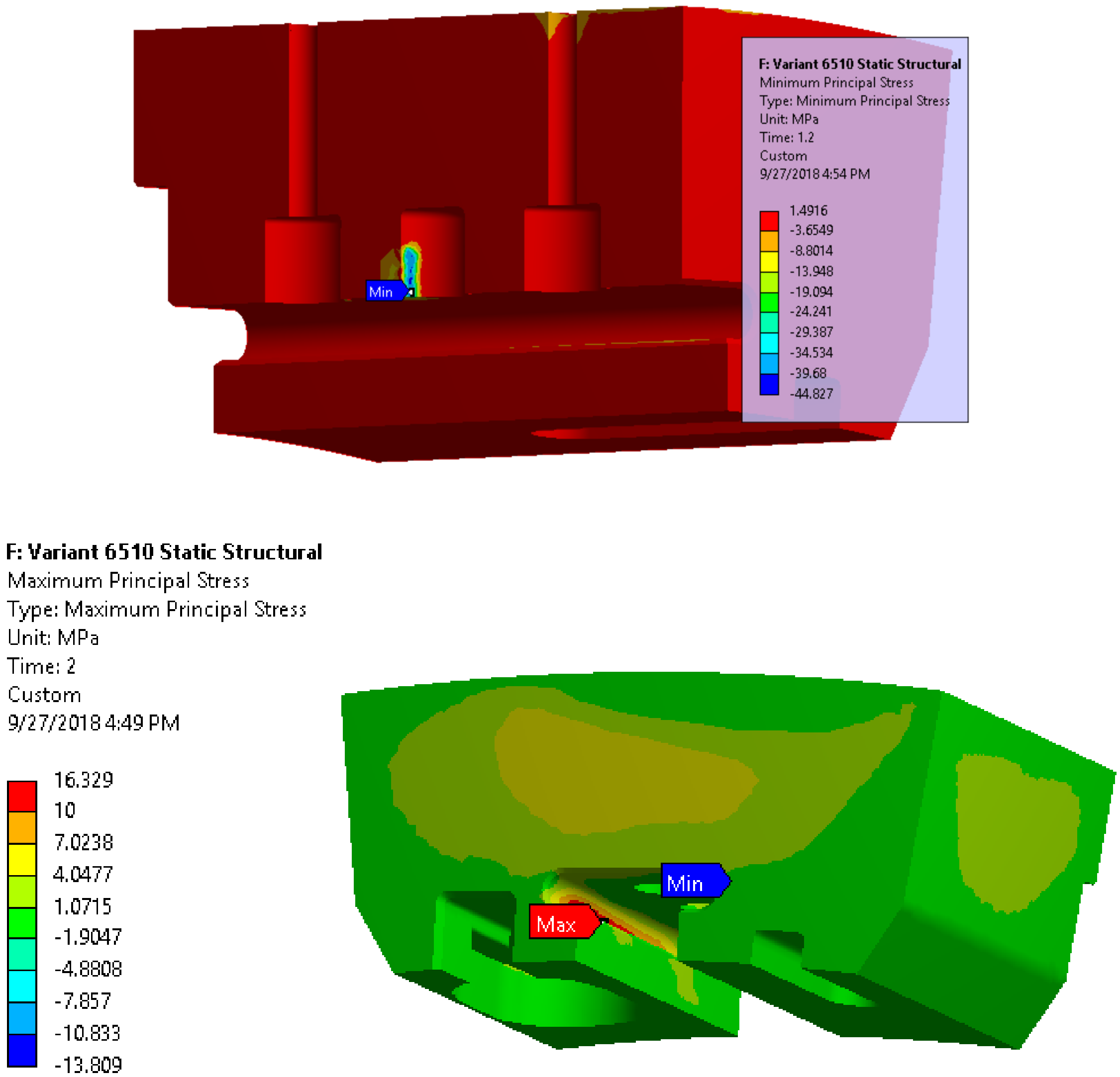


Figure 24: Variant Tile Stresses with 6510

6 Conclusion

The following results are summarized in section 1.

6.1 Tiles

The tile material is POCO TM. POCO TM has a tensile strength of 41 MPa and compressive strength of 110 MPa. Per section 2.5.2.4 of Ref. 7.4, the allowable stress for carbon tiles is ½ of the ultimate tensile and compressive stresses. Thus, the acceptance criterion for the tiles is 20.5 MPa in tension and 55 MPa in compression.

The maximum stress from all the scenarios evaluated is 21.3 Mpa in tension and 54.9 Mpa in compression. The maximum tension criteria of 54.9 MPa falls within the acceptance criterion of 55 MPa with a margin of 0.2%. The maximum compression value of 21.3 MPa exceeds the acceptance criterion of 20.5 MPa.

The secondary tile material evaluated is Graphite 6510. Graphite 6510 has a tensile strength of 38 MPa and compressive strength of 130 MPa. Per section 2.5.2.4 of Ref. 7.4, 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 the 6510 analysis evaluated is 16.3 Mpa in tension and 44.8 Mpa in compression. The maximum tension value of 16.3 falls within the acceptance criterion of 19 MPa with a margin of 14.2%. The maximum compression value of 44.8 MPA falls within the acceptance criterion of 65 MPa with a margin of 31.1%.

6.2 T-Bar

The T-Bar material is INCONEL Alloy 718. INCONEL Alloy 718 has a yield stress of 1,034 Mpa. The design tresca stress (S_m) value is 2/3 of the material yield stress (Guidance per section 2.4.1.1 of Ref. 7.4) which results in an S_m value of 689.3 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. 7.4) as follows: $1.5(K)(S_m)=1.5(1)(689.3\ \text{MPa})=1{,}034$ 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. 7.4.

The maximum T-bar stress from row 5 and 6 analysis from all the scenarios evaluated is 72.3 Mpa which is less than the peak allowable stress of 1,034 MPa. Thus, the T-bars satisfy the stress acceptance criteria. With an 93% margin.

6.3 Shear Pin

The shear pin material is INCONEL Alloy 718. 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 13.9 MPa. This maximum stress provides a 95.2% margin.

6.4 Bolts

6.4.1 Basic Stress Limits

The bolt material is INCONEL Alloy 718. INCONEL Alloy 718 has a yield stress of 1,034 Mpa. Taking the design tresca stress (S_m) as 2/3 of the material yield stress (Guidance per section 2.4.1.1 of Ref. 7.4) results in an

S_m value of 689.3 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. 7.4) as follows: $1.5(K)(S_m)=1.5(1)(390\ MPa)=1{,}034\ MPa$. The multiplier "K" is conservatively assigned a value of 1.0 to reflect normal operating conditions per section 2.4.1.5 of Ref. 7.4.

The maximum bolt stress from all the scenarios evaluated is 115.2 Mpa which is less than the peak allowable stress of 1,034 MPa. Thus, the bolts satisfy the stress acceptance criteria with a 88.9% margin.

6.4.2 Preload Stress Limits

Per section 2.4.1.4.3 of Ref. 7.4, the bolt preload stress is not to exceed 0.75 of the yield stress (S_y). Using the yield stress of 1,034 MPa results in a maximum preload stress acceptance criterion of 775.5 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 1500 N results in a bolt shank preload stress of $(1500N/1.044E\text{-}4\ m^2)*10^{-6} = 14.4\ MPa$. The preload stress of = 14.4 MPa is less than the peak allowable preload stress. Thus, the bolts satisfy the preload stress acceptance criteria.

7 References

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7.4 NSTX-CRIT-0001-02, "NSTX (National Spherical Torus Experiment) Structural Design Criteria" dated January 2016