Fermi National Accelerator Laboratory
PPD / Mechanical Support / Engineering Analysis

Finite Element Analysis of Strip lines of Horn 1

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Finite element analysis is done for the NuMI Accelerator Improvement Project with the NOvA Horn 1 Stripline Geometry as it currently exists, for operating at a maximum power of 1MW. First thermal analysis is done to calculate the temperature profile of the stripline. Then structural analysis is done to get the stress distributions and stress cycles to predict the fatigue life of the stripline.

1. Finite Element Model

Strip lines for horn 1 is shown in Figure 1. It is generated from team center document F10057717. Assume left and right are symmetric, so we model only four of the eight striplines.

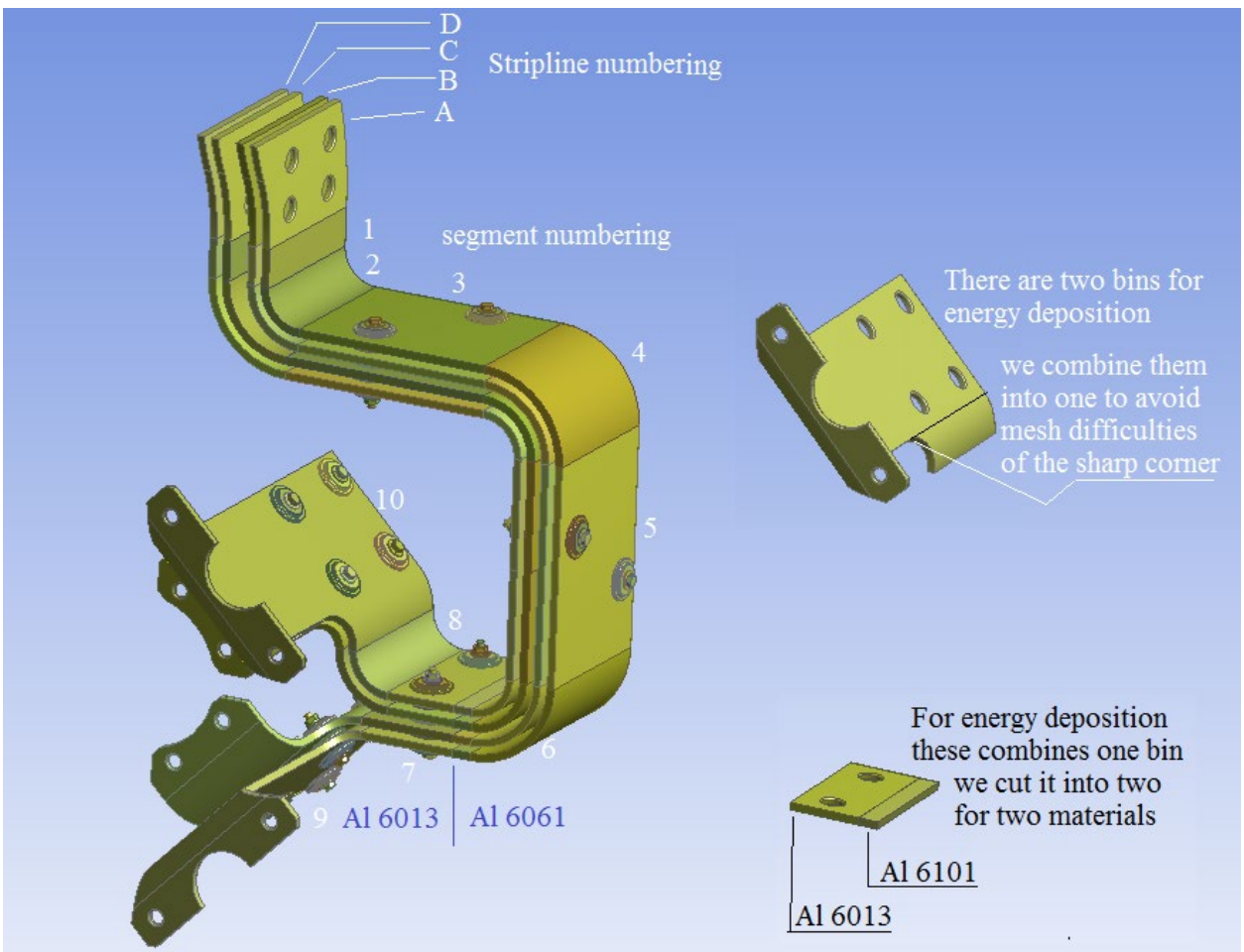


Figure 1 Strip lines for Numi Horn 1

The striplines are made of aluminum 6101-T6, they are 3/8 inch thick and 8 inches wide. The bottom portion of the striplines are made of Al 6013-T6

The material data are basically copied from Yun He's analysis (*Thermal and Structural Analysis of Horn1 Stripline,* Yun HE, 4/16/2009). We list material properties data in Table I. The resistivities of aluminum 6061_T61 and 6013-T6 are specified as a function of temperature (from Cory F. Crowley's *Aluminum Alloy Resistivity Study*)

Table I. Material Properties used in the Analysis

	Aluminum 6101_T6	Ceramics Zirconia	Titanium 6Al-4V
ρ (kg/m^3)	2700	3920	4430
E (GPa)	69	370	114
ν	0.33	0.22	0.34
α (μm/m-C)	23.4	8.2	8.6
k (W/m-C)	200	2.2	6.7
C (J/kg-C)	896	880	526
σ (Ω-m)	-	1e12	178e-8

	Resistivity (Ohm-cm)	
Temp (C)	6101-T61	6013-T6
25	3.0426E-06	3.9980E-06
40	3.2373E-06	4.2367E-06
60	3.4907E-06	4.4918E-06
80	3.7370E-06	4.7243E-06
100	3.9825E-06	4.9639E-06

2. The Thermal Loads

There are two kinds of loads for thermal analysis. First, when electric current pulse goes through the strip lines, there is Joule heating; second, when high energy particle beam hit the target, beam and its shower will interact with the strip lines and leave some energy in the material. The first is easy to calculate, the joule heating density is simply σj^2. The beam heating data are provided with MARS simulation.

There is a current pulse every 1.2 second with length of 2.3 ms and peak current of 200 kA. We can approximate the current pulse as half sine wave. The average current in 2.3 ms is 141421 A. Divided by 4, we have average current in each strip line of 35355 A. If we averaged over 1.2 s, the current is 1548 A in each strip line. A static case run by input current through the stripline model gives joule heating as shown in Figure 2. The joule heating values per current pulse are listed in Table II.

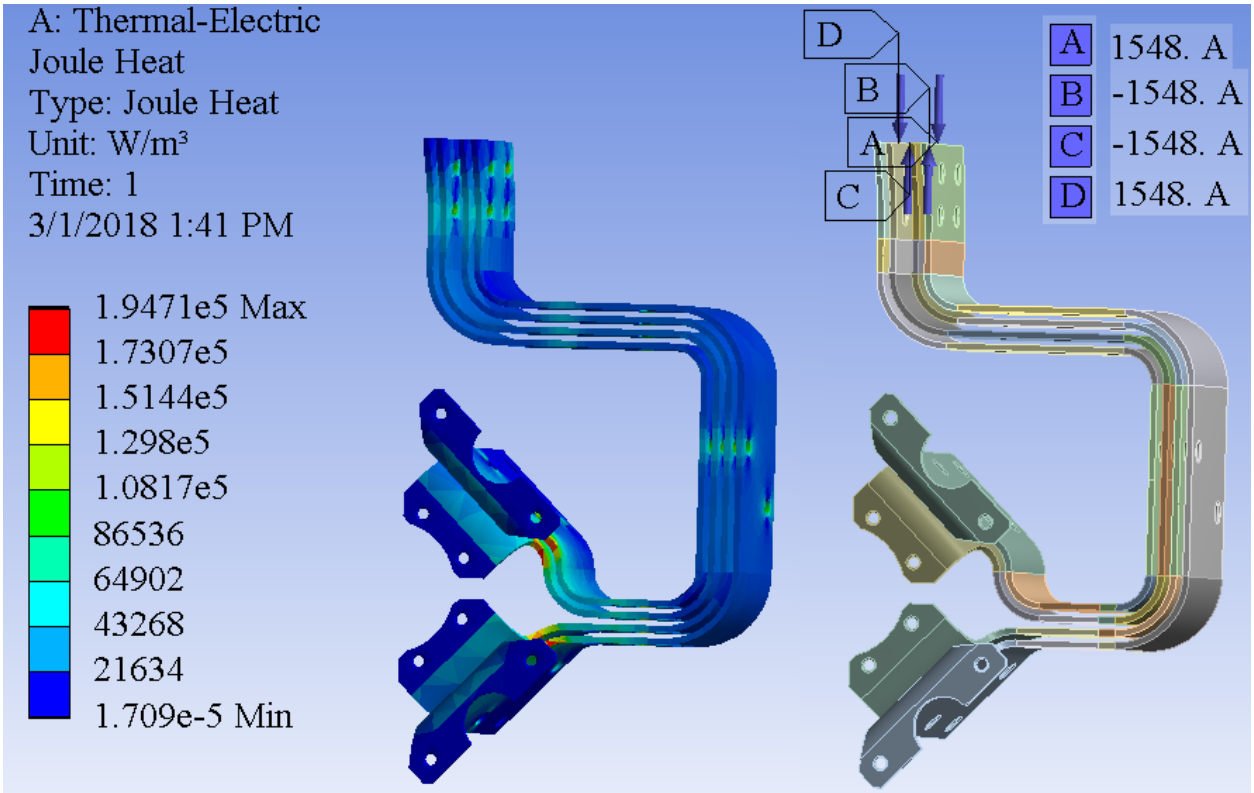


Figure 2. Joule heating in striplines

Table II. Joule heating per current pulse in stripline segments

seg #	J/m^3	seg #	J/m^3	seg #	J/m^3	seg #	J/m^3
a0	42463	b0	44153	c0	44402	d0	42685
a1	65100	b1	70511	c1	71076	d1	67656
a2	43335	b2	48262	c2	45723	d2	39293
a3	37030	b3	41408	c3	40848	d3	36689
a4	34996	b4	42545	c4	48294	d4	43627
a5	35534	b5	41158	c5	41097	d5	35672
a6	35193	b6	38314	c6	41396	d6	42920
a7	51698	b7	57237	c7	63881	d7	56462
a9	34506	b9	32719	c8	50816	d8	53413
				c10	32555	d10	34779

Beam heating data is provided in the unit of GeV/cm^3 per proton, there are 6.5e13 protons in each pulse, and 1 GeV = 1.6e-10 J. Therefore, the data should be multiplied by 6.5e13*1.6e-10 = 10,400 to get the total energy deposition in the unit of J/cm^3, or by 1.04e10 to get the data in the unit of J/m^3. Table III list the beam heating data.

Table III. Beam heating per beam pulse in stripline segments

seg #	J/m^3	seg #	J/m^3	seg #	J/m^3	seg #	J/m^3
a0	82285	b0	82742	c0	82004	d0	82493
a1	109720	b1	110344	c1	111592	d1	111280
a2	142584	b2	153400	c2	161408	d2	176696
a3	121160	b3	131144	c3	142272	d3	157768
a4	93382	b4	97136	c4	102378	d4	116480
a5	119184	b5	123968	c5	132392	d5	146744
a6	149552	b6	157352	c6	165152	d6	172848
a7	248144	b7	264264	c7	234520	d7	230464
a9	381056	b9	429936	c8	389064	d8	379392
				c10	441272	d10	397904

Compare tables II and III, we see that the beam heating is about 2 time that of joule heating on the top of the striplines, and about 10 times the joules heating on the bottom of the striplines. Table IV list the combined heat loads per pulse.

Table IV. Total heating Load per pulse in stripline segments

seg #	J/m^3	seg #	J/m^3	seg #	J/m^3	seg #	J/m^3
a0	124748	b0	126895	c0	126406	d0	125177
a1	174820	b1	180855	c1	182668	d1	178937
a2	185919	b2	201662	c2	207131	d2	215989
a3	158190	b3	172552	c3	183120	d3	194457
a4	128377	b4	139681	c4	150671	d4	160107
a5	154718	b5	165126	c5	173489	d5	182416
a6	184745	b6	195666	c6	206548	d6	215768
a7	299842	b7	321501	c7	298402	d7	286927
a9	415562	b9	462655	c8	439880	d8	432805
				c10	473827	d10	432683

We see the maximum heating load is 473827 J/m^3 per pulse on segment c10. The density of aluminum is 2700 kg/m^3, and specific heat is 896 J/kg-C, so the heat capacity of aluminum is 2700*896 = 2419200 J/m^3-C. Therefore, the maximum temperature increase after the heating pulse is (assume during such short time there is no any heat transfer taking place) 473827/2419200 = 0.196 C. Therefore, static temperature will be good enough.

3. Thermal Analysis

We specify the temperature at inner conductor end as 45 C and that at outer conductor end as 55 C (Figure 4). At top end of strip lines, we copy that from Yun He, specify as 80 C. These boundary conditions are shown in Figure 3. The strip lines are cooled by forced air flow. To increase the efficiency of air cooling,

some improvements are done to reflect air flow directly to the flag surfaces of the strip lines. New cooling film coefficients are specified by Cory Crowley, and these are listed in Table V. The air temperature is assumed to be 30 C.

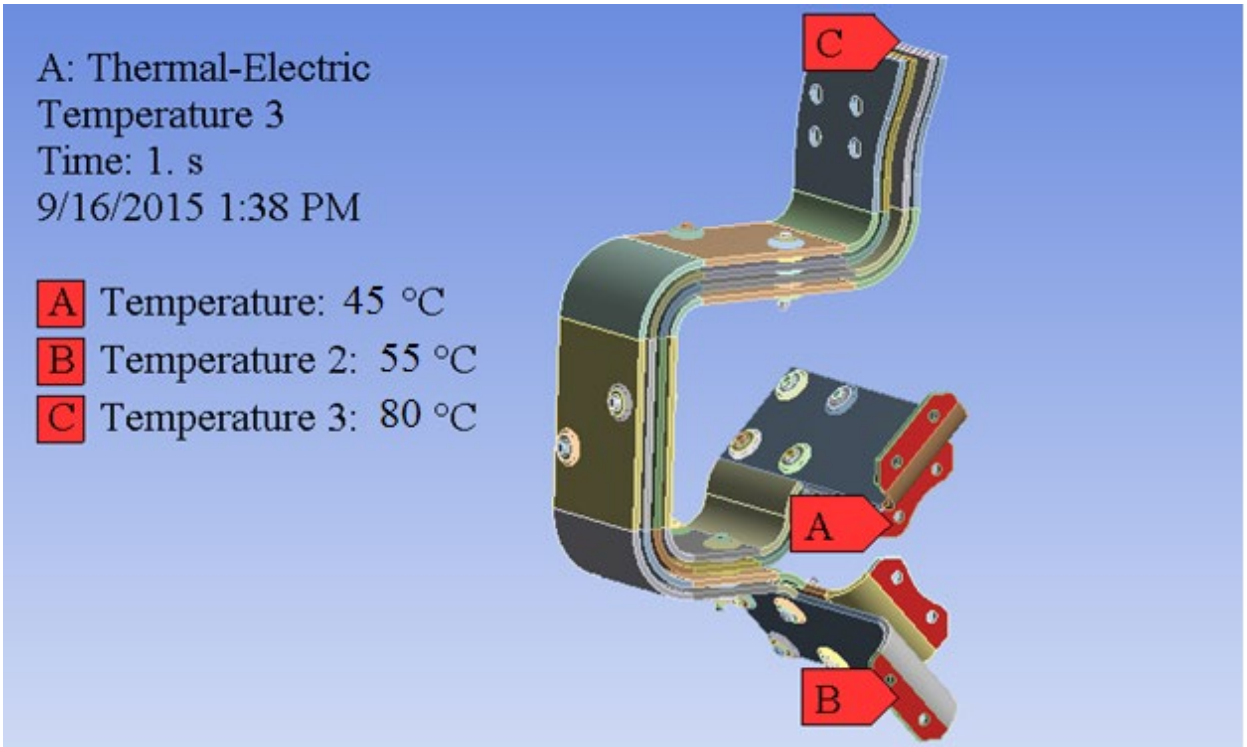


Figure 3. Temperature Boundary conditions

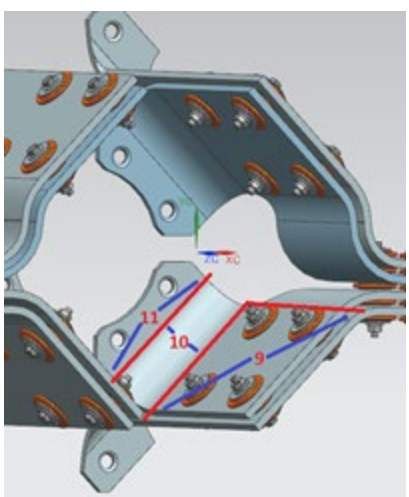


Figure 4. Cooling surface 9, 10 and 11

Table V. Surface Cooling Film Coefficients (W/m^2-C)

segment #	External	internal		
1	5	2		
2	15	5		
3	36	5		
4	36	5		
5	36	5		
6	36	5		
7	36	5		
8	15	5		
	outer		inner	
	External	internal	External	internal
9	28	5	18	5
10	10	5	10	5
11	10	NA	10	NA

The temperature calculated is plotted in Figure 5. The maximum temperature can reach 140 C in stripline C.

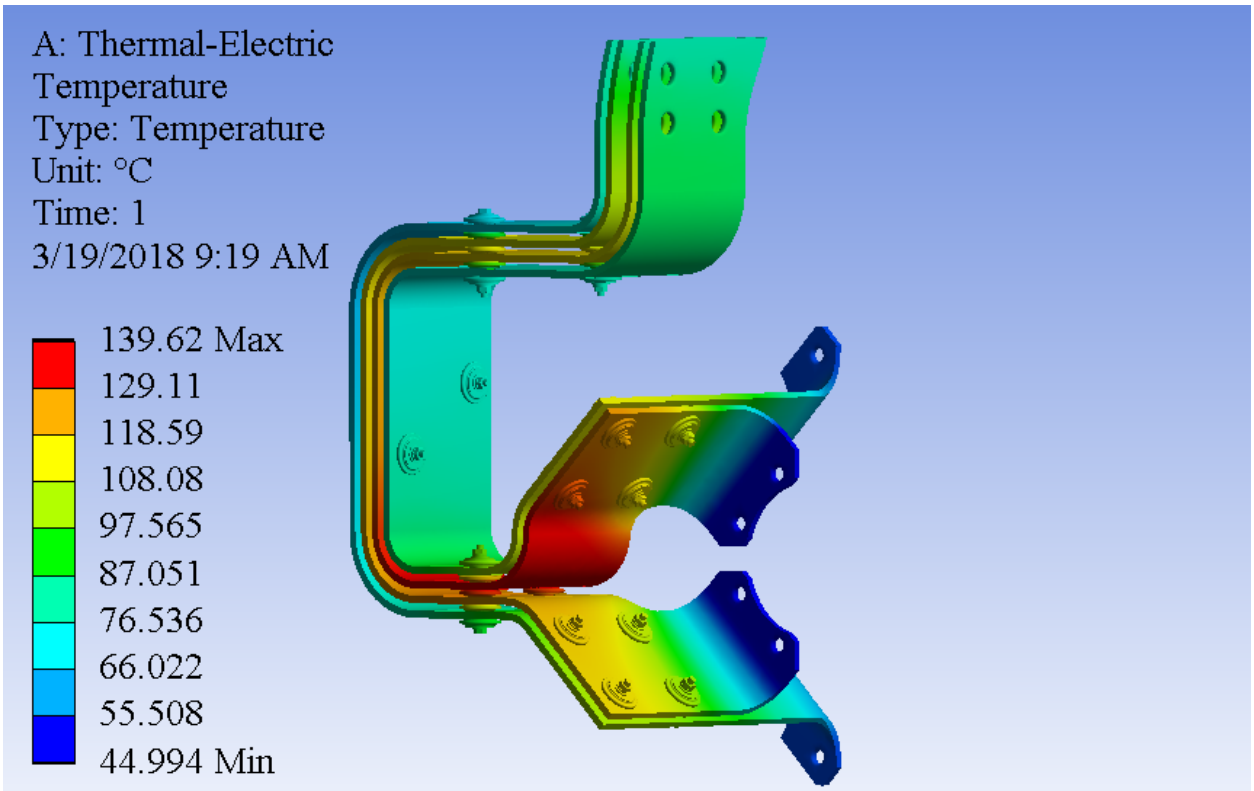


Figure 5. Temperature distribution in striplines

4. Magnetic Load

When we calculate stress of the strip lines, we have to consider magnetic load. The magnetic load on strip lines can be calculated as **f** = **j**x**B**. Where **j** is current density and **B** magnetic flux density. We use classic ANSYS to calculate the magnetic force.

Table VI Magnetic pressure on strip lines (Pa)

	strip line			
segment	A	B	C	D
1	31463	32349	34353	34057
2	38836	35435	37497	34444
3	34543	35857	36144	34871
4	31012	33584	31833	32795
5	31525	35893	35981	34607
6	30984	33584	31876	32737
7	35053	36538	37748	35894
8	38782	36807	32378	31660
9	14902	19844	19318	14578

10	-10633	20622	20138	10794

The magnetic pressure is obtained by divide the total magnetic force with outer surface (for strip line 1, the magnetic force pushes it outwards, the outer surface facing outwards, for strip line 2, the magnetic force pushes it inwards, the outer surface facing strip line 1, etc.) The results are listed in Table VI. These results are based on the peak current, 200 kA total or 50 kA for each strip line.

5. Stress Calculation

The stripline model is fixed on both ends (top and bottom). The loads we have are 1) Gravitational acceleration 9.8 m/s^2 (weight), 2) Bolts preload (26688 Newtons per bolt), 3) Thermal load (temperature previously calculated), and 4) Magnetic force as discussed in section 4.

We run two load cases: 1) with gravitation, bolt preload and thermal load; 2) add magnetic load.

Figure 6 plotted the displacements of these load cases. It can be seen, that the displacement is mainly due to gravitation and thermal expansion. The displacement caused by magnetic force is small (see Figure 7).

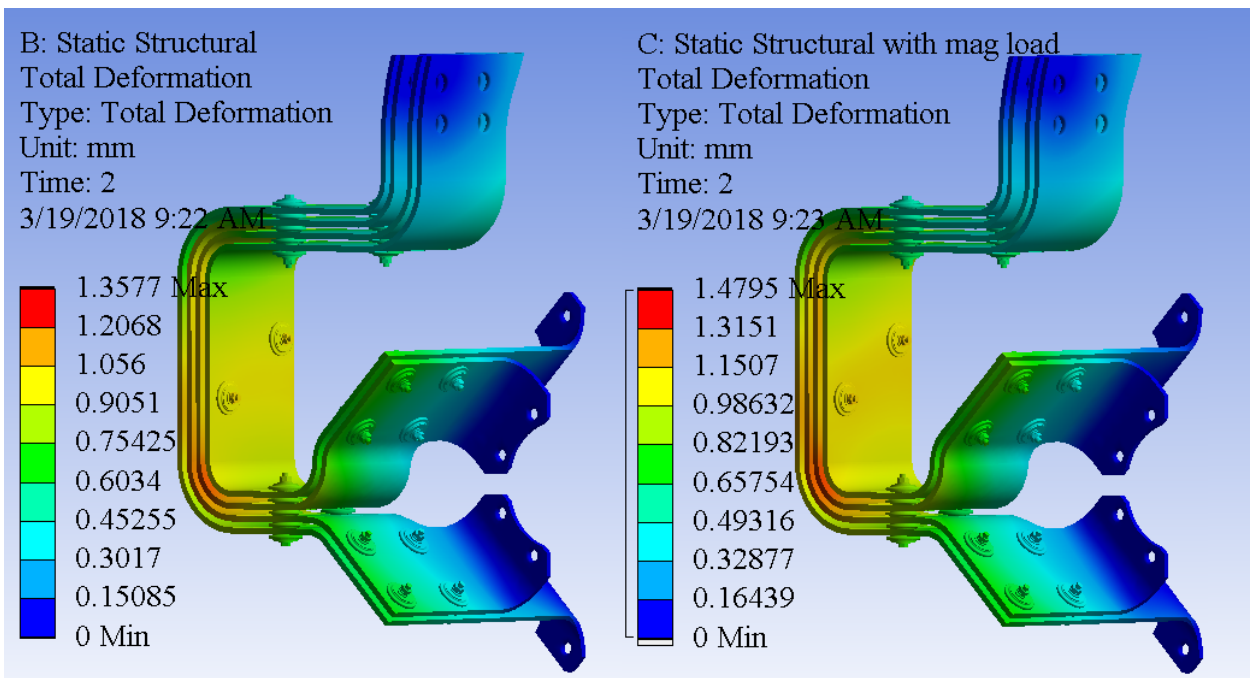


Figure 6 Displacement of the strip lines (without magnetic load and with magnetic load)

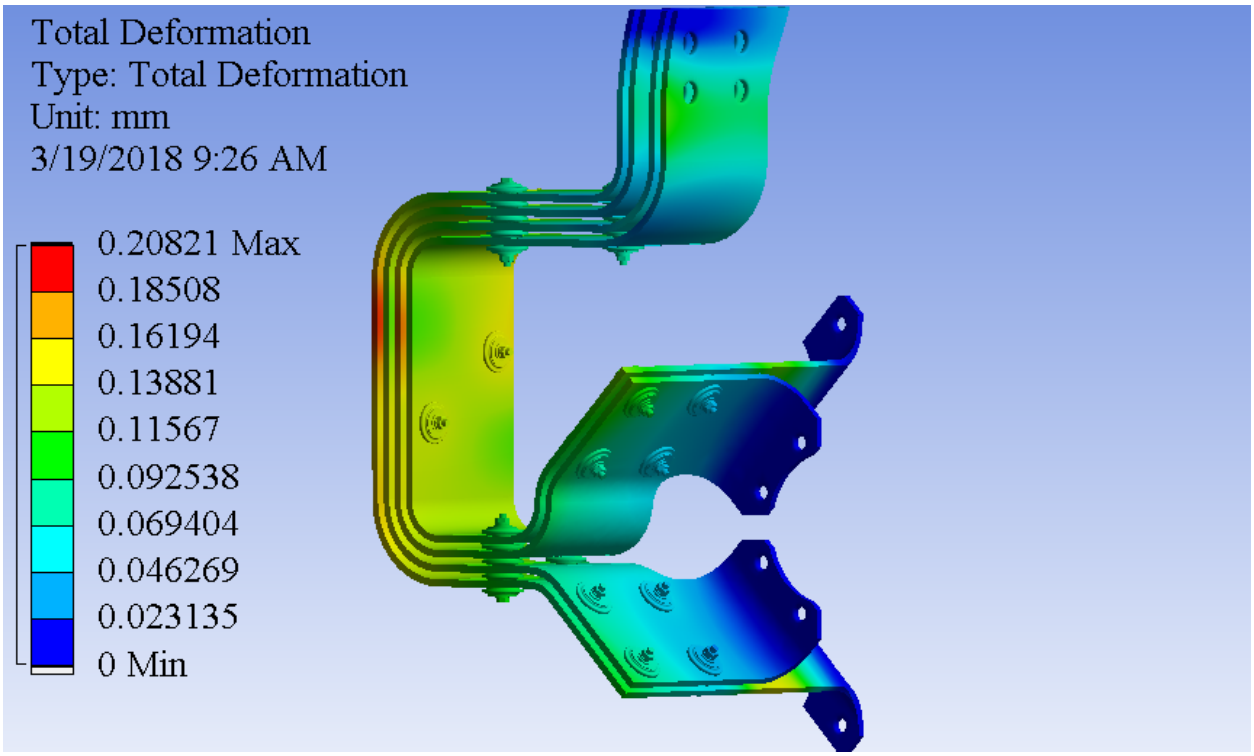


Figure 7. Displacement difference between load case 2 and 1 (magnetic load only)

Figure 8 shows the stress for load case 1 (without magnetic load). Figure 9 plotted the stress for load case 2 (with magnetic load). The difference in general stress profiles for these two load cases is not that significant. In Figure 10 we plotted the differences between these two cases.

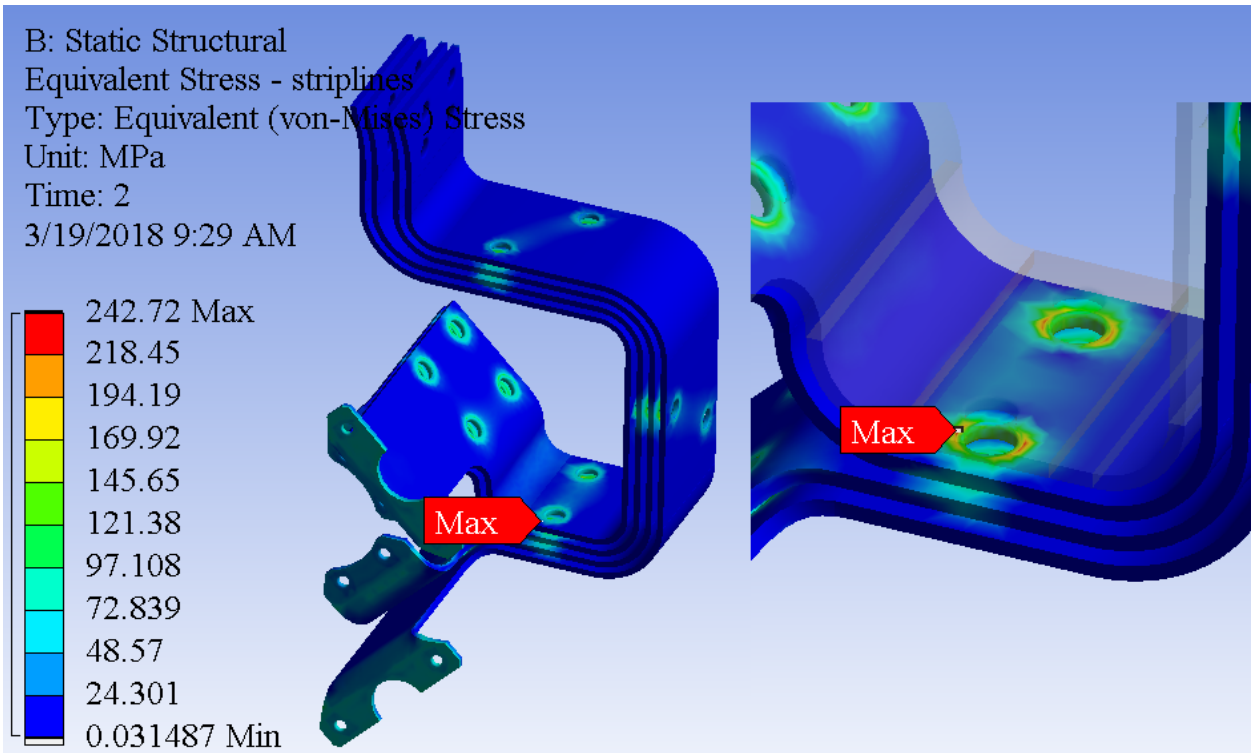


Figure 8. Equivalent stress for load case 1 (thermal load only)

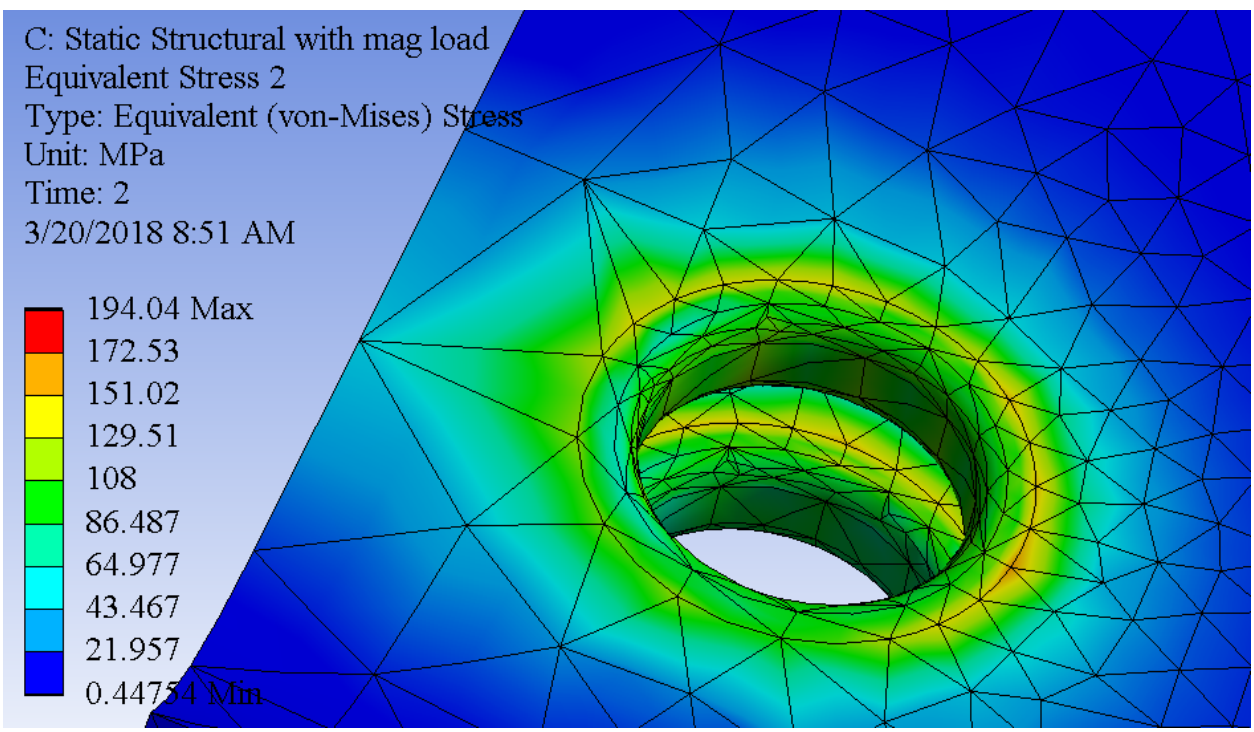


Figure 9. Stress near bolt hole with our original mesh

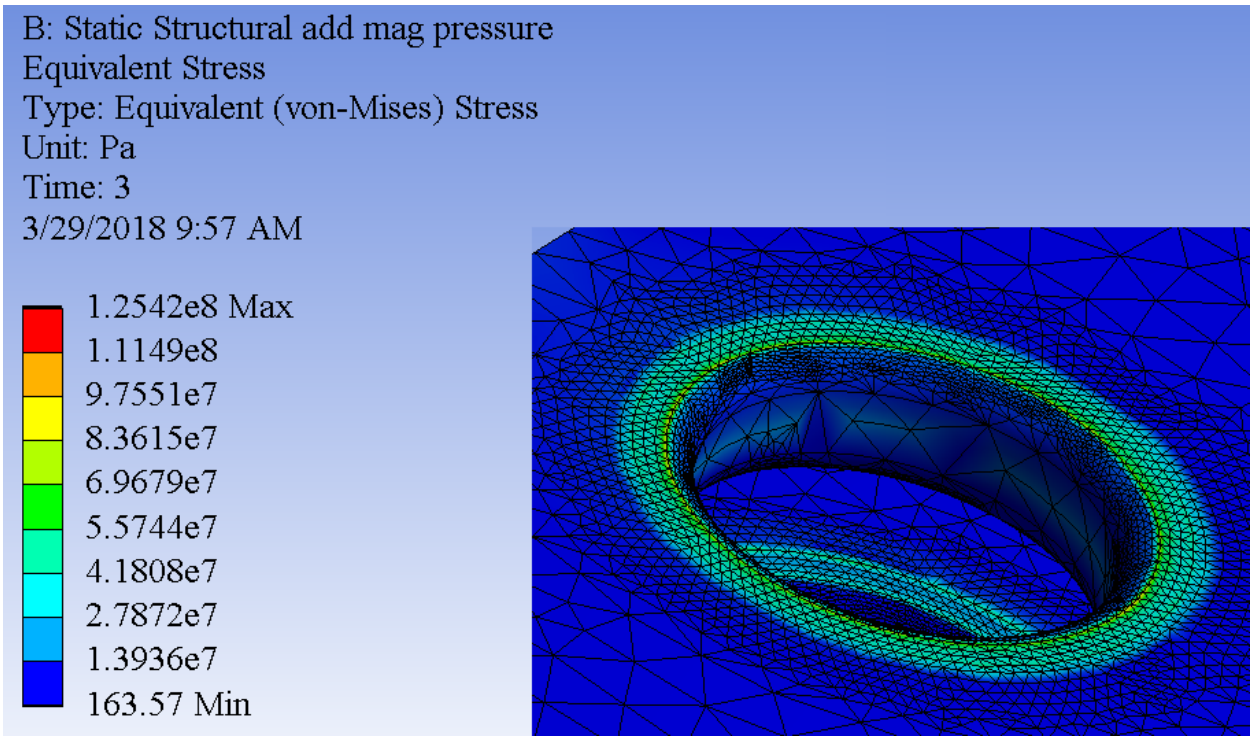


Figure 10. Stress near bolt hole with a finer and better mesh

Maximum stress near bolt hole is 242 MPa. Actually, at the bolt hole we have contact surface area of 300 mm^2, the bolt load is 26688 N, therefore the average stress is 87 MPa. The higher stress concentration is caused by coarse mesh near the contact area edge. If we use a finer mesh, we can reduce the stress concentration. This can be seen from Figures 9 and 10.

Figure 11 plotted stress of the bolt. Bolt cross sectional area = 71 mm^2, stress = 26688/71 = 375 MPa. The high stress concentration near the nut/washer should be neglected here. We need to do not-linear analysis to get rid of this stress concentration.

Figures 12 and 13 plotted stress for load case 2.

Figure 14 is the stress calculated from the difference between the two load cases.

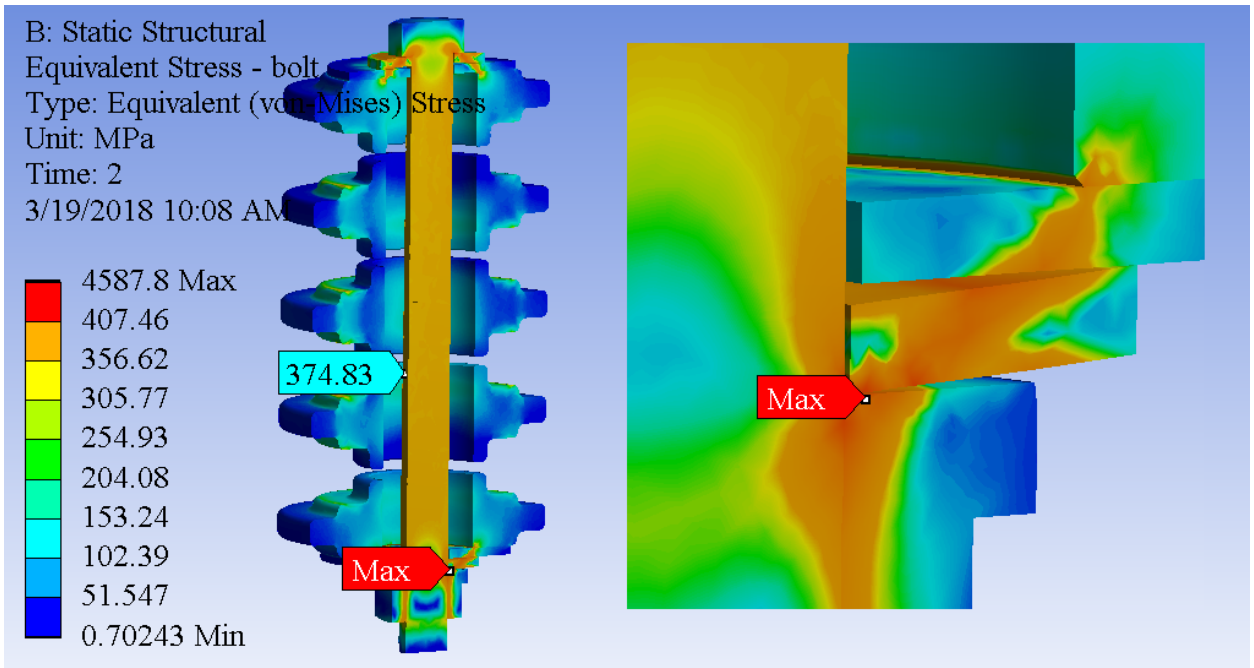


Figure 11. Stress of bolt for load case 1.

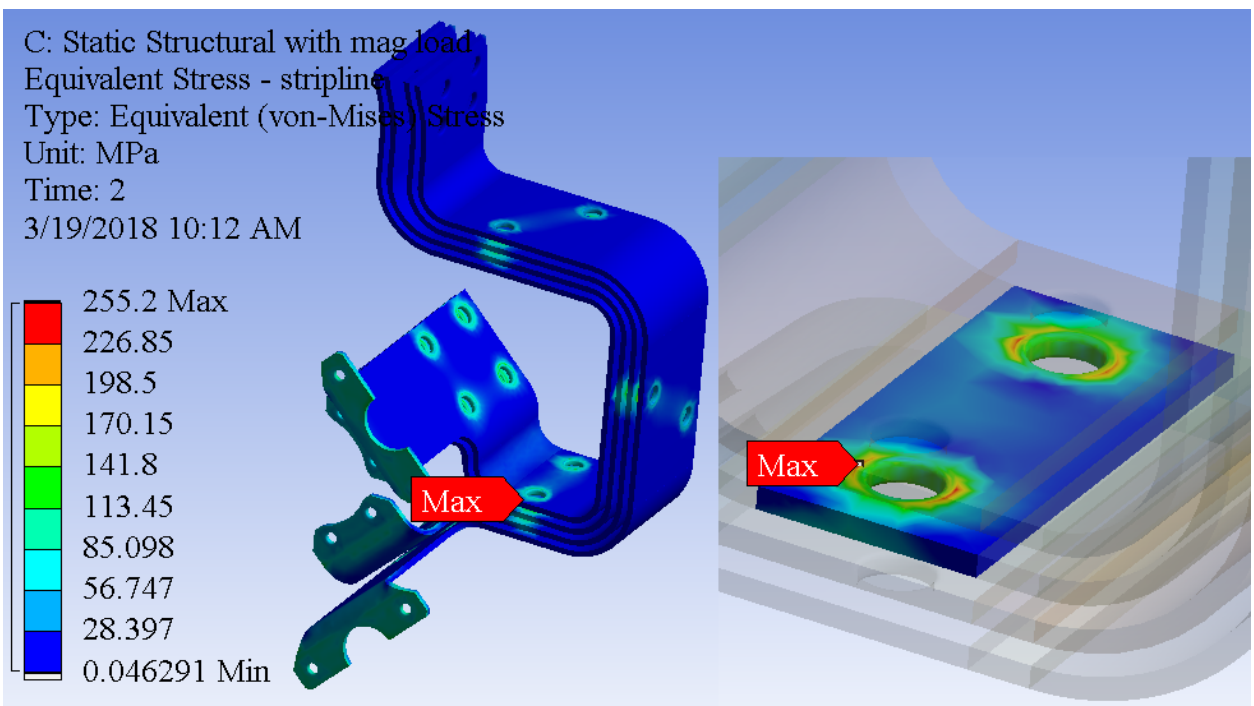


Figure 12. Equivalent stress of striplines for load case 2 (with magnetic load)

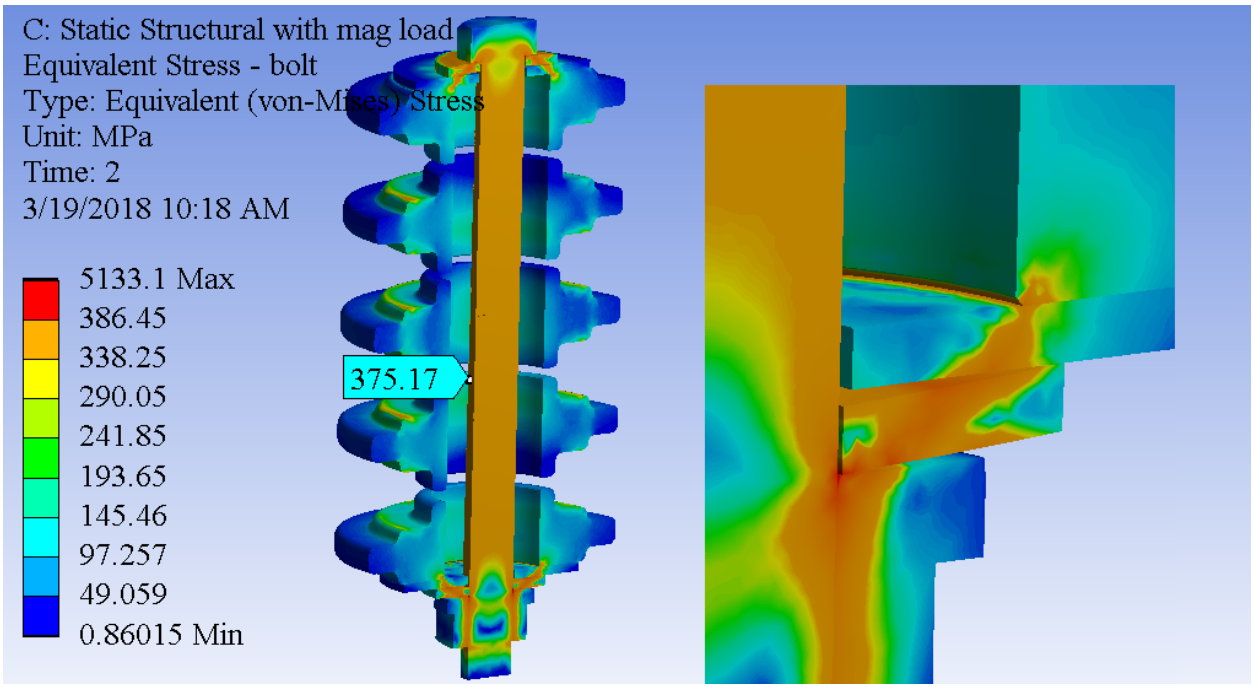


Figure 13. Equivalent stress of bolt for load case 2 (with magnetic load)

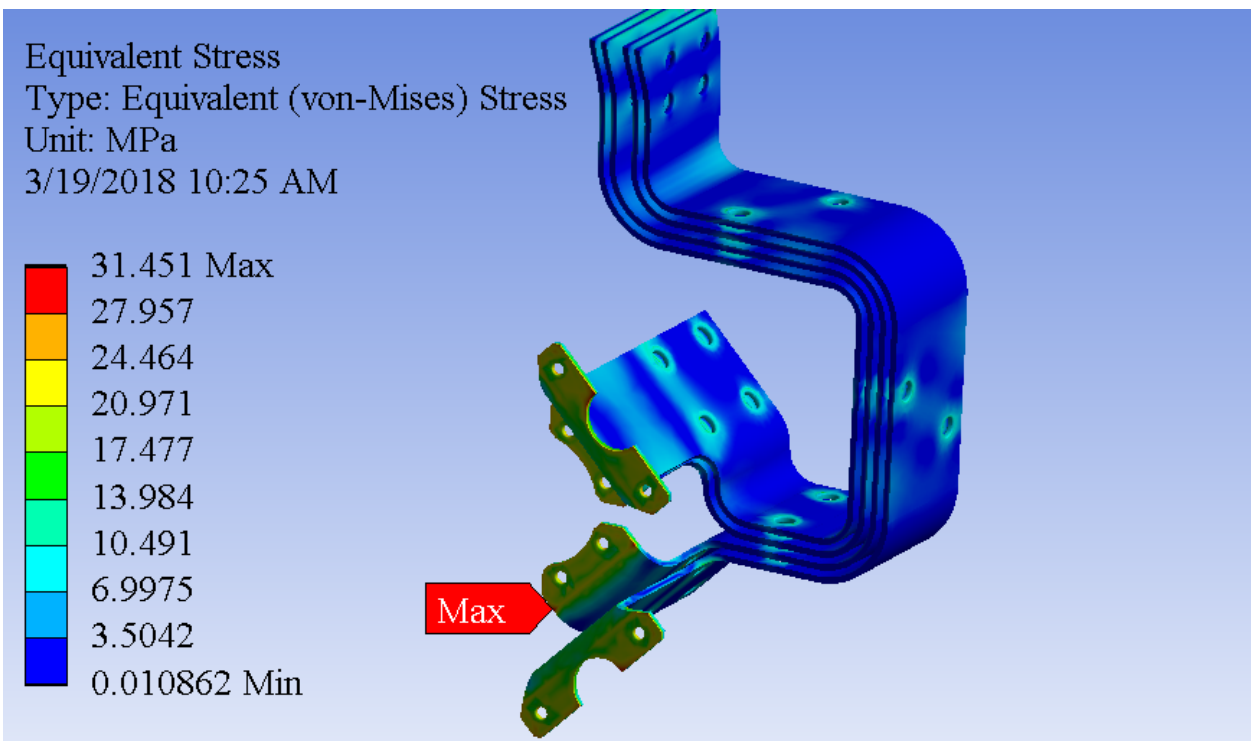


Figure 14. Stress from the differences between the two load cases

From the results we see the high stress occurs near bolt holes. Hence in the following we calculate the stress compared with the yield stress, ultimate stress and fatigue stress for these segments of the strip lines. We

calculate ratio Su/Smax, Sy/Smax and fatigue safety factor using Goodman equation: Sa/Sf + Sm/Su = 1/SF. Where Sa is alternate stress, Sm is mean stress, Sf is fatigue stress and Su ultimate stress, SF is safety factor for selected fatigue life. We use following material properties:

Table V. Material strength used to calculate safety factors

Alloy/Temper	Ultimate stress (MPa)	Yield stress (MPa)	No of cycles	Fatigue Stress (MPa)
6101-T6	200	172	10^7	90
			10^8	60
6013-T6	311	286	10^7	172
			10^8	124

We consider three positions: Aluminum 6101-T6 bolt hole, Aluminum 6013-T6 bolt hole and aluminum 6013-T6 at connection. These positions are shown in Figure 15. These calculations are shown in Figures 16~21. We avoid the numerical stress concentration and take a less severe value. These value are summarized in Table VI.

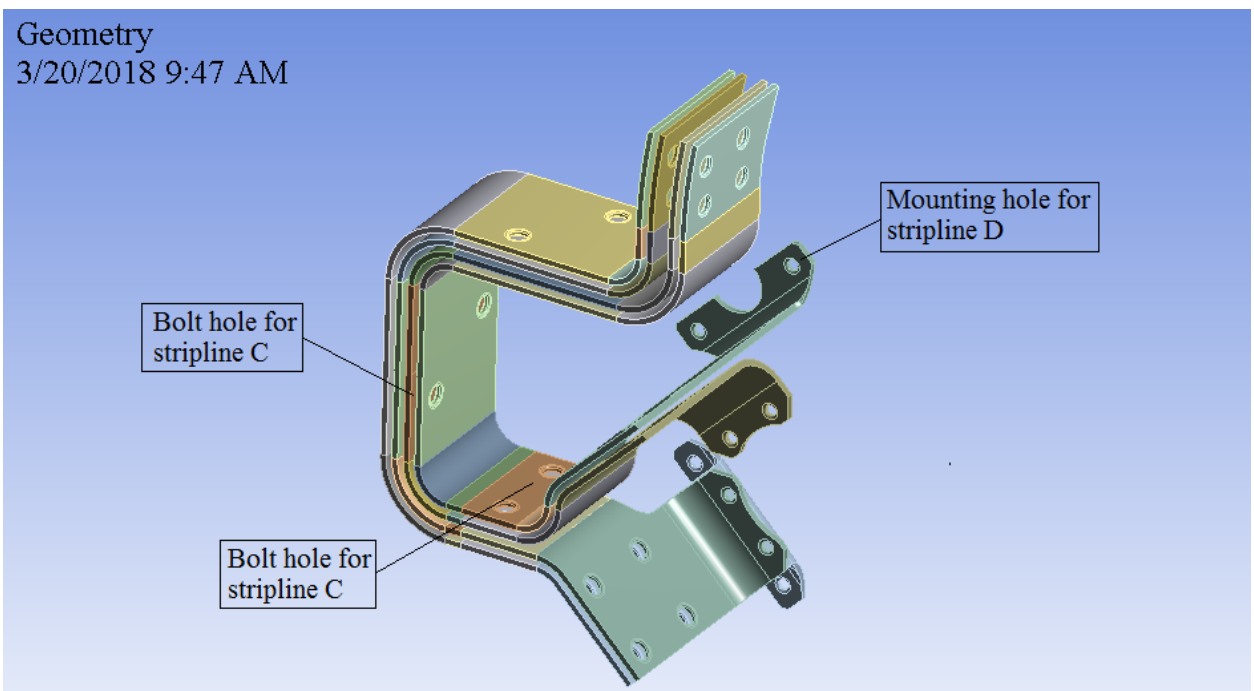


Figure 15. Three positions for stress calculation.

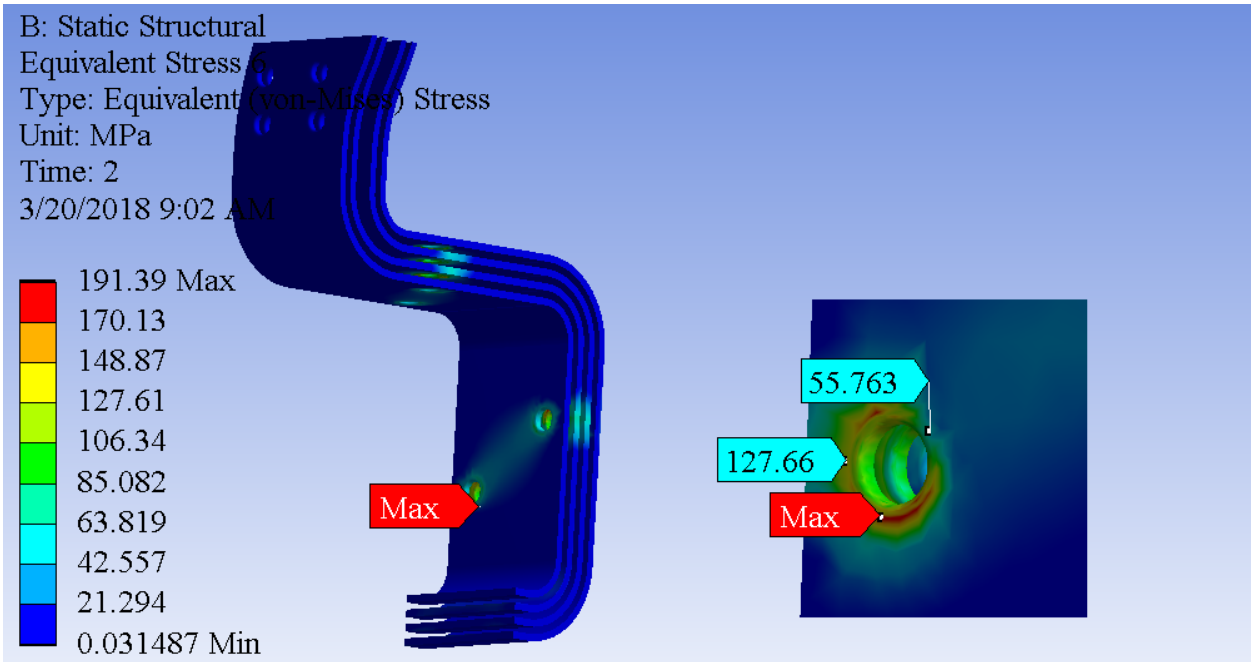


Figure 16. Stress near bolt hole for material aluminum 6101-T6 (load case 1)

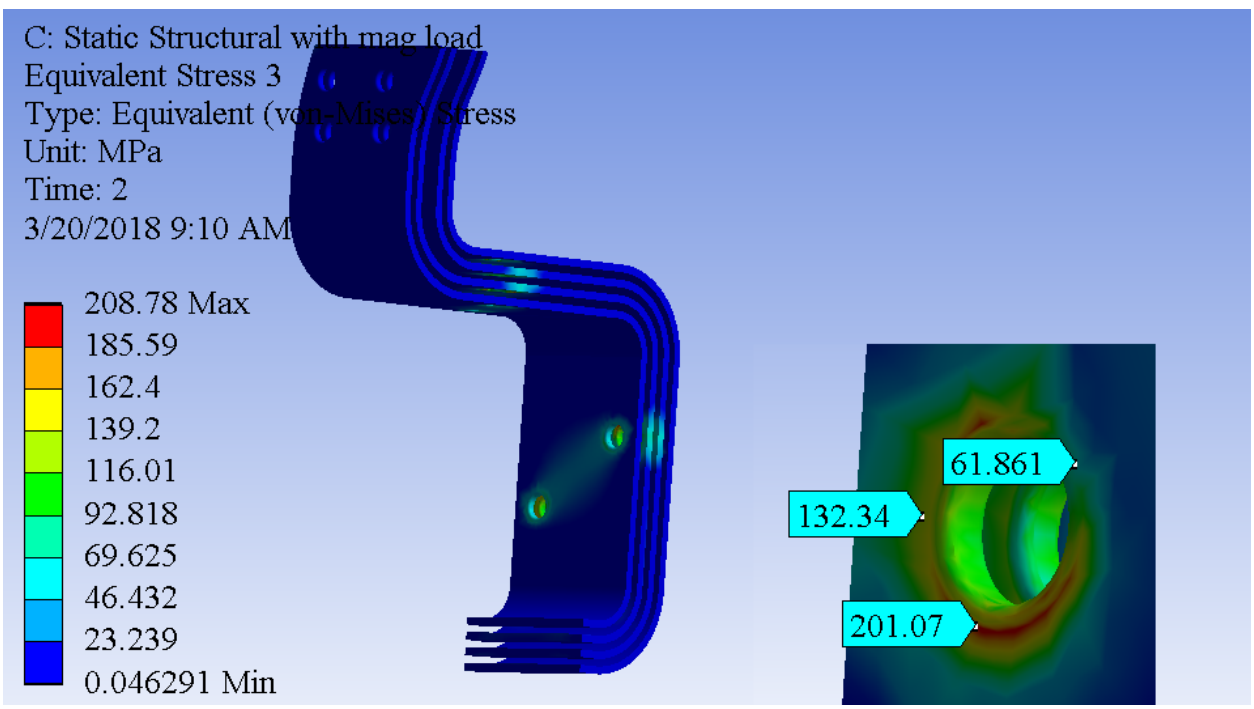


Figure 17. Stress near bolt hole for material aluminum 6101-T6 (load case 2)

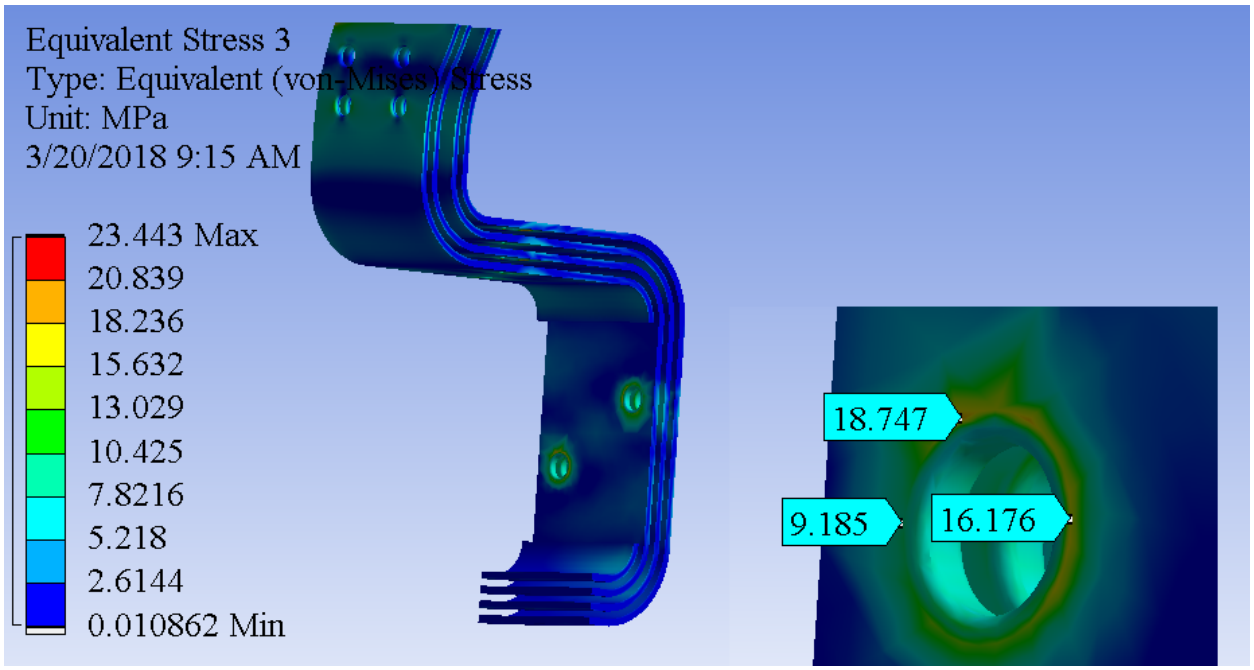


Figure 18. Stress near bolt hole for material aluminum 6101-T6 (load case difference)

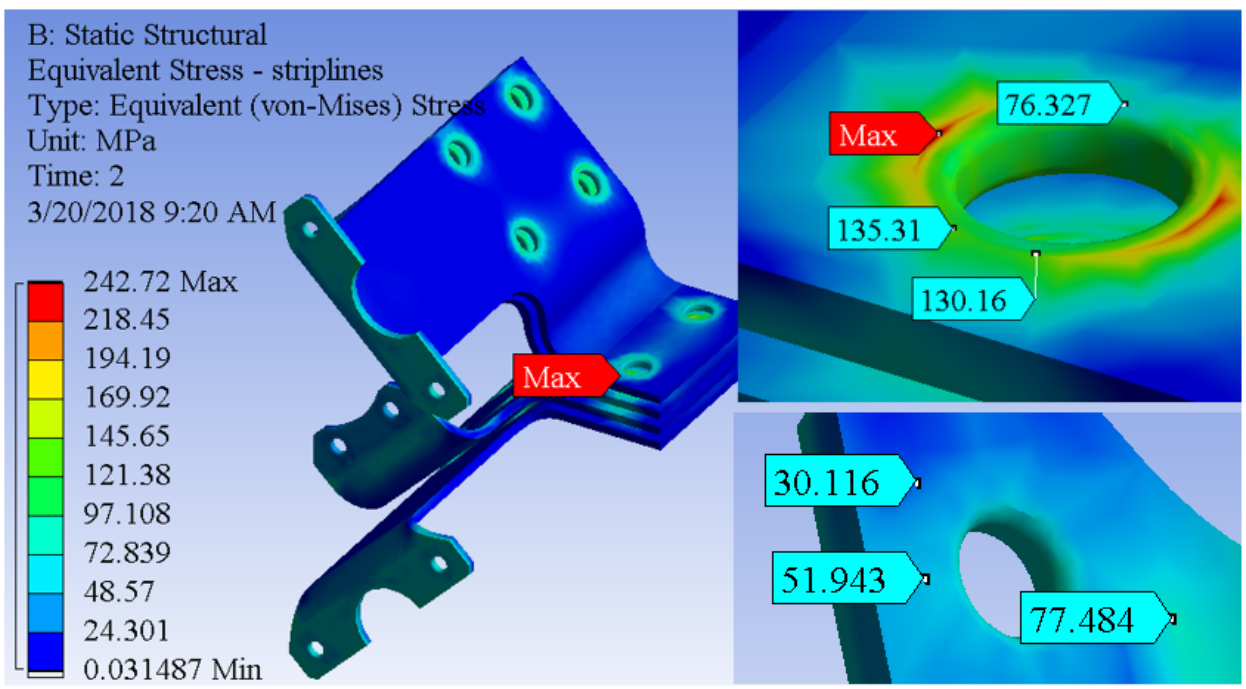


Figure 19. Stress near bolt hole for material aluminum 6013-T6 (load case 1)

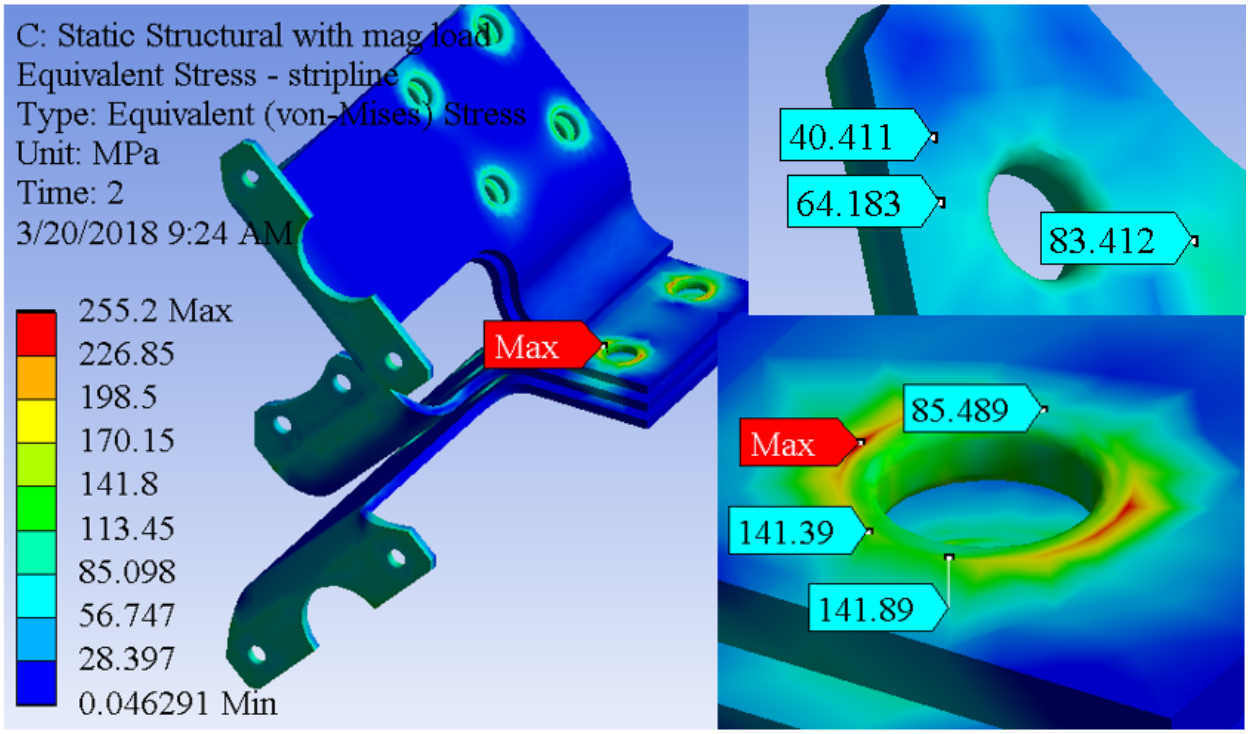


Figure 20. Stress near bolt hole for material aluminum 6013-T6 (load case 2)

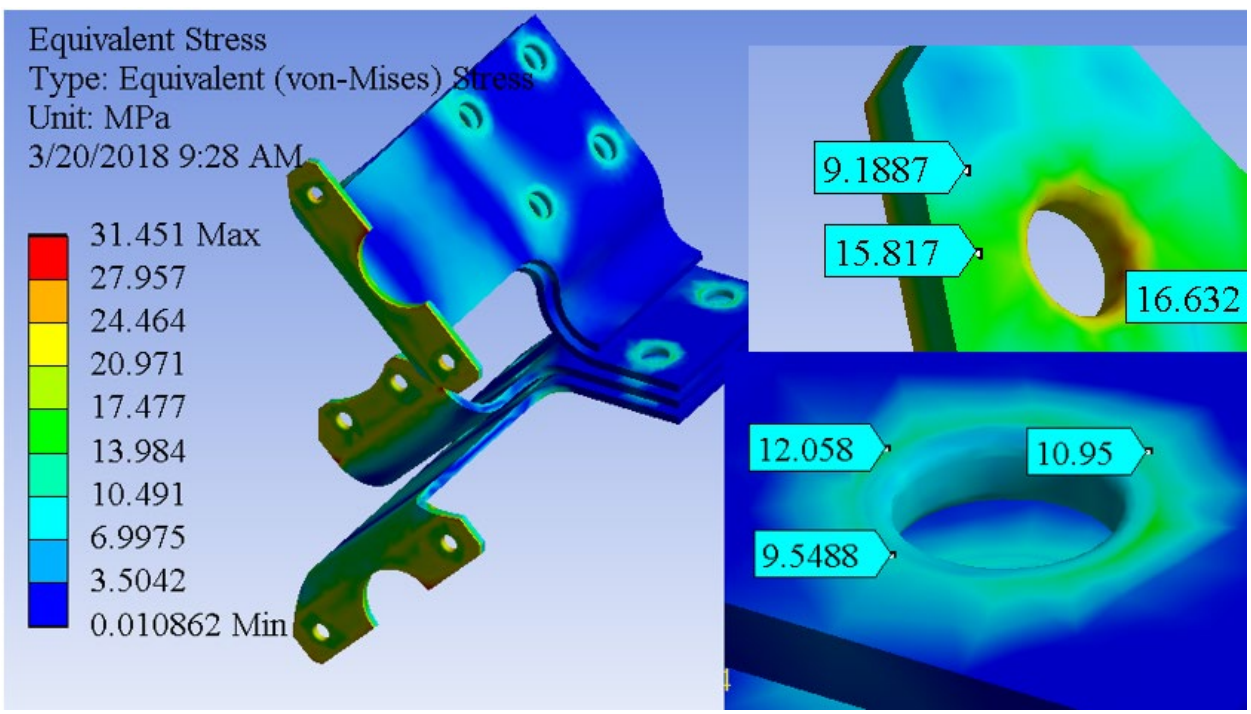


Figure 21. Stress near bolt hole for material aluminum 6013-T6 (load case difference)

Table VI. Safety factors

		Stress (MPa)			Stress ratio		Fatigue Safety Factor (10^8)
material	position	Smax	Sm	Sa	Su/Smax	Sy/Smax	
6101	Bolt hole	132	124	8	1.5	1.3	1.3
6013	Bolt hole	141	135	6	2.2	2.0	2.0
6013	connection	65	57	8	4.7	4.4	4.0

Conclusions:

1) The higher strength of 6013-T6 material will help preventing failure of the strip line.
2) Since the alternate stress is quite small compared with mean stress, mean stress dominates in Goodman equation used to calculate the fatigue safety factor. Since the mean stress is caused by bolt pretension. This kind of stress is called secondary stress because it is caused by the displacement. As time goes on, the stress will lose. Therefore actual fatigue safety factor may be higher than what we put in the table.
3) The stripline temperature is too high as it is under present cooling condition. We need improve the cooling efficiency.

Appendix, Material strength data

Typical Mechanical Properties of Aluminum 6101						
Temper	**Tensile**					**Hardness**
	Ultimate		**Yield**		**Elongation**	**Brinell**
	KSI	MPA	KSI	MPA	%	
T6	29	200	25	172	15	71

From *Properties of Aluminum Alloys: Fatigue Data and Effect of Temperature*, we have fatigue strength of 90 MPa for 10 million cycles and 60 MPa for 100 million cycles for R = -1.

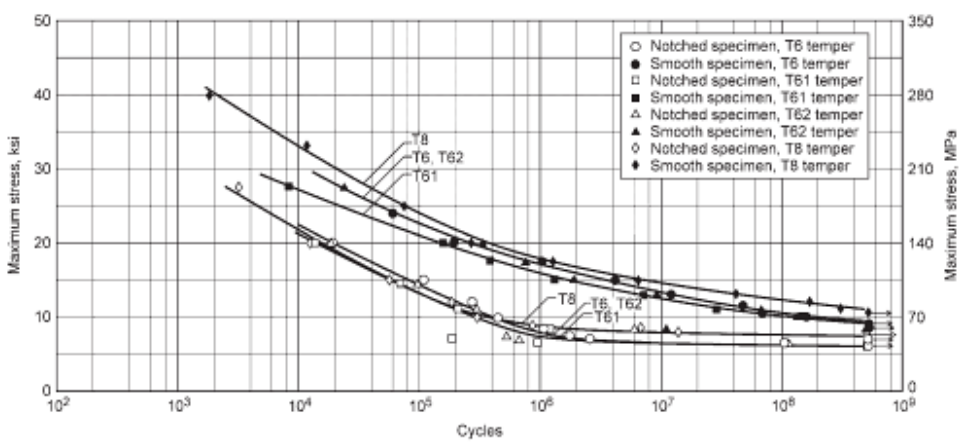
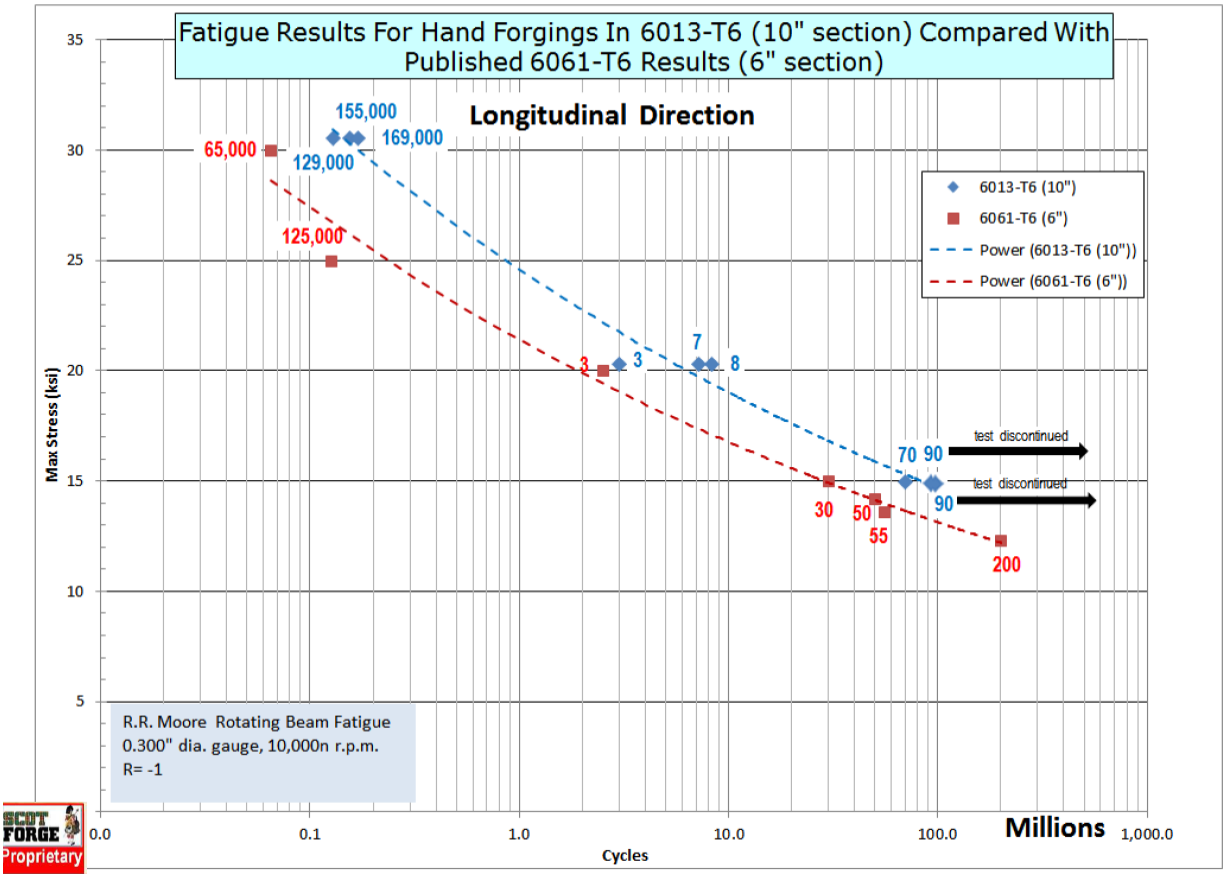


Fig. 6101.RB01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 6101-T6, T61, T62, and T8 rolled and drawn rod, smooth and sharply notched specimens

FATIGUE PROPERTIES - Improved fatigue is realized for 6013 –T6 as compared to 6061-T6.



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