MECH 4450 Term Project Report

Project 2 (Static structure)

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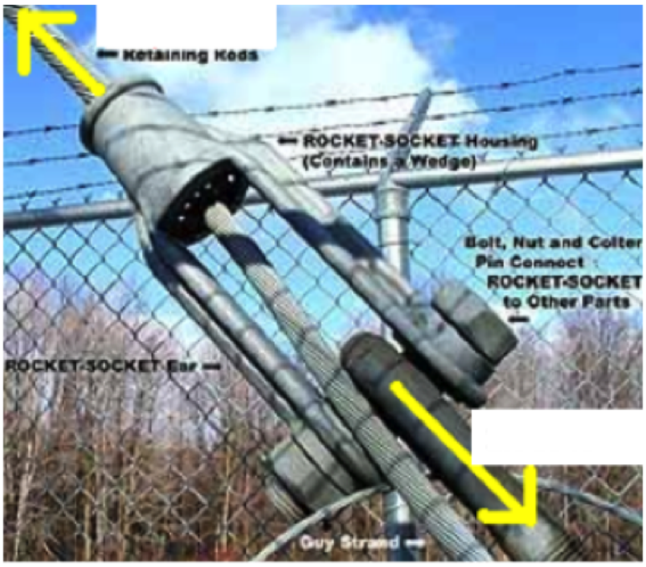
Contents

1 Introduction

1.1 Description of the problem

The cable anchor is a component at the end of the guy wire that helps to anchor the guyed tower as the picture below shows. It is widely used in engineering structures, such as broadcast transmission towers, bridges and so on. The problem is to analyze the load of the anchor, and to optimize the design.



In the analysis part, it is need to find out the points where failure is most possible to happen. In other words, the place where maximum local stress occurs. The design part will be discussed below.

Commercial finite element analysis software suite ANSYS will be used for the entire workflow including 3D modeling, FEM analysis and optimization.

1.2 Design objectives

- The safety factor is required to be at least 2.
- The weight of the structure should be minimized.
- Dimensions should be adjusted in a way that other components (the guy wire and the bolt) will also have a good safefy factor, and the connection between the anchor and other components are safe enough. For example, decrease $D2$ may increase the safety factor and reduce the weight of the anchor itself, but it will reduce the safety factor of the bolt significantly.
- When possible, avoid hurting people (rounded corners will be preferred); manufacturability will also be considered.

- Preserve the fundamental shape of original design. The general shape of the frame should be kept consistent with the original design. Redesigning from scratch is therefore not desired. The fixed dimensions should also be respected.

1.3 Conditions

The material used to build the cable anchor is structural steel.

Some dimensions are fixed. $H9 = 25\,\text{cm}$, $V7 = 6\,\text{cm}$, $D1 = 6\,\text{cm}$.

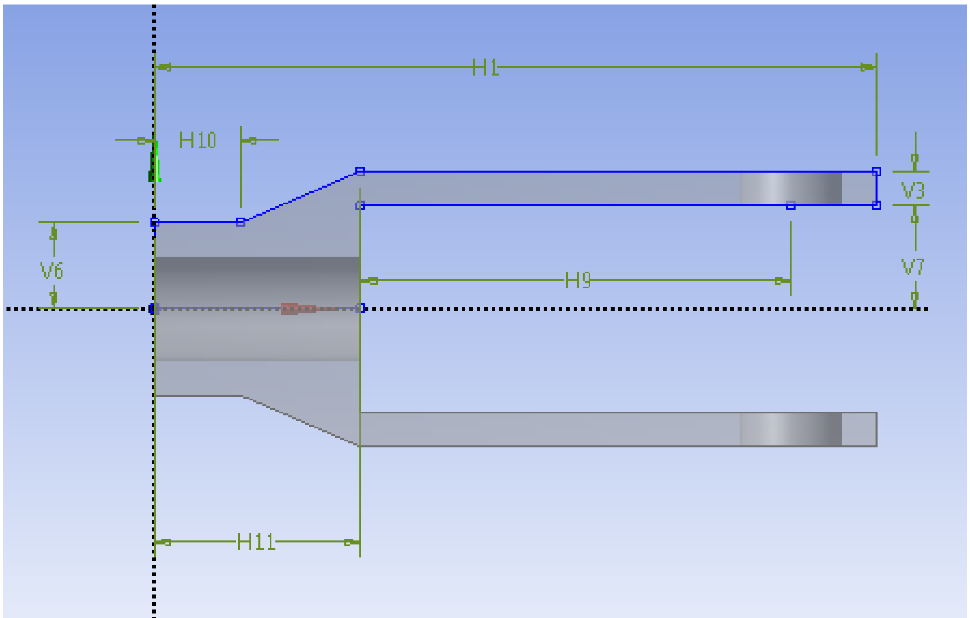
The cable anchor will be loaded with a axial force of $2 \times 10^5 N$. On one side, the force will be exerted on the guy wire via a cylindrical surface in a form of frictional force. It can be treated as a fixed support. One the other hand, the force is balanced using a bolt put through two holes. Bearing load can be assumed for the situation.

Symmetrical model can be assumed.

2 Program modelling

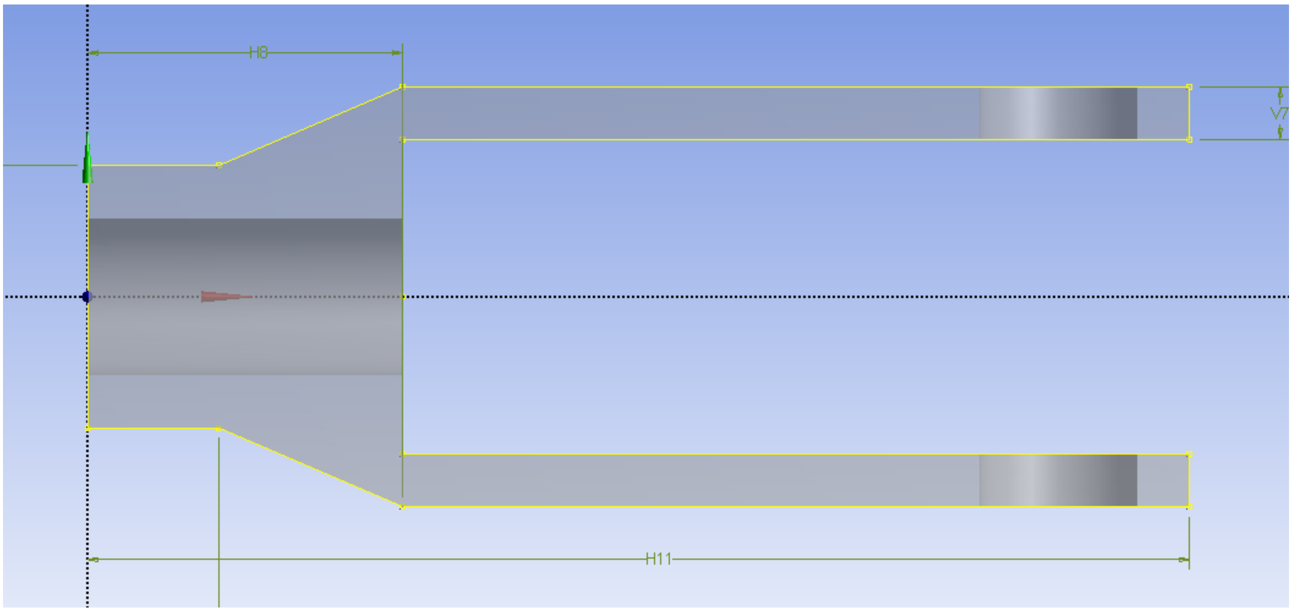
2.1 Geometry

The top view of original design is shown below:

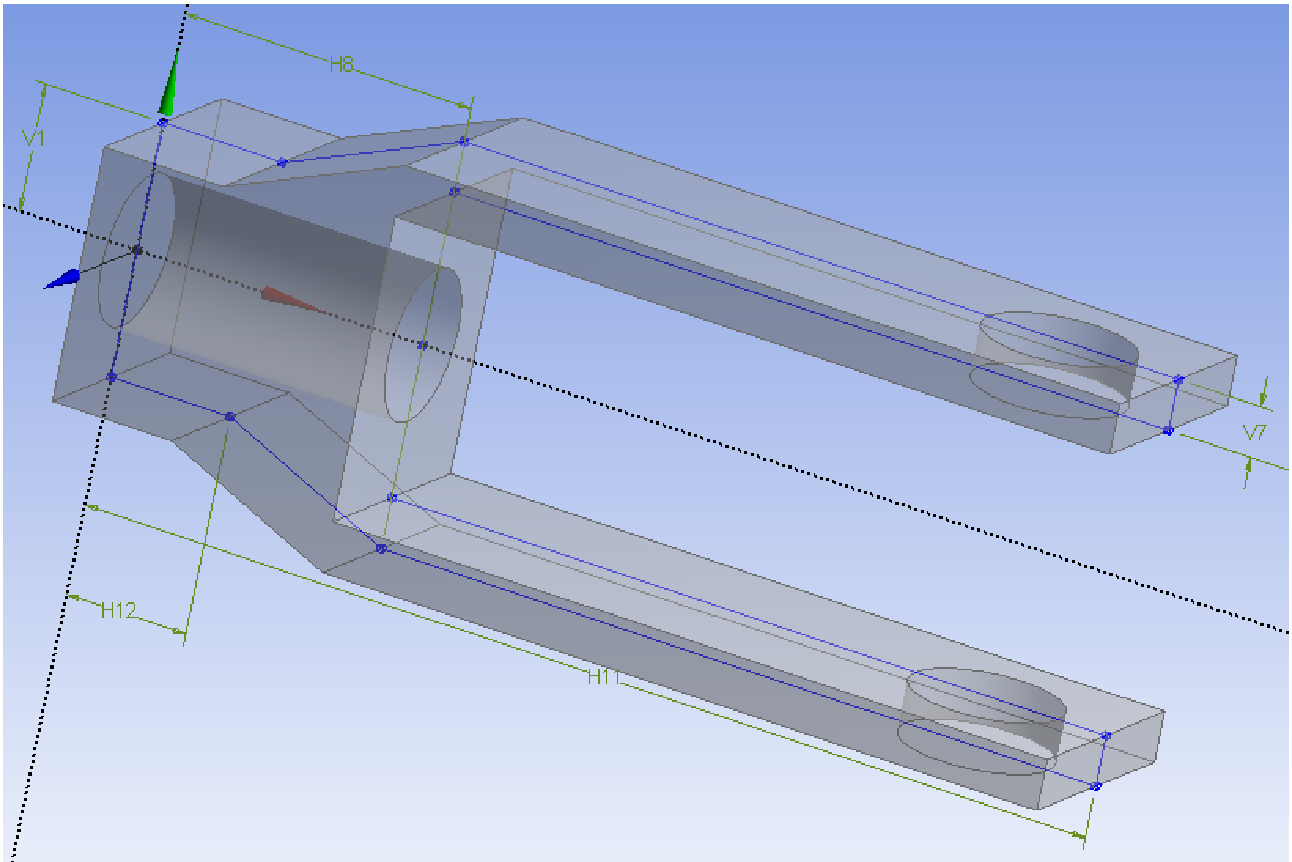


Where $H1 = 42\,\text{cm}$, $H10 = 5\,\text{cm}$, $H11 = 12\,\text{cm}$, $H9 = 25\,\text{cm}$, $V3 = 2\,\text{cm}$, $V6 = 5\,\text{cm}$, $V7 = 6\,\text{cm}$, diameters of all holes are 6 cm.

It is resembled as below:



The 3D model built is then as below, where the height of the component is assumed to be 10 cm:



The dimensions (except the fixed ones), are set as design parameters for the convinience of optimization.

2.2 Boundary conditions

The boundary conditions are the loads, where symmetric properties on both axis can be assumed.

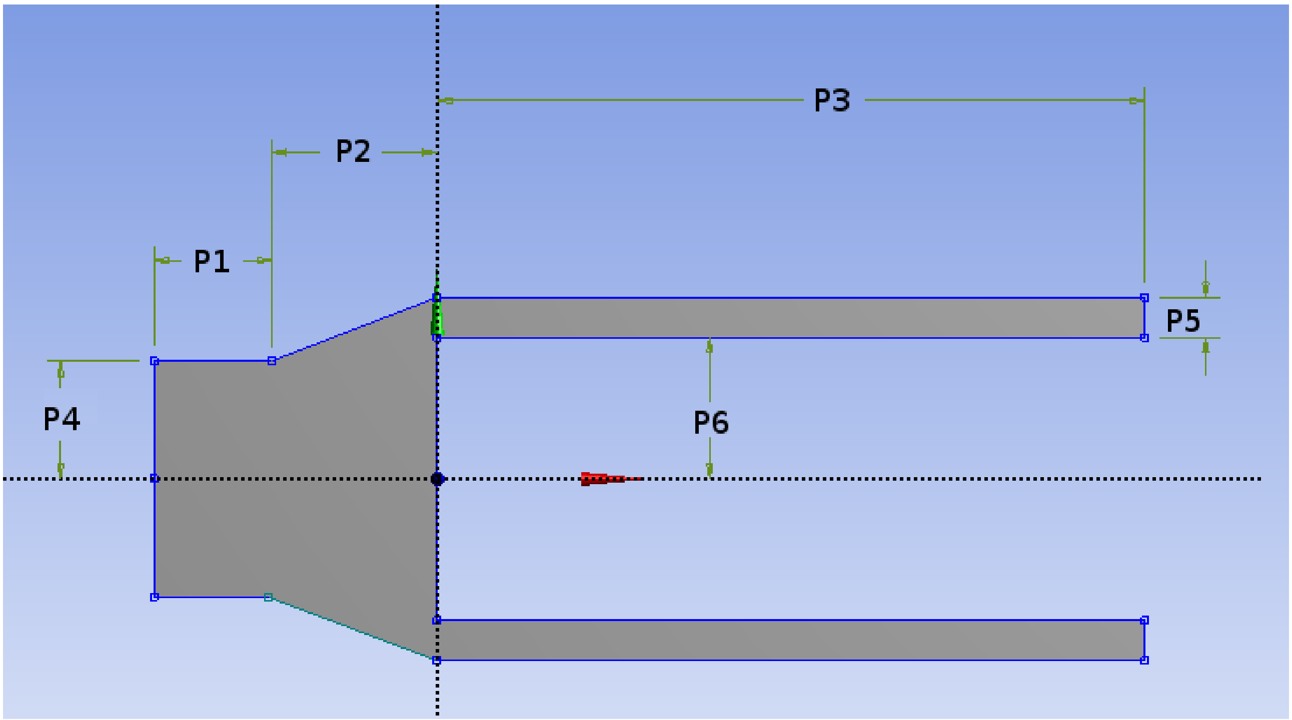
On the side of the guy wire, it can be treated as fixed support. One the other side, bearing load can be assumed to be each $1 \times 10^5 N$, and excerted at the wholes. See the parts below for a fihure demonstrating it.

2.3 Parameters to optimize

2.3.1 Optimization of dimensions only

In this stage, only the dimensions marked on the provided figure will be optimized. Theshape and topology of the anchor will not be changed. In other words, the optimization will be limited to changing the numbers provided.

To make optimization easier, another set of parameters will be used (note that P6 is not used as the dimension is fixed):



$$
\begin{aligned}
P1\,\mathrm{cm} &= H10 \\
P2\,\mathrm{cm} &= H11 - H10 \\
P3\,\mathrm{cm} &= H1 - H11 \\
P4\,\mathrm{cm} &= V6 \\
P5\,\mathrm{cm} &= V3 \\
P7\,\mathrm{cm} &= HEIGHT/2 \\
P8\,\mathrm{cm} &= D2
\end{aligned}
$$

These parameters will be used in the optimization part of this report.

2.3.2 Slight shape modification

In this stage, in addition to dimensional changes, the shape itself will change a little bit.

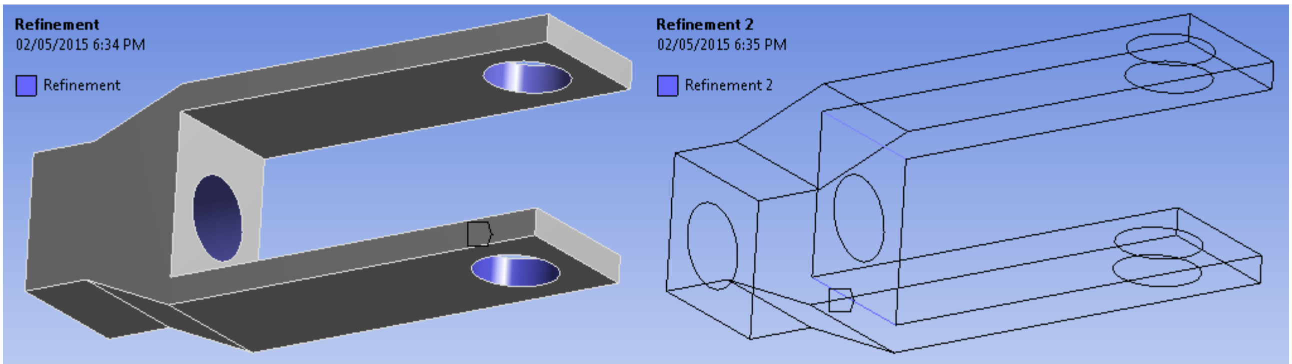
Some rounded corner (fillets/chamfers) will be added, and an additional extruded structure may be annexed. See the optimization part for details.

3 FEM analysis

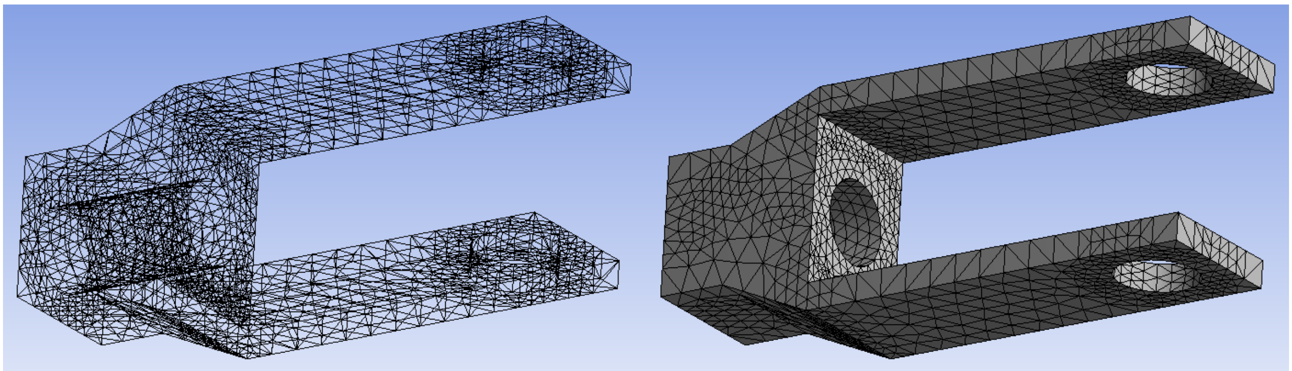
3.1 Mesh setup

As this is a 3D model, elements of tetrahedron shapes are used.

For the mesh, two refinements are added as below, where the first one (*Refinement*) is for the cylindrical surface of loading, and the second one (*Refinement 2*) is for the sharp edges of 90 degree where stress concentration might occur. More refinements will be added in optimization stage to accomodate the changed shape. See the optimization part for details.

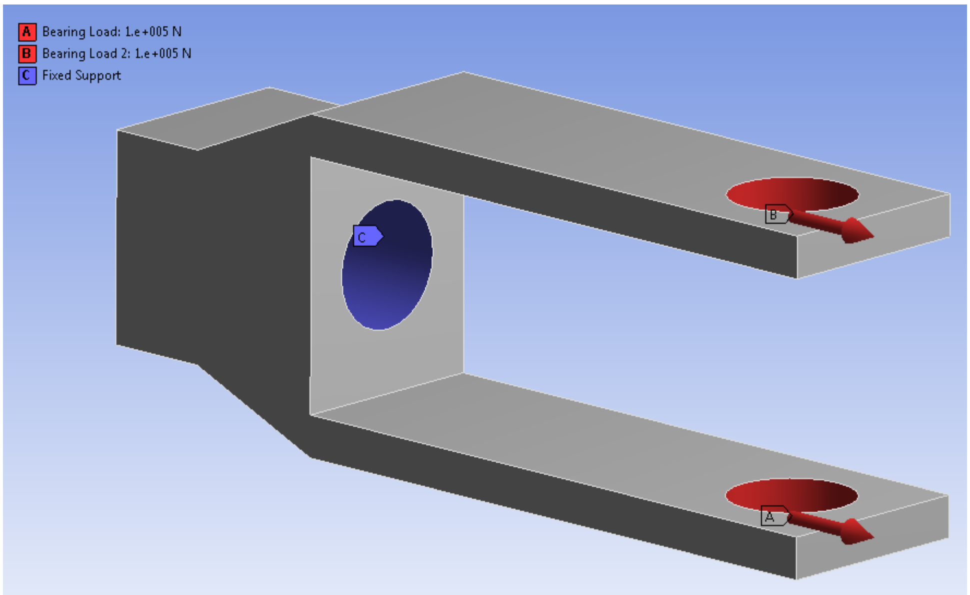


The overall mesh with a size of 2 cm is shown below:



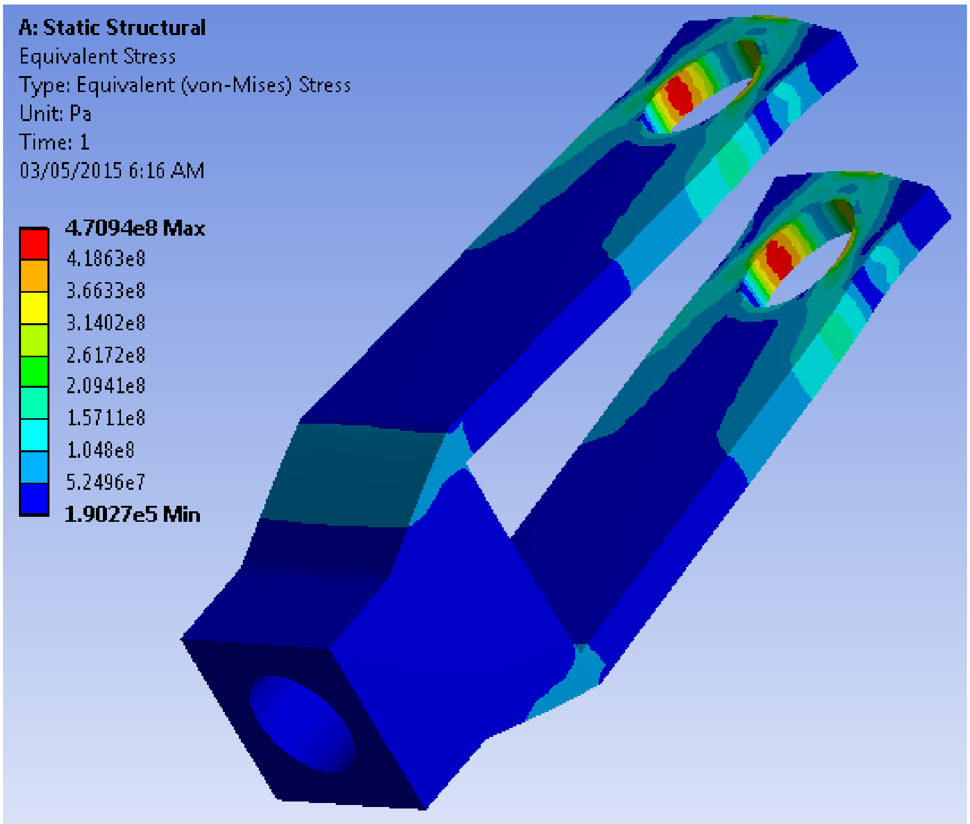
3.2 Boundary conditions setup

As discussed in previous parts, the load from the guy wire is treated as a fixed support, and the load from the bolt is treated as two bearing loads.



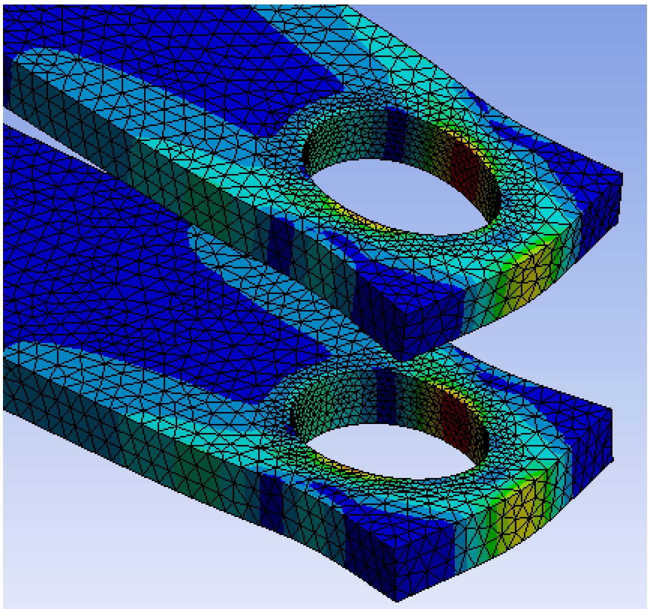
3.3 Results

The maximum principle stress is found to be around 480MPa.

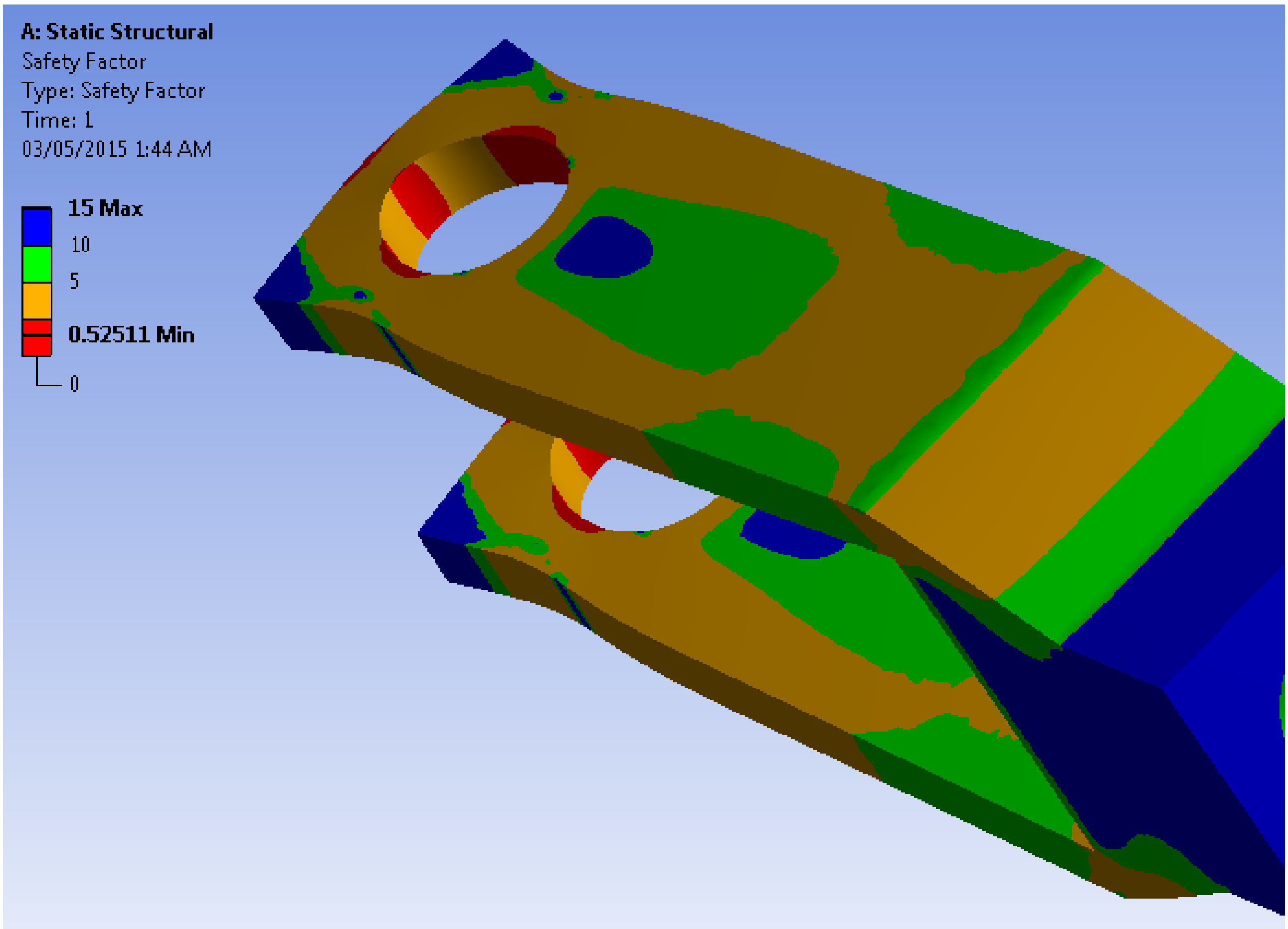


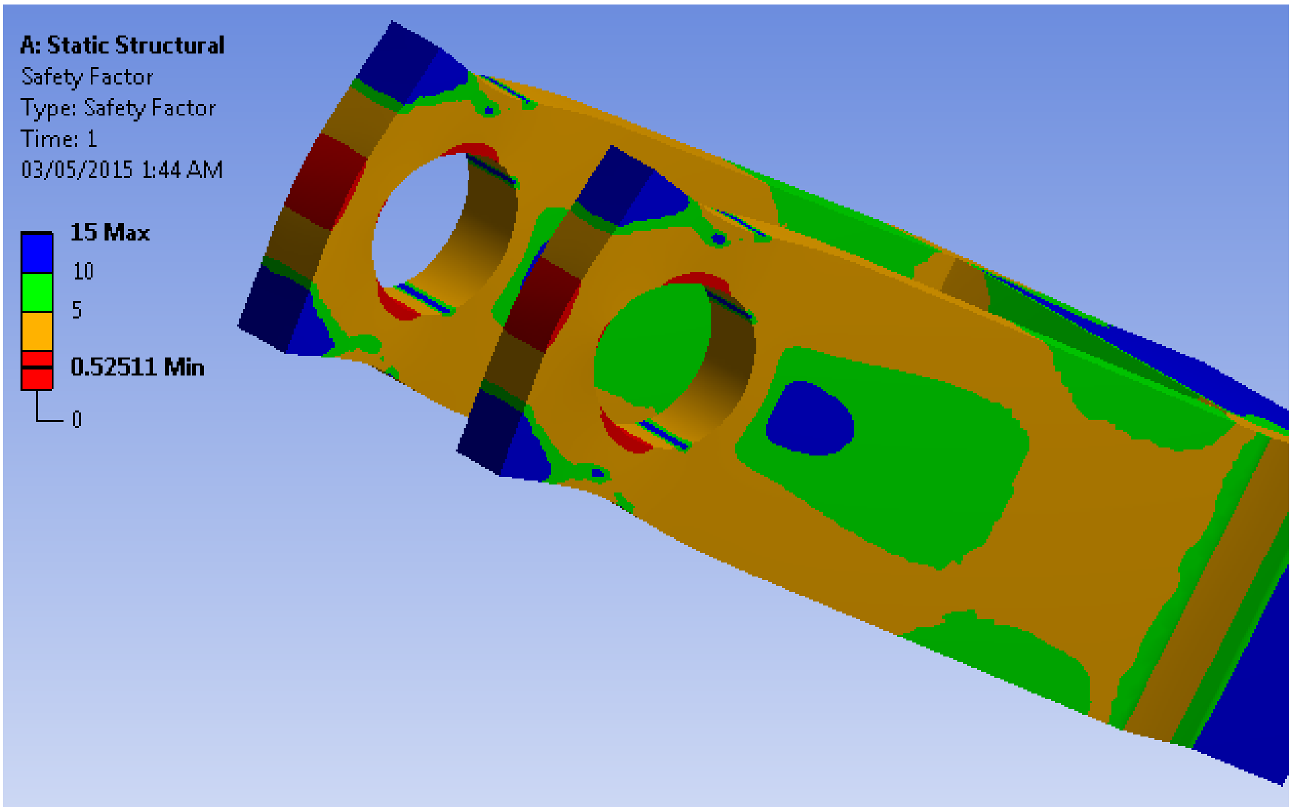
As fixed support is assumed on the side of guy wire, and the origin of the coordinate system is also on that side, the maximum displacement is at the right end, around 0.39mm. Figures can be found in the convergence study part.

We can clear see that the maximum stress is at the four symmetric points: the side end of the wholes. They are exactly the points where failure is most possible to happen. An enlarged figure below shows it better:



As uniform material properties is assumed, the local safety factor would be proportional to the local principle stress. The local safety factors are shown below:

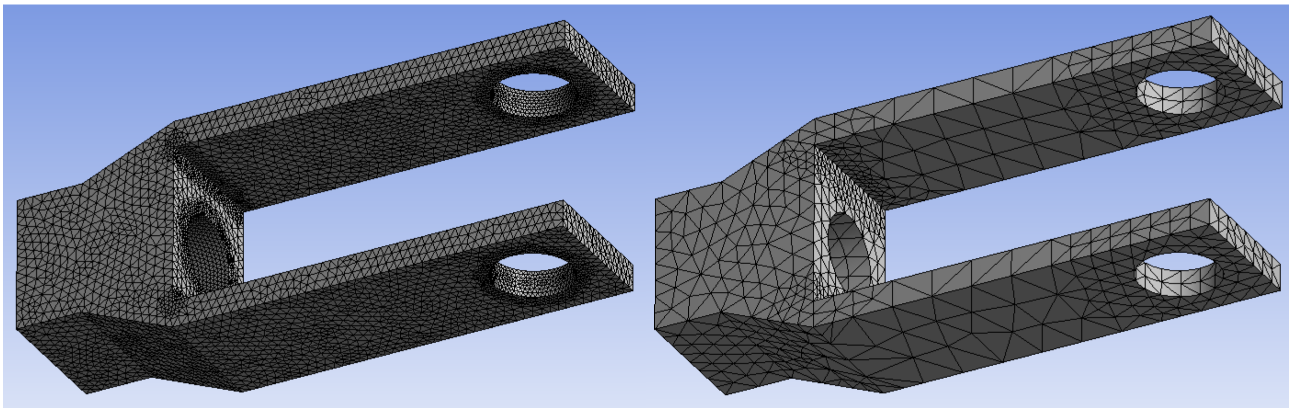




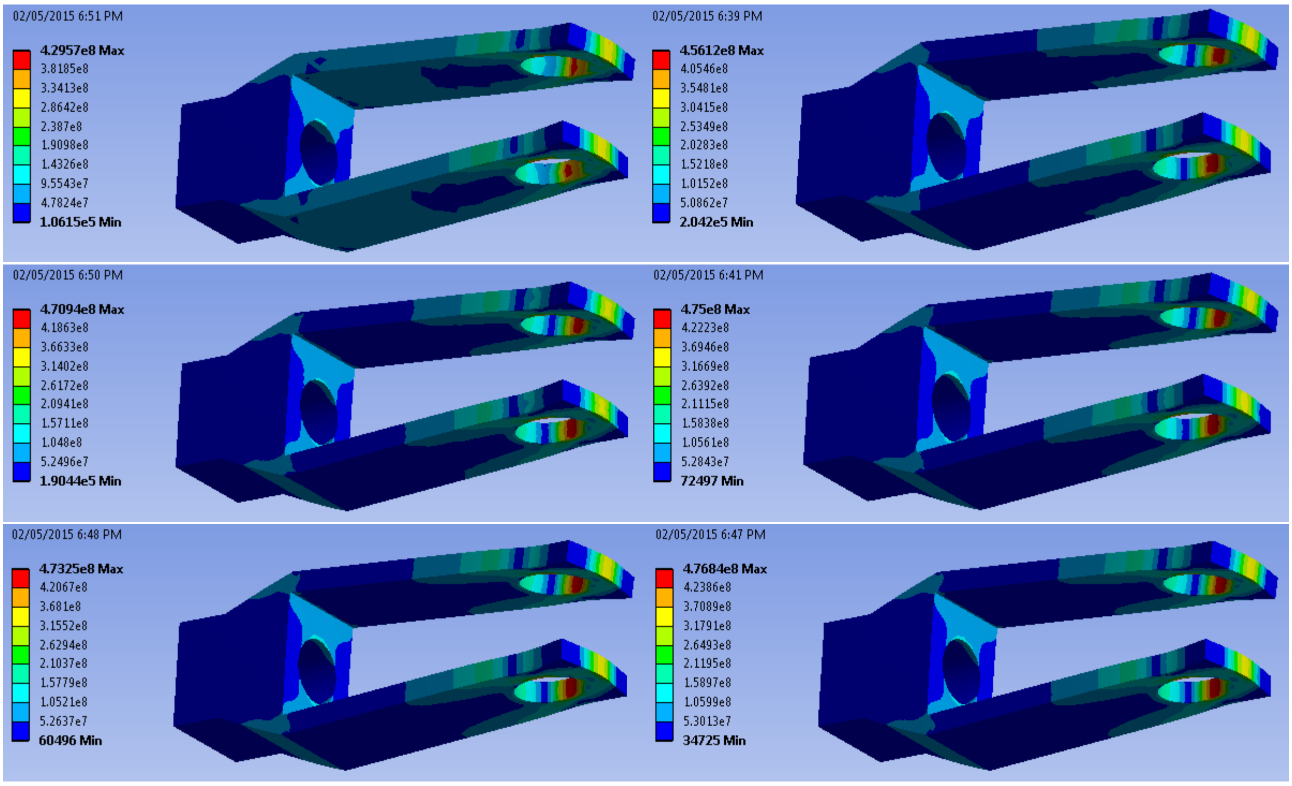
Clearly, as the minimum safety factor is around 0.5, the original design does not meet the requirements.

3.4 Convergence study

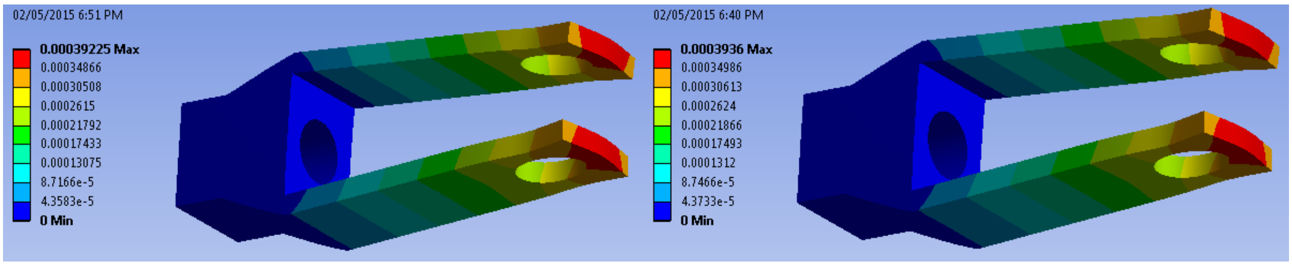
For convergence study, mesh sizes of 3 cm, 2 cm, 1.5 cm, 1 cm, 0.8 cm and 0.65 cm are used. The mesh of minimum (0.65 cm) and maximum (3 cm) mesh size are shown below:

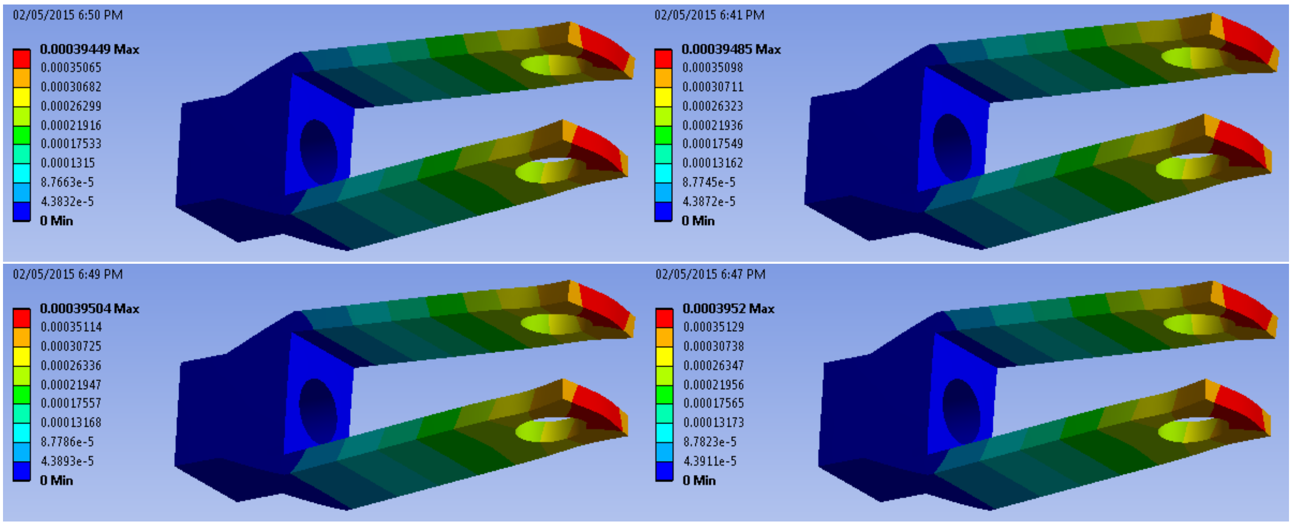


The results for principle stresses are below, listed in size-decreasing order.

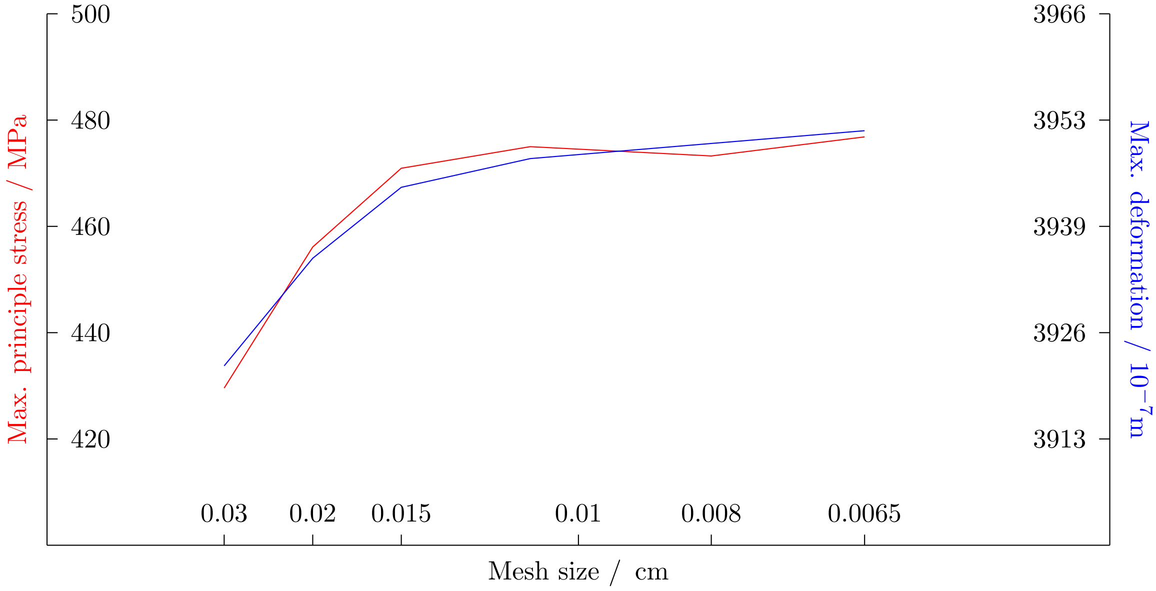


The results for deformations are below, listed in size-decreasing order.





The change of both results with mesh sizes can be plotted below (x-axis in reciprocal scale):



We can see it converges. Therefore the results are reasonable and reliable.

4 Optimization

The general target of optimization is to achieve a mass (weight) as low as possible, while keeping a safety factor larger than 2.

4.1 Optimization of dimension only

4.1.1 Manual optimization for individual parameters

Change one parameter at a time, while keeping other parameters the same as original design:

P1 $= H10$

Table of Design Points

	A	B	C	D	E	F	G	H	I	J	K
1	Name	P1 - H10								P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	1.5	7	30	5	2	6	5	6	0.52684	14.985
4	DP 1	2	7	30	5	2	6	5	6	0.52749	15.266
5	DP 2	2.5	7	30	5	2	6	5	6	0.52487	15.548
6	DP 3	3	7	30	5	2	6	5	6	0.52703	15.829
7	DP 4	3.5	7	30	5	2	6	5	6	0.52715	16.111
8	DP 5	4	7	30	5	2	6	5	6	0.52639	16.392
9	DP 6	4.5	7	30	5	2	6	5	6	0.52718	16.674
10	DP 7	5	7	30	5	2	6	5	6	0.52502	16.955
11	DP 8	5.5	7	30	5	2	6	5	6	0.52565	17.237
12	DP 9	6	7	30	5	2	6	5	6	0.52617	17.518
13	DP 10	6.5	7	30	5	2	6	5	6	0.52718	17.8

It can be seen that $H10$ can be reduced to save weight without decreasing safety factor greatly.

P2 $= H11 - H10$

Table of Design Points

	A	B	C	D	E	F	G	H	I	J	K
1	Name		P2 - H11_MINUS_H10							P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	5	4	30	5	2	6	5	6	0.52542	14.913
4	DP 1	5	4.5	30	5	2	6	5	6	0.5281	15.253
5	DP 2	5	5	30	5	2	6	5	6	0.52711	15.594
6	DP 3	5	5.5	30	5	2	6	5	6	0.52604	15.934
7	DP 4	5	6	30	5	2	6	5	6	0.52718	16.275
8	DP 5	5	6.5	30	5	2	6	5	6	0.5263	16.615
9	DP 6	5	7	30	5	2	6	5	6	0.52573	16.955
10	DP 7	5	7.5	30	5	2	6	5	6	0.52623	17.296
11	DP 8	5	8	30	5	2	6	5	6	0.52653	17.636
12	DP 9	5	8.5	30	5	2	6	5	6	0.52607	17.977
13	DP 10	5	9	30	5	2	6	5	6	0.52626	18.317

It can be seen that $H11$ can be reduced to save weight without decreasing safety factor greatly. Combined with the previous entry, we can seen that $H11$ can be reduced without decreasing safety factor greatly.

P3 $= H1 - H11$

Table of Design Points

	A	B	C	D	E	F	G	H	I	J	K
1	Name			P3 - H1_MINUS_H_11						P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	5	7	28.5	5	2	6	5	6	0.23485	16.484
4	DP 1	5	7	29	5	2	6	5	6	0.41948	16.641
5	DP 2	5	7	29.5	5	2	6	5	6	0.46876	16.798
6	DP 3	5	7	30	5	2	6	5	6	0.52573	16.955
7	DP 4	5	7	30.5	5	2	6	5	6	0.58544	17.112
8	DP 5	5	7	31	5	2	6	5	6	0.63799	17.269
9	DP 6	5	7	31.5	5	2	6	5	6	0.67988	17.426
10	DP 7	5	7	32	5	2	6	5	6	0.71533	17.583
11	DP 8	5	7	32.5	5	2	6	5	6	0.73318	17.74
12	DP 9	5	7	33	5	2	6	5	6	0.75157	17.897
13	DP 10	5	7	33.5	5	2	6	5	6	0.76701	18.054

It can be seen that reducing $H1 - H11 - H9$, which is the part outer than the bearings, can reduce the safety factor greatly. That value should be increased instead.

P4 $= V6$

Table of Design Points

	A	B	C	D	E	F	G	H	I	J	K
1	Name				P4 - V6					P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	5	7	30	3.5	2	6	5	6	0.52796	14.963
4	DP 1	5	7	30	3.75	2	6	5	6	0.52699	15.295
5	DP 2	5	7	30	4	2	6	5	6	0.5274	15.627
6	DP 3	5	7	30	4.25	2	6	5	6	0.52665	15.959
7	DP 4	5	7	30	4.5	2	6	5	6	0.52713	16.291
8	DP 5	5	7	30	4.75	2	6	5	6	0.52621	16.623
9	DP 6	5	7	30	5	2	6	5	6	0.52573	16.955
10	DP 7	5	7	30	5.25	2	6	5	6	0.52717	17.287
11	DP 8	5	7	30	5.5	2	6	5	6	0.52592	17.62
12	DP 9	5	7	30	5.75	2	6	5	6	0.52592	17.952
13	DP 10	5	7	30	6	2	6	5	6	0.52729	18.284

It can be seen that $V6$ can be reduced to save weight, and safety factor will not be influenced.

P5 $= V3$

	A	B	C	D	E	F	G	H	I	J	K
1	Name					P5 - V3				P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	5	7	30	5	1.7	6	5	6	0.44522	15.509
4	DP 1	5	7	30	5	1.85	6	5	6	0.48499	16.232
5	DP 2	5	7	30	5	2	6	5	6	0.52573	16.955
6	DP 3	5	7	30	5	2.15	6	5	6	0.56695	17.679
7	DP 4	5	7	30	5	2.3	6	5	6	0.60401	18.402
8	DP 5	5	7	30	5	2.45	6	5	6	0.64471	19.125
9	DP 6	5	7	30	5	2.6	6	5	6	0.68663	19.848
10	DP 7	5	7	30	5	2.75	6	5	6	0.72751	20.572
11	DP 8	5	7	30	5	2.9	6	5	6	0.76949	21.295
12	DP 9	5	7	30	5	3.05	6	5	6	0.81136	22.018
13	DP 10	5	7	30	5	3.2	6	5	6	0.85533	22.741

It can be seen that increasing $V3$ can increase the safety factor greatly.

P7 $= HEIGHT/2$

	A	B	C	D	E	F	G	H	I	J	K
1	Name							P7 - HALF_HEIGHT		P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	5	7	30	5	2	6	3.5	6	0.21677	10.803
4	DP 1	5	7	30	5	2	6	3.8	6	0.30414	12.034
5	DP 2	5	7	30	5	2	6	4.1	6	0.37432	13.264
6	DP 3	5	7	30	5	2	6	4.4	6	0.43051	14.495
7	DP 4	5	7	30	5	2	6	4.7	6	0.47958	15.725
8	DP 5	5	7	30	5	2	6	5	6	0.52502	16.955
9	DP 6	5	7	30	5	2	6	5.3	6	0.56828	18.186
10	DP 7	5	7	30	5	2	6	5.6	6	0.61022	19.416
11	DP 8	5	7	30	5	2	6	5.9	6	0.64732	20.647
12	DP 9	5	7	30	5	2	6	6.2	6	0.68422	21.877
13	DP 10	5	7	30	5	2	6	6.5	6	0.71556	23.107

It can be seen that increasing the height will increase safety factor greatly. However, the weight will also be increased greatly.

P8 $= D2$

Table of Design Points

	A	B	C	D	E	F	G	H	I	J	K
1	Name								P8 - D2	P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units										kg
3	Current	5	7	30	5	2	6	5	4.5	0.68234	17.344
4	DP 1	5	7	30	5	2	6	5	4.8	0.65681	17.275
5	DP 2	5	7	30	5	2	6	5	5.1	0.63515	17.202
6	DP 3	5	7	30	5	2	6	5	5.4	0.60119	17.124
7	DP 4	5	7	30	5	2	6	5	5.7	0.56603	17.042
8	DP 5	5	7	30	5	2	6	5	6	0.52573	16.955
9	DP 6	5	7	30	5	2	6	5	6.3	0.48234	16.864
10	DP 7	5	7	30	5	2	6	5	6.6	0.44086	16.769
11	DP 8	5	7	30	5	2	6	5	6.9	0.39447	16.669
12	DP 9	5	7	30	5	2	6	5	7.2	0.34768	16.565
13	DP 10	5	7	30	5	2	6	5	7.5	0.30253	16.456

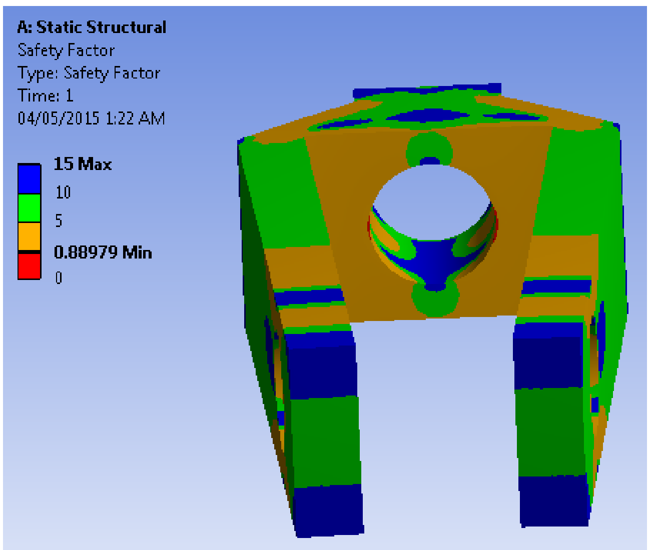
It can be seen that reducing $D2$ will increase the safety factor, and reduce the weight slightly. However, as reducing $D2$ will decrease the safety of the bolt significantly, it's preferred that $D2$ is kept at 6 cm and not changed.

As P5($V3$) is the most important factor, we focus more on changing $P5$.

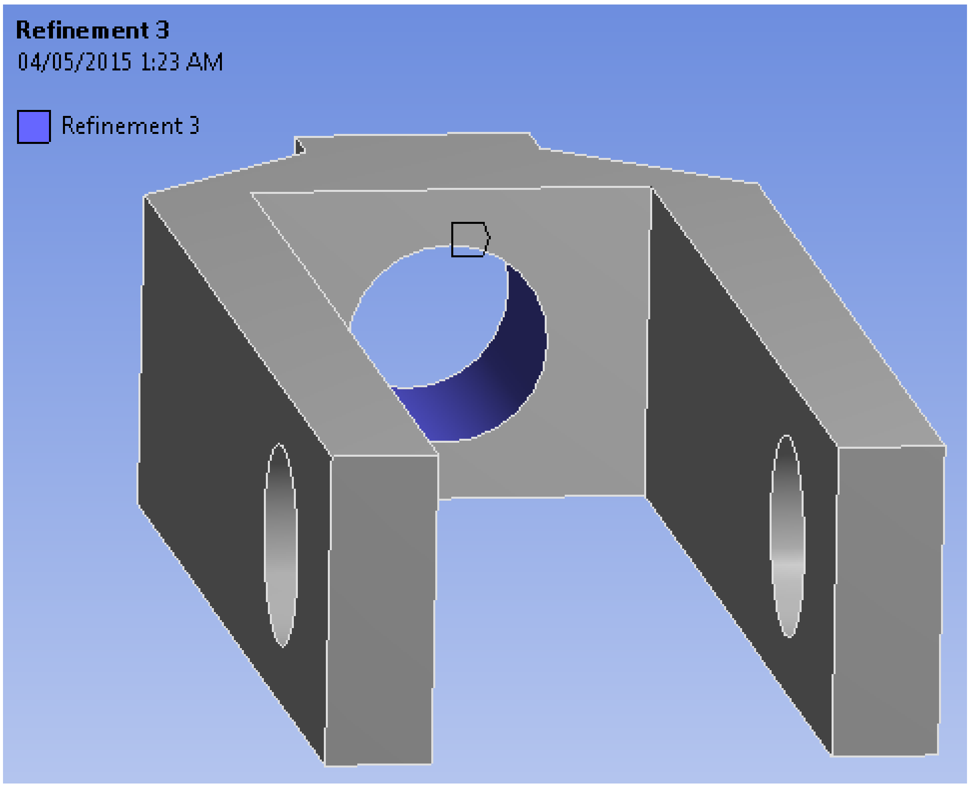
According to the result of iteration 1, we try the following values will be used for other parameters:

$$P1 = 1.5$$
$$P2 = 4$$
$$P3 = 33.5$$
$$P4 = 3.5$$
$$P7 = 4.7$$

However, this resulted to stress concentration on the cylindrical surface of $D1$.



Therefore, we add mesh refinement to the edge of the hole $D1$ to acquire better results. We found that $P2$ cannot be radically reduced, otherwise the cylindrical surface of $D1$ may fail.



As manual optimization is too slow when the number of parameters is large, optimization feature provided by ANSYS is used instead.

4.1.2 Automatic optimization

In this stage, "Direct optimization" feature is used. The mesh size to be used is 0.8 cm, as the license does not permit smaller mesh sizes.

The targets are set as "keep safety ratio above 2" and "try to minimize the mass". According to the general idea got in the manual optimization phase, the following settings are used:

Outline of Schematic B2: Optimization

	A	B
1		Enabled
2	Optimization	
3	Objectives and Constraints	
4	P9 >= 2	
5	Minimize P10	
6	Domain	
7	Static Structural (A1)	
8	P1 - H10	☑
9	P2 - H11_MINUS_H10	☑
10	P3 - H1_MINUS_H_11	☑
11	P4 - V6	☑
12	P5 - V3	☑
13	P7 - HALF_HEIGHT	☑
14	P8 - D2	☐
15	Results	

Table of Schematic B2: Optimization

	A	B	C
1	Optimization Domain	Lower Bound	Upper Bound
2	P1 - H10	0	5
3	P2 - H11_MINUS_H10	2.5	8.5
4	P3 - H1_MINUS_H_11	30	36
5	P4 - V6	3.25	5.75
6	P5 - V3	1.5	11.5
7	P7 - HALF_HEIGHT	3.25	6.5

The following results are acquired:

Outline of Schematic B2: Optimization

	A	B	C
1		Enabled	Monitoring
2	Optimization		
3	Objectives and Constraints		
4	P9 >= 2		
5	Minimize P10		
6	Domain		
7	Static Structural (A1)		
8	P1 - H10	☐	
9	P2 - H11_MINUS_H10	☑	
10	P3 - H1_MINUS_H_11	☑	
11	P4 - V6	☑	
12	P5 - V3	☑	
13	P7 - HALF_HEIGHT	☑	
14	P8 - D2	☐	

Table of Schematic B2: Optimization

	A	B	C	D
1	Optimization Study			
2	Minimize P10	Goal, Minimize P10 (Default importance)		
3	P9 >= 2	Strict Constraint, P9 values greater than or equals to 2 (Default importance)		
4	Optimization Method			
8	Candidate Points			
9		Candidate Point 1	Candidate Point 2	Candidate Point 3
10	P2 - H11_MINUS_H10	7.9752	8.1271	7.9655
11	P3 - H1_MINUS_H_11	34.788	34.197	34.505
12	P4 - V6	5.7576	5.7154	5.9607
13	P5 - V3	4.1979	4.3424	4.2897
14	P7 - HALF_HEIGHT	5.6244	5.6391	5.9479
15	P9 - Safety Factor Minimum	★★★ 2.0099	★★★ 2.0392	★★★ 2.0155
16	P10 - Solid Mass (kg)	★ 33.95	★ 34.669	− 36.683

Rounding the values, we have the following run:

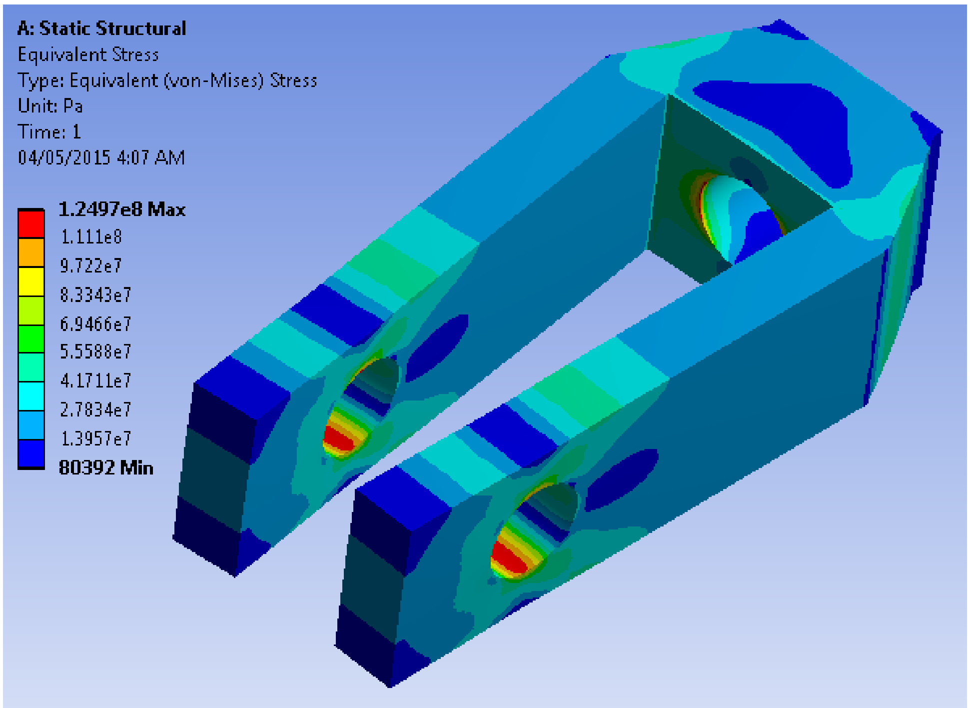
	A	B	C	D	E	F	G	H	I	J
1	Name	P1 - H10	P2 - H11_MINUS_H10	P3 - H1_MINUS_H_11	P4 - V6	P5 - V3	P7 - HALF_HEIGHT	P8 - D2	P9 - Safety Factor Minimum	P10 - Solid Mass
2	Units									kg
3	Current	0.7	8	34.8	5.75	4.2	5.62	6	2.0004	33.966

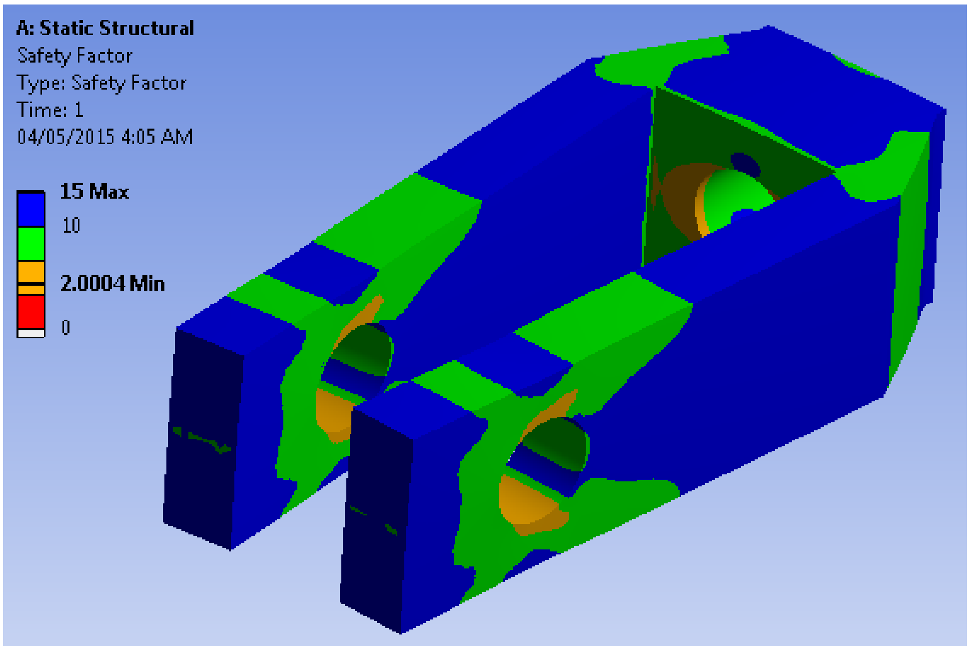
The optimization workflow yielded a result of:

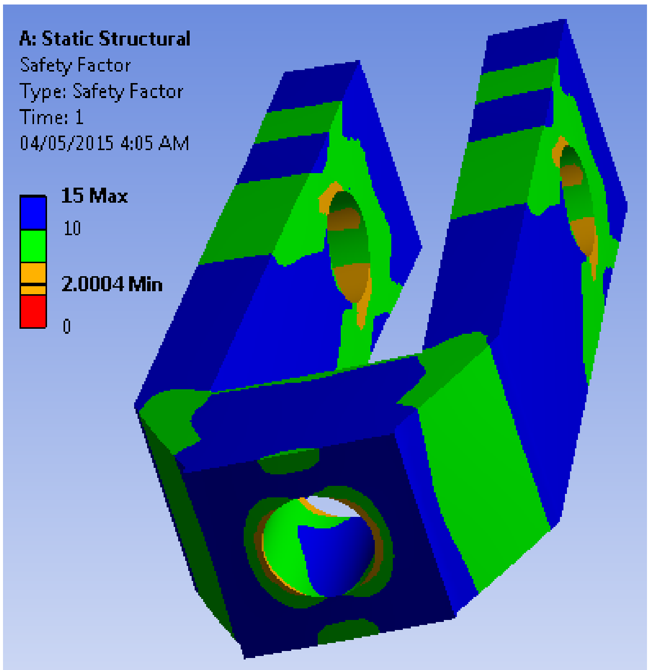
$$
\begin{aligned}
H10 &= P1\,\text{cm} = 0.7\,\text{cm}\\
H11 &= (P1 + P2)\,\text{cm} = 8.7\,\text{cm}\\
H1 &= H11 + P3\,\text{cm} = 8.7\,\text{cm} + 34.8\,\text{cm} = 43.5\,\text{cm}\\
V6 &= P4\,\text{cm} = 5.75\,\text{cm}\\
V3 &= P5\,\text{cm} = 4.2\,\text{cm}\\
Height &= P7 * 2\,\text{cm} = 11.24\,\text{cm}\\
D2 &= 6\,\text{cm}
\end{aligned}
$$

In this case, minimum local safety factor is a tiny bit above 2, and the mass of the anchor is 33.97 kg.

The corresponding model is built below:







The mass is verified as

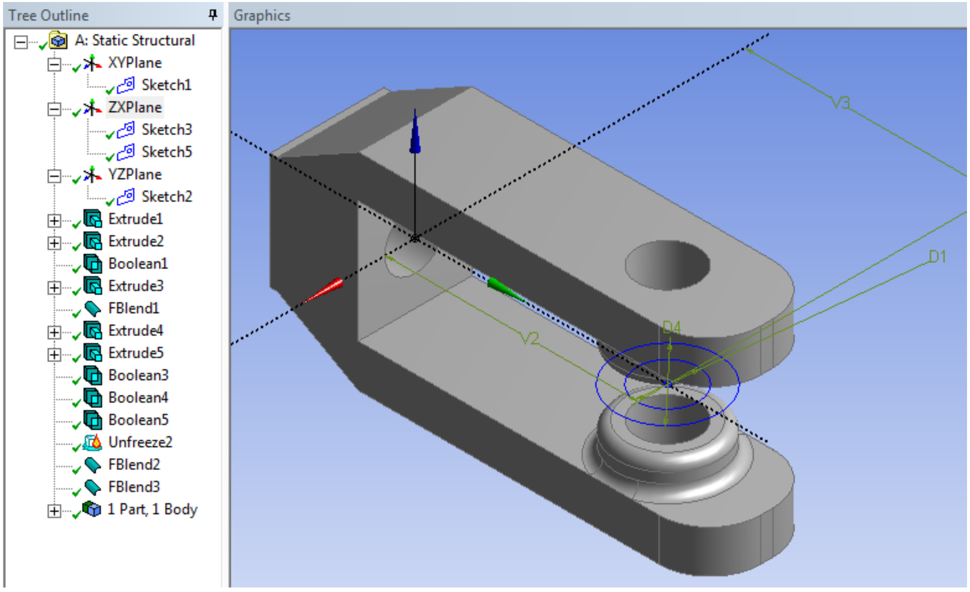
Material	
Assignment	Structural Steel
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Properties	
Volume	4.3269e-003 m^3
P Mass	33.966 kg
Centroid X	0.1071 m
Centroid Y	3.8364e-019 m
Centroid Z	-1.1895e-018 m
Moment of Inertia Ip1	0.22556 kg·m^2
Moment of Inertia Ip2	0.59468 kg·m^2
Moment of Inertia Ip3	0.74242 kg·m^2

4.2 Slight shape modification

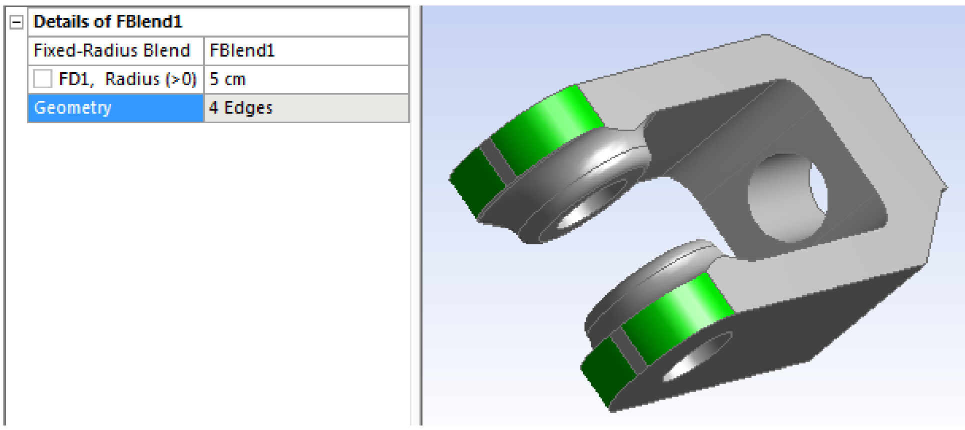
4.2.1 Shape modifications

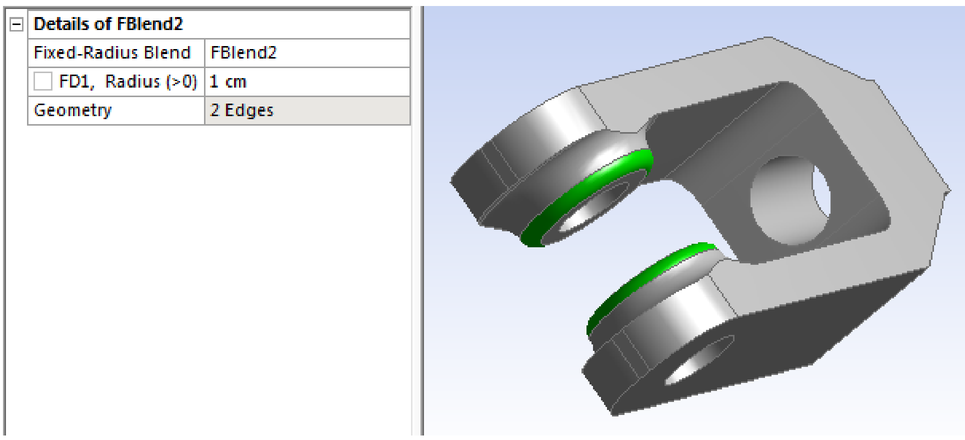
In this stage, two changes are made basing on the optimized dimension above.

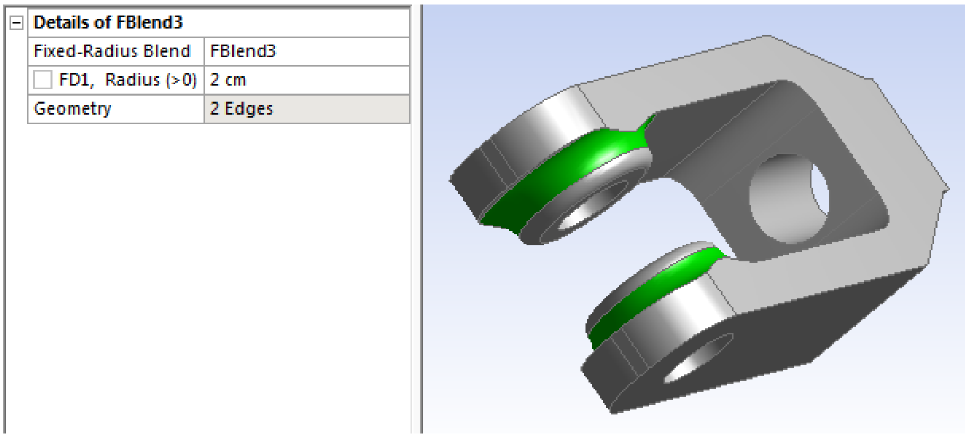
The first change is annexing an extruded part at the holes where the bolt will be put. It can increase the area to support the bolt, as shown below. The inner diameter is consistent with $D2$, which is now fixed to be $6cm$. The outer diameter and the height are variable.

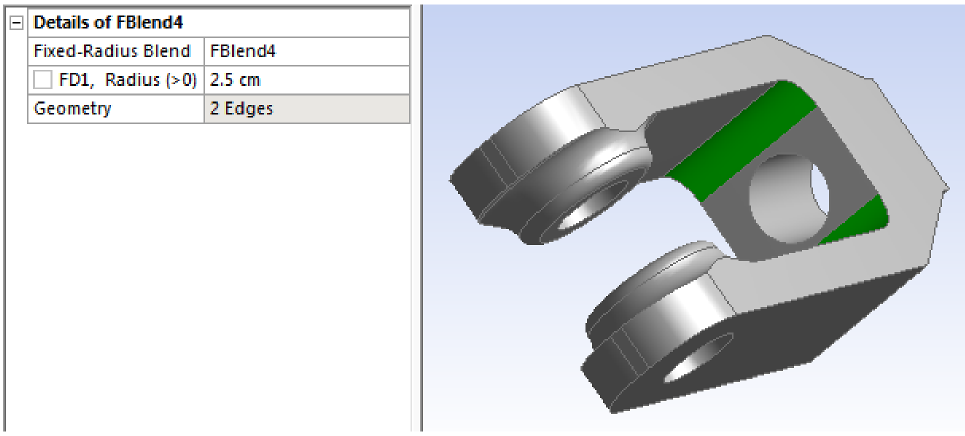


The second change is to add rounded corners at all edges. Not only can it reduce the stress concentration, it can also prevent people get hurt by sharp edges. The annexed extruded part, the end of two legs and the base of two legs are partucularly. To be exact, the radii at the end of legs are 5 cm, the radii at the top edge of extruded parts are 1 cm, the radii at the bottom of the extruded parts are 2 cm, and the radii at the base of the legs are 2.5 cm. Screenshots are attached below:

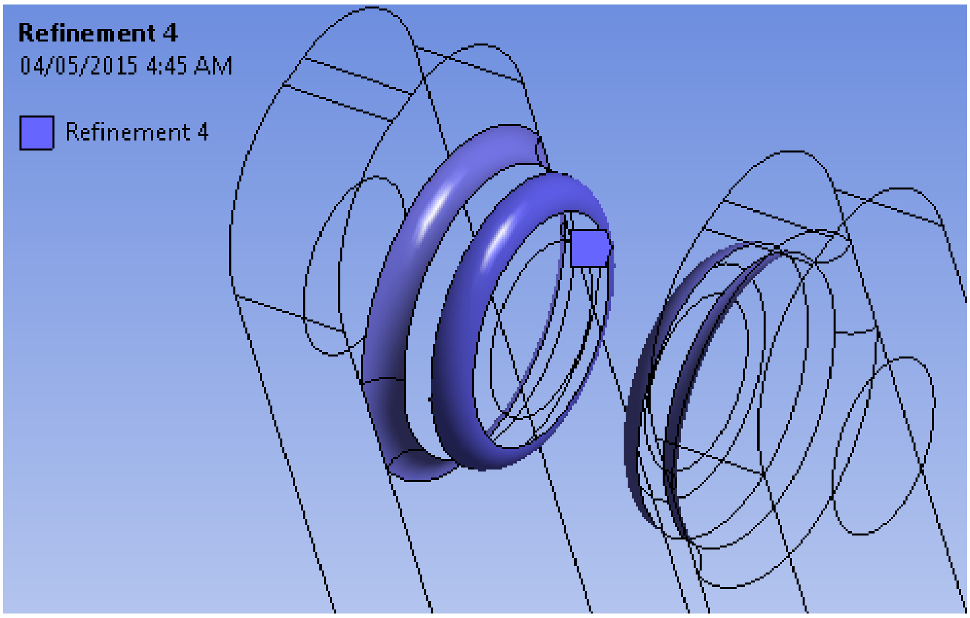




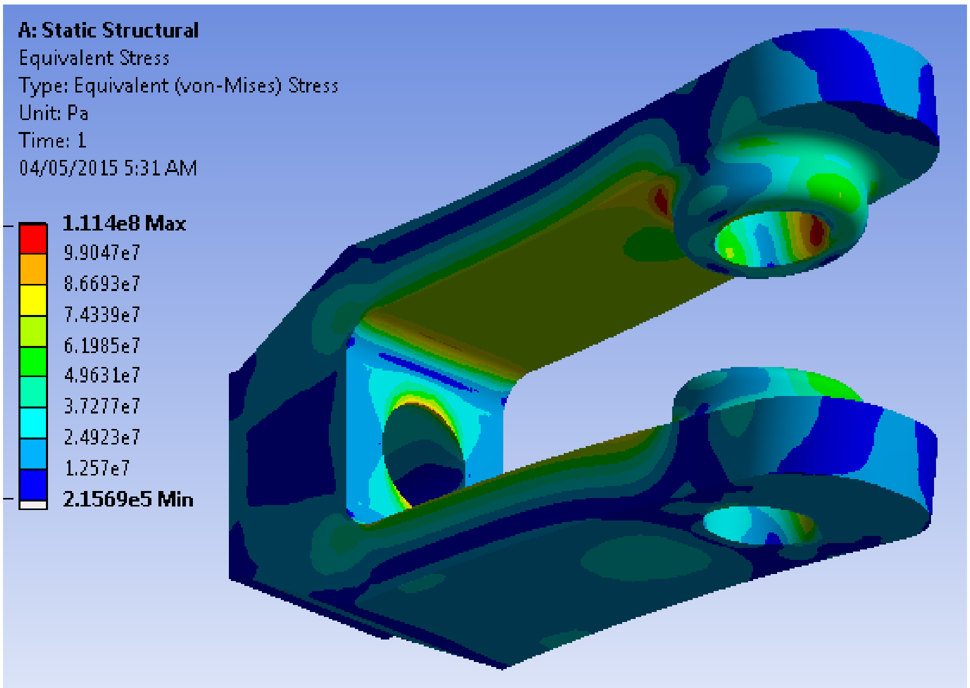




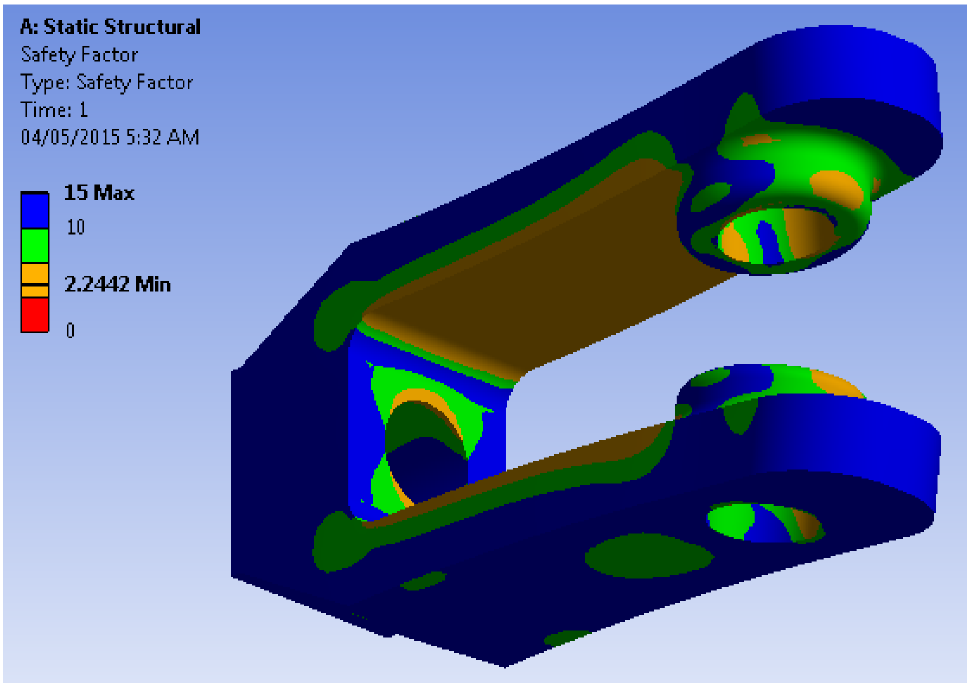
Additional mesh refinements are needed, as shown below:



The local principle stresses are shown below:



The local safety factor is shown below:



From the images, it can be seen that the local principle stress is reduced at the holes for the bolt. The minimum local safety factor is increased from 2 to 2.24, while the weight is almost the same. Therefore the modification is effective.

4.2.2 Further dimensional optimization

Similar to before, the height and the outer diameter of the extruded part can be changed. Further optimization process is neccessary to optimize the parameters. As other parameters (e.g. $V3$) can be reduced after the shape modification to save weight, these original parameters also need to be included in the optimization workflow.

The new parameters are namely $P11$ cm, the outer diameter, and $P12$ cm, which is 3 cm minus the height of the extruded part. It can be seen that $2 \times P12 \geq D1$, say $P12 \geq 3$; otherwise it might cause inconvinience for the installation of the guy wire.

/* WORK IN PROGRESS */

The dimensions might not be optimum, as the running optimization flow in ANSYS in the lab is very slow, so only a few samples of design parameters are tested. It would be better if we can rent Tianhe-2 supercomputer to compute.

Further shape modifications are also possible, including using non-uniform crosssesctional area for two arms, using rounded shape at the end for holding the guy wire, and annexing extruded part on the hole for the guy wire, similar to the modifications at the holes for the bolt. Those approaches can reduce weight by using less material using smaller dimensions, while keeping acceptable safety factor by reinforcing the places where local strss is high. Using rounded shape for all parts can reduce the weight and reduce stress concentration at corners. However, those design are not simulated due to time limit.

5 Conclusion

In this design project, the stress of anchor under loading is simulated, and the dimensions and shape of it are optimized using ANSYS finite element analysis tool.

The principles of optimization is discussed. The boundary conditions are set as fixed support and bearing loads. Tetrahedron shaped elements are used to form the mesh, with edges and load points particularly refined. The convergence studies showed that the results are reliable. Notice as the mesh size cannot be further reduced due to ANSYS license limit, the results might not be accurate enough.

We found that the maximum stress is likely to occur at four points, which are the side of the cylindrical surfaces for the bolt. We therefore optimize the design accordingly. Increasing $V3$ worked well for this. $H10$ and $H11$ can be reduced to save weight, yet $H11 - H10$ should not be changed much, otherwise the whole for the guy wire might fail.

In addition to the fixed dimensions in the problem description, $D2$ is not changed either, in order to work well with the bolt safely. In a general target of “reduce weight as much as possible as long as safety factor stays above 2”, “direct optimization” feature provided by ANSYS is used to search for improved parameters.

Modifying the dimension values only, an minimum mass of 33.97 kg can be achieved while satisfying the safety factor requirement of 2.

After adding fillets and annexing an extruded tube to hold the bolt, an minimum mass of 33.97 kg can be achieved while satisfying the safety factor requirement of 2.

6 Appendix

The exported ANSYS project files including the simulation results are downloadable below.

Original design `https://github.com/kmxz/mech4450project/blob/master/s1.wbpj`.

Optimized design, only dimensions changed `https://github.com/kmxz/mech4450project/blob/master/s2.wbpj`.

Optimized design, with slight shape modification `https://github.com/kmxz/mech4450project/blob/master/s3f.wbpj`.

Raw optimization results not included in the report are available at

Only dimensions changed `https://github.com/kmxz/mech4450project/tree/master/optimization_results`.

With slight shape modification `https://github.com/kmxz/mech4450project/tree/master/shape_optimization_results`.