Temple University

College of Engineering

Department of Mechanical Engineering

Computer-Aided Mechanical Design

MEE 3117

Tuesday/Thursday Class

Bolts Project

Kaci Walter and Jakob Werle

Introduction

The intentions of this project are to design an assembly of plates and fasteners that support an external load and meet design criteria. The task emulates a real-life engineering project which includes strict geometrical as well as design constraints.

The assembly is comprised of a steel plate sandwiched between two aluminum plates and squeezed together by the designer's choice of nuts and bolts. The number and pattern of fasteners used should be chosen to meet a FOS (factor of safety) and C-factor of 1.5 and 0.2 - 0.3 respectively and minimize the stress in the plates. The outer plates will be 10mm thick 2024-T3 aluminum and the inner plate will be 30mm thick AISI 1020 steel. The designer can choose any shape and size for the plates up to a 6in x 6in square. In addition to the assembly, an external load will be placed in the middle of the top plate, directly upward.

Procedure

The following method was used to design the bolt and plate assembly. To start, a 30-mm thick steel plate was created as a new part in SolidWorks. A second new part was created consisting of a 10-mm thick aluminum plate. For both parts, the dimensions in height and width were 6x6-inches. An assembly was created in which the aluminum plates are sandwiched between the steel plate. In the assembly file, bolt holes were placed through the three plates with a cut extrude. A static simulation was started was started in SolidWorks simulation. A global location connection was established as contact. A local connection was established as contact between the top and bottom faces of the two aluminum plates and steel plates accordingly. An 18kN compression force was placed on the bolts to simulate a clamping force preload. An external tensile load of 10kN force was applied to the center of the top plate. The bottom face of the plate was fixed. The cylindrical faces of the bolt holes were fixed in such a manner that the plates could not rotate. For the iteration to the accepted, the c-value must be between 0.2 and 0.3 for each bolt. In addition, the minimum factor of safety of 1.5 for the bolts.

To theoretically validate the results, the bolts were evaluated as a bolted joint. Throughout the bolt preload, the bolt is stretched while the members in grip are compressed. As the external load is applied, the bolt stretches further while the members decompress. With this in mind, the joint and bolts can be modeled as springs in parallel. The calculation to determine the bolt stiffness, member stiffness/frustum, c-factor, bolt axial stress, and factor of safety in the bolt can be found in the Appendix. Finally, the theoretical and SolidWorks values for c-factor, axial stress and factor of safety were compared.

Fixtures and Loads

The assembly was fixed on the bottom aluminum plate face and a 10kN tensile force was applied to a point at the center of the top face of the assembly. A bolt connector was applied to each hole in the assembly. The figure below presents the visualization of these fixtures, loads, and bolts.

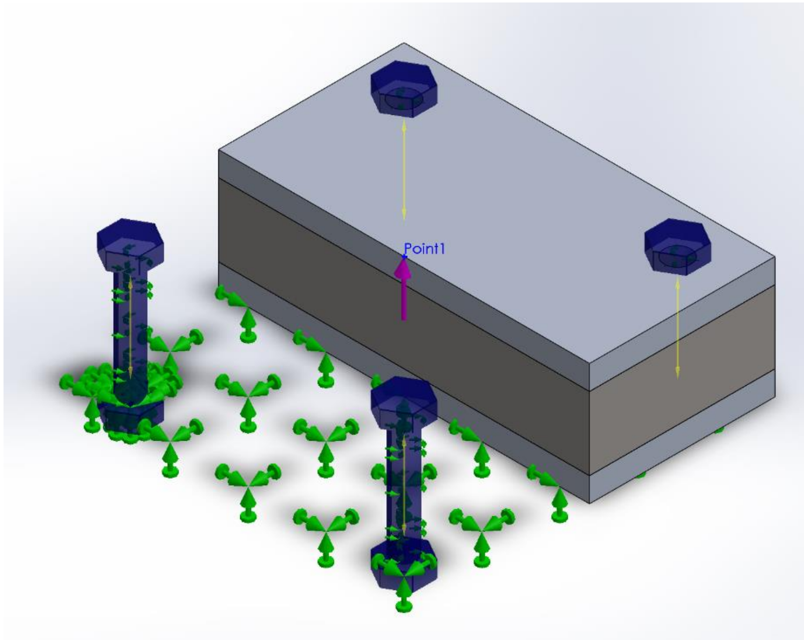


Figure 1. Applied fixtures, loads and bolts.

Results

The final geometries for the designed bolt and plate assembly can be found in Table 1. The results of the SolidWorks bolt simulation and theoretical bolt calculations are presented in the following sub-sections.

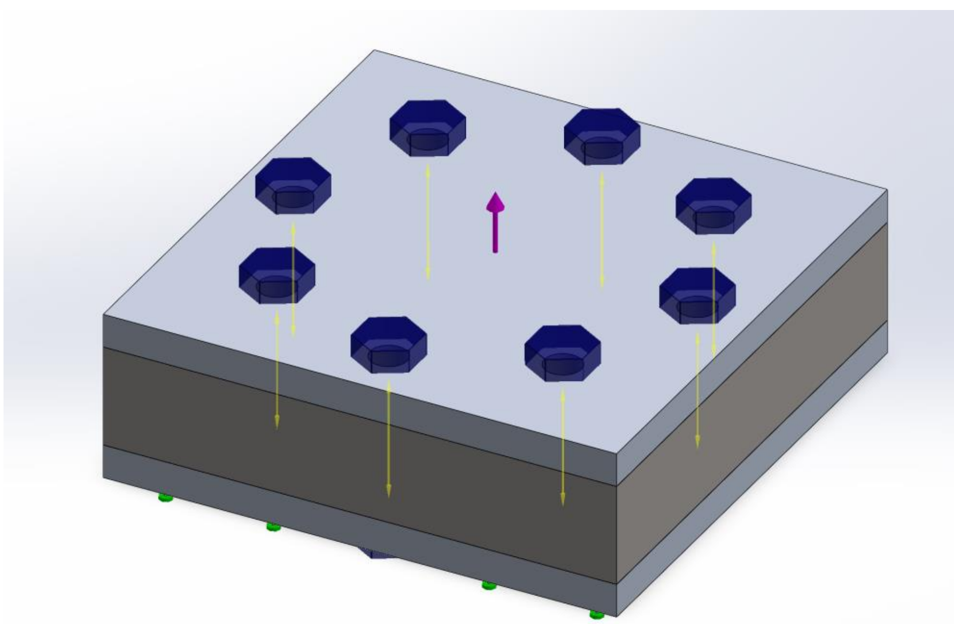


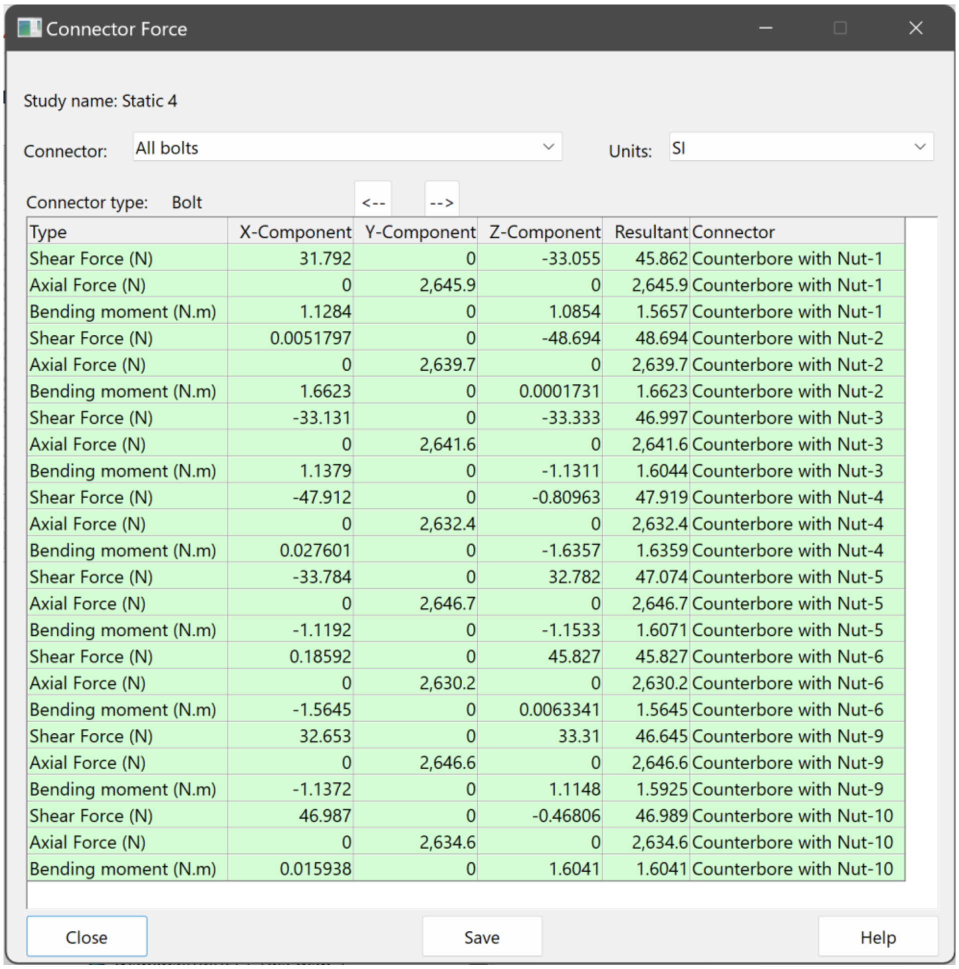
Table 1. Final Bolt Assembly Metrics

Plate WxL (in)	Bolt size (mm)	thread pitch (thread/mm)	Number of bolts

6 x 6	10	1.5	8

Forces in Bolts

Below is an image of the bolt and pin results. The axial forces for each bolt are expressed in Table 2.



Connector Force

Study name: Static 4

Connector: All bolts   Units: SI

Connector type: Bolt   <--   -->

Type	X-Component	Y-Component	Z-Component	Resultant	Connector
Shear Force (N)	31.792	0	-33.055	45.862	Counterbore with Nut-1
Axial Force (N)	0	2,645.9	0	2,645.9	Counterbore with Nut-1
Bending moment (N.m)	1.1284	0	1.0854	1.5657	Counterbore with Nut-1
Shear Force (N)	0.0051797	0	-48.694	48.694	Counterbore with Nut-2
Axial Force (N)	0	2,639.7	0	2,639.7	Counterbore with Nut-2
Bending moment (N.m)	1.6623	0	0.0001731	1.6623	Counterbore with Nut-2
Shear Force (N)	-33.131	0	-33.333	46.997	Counterbore with Nut-3
Axial Force (N)	0	2,641.6	0	2,641.6	Counterbore with Nut-3
Bending moment (N.m)	1.1379	0	-1.1311	1.6044	Counterbore with Nut-3
Shear Force (N)	-47.912	0	-0.80963	47.919	Counterbore with Nut-4
Axial Force (N)	0	2,632.4	0	2,632.4	Counterbore with Nut-4
Bending moment (N.m)	0.027601	0	-1.6357	1.6359	Counterbore with Nut-4
Shear Force (N)	-33.784	0	32.782	47.074	Counterbore with Nut-5
Axial Force (N)	0	2,646.7	0	2,646.7	Counterbore with Nut-5
Bending moment (N.m)	-1.1192	0	-1.1533	1.6071	Counterbore with Nut-5
Shear Force (N)	0.18592	0	45.827	45.827	Counterbore with Nut-6
Axial Force (N)	0	2,630.2	0	2,630.2	Counterbore with Nut-6
Bending moment (N.m)	-1.5645	0	0.0063341	1.5645	Counterbore with Nut-6
Shear Force (N)	32.653	0	33.31	46.645	Counterbore with Nut-9
Axial Force (N)	0	2,646.6	0	2,646.6	Counterbore with Nut-9
Bending moment (N.m)	-1.1372	0	1.1148	1.5925	Counterbore with Nut-9
Shear Force (N)	46.987	0	-0.46806	46.989	Counterbore with Nut-10
Axial Force (N)	0	2,634.6	0	2,634.6	Counterbore with Nut-10
Bending moment (N.m)	0.015938	0	1.6041	1.6041	Counterbore with Nut-10

Close   Save   Help

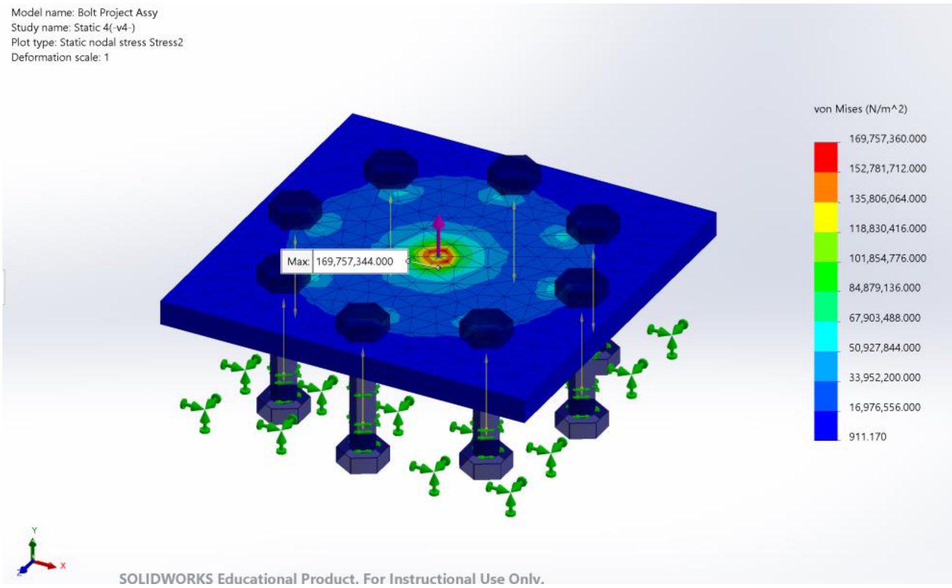
Table 2. Axial Forces in Bolt

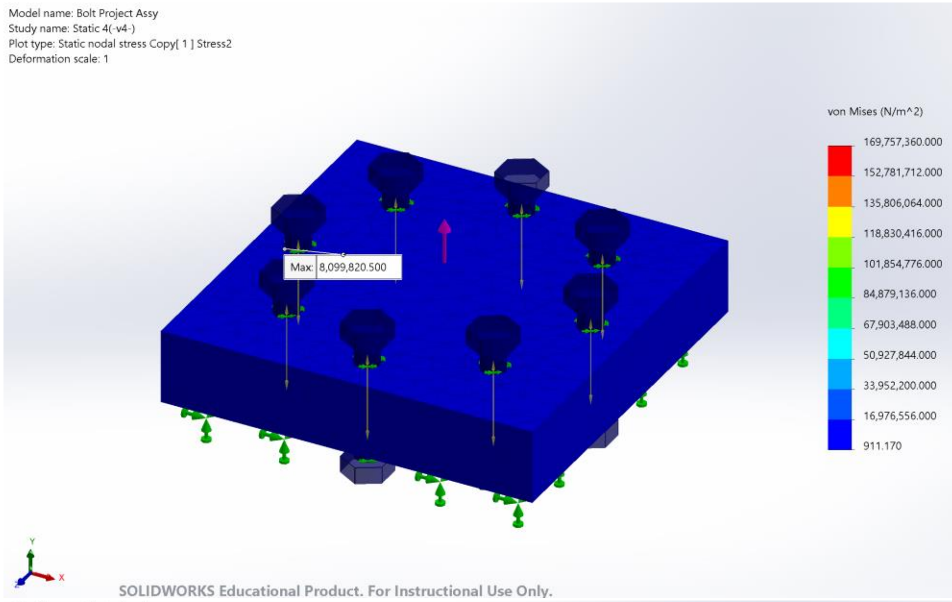
Bolt Number	Axial Stress (N)
1	2,645.90
2	2,639.70
3	2,641.60
4	2,632.40
5	2,646.70
6	2,630.20
7	2,646.60

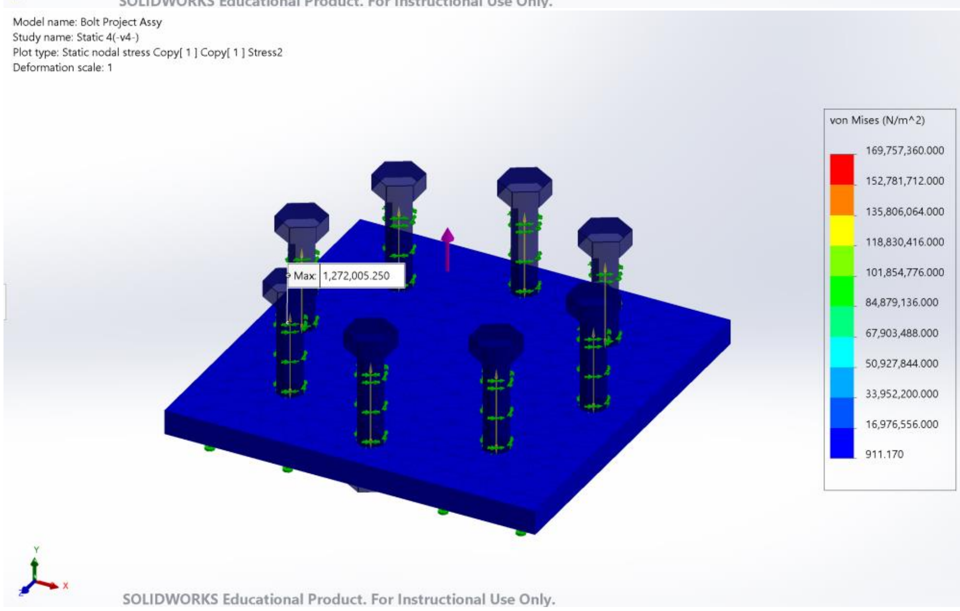
8	2,634.60

Stress in Plates

Table 3 expresses the maximum stresses found in each plate.




Model name: Bolt Project Assy
Study name: Static 4(-v4-)
Plot type: Static nodal stress Copy[1] Stress2
Deformation scale: 1
von Mises (N/m^2)
169,757,360.000
152,781,712.000
135,806,064.000
118,830,416.000
101,854,776.000
84,879,136.000
67,903,488.000
50,927,844.000
33,952,200.000
16,976,556.000
911.170
Max: 8,099,820.500
Y
X
SOLIDWORKS Educational Product. For Instructional Use Only.


Model name: Bolt Project Assy
Study name: Static 4(-v4-)
Plot type: Static nodal stress Copy[1] Copy[1] Stress2
Deformation scale: 1
von Mises (N/m^2)
169,757,360.000
152,781,712.000
135,806,064.000
118,830,416.000
101,854,776.000
84,879,136.000
67,903,488.000
50,927,844.000
33,952,200.000
16,976,556.000
911.170
Max: 1,272,005.250
Y
X
SOLIDWORKS Educational Product. For Instructional Use Only.

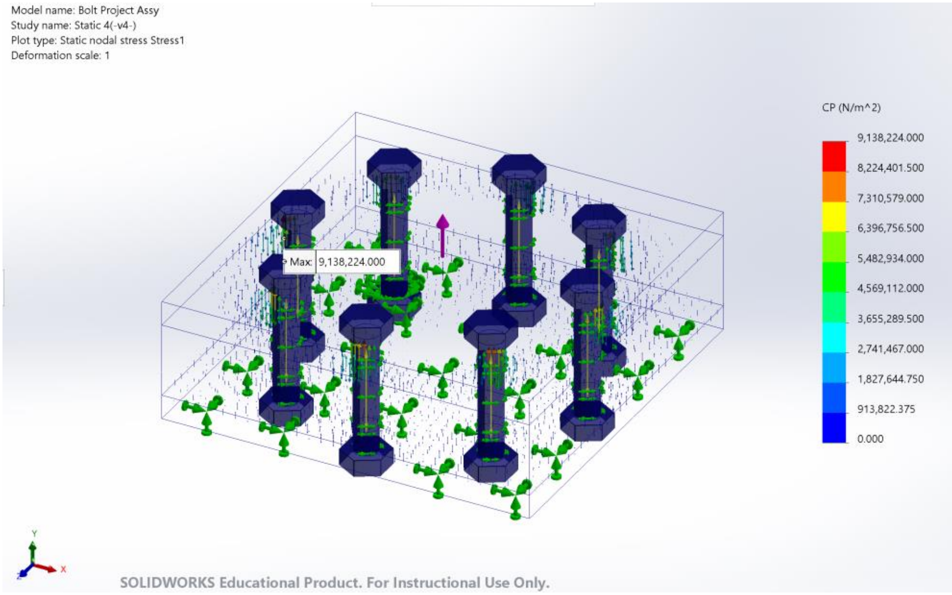


Table 3. Maximum Stress in Plates

Plate	Max Stress (N/m^2)
Aluminum Top	1.70 e8
Steel Mid	8.01 e6
Aluminum Bot	1.27 e6

Bolts Factor of Safety

The safety factor for each bolt is displayed in Table 4. The safety factor for each bolt is larger than the required 1.5.

Table 4. Factor of Safety Per Bolt

Bolt Number	Factor of Safety

1	13.97
2	13.76
3	13.89
4	13.84
5	13.86
6	14.04
7	13.90
8	13.91

Factory of Safety of Plates

The minimum factor of safety is conveyed for each plate in Table 5. The smallest factor of safety was in the top aluminum plate with a value of 1.743.

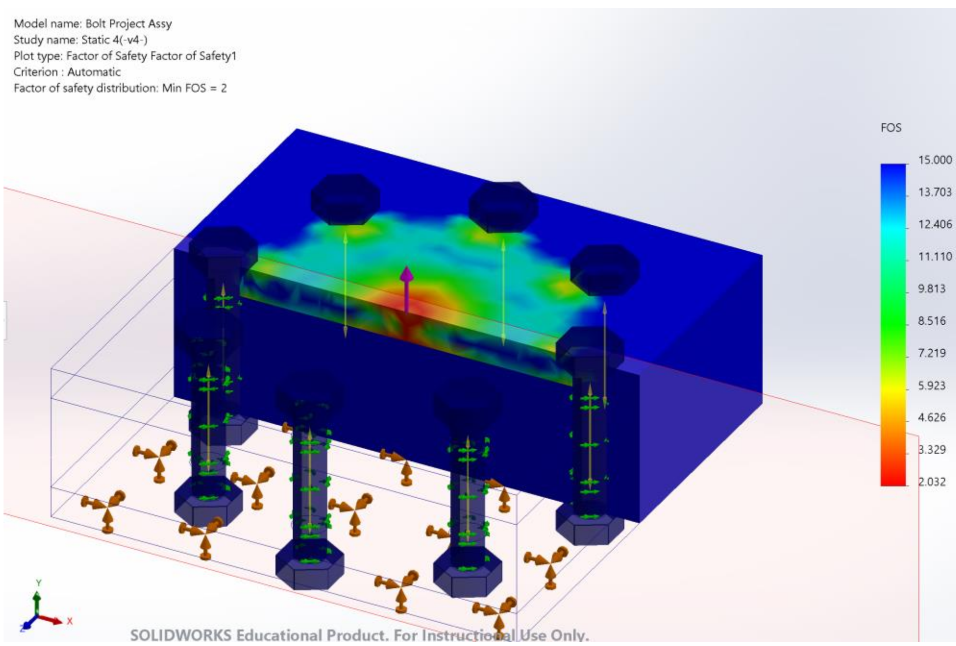


Table 5. Factor of Safety per Bolt

Plate	Factor of Safety
Aluminum Top	2.032
Steel Mid	43.41
Aluminum Bot	271.2

Bolts Theory

The following equations were used to compute the theoretical c-factor, axial, and the factor of safety for the bolts. First the length of the threaded portion of the bolt was computed:

$$l_d = L - L_T$$

Where Ld is the unthreaded portion of grip, L is the entire length of the bolt, and Lt is the length of the threaded portion of the bolt. In this project, the bolts selected were all fully threaded.

The length of the threaded portion of the bolt is found by equation:

$$l_t = l - l_d$$

Where Lt is the threaded portion in grip.

Next the area of the unthreaded portion, Ad, is computed:

$$A_d = \frac{\pi d_d^2}{4}$$

Where d_d is the diameter of the unthreaded portion.

The fastener stiffness, kb, is solved through the equation:

$$K_b = \frac{A_d A_t E}{A_d l_t + A_t l_d}$$

Where E is the tensile strength of the bolt and At is found through table 8-1 of Shigley's Mechanical Engineering Design.

The member stiffness, Km, with consideration of the frusta is computed with equations:

$$K_m = \frac{0.5774\pi E d}{2\ln\left(5\frac{0.5774l + 0.5d}{0.5774l + 2.5d}\right)}$$

Where E is the tensile strength of the member, l is the thickness of the member, and d is the diameter of the hole within the member.

The total member stiffness, Km_total, is calculated considering the members are in parallel. The equation used is the following:

$$K_{m_{total}} = \left(\frac{1}{k_{m1}} + \frac{1}{k_{m2}} + \frac{1}{k_{m3}}\right)^{-1}$$

The fraction of external load P carried by the bolt, C, is calculated as:

$$C = \frac{K_b}{K_b + K_m}$$

The factor of safety, np, is calculated through equation:

$$n_p = \frac{S_p A_t}{C\left(\frac{P_{total}}{N}\right) + F_i}$$

Where Sp is the proof strength of the bolt, Fi is the preload of the bolt, Ptotal is the total external tensile load applied to the joint, and N is the number of bolts.

The results for the selected bolts and plates assembly are displayed in Table 6.

Table 6. Results of Bolt Theoretical Calculations

np	17.869
Fb (N)	2461.77
C	0.17

Discussion

Various Designs Considered

Before the final design was selected, two additional iterations were explored. Table 7 displays the iteration considered, geometries, bolt selection and reason for failure. With smaller bolts the observation was that the c-value was higher than the constraint. For larger bolts, the resultant c-value was closer to what was acceptable. The number of bolts had the greatest influence on the factor of safety of the bolts.

Table 7. Bolt Assembly Iterations

Iteration No.	Plate WxL (in)	Bolt size (mm)	Thread Pitch (thread/mm)	Qty Bolts	Pattern
1	6 x 6	10	1.5	4	Square corners
2	6 x 6	20	2.5	4	Square corners
3	6 x 6	10	1.5	8	Square corners and midpoints
4	6 x 6	10	1.5	8	Circle

Another design criteria for the bolt and plate assembly was that it must have realistic dimensions. To ensure the selected bolts were realistic, a “Medium-Strength Class 8.8 Steel Hex Head Screw” was found on McMaster Carr. As only 10 bolts were needed, the market price of $10.46 (per qty of 10) for the bolts shows that the option is viable.

Comparison of Theory and SolidWorks

The results between the theoretical values and the SolidWorks values are shown in Table 8. The percentage error between the theoretical and SolidWorks for C-value was qutie high. The stiffness value for each member was solved separately to account for each frustrum in the joint. The alpha value or apex angle of the frustra is used as 30 degrees. The graph in figure 2 depicts a dimensionless plot of the stiffness versus aspect ratio of the members. The source of this plot is Shigley’s Mechanical Engineering Design Textbook figure 8-16. The plot displays the relative accuracy of each method in comparison to finite element analysis. The Mischke 30-degree method was used to output the theoretical results for the bolt assembly. In reference to the graph this method has a lower accuracy in computing the frustra in comparison to the FEA method. Thus, the source of uncertainty lies in the computation of the frustra for each member.

When iterating bolt choices and hole patterns in Solidworks simulation, a significant take away was that the number of bolts had a larger effect on C-factor than the dimension of the bolts. After the number of bolts, the geometry of the pattern came into play. It could be seen in the 3rd iteration that bolts nearer to the external load took on a greater axial load, and subsequently had a higher C-factor. During the next iteration, the bolts were placed equidistant from the external load and the bolts had uniform axial loads. The technique used for theoretical C-factor calculations did not account for hole pattern or external loading. These topics must be a factor in the overall loading of the bolts which shows another discrepancy between the methods of designing bolts.

Table 8. Comparison of Theory with SolidWorks

Variable	Theoretical Value	SolidWorks Value	% Difference
np	17.869	13.9	-22.2 %
Fb (N)	2461.77	2637.9	7.2 %
C	0.17	0.264	55.8 %

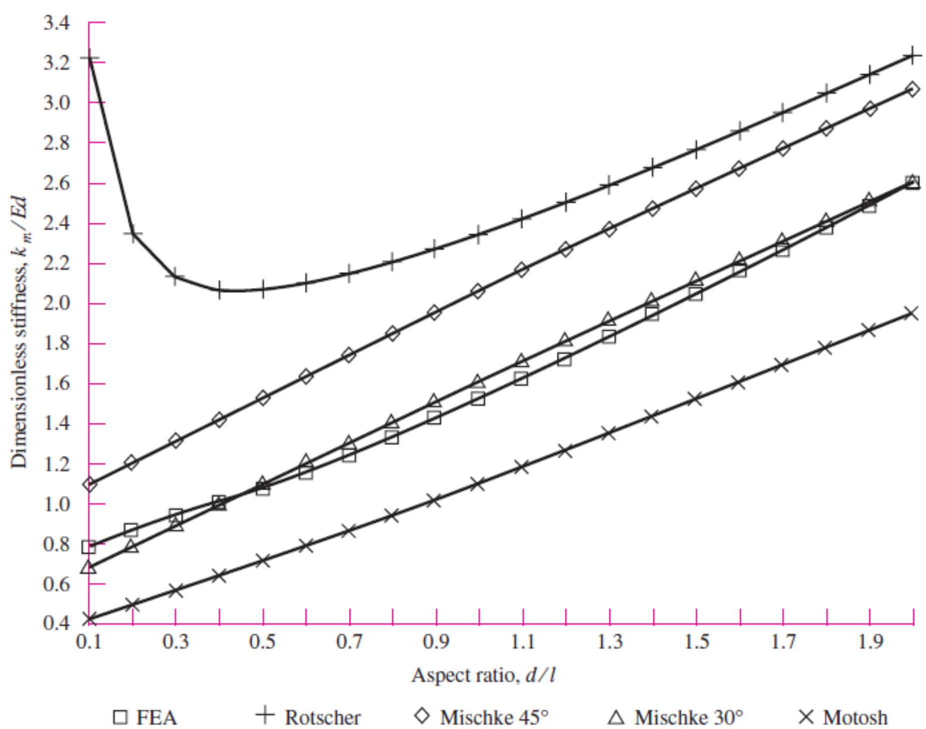


Figure 2. Dimensionless Plot of Stiffness versus Aspect Ratio for Each Method

Summary

Overall, the bolt assembly with 6 x 6 plate size and 10mm bolts in a circular pattern upheld the geometric design constraints of a c-factor between 0.2 and 0.3 and factor of safety greater than 1.5. The theoretical calculations were computed in excel to evaluate the bolt with the given loads and material factors of the plates. As the bolt simulations took an extended period of time to run, the theoretical calculations were used to predict the results of the simulation. However, there was a significant difference between the theoretical c-value and the c-value computed by FEA. It was determined that the greatest source of uncertainty was likely from the computation of the member stiffness of frustrum. Per table 2, the results from the simulation were determined as more trustworthy and the final design was determined based on these results. Realistic bolt sizes were determined by finding the bolts to purchase online through McMaster Carr. To conclude, the project displayed multiple processes to design a bolt and multiple plate assembly through SolidWorks and theoretical calculations to ensure that the bolts do not fail. To support both the SolidWorks and Theoretical calculations physical testing should be implemented to support design decisions.

Appendix

Image of Excel for Theoretical Calculations

Givens				
N (# of bolts)	8			
Clamping force [KN]	18	18000		
External load [KN]	10	10000		
S_p	400	7.58E+08		
C factor	must be between 0.2 - 0.3			
Factor of Safety	must be atleast 1.5			
Fasteners				
E_bolt [GPa]	210	2.1E+11	Pa	
Threaded Portion			**Nominal Size**	
d_M [mm]	10		M10 x 70mm	
d_m [mm]				
A_t [mm^2]	58	0.000058	m^2	from table 8-1
l_t [mm]	50	0.05	m	
A_d [mm^2]	78.53982	7.85E-05	m^2	
Plates				
Aluminum Plates				
Thickness [mm]	10	0.01		
E [GPa]	72.4	7.24E+10		
d [mm]	11	0.011		
l (m)	6 in			
Steel Plate				
Thickness [mm]	30	0.03		
E [GPa]	200	2E+11		
d [mm]	11	0.011		

F_i [KN]	2.25	2250	
P [KN]	1.25	1250	
K_b	243600000		
K_m	1194312538.94	do it per the material and take the reciprocal	
C	0.169	Say that the frustrum is a source of error	
n_p	17.87		
Fb	2461.765314	N	

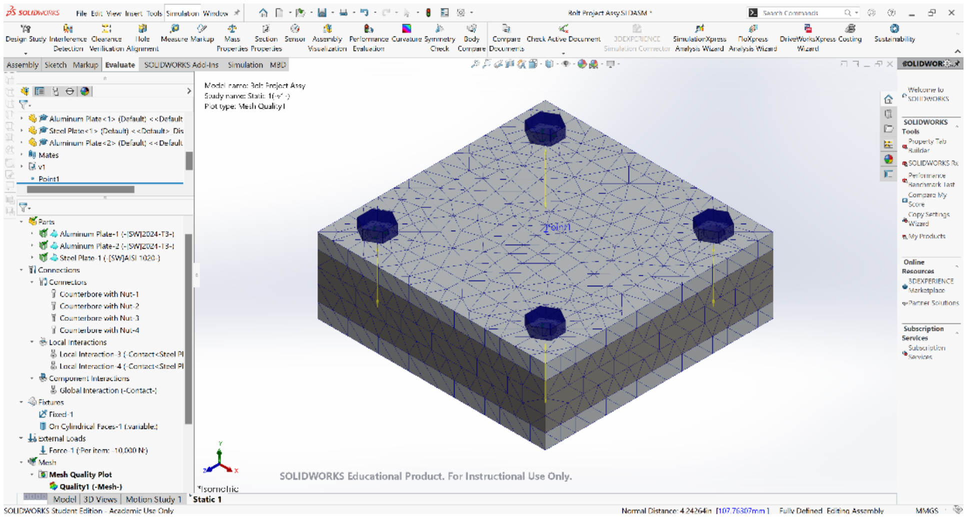
np=(Sp*At)/(C*P+Fi)

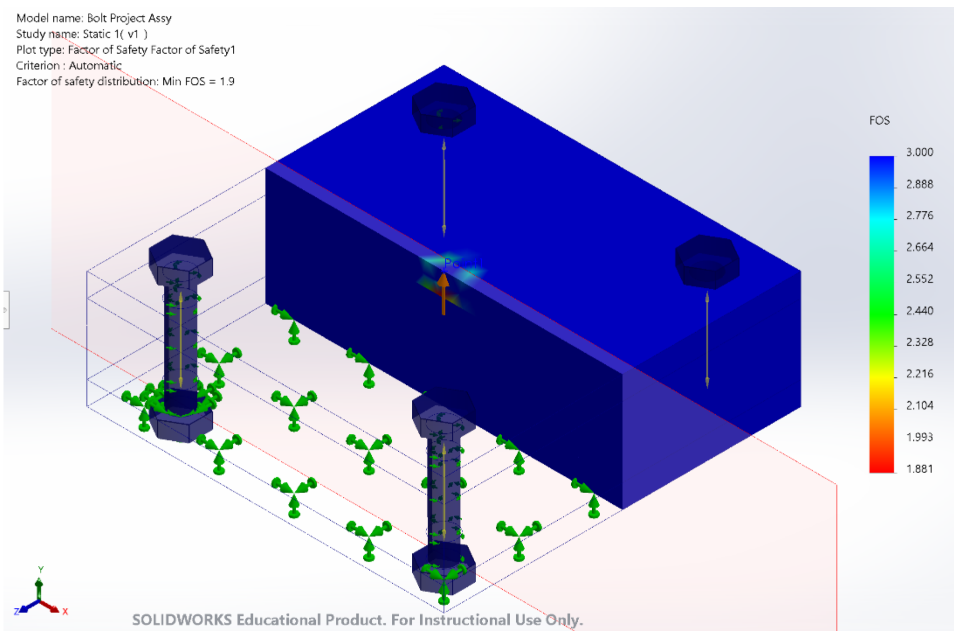
Km_Al	3155008225
Km_St	4916686774
Km_recip	8.37302E-10
Km_total	1194312538.94

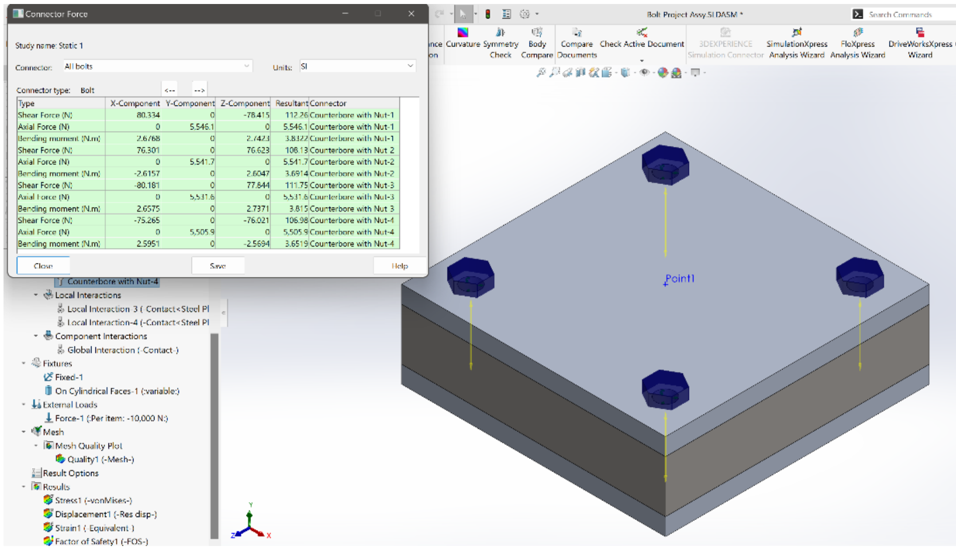
Km_total = (1/Km_Al1 + 1/Km_St + 1/Km_Al2)^-1

Variable	Theoretical Value	SolidWorks Value	% Difference
np	17.869	13.9	-22.2 %
Fb (N)	2461.77	2637.9	7.2 %
C	0.17	0.264	55.8 %

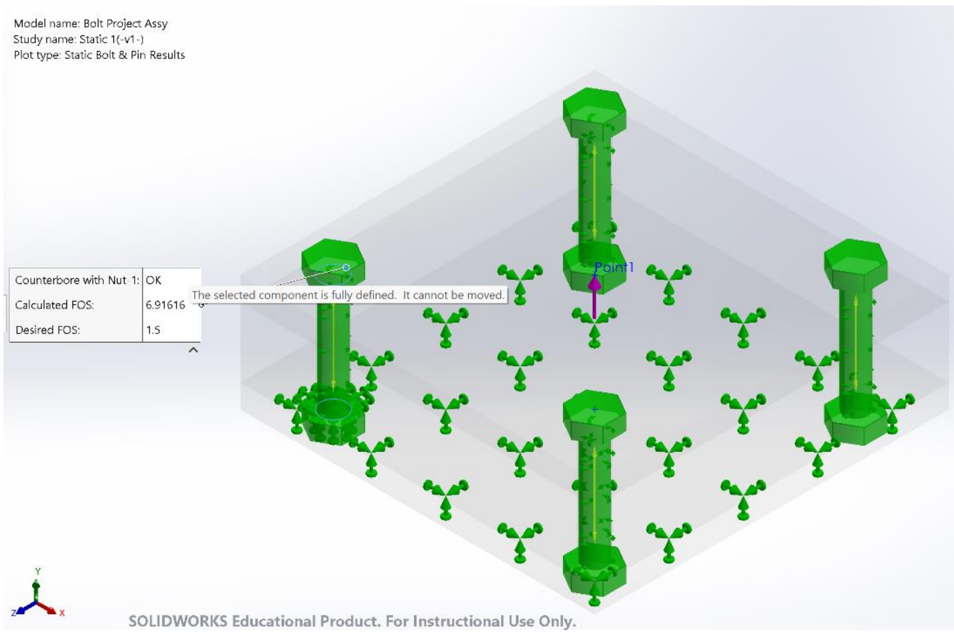
Image of Plots from a Testing Iteration

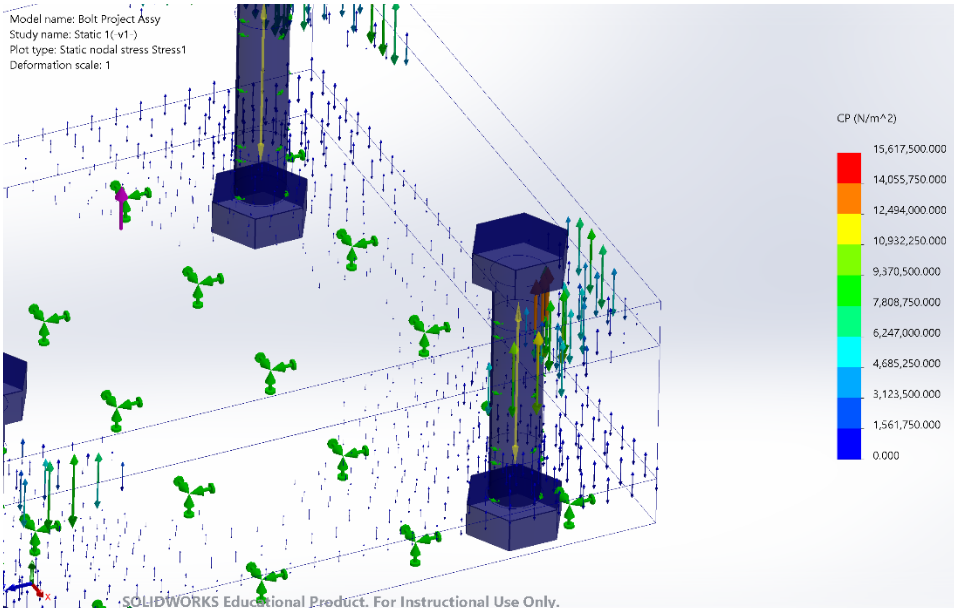






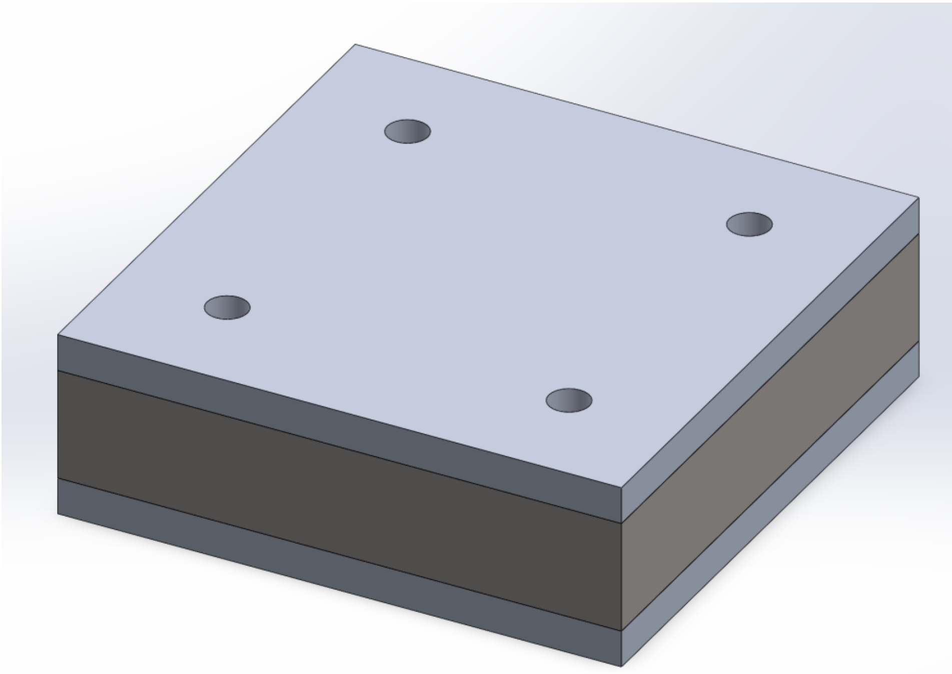
Type	X-Component	Y-Component	Z-Component	Resultant	Connector
Shear Force (N)	80.334	0	-78.415	112.26	Counterbore with Nut-1
Axial Force (N)	0	5,546.1	0	5,546.1	Counterbore with Nut-1
Bending moment (N.m)	2.6768	0	2.7423	3.8322	Counterbore with Nut-1
Shear Force (N)	76.301	0	76.623	108.13	Counterbore with Nut-2
Axial Force (N)	0	5,541.7	0	5,541.7	Counterbore with Nut-2
Bending moment (N.m)	-2.6157	0	2.6047	3.6914	Counterbore with Nut-2
Shear Force (N)	-80.181	0	77.844	111.75	Counterbore with Nut-3
Axial Force (N)	0	5,531.6	0	5,531.6	Counterbore with Nut-3
Bending moment (N.m)	2.6575	0	2.7371	3.815	Counterbore with Nut-3
Shear Force (N)	-75.265	0	-76.021	106.98	Counterbore with Nut-4
Axial Force (N)	0	5,505.9	0	5,505.9	Counterbore with Nut-4
Bending moment (N.m)	2.5951	0	-2.5694	3.6519	Counterbore with Nut-4

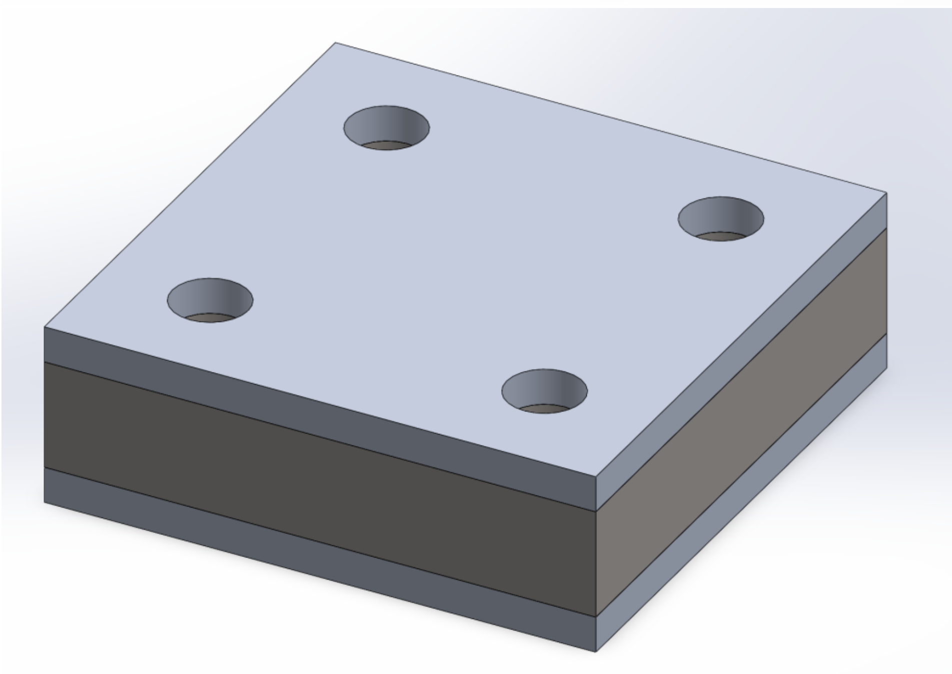


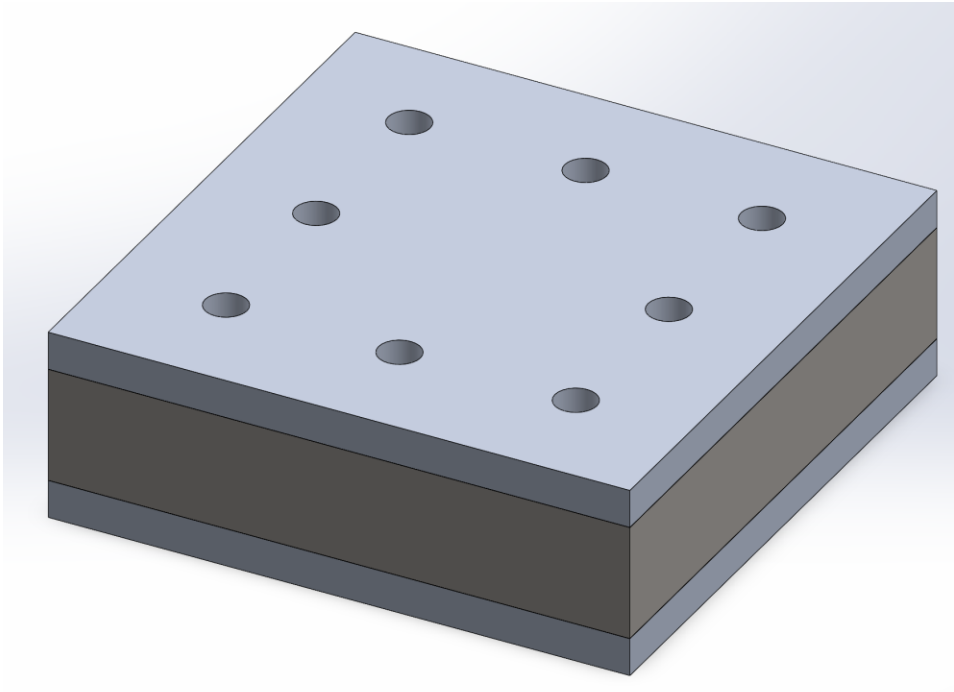


Model name: Bolt Project Assy
Study name: Static 1(-v1-)
Plot type: Static nodal stress Stress1
Deformation scale: 1
CP (N/m^2)
15,617,500.000
14,055,750.000
12,494,000.000
10,932,250.000
9,370,500.000
7,808,750.000
6,247,000.000
4,685,250.000
3,123,500.000
1,561,750.000
0.000
SOLIDWORKS Educational Product. For Instructional Use Only.

Iterations 1 through 4 in Order







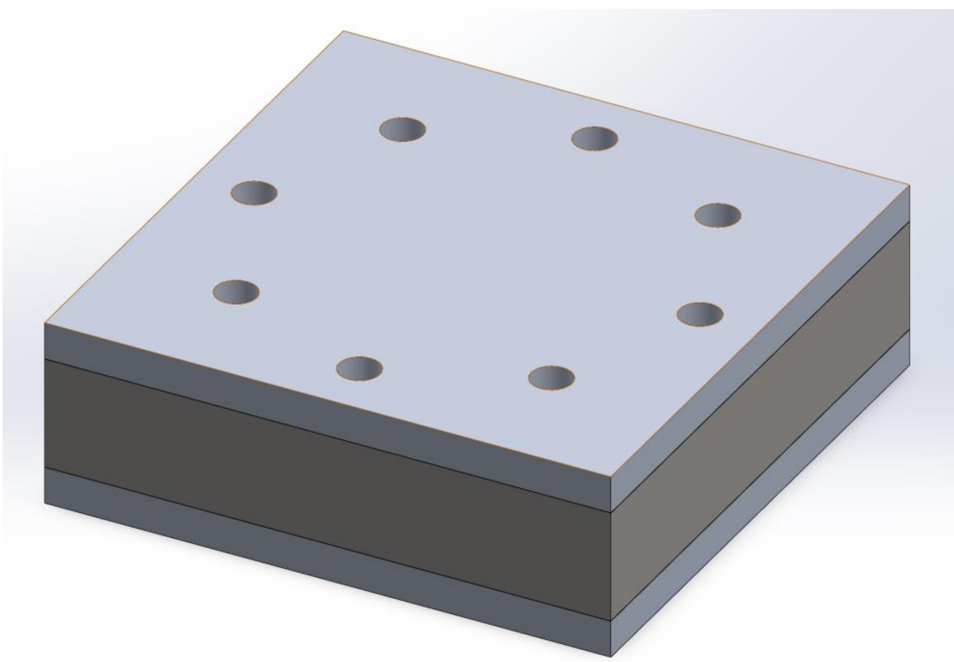


Image of Mcmaster Carr Bolts Used for Dimensions