

University of Pittsburgh
Swanson School of Engineering

Mechanical Design II
Professor Stephen Ludwick

Design Project #3
**Pressure Vessel Bolted
Joint**

June 9, 2011

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1. Project Definition

The goal of this project is to design analyze a bolted joint used to attach a flange/head to a cylinder pressure vessel. The pressurized cylinder is made to be made of cast iron and the cylinder head is to be made of low-carbon steel. The vessel is to hold a static pressure of 5MPa. Determination of a proper size, grade, number of bolts, and torque specification is to be determined to give a factor of safety of at least 3. Cost should also be kept in mind as well as ability to assemble this vessel. Along with choosing a sufficiently strong bolt, washers and nuts must also be selected.

2. Functional Requirements

1. Must withstand an internal pressure of 5MPa
2. Factor of safety of at least 3
3. Joint constant less than 1 (preferably around 0.2)
4. Ability to assemble using a torque wrench
5. Cast-Iron member
6. Low-Carbon-steel cylinder head
7. Diameter of bolt circle of 150mm

3. Parts Specification

The parts for this project were selected from McMaster-CARR's online catalogue of parts. Initially, the bolt length was determined and an initial guess of bolt diameter (0.5") was used to find a bolt. The bolt chosen was heavy hex head steel ASTM A193 Grade B7. The bolt is a 1/2"-13 2" bolt with 1 1/4" of thread. Recommended by Mc-Master CARR, a nut of the same material was selected. The nut is a 1/2"-13 with a height of 31/64". Also recommended by McMaster-CARR was a steel ASTM F436, Type 1 washer with variable height from .09"-0.18" with a bore diameter of 17/32". The dimensions of the cylinder and cylinder head were determined to meet the bolt circle diameter requirement and to meet the assembly requirement. For parts list and costs see *Appendix B*.

4. Material Selection and Design Specifications

For most parts, the materials were given. The cylinder head, bolts, nuts, and washers are all steel. The cylinder head is a low-carbon-steel (AISI 1020). The bolts and nuts are ASTM A193 Grade B7 steel (typically high strength carbon alloy steel; AISI 4140/4142 quenched and tempered).

The washers are ASTM F436, Type 1 steel (hardened plain steel). The vessel was chosen to be Grade 25 Cast-Iron.

5. Calculations

See *Appendix A*. Calculations were first made to determine the length of bolt needed, and then to determine the thread length on those bolts. Next, the bolt stiffness was calculated. Then, the member stiffness was calculated using pressure cones formed by a 30° angle from the surface of the bolt. Four pressure zones were needed to perform this calculation. Once the bolt and member stiffness's were calculated, the bolt constant was determined. We also needed to calculate the loads on the bolts and from the internal pressure. Finally, the number of bolts necessary to have a safety of 3 and to withstand the bolt load was determined. Also, the number of bolts necessary to have a safety factor of 3 and to prevent separation was calculated. The higher of the two bolt numbers was chosen and factors of safety were recalculated. With the number of bolts required now determined, we can establish the pattern for tightening the bolts. The bolts should be all torqued to 50% the final torque, then 75%, then 90%, then 100%, making sure to follow the assigned pattern each time. From *Figure 6* we can see that there is sufficient area around the bolts and between the bolts and the cylinder to use a torque wrench to install the parts; provided the average diameter of a 7/8" socket is 1.3125". See *Appendix C* for Excel worksheet and more detailed calculation values.

6. CAD

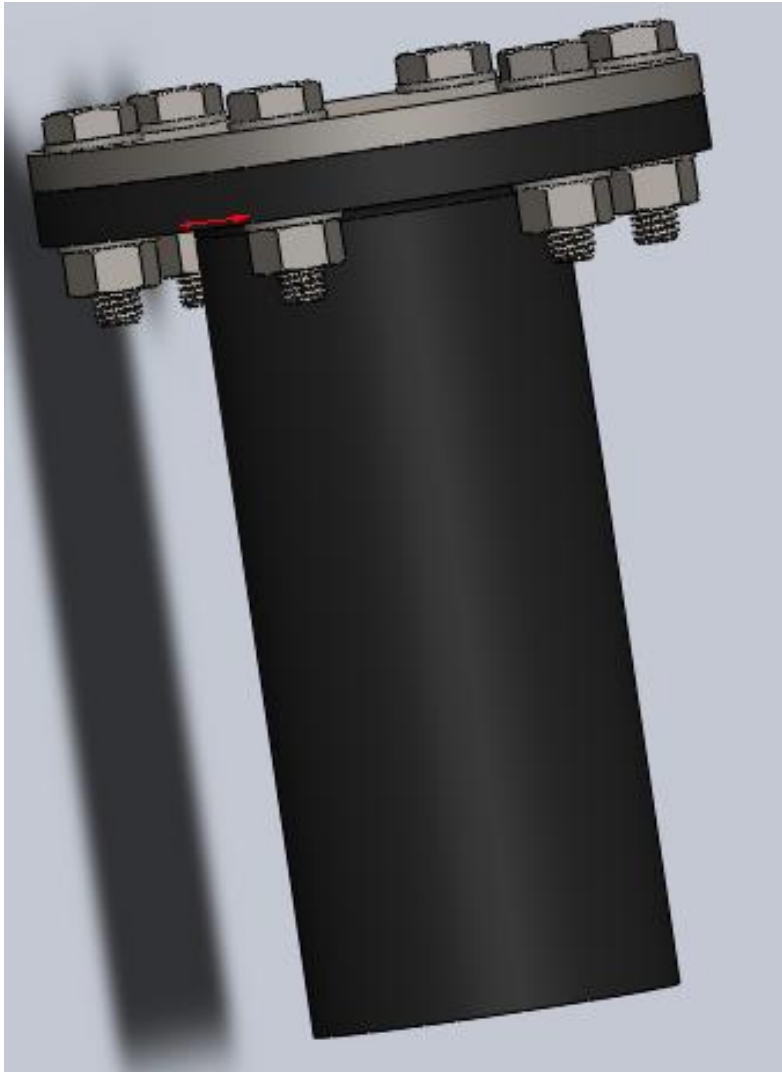


Figure 1. Assembled view

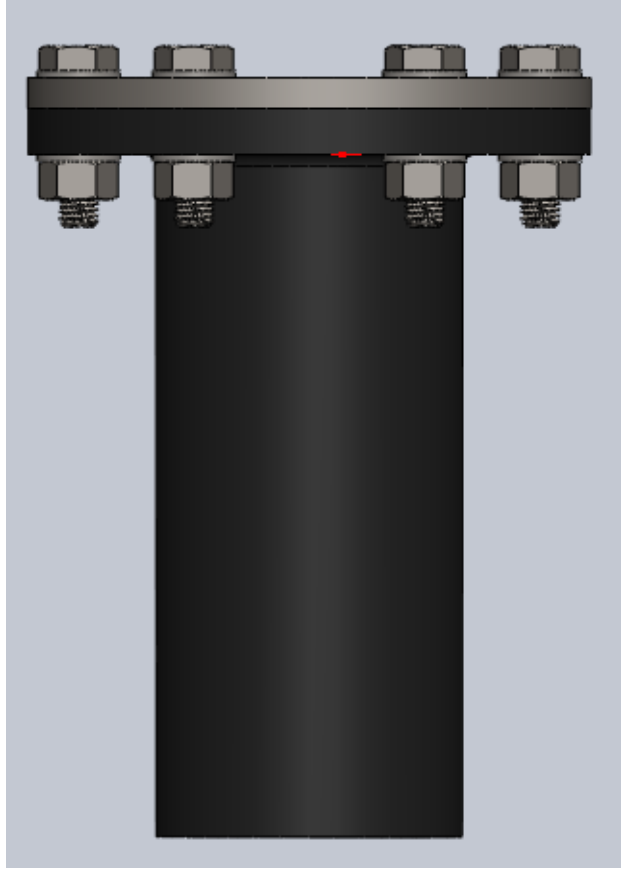


Figure 2. Assemble side view

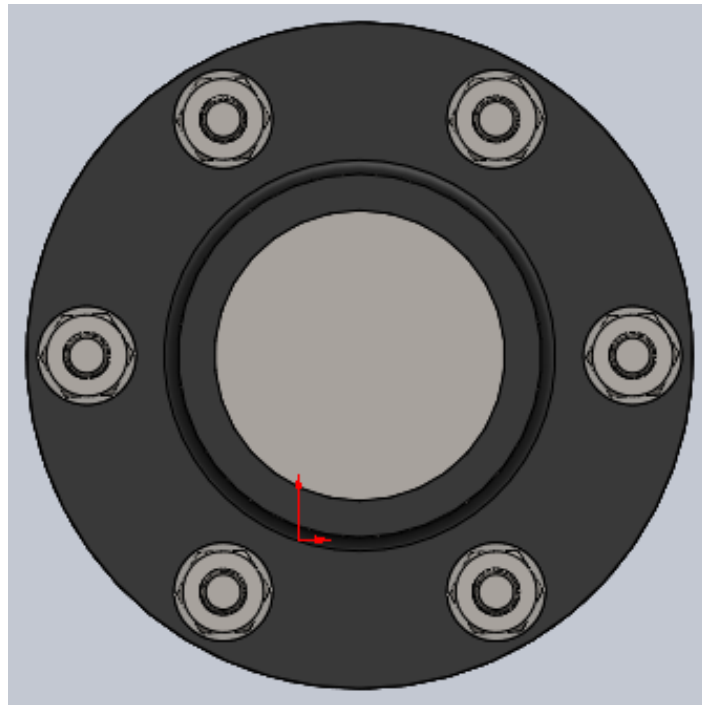


Figure 3. Assembled top view

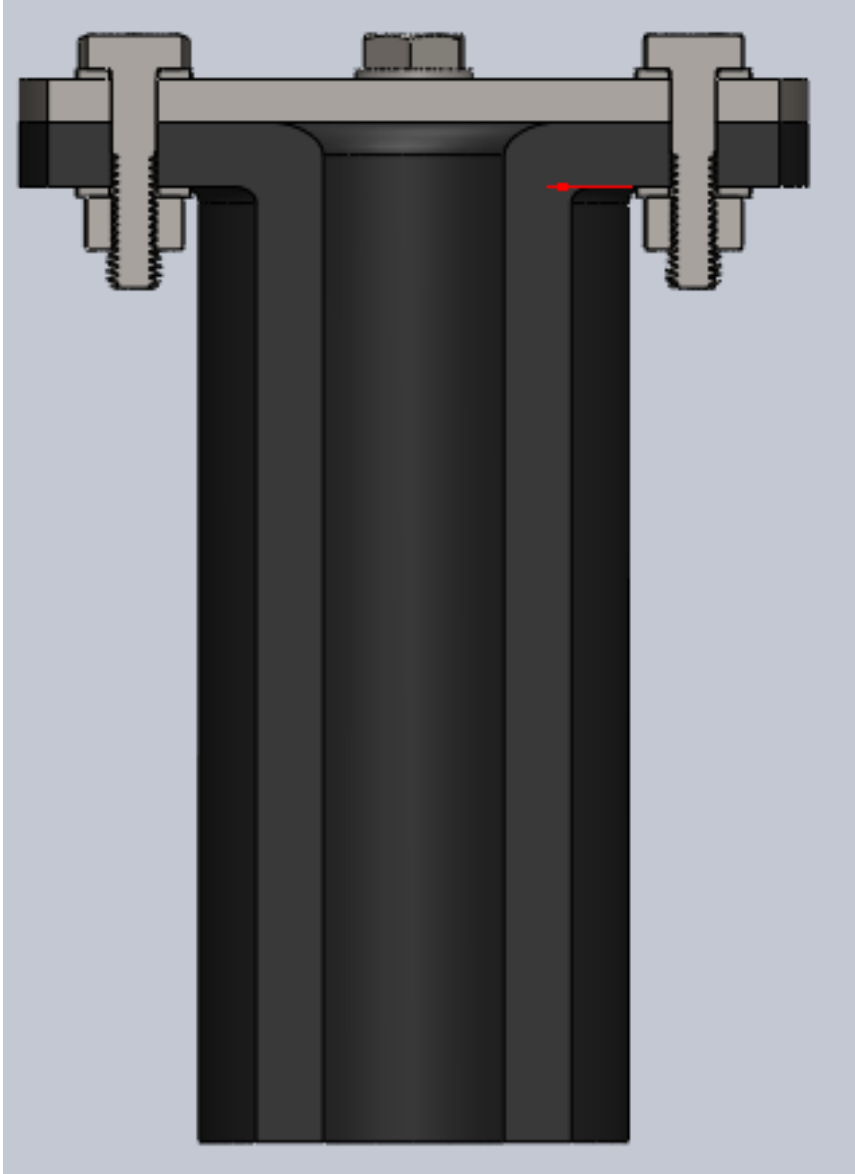


Figure 4. Sectioned view showing fileted cylinder and cut-out of bolt/washer/nut assembly

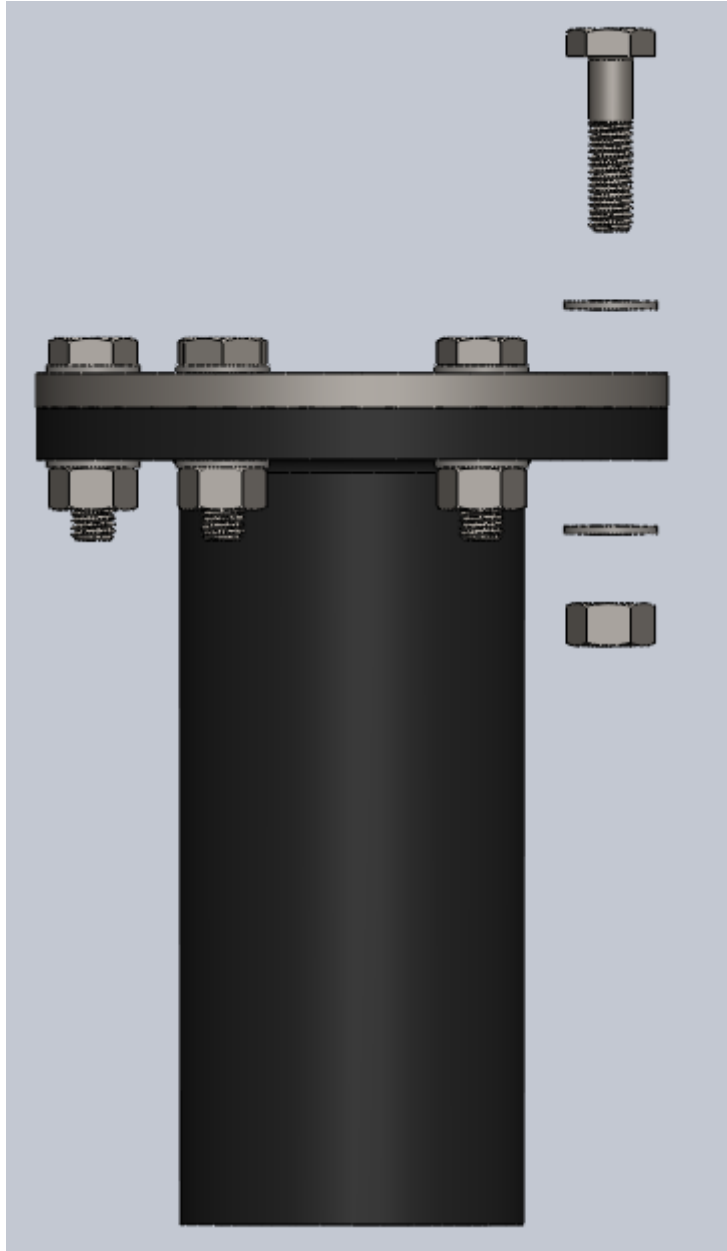


Figure 5. Exploded view of one bolt

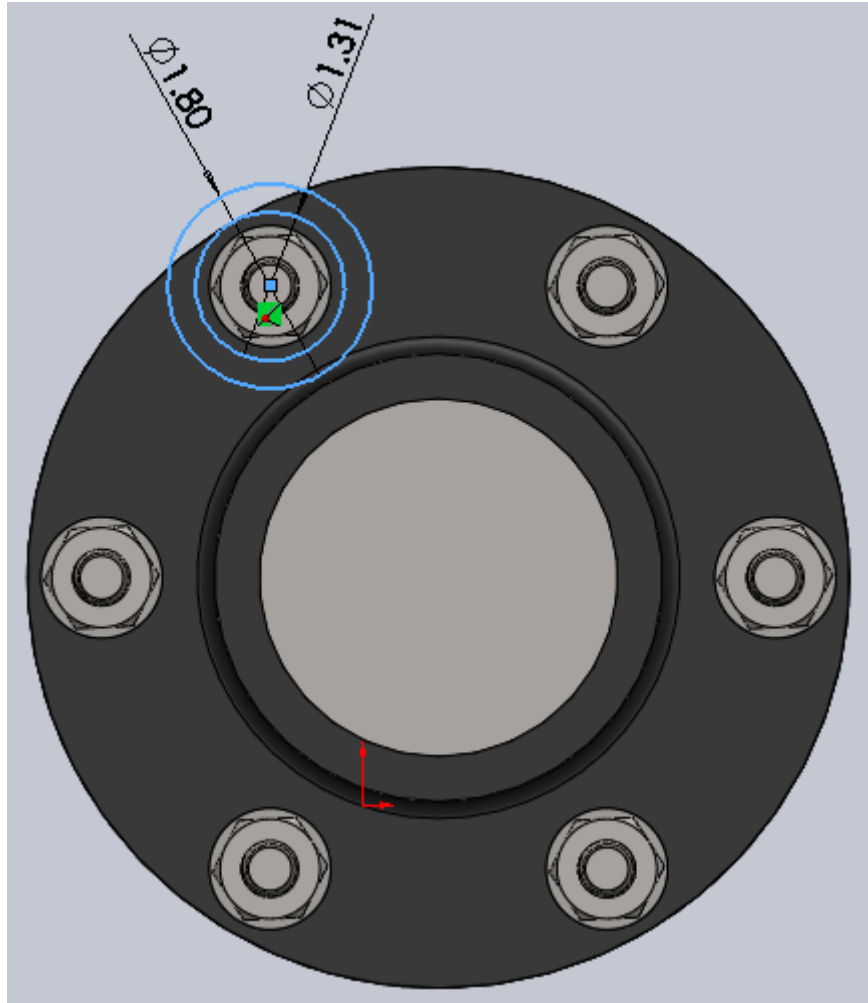


Figure 6. Showing the dimensions of a socket/wrench compared to the assembly geometry

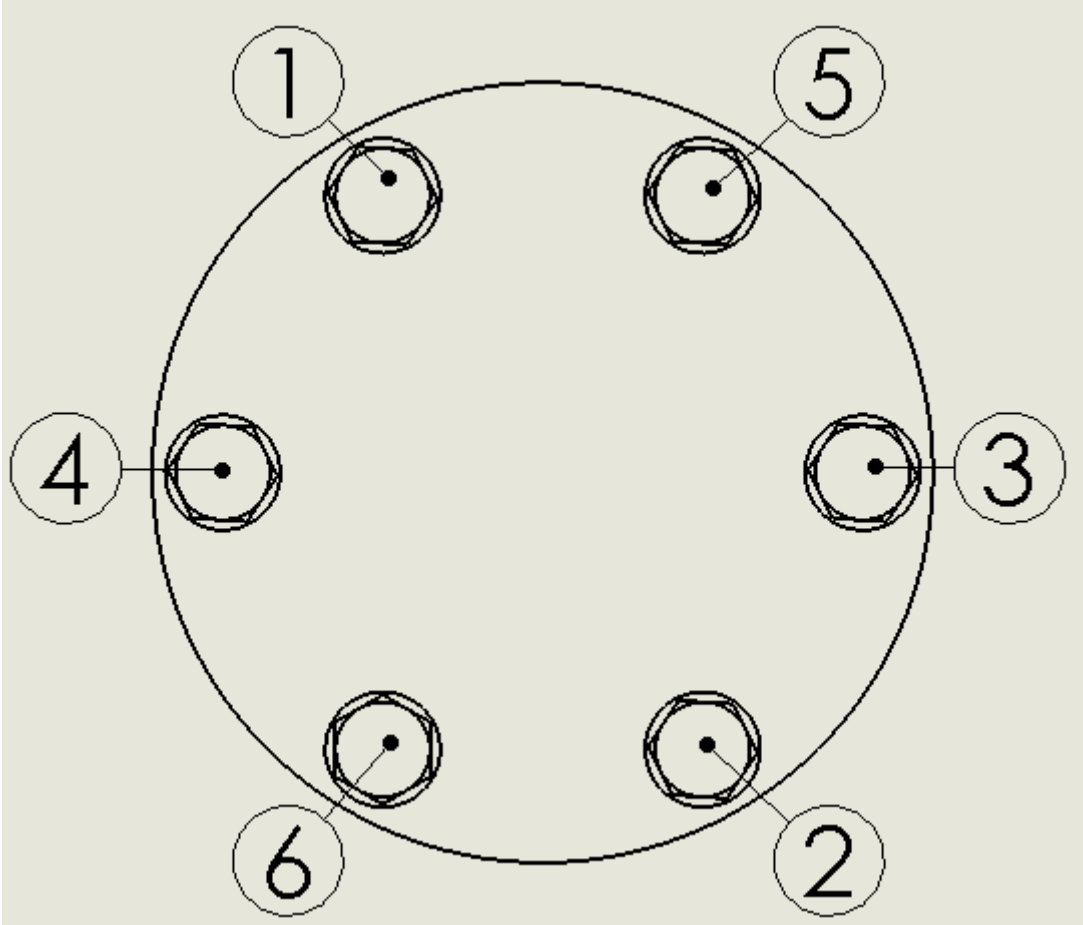


Figure 7. Proper torquing sequence

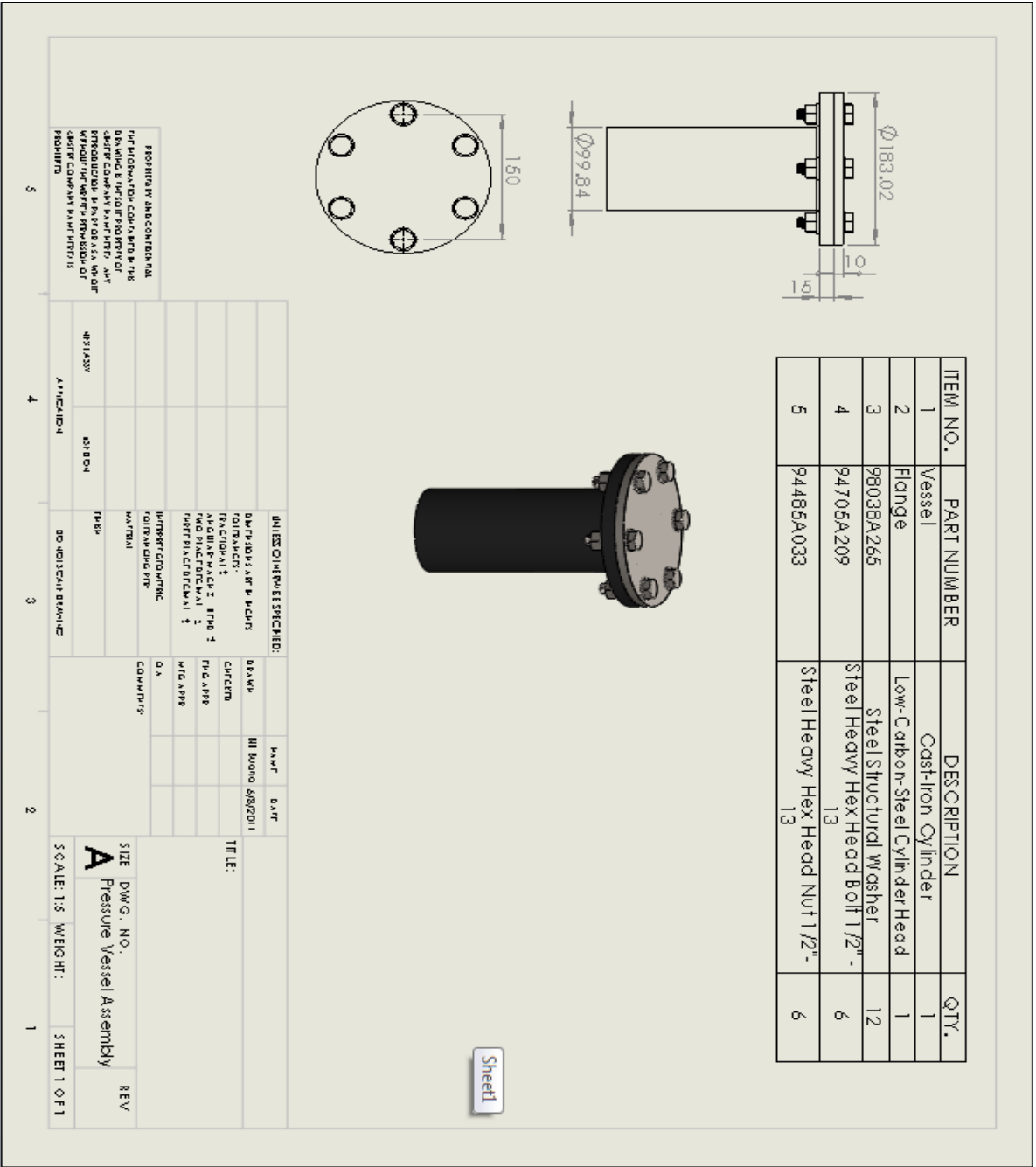


Figure 8. Drawing of assembly

7. Finite Element Analysis

Finite Element Analysis was performed for the bolted joint region of the pressurized cylinder using ANSYS WorkBench. In order to simplify the calculation, symmetry was created for the entire assembly to only analyze one bolt. The structural analysis was done in a three step process. 1) The base of the cylinder was rigidly supported 2) the bolt pretension was applied 3) an internal pressure of 1/6 the total internal pressure was applied while retaining the two previous forces. As seen from *Figure 9* the cylinder head remained in contact with the vessel, as we expected from our calculation of the separation factor of safety. In *Figure 10* we can see the equivalent (von-Mises) stress. As expected from our calculations the greatest stress is felt by the nut. Seen in *Figure 11* the factor of safety for the bolt had a wide range. The majority of the bolt has a very high factor of safety, as was expected from the hand calculations. There are however, areas of the bolt with a very poor factor of safety. My explanation for this result is that this must be a result of creating the symmetry part and the lack of support. I was unable to determine how to correct this without analyzing the entire vessel in WorkBench, which would require a large amount of time and computer resources. *Figure 12* shows the total deformation of the assembly. There is kind of a pressure cone present as we would expect. The greatest deformation is at the corners of the flange and cylinder. According to the process we took to create the symmetry, ANSYS should assume a duplicate piece as what is shown is connected to each side. I cannot explain why the deformation is greatest at the points other than the fact that ANSYS is not accounting for the other pieces of the cylindrical vessel as deformation should not be present at those places.

8. Conclusion

In concluding this design and analysis of a bolted joint used in pressure vessel application, we can look at many aspects. The cost of our design was fairly cheap. Also, the ability to assemble our design is easy and straightforward using well established techniques. Analysis of our parts/design resulted in a sufficient factor of safety (4.63 against load factor and 3.5 against joint separation). Upon analysis of the bolts in ANSYS WorkBench, we saw similar results for the majority of the bolt/member, but had a strange and very low factor of safety in small areas of the bolt where it attaches to the nut. Explanation for this was done in the Finite Element Analysis

Section. In conclusion, a satisfactory bolted joint has been designed which meets the design requirements outlined previously.

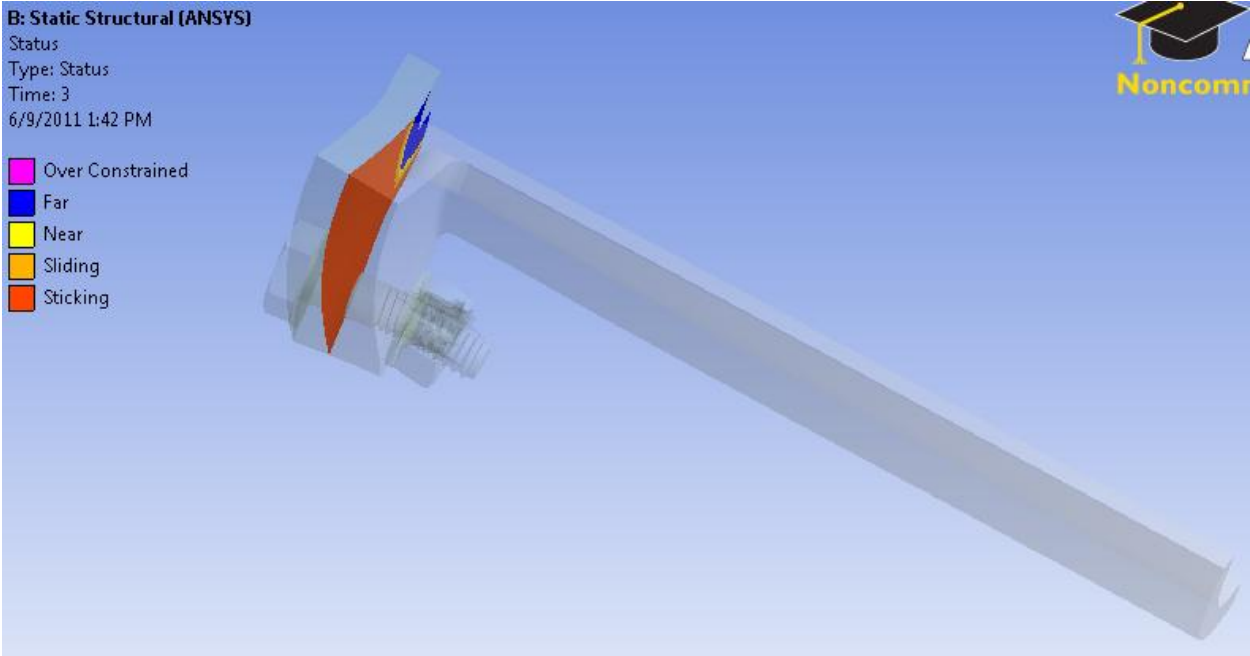


Figure 9. Surface contact between cylinder and cylinder head

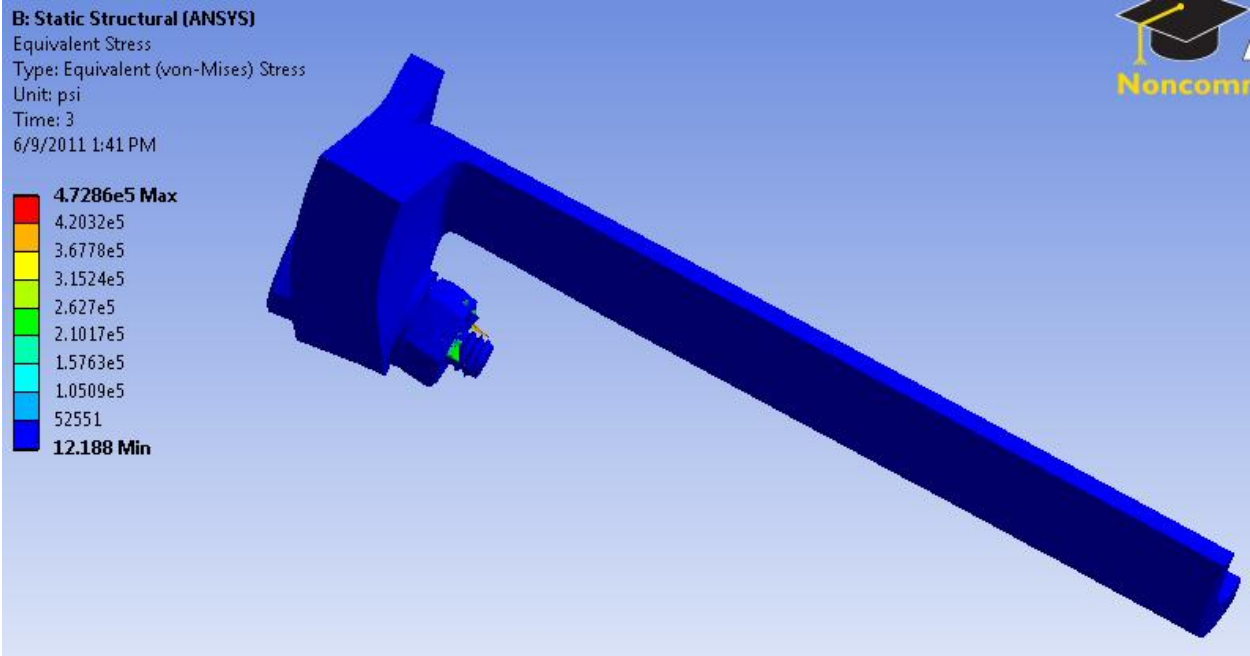


Figure 10. Equivalent (von-Mises) Stress

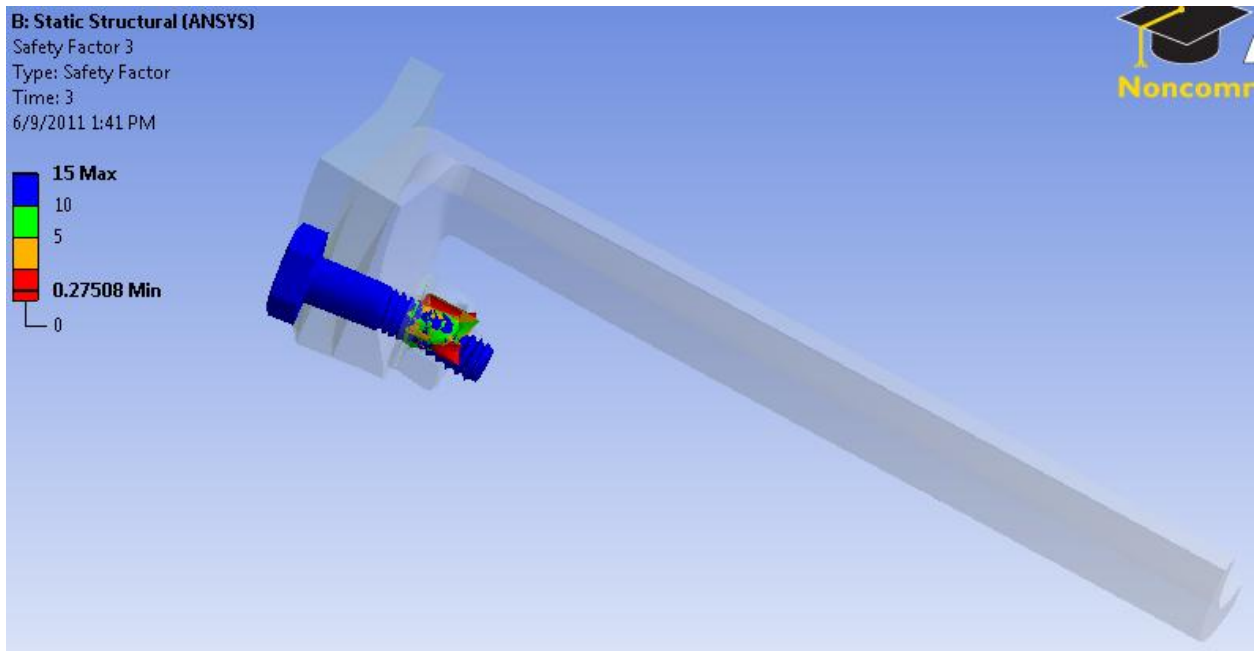


Figure 11. Bolt Safety Factor

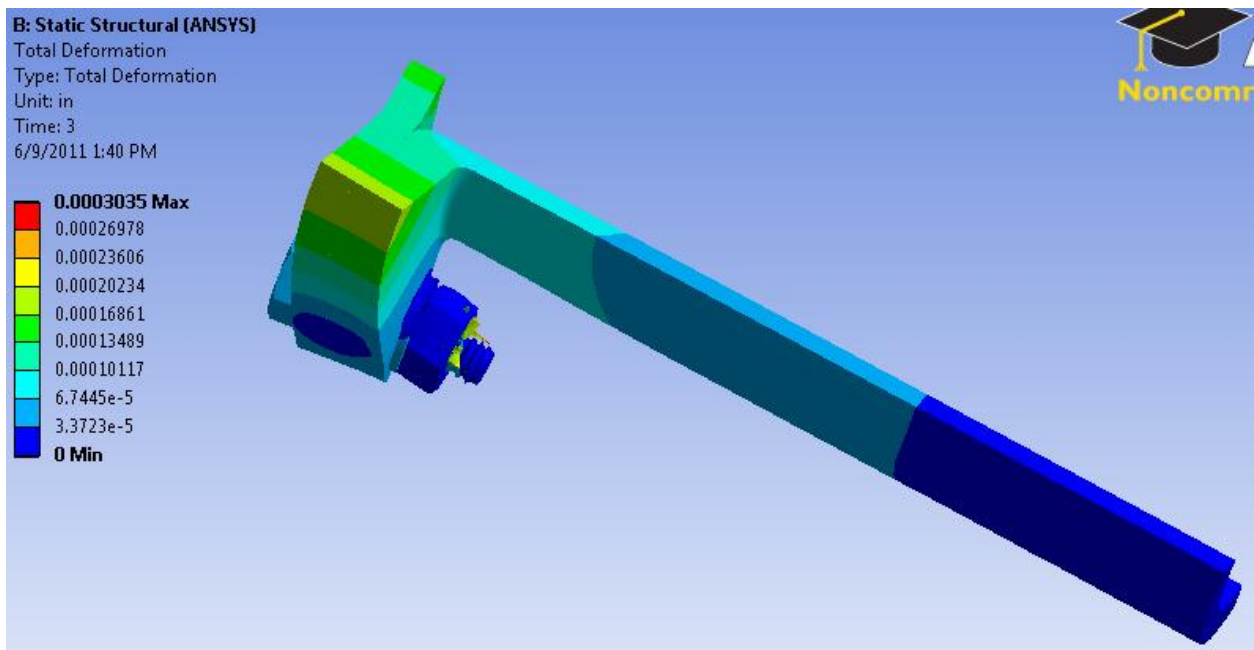


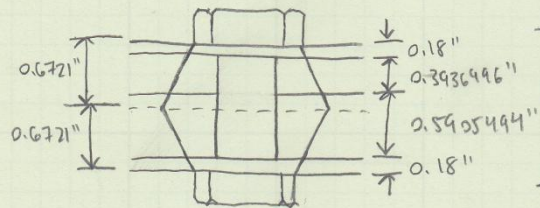
Figure 12. Total Deformation

Appendix A

Steel: $E = 30.02 \times 10^6 \text{ Psi} = 207 \text{ GPa}$

Grade 25 Cast-Iron: $E = 14 \times 10^6 \text{ Psi}$

Bolt Dimensions



$$\left. \begin{array}{l} 0.18'' \\ 0.3936996'' \\ 0.25905494'' \\ 0.18'' \end{array} \right\} l = 1.3442''$$

bolt height = $\frac{7}{16}''$
 + 2 thread length = $\frac{2}{13}''$

$$L = \frac{7}{16} + 1.35 + \frac{2}{13} = 1.95'' = 2'' \text{ Bolt}$$

$$L_T = 2d + \frac{1}{4} = 2\left(\frac{1}{2}\right) + \frac{1}{4} = 1.25'' \text{ (Eq. 8-17)}$$

$$l_0 = 2'' - 1.25'' = 0.75''$$

$$l_t = l - l_0 = 1.3442 - 0.75 = 0.5942''$$

Bolt Stiffness

$$\frac{1}{k_b} = \frac{l_0}{EA_s} + \frac{l_t}{EA_t}$$

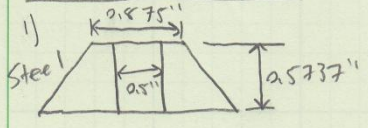
$$A_t = 0.1419 \text{ in}^2$$

$$A_s = \frac{\pi(0.5)^2}{4} = 0.19635 \text{ in}^2$$

$$k_b = \frac{A_s A_t E}{A_s l_t + A_t l_0} = \frac{(0.19635)(0.1419)(30.02 \times 10^6)}{(0.19635)(0.5942) + (0.1419)(0.75)} = \boxed{3.747 \frac{\text{Mlbf}}{\text{in}} = K_b}$$

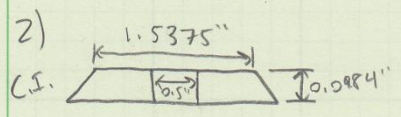
42-281 30 SHEETS EYE-EASE® 5 SQUARES
 42-282 30 SHEETS EYE-EASE® 5 SQUARES
 42-283 200 SHEETS EYE-EASE® 5 SQUARES
 National Brand

Member Stiffness

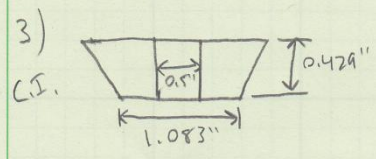


$$k = \frac{(0.5774) \pi E d}{\ln \left[\frac{(1.155t + 0-d)(0+d)}{(1.155t + 0+d)(0-d)} \right]}$$

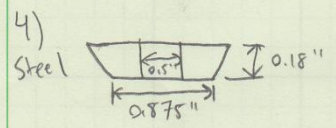
$$K_1 = 43.57 \frac{\text{Mlb}_f}{\text{in}}$$



$$K_2 = 255.5 \frac{\text{Mlb}_f}{\text{in}}$$



$$K_3 = 33.98 \frac{\text{Mlb}_f}{\text{in}}$$



$$K_4 = 9.061 \frac{\text{Mlb}_f}{\text{in}}$$

$$K_m = \left[\frac{1}{43.57} + \frac{1}{255.5} + \frac{1}{33.98} + \frac{1}{9.061} \right]^{-1} = 14.85 \frac{\text{Mlb}_f}{\text{in}} = K_m$$

$$C = \frac{k_b}{k_b + K_m} = \frac{3.747}{3.747 + 14.85} = 0.2014 = C$$

Loading Calculations

$$F_i = 0.75 F_p \quad (\text{Eq. 8-30})$$

$$F_p = S_p A_t \quad (\text{Eq. 8-31})$$

$S_p = 87 \text{ kpsi}$ ← online source

$$F_i = 0.75 (87) (0.1419) = 9.26 \text{ kip}$$

$$T = K F_i d = 0.2 (9260) (0.5) = 926 \text{ lb}_f$$

National Brand
42 SHEETS EYE CASE - 8 SQUARES
42 SHEETS EYE CASE - 8 SQUARES
42 SHEETS EYE CASE - 8 SQUARES

Bolt Load ($n=3$)

$$n = \frac{S_p A_t - F_i}{C(P/N)} \quad (\text{Eq. 8-28})$$

$$\Rightarrow N = \frac{CnP}{S_p A_t - F_i}$$

$$\text{where } P = \frac{F}{A} \Rightarrow F = AP = \frac{\pi (5.905494)^2}{4} (725.1887 \text{ psi})$$

$$F = 19.863 \text{ kip}$$

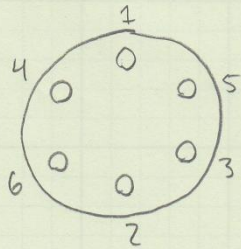
$$N = \frac{(0.2014)(3)(19.863)}{87(0.1419) - 9.26} = 3.89 = 4 \text{ bolts}$$

Separation ($n_0=3$)

$$n_0 = \frac{F_i}{\left(\frac{P}{N}\right)(1-C)} \quad (\text{Eq. 8-29})$$

$$\Rightarrow \frac{P}{N} n_0 = \frac{F_i}{1-C} \Rightarrow N = \frac{(1-C)P n_0}{F_i}$$

$$N = \frac{(1-0.2014)(19.863)(3)}{9.26} = 5.14 = \boxed{6 \text{ bolts}}$$

Tightening Sequence

Appendix B

<u>Retailer</u>	<u>Part #</u>	<u>Description</u>	<u>Cost for 1</u>	<u>Quantity</u>	<u>Total Part Cost</u>
mcmaster.com	94705A209	Grade B7 Alloy Steel Heavy Hex Head Bolt 1/2"-13 Thread, 2" Length	\$2.58	6	\$15.48
mcmaster.com	94485A033	ASTM A194 Grade 7 Alloy Steel Heavy Hex Nut 1/2"-13 Thread Size, 7/8" Width, 31/64" Height, packs of 10	\$6.30/pack of 10	1	\$6.30
mcmaster.com	98038A625	Plain Steel Structural Bolt Washer 1/2" Screw Size, 1-1/16" OD, .09"-.18" Thick, packs of 100	\$9.87/pack of 100	1	\$9.87
				<u>Total Cost:</u>	\$31.65

Works Cited

- [1] Shigley, Joseph Edward., Charles R. Mischke, and Richard G. Budynas. *Mechanical Engineering Design*. New York, NY: McGraw-Hill, 2004. Print.
- [2] "American Fastener - ASTM, SAE, and ISO Grade Markings." *Industrial Fastener Supplier Stainless Steel, Specialty, Standard, and Precision Fasteners*. Web. 09 June 2011. <http://www.americanfastener.com/technical/grade_markings_steel.asp>.
- [3] American Water Works Association, comp. *Steel Pipe: a Guide for Design and Installation*. 4th ed. 2004. *Google Books*. Web. 6 June 2011. <http://books.google.com/books?id=PZjUnOUN928C&pg=PA169&lpg=PA169&dq=ASTM+A193+Grade+B7+proof+load&source=bl&ots=IOS3JtxWzk&sig=AWg0jrg5IwLOvyubp_MMOCwfk0&hl=en&ei=o6DfTeieKuXL0QGpioWSCA&sa=X&oi=book_result&ct=result&resnum=6&ved=0CEIQ6AEwBQ#v=onepage&q=ASTM%20A193%20Grade%20B7%20proof%20load&f=false>.
- [4] "Bolt Torque Chart | Portland Bolt." *Anchor Bolts and Construction Fasteners - Portland Bolt*. Web. 09 June 2011. <<http://www.portlandbolt.com/technicalinformation/bolt-torque-chart.html>>.
- [5] "Torque-Tension Relationship for ASTM A193 B7 Bolts and Studs." *PDF Search Engine, Free PDF Download*. Web. 09 June 2011. <http://printfu.org/read/torque-tension-relationship-for-astm-a193-b7-bolts-and-studs-60be.html?f=1qeYpurpn6Wih-SUpOGunKWnh8De6NbpzZLE19fh3dXjjbFR29fZ3dfT49rS3pTM5N-FrcLKspSplqmlibCrhrfc0eDilsbizIXD5t7S54iw4J-eqZjZ6Iqg46yan66I3-LY4NzmtcTN0dWUpOGul6-Py46q6Z-roJ-S2t3i5KCKnNzj5qTL1dvZ1eDK2qLJ5NqUz97k2dnW2Z_YztLnleXRy5vD5dfI3cqdxs7c58_k24qen7nN1drZlaSZ1OPYmp-Vrqak1djOh6vv>.
- [6] "Bolt Pattern Torque Sequences." *MillwrightMasters.com Home*. Web. 09 June 2011. <http://www.millwrightmasters.com/School/bolt_pattern_torque.htm>.
- [7] "McMaster-Carr." McMaster-Carr. 20 Jan 2011. 5 June 2011. <http://www.mcmaster.com/>
- [7] "Bolt Tightening Procedure." Piping Designer, LLC. 29 May 2011. 8 June 2011. <http://piping-designer.com/Bolt_Tightening_Procedure>

Appendix C

Material Properties

ASTM A193 Grade B7 Steel Bolt

E, modulus of elasticity of bolt

S_p, proof strength from online source

3.00E+07	psi
8.70E+04	psi

Given, In Table, or Found On-line

Calculated Value

Bolt Stiffness

A_t = tensile-stress area (Tables 8-1,8-2)

l_t = length of threaded portion of grip

A_d = major-diameter area of fastener

l_d = length of unthreaded portion in grip

1.42E-01	in ²
0.5942	in
1.96E-01	in ²
0.75	in

k_b = bolt stiffness =

3.7466E+06

l_t = l - l_d

l_d = L - L_T

Member Stiffness

Cast Iron Grade 25

D =

d =

t =

E = modulus of elasticity of member

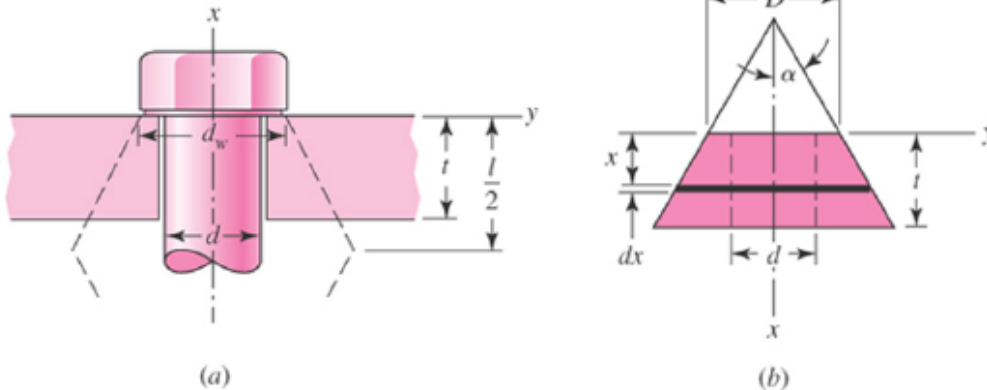
k_i =

	Cone 1	Cone 2	Cone 3	Cone 4	
D =	0.875	1.54E+00	1.08E+00	0.875	in
d =	0.5	0.5	0.5	0.5	in
t =	0.5737	0.09845	0.49205	0.18	in
E = modulus of elasticity of member	3.00E+07	1.40E+07	1.40E+07	3.00E+07	psi
k _i =	4.3575E+07	2.5552E+08	3.3977E+07	9.0612E+07	

k_m = member stiffness =

1.4852E+07

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$$d\delta = \frac{P dx}{EA}$$

∴

$$k = \frac{\pi E d \tan \alpha}{\ln \frac{(2t \tan \alpha + D - d)(D + d)}{(2t \tan \alpha + D + d)(D - d)}}$$

$$\alpha = 30^\circ$$

$$k = \frac{0.5774 \pi E d}{\ln \frac{(1.155t + D - d)(D + d)}{(1.155t + D + d)(D - d)}}$$

(Dr. Ludwick Slideshow)

F_i = preload	9.26E+03	lbf
P = external tensile load	1.99E+04	lbf

$$F_i = 0.75F_p \quad (\text{Eqn 8-30})$$

$$F_p = A_t S_p$$

C = fraction of P carried by bolt	0.2014
$1 - C$ = fraction of P carried by members	0.7986

$$C = k_b / (k_b + k_m)$$

K = torque coefficient	0.2	
d = bolt diameter	0.5	in
T = Torque required for preload	926	lbf

$$(\text{Eqn 8-27})$$

n = load factor	3	$n > 1$ ensures that the bolt stress is less than proof strength
N = number of bolts	4	to satisfy bolt load
N = number of bolts	6	to prevent separation
D_b = bolt circle diameter	5.905494	in
n = load factor w/ N bolts	4.63	Eq. 8-28
n_0 = safety factor against joint separation	3.502	Eq. 8-29

P_b = portion of P taken by bolts	4001	lbf
P_m = portion of P taken by members	15862	lbf
$F_b = P_b + F_i$ = resultant bolt load	9926	lbf
$F_m = P_m - F_i$ = resultant member load	6603	lbf

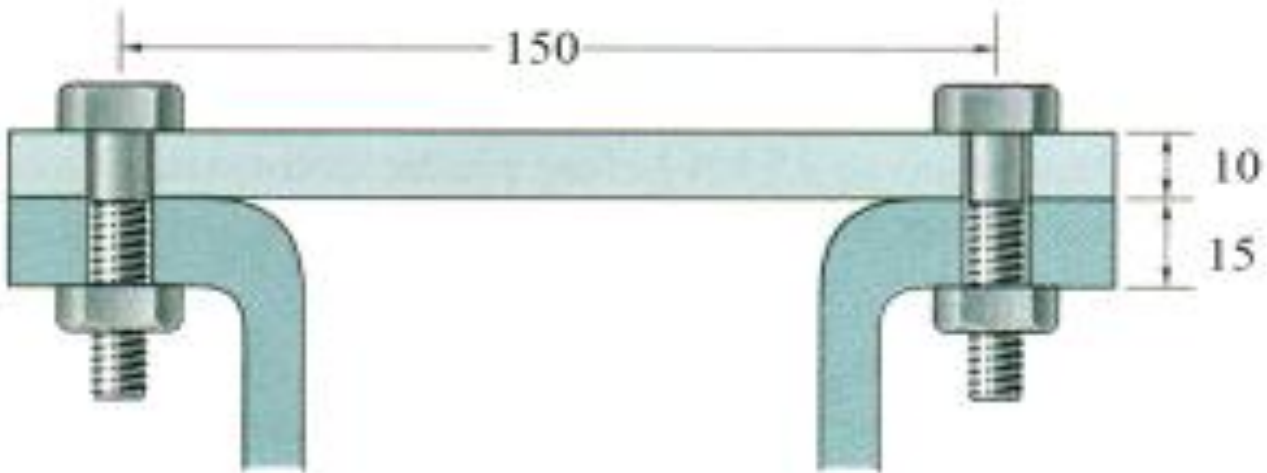
σ_i = preload stress	65250	psi
σ_b = service load stress	69950	psi

Nut Thickness	0.484375	in
Bolt Length	2	in
Washer Thickness	0.18	in

Cylinder Lip Height	0.590549 in
Flange Height	0.3937 in
Washer Height	0.18 in
Nut Height	0.484375 in
L = bolt length	2 in
L _T = thread length	1.25 in

$L_T = 2d + .25$ (Eq. 8-13)

I = grip 1.344249 in



McMASTER-CARR CAD	PART NUMBER	94705A209
	Steel Heavy Hex Head Structural Bolt	

<http://www.mcmaster.com>
 © 2009 McMaster-Carr Supply Company

Unless otherwise specified, dimensions are in inches. Information in this drawing is provided for reference only.

