Design and Construction of a Portable Gantry Hoist

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2013

TITLE : Design and Construction of a Portable Gantry Hoist

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DATE SUBMITTED : December 5, 2013

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ACKNOWLEDGEMENTS

I would like to thank Dr. Mark Zohns for all of his time working with me on my project and broadening my experiences. I would also like to thank Paramount Citrus for allowing me to use some of their tools to build my project, and Tim Hutcheson for his help and support while assembling the project.

ABSTRACT

This report covers the design of a portable gantry hoist with a custom frame design. The design was based off of the materials that were available and practical for this project to save money. The portable gantry hoist will be rated for a 2 ton capacity. The casters, trolley, and hoist were the only parts purchased.

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INTRODUCTION

Background

Portable lifting equipment is a large component of any mechanical shop. This can be achieved through the use of forklifts, chain lifts, etc. While motor-powered equipment is expensive and requires maintenance and fuel, manually operated lifts are inexpensive and do not require much or any maintenance. Ease of maneuverability is a big issue for most shops along with variable terrain.

Justification

The plan for this project is to design and build an overhead lift with a chain hoist that can be broken down and easily moved to different job sites and have a 2 ton lifting capacity. Using materials that are already available will cut down on costs and allow for more money to be put into a higher quality hoist. The caster wheels will be a high strength solid rubber wheel so there are no problems with flat tires while it still has the ability to be maneuvered in more hostile terrains such as soft soil and gravel driveways. They will also have to have a higher load rating than the 2 ton rated capacity to account for the extra weight of the frame, hoist, and trolley. Building a custom hoist will allow for plenty of customization and personal additions to the basic overhead hoist design such as racks for tools, parts, and other items could be useful in the work area.

Objectives

The design will consist of a breakdown of the materials used to find the maximum bending moment in the center of the wide flange beam for the maximum holding capacity. The casters will possibly be the limiting factor on the design since they generally have low load ratings and are expensive and hard to find for load ratings above 1500 lbs. A simple cost analysis will be done also to compare the price of purchasing a frame, buying materials to build one, and using what is available to build a gantry hoist.

LITERATURE REVIEW

LK Goodwin CO. is a material handling equipment company that sells many types of hoist's and cranes for certain applications. Looking through their list of portable hoists, a 2 ton has a cost around $2500 for a non-adjusting height crane and would have an equivalent rating to the one being designed. These hoists come with casters but the trolley and chain hoist must be purchased separately. Below is an example of a basic portable gantry hoist design.

Figure 1: Basic "A" frame gantry hoist (LK Goodwin 2012)

This design is relatively easy to assemble while it is lying down but would most likely require two people to stand up. Using two people to stand up the hoist after assembly seems to be an unavoidable factor in the design.

The Cal Poly Rose Float club has a gantry hoist (3 ton Capacity) which was quickly examined to get a different idea of how the column and frame could be designed. After looking at the frame it was easy to see that the legs were designed poorly; they were built with 3"X6"X3/16" rectangular tube which is strong but the "A" frame design means the legs will start deflect due to the resolving bending moment and the rectangular tube was oriented to bend about its weaker axis seen in Figure 2. This also allows for someone to be underneath the frame when it could potentially fail making it a severe safety hazard.

The hoist beam is an S15X42.9 and spans around 26ft without support of the compression flange making its L_b value 26ft as shown in Figure 3. Adding support (drawn in Figure 3) would reduce the travel of the trolley slightly but would improve the overall safety of the design by reducing the beam's L_b value. This is a very long length to span without supporting the compression flange and using the AISC Steel Manual page 3-82 the beam's L_p=4.41ft and L_r=16.8ft. Since $L_b > L_r$ the critical force F_{cr} was calculated and found to be 15,100 lbs which means the 3 ton capacity is allowable.

Figure 2: Rose Float "A" frame gantry hoist

Figure 3: Rose Float gantry hoist, no support of the compression flange

Grainger has a large selection of casters with a wide range of load bearing capacities. Grainger Item # 1NVT6 is a swivel caster with a rating of 1650lbs/caster making it a possible choice for this design. Using four casters would be able to hold 6600lbs which would satisfy the assumed 2 ton desired load capacity.

Figure 4: Caster wheel 1650 lbs capacity (Grainger 2012)

They run about $66/caster which seems typical for casters above 1500lbs. The caster wheels will be the limiting factor for this hoist and they will determine the load capacity that will be printed on the side.

The trolley chosen was a JET 2 ton manual trolley; this trolley is meant for beams from 4-8 in in width. The hoist is designed for 4000 lbs so the 2 ton trolley will meet the capacity required for the design and will be compatible with the hoist since they are the same brand.

Figure 5: Jet 2-ton trolley (CPO Jet Tools 2013)

The AISC Steel manual will be the book used to help calculate the maximum load the beam available can handle and how much the beam will deflect with the assumed load on it. The compression flange is the main factor to design around when using a beam whether it is an “S” or “I” beam. This can also be used for the column calculations to find what point load will cause the columns to buckle. Shigley’s Mechanical Engineering Design book shows how to calculate the loads on the beam supports and gussets along with the Mohr’s circle to find the max shear and normal stresses. This will help find the Factor of Safety for the frame of this design.

Figure 6: Jet 3.2-ton hoist (CPO Jet Tools 2013)

PROCEDURES AND METHODS

Design

The design was based off of previously built gantry hoists. The Rose Float hoist was used as a design to avoid especially the "A" frame section used for the supports. The material used was based on what was available and what would be a strong but not overkill to avoid adding too much weight on the casters. The upright supports were made to be cut at 45 degrees to make it easy to cut. The pipe gussets were made at a sharper angle because that allowed the trolley to have a wider distance to move back and forth. The specifications for the members can be found in Appendix A. The material that was available was the S10X25.4, which had already been cut at 10ft, the 4X4X3/16, the W6X12, miscellaneous plate, and 3in pipe.

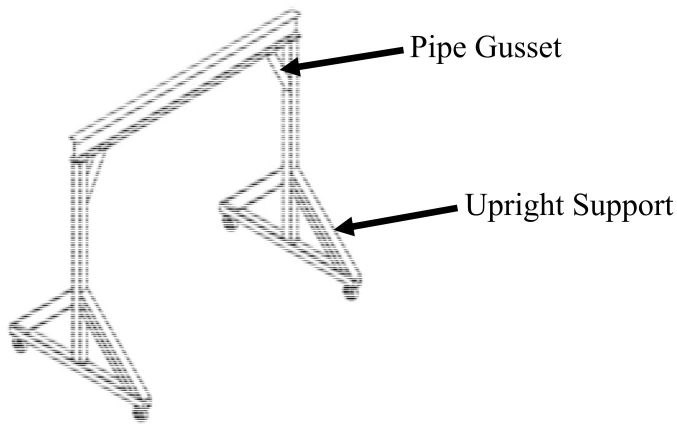

Figure 7. SolidWorks design.

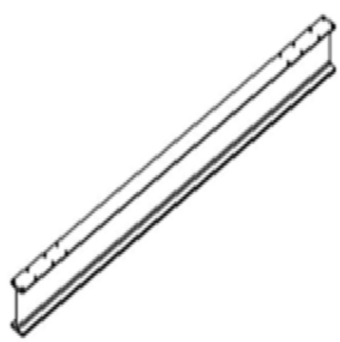

Figure 8. S10X25.4

The calculations were done on the beam, the upright (column), and the caster mount. The beam span was 10ft with a L_b of 7ft giving a maximum allowable moment for this beam to be 45.98 kip*ft and an allowable point load of 18.39 kips. The caster mount had several factors that would affect it and a worst case scenario was created and a finite element analysis was done to make sure the mount would hold. The worst case static was if the hoist was fully loaded (4000 lbs) and was being pushed by someone against something like a curb. The caster moves off-center applying a torque around the caster mount along with the force against the side by the person pushing and the force of the loaded beam on the caster mount. The max stress was about 17,500 psi which is below the max bending stress of 0.6 F_y 27,600 psi. For any impact loading the force applied would be assumed to be which the beam can hold. The design calculations can be seen in Appendix B.

Fabrication

A basic design was made first to get an idea of how much metal was needed and what materials were available to be used to build the hoist. A few rough dimensions were estimated such as the caster height, which varies based on wheel material, and overall height of the hoist. The width however, was set by the availability of the beam which was already at 10ft. Once a basic design was drawn up and the available material was evaluated, the design was drawn in SolidWorks and assembled. From the SolidWorks models of each part the dimensions were drawn out and each part drawing was used for a cut list. Parts drawings can be found in Appendix A for later reference.

All the material was loaded up and taken to one of the shops at Paramount Citrus to cut the majority of the material to length using a band saw as shown in the figures below.

Figure 9. Trailer loaded with material.

Figure 10. Material cut in band saw.

Figure 11. Material cut to length.

The only material that had to be cut afterwards with a cutoff wheel were the bottom flanges on the uprights and the 3” pipe that had to be marked with an angle finder and custom cut with a cutoff wheel.

Figure 12. Bottom plate cut to match caster mount piece.

The pipe gusset was cut to have a steeper angle to allow the trolley to move farther across the beam. It was harder to make the cut with a cutoff wheel instead of being able to use the band saw so the cut may have been less accurate but welding would fill in any gaps.

Figure 13. Pipe gusset cut.

Drilling the holes for the mounting plates on the beam was done with a magnetic base portable drill press borrowed from Paramount Citrus. The mounting plates were clamped to the beam and 5/8" holes were drilled through both the plate and beam at the same time. The magnetic drill made drilling the holes much easier than it would have been with a normal hand held drill. The magnet base was very smooth to operate and was much faster than a hand drill avoiding worrying about catching the bit and twisting everything up.

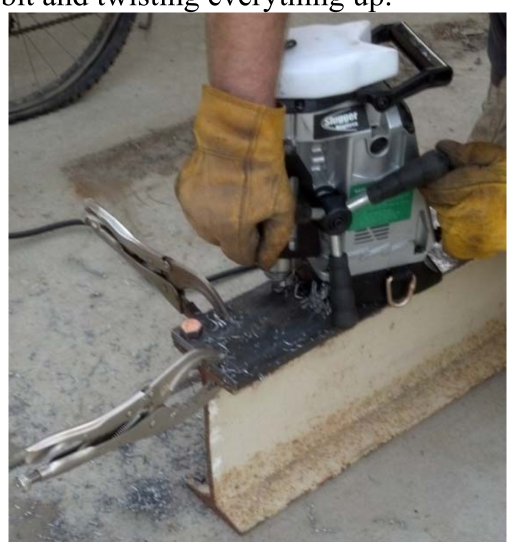

Figure 14.Drilling holes.

Once the holes were drilled the plates were bolted down to the beam and the uprights and pipe gussets were tack welded in place. They were taken off after for finish welding to avoid getting weld on the bolts, washers, and nuts.

Figure 15. Uprights and gussets tack welded and ready for finish welding.

After they were welded up the bottom caster mount box had 1/2” holes drilled in it using a pattern that was drawn in AutoCAD for the narrowest caster mounting option. Then the wide flange beam gussets were tacked and welded on. Everything was finish welded with 21.0 voltage setting and 250 wire speed.

Figure 16. Complete uprights being finish welded.

Figure 17. Finish welds.

After the two uprights were built they and the hoist beam were cleaned with a wire wheel and acetone to be prepped for painting, first with a coat of primer from spray cans then a rolled on finish coat to have a thick and heavy coat in case it was scratched while being assembled. The paint scheme chosen was Cal Poly colors.

Figure 18. Primed and painted parts.

The load rating was painted on the sides of the beam gussets with a stencil. Rating is for 4000lbs or 2 tons.

Figure 19. Load rating.

The next objective was to assemble and stand up the hoist. The casters were attached after so the hoist would not bounce on them as it was stood up. Assembly did take some time getting the beam set at the right angle to bolt the uprights to it. Getting the bolt holes to match up also required some influencing of the pipe gussets since they had pulled slightly during the welding process. Once it was bolted together the hoist was tilted up using a Massey Ferguson tractor with a hook attachment in Figure 20. Once the hook was maxed out a chain was tied around the top and to the back of a truck and pulled the rest of the way. The hoist did not fall all the way back over since the velocity was essentially zero while it was being stood up so there was no added energy to make it tilt over the other side as the energy was lost through each tipping impact.


Figure 20. Standing up the gantry hoist.

The final step was attaching the casters to the base. The casters were attached by lifting the box tube on one end with a pry bar to get a jack under it, then lifting the rest of the way with the jack and stacking wood blocks for it to sit on while bolting on the casters.

Figure 21. Casters.

The finished product was rolled around to make sure it moved easily. Once it was rolling the bolts for the beam were all tightened once more in case they loosened while moving and standing the hoist. A trolley and hoist were borrowed and attached for testing.

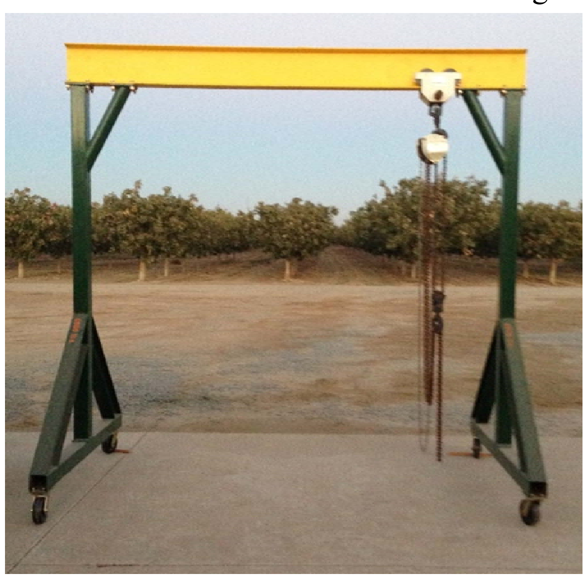

Figure 22. Final product, gantry hoist.

RESULTS

The hoist was tested by lifting a 265 Massey Ferguson to make sure it could hold the weight it is rated for. According to the Nebraska Tractor Test, the Massey Ferguson weighs 8,200lbs operational with ballast (Nebraska 1975). The back was picked up without any failure and weighs in at 6000lbs (Nebraska 1975). This weight is enough to satisfy the ANSI B30.2 Section 2-2.2.2 (d) standardized 125% of the rated capacity that a hoist must be able to lift for its load rating so the design is adequate.

Figure 23. Tractor lifted and fully supported by hoist.

Figure 24. Tractor off the ground roughly 8in.

DISCUSSION

Having materials available was a large benefit for this project saving around $1,360 as shown in Table 1 below. A JET 2 ton trolley and the ratcheting 3.2 ton hoist would cost roughly $800 and the casters were $70 a piece shipped. The complete hoist with trolley and lift would cost around $2,460 so the metal is a huge factor in pricing. A more in depth structural analysis should be performed to find areas that could be made cheaper and lighter if the materials would have to be purchased in order to save money.

Steel Size	Quantity (/20ft)	Total Cost ($)
3" sch 40 pipe	1	$ 150.00
4"X4"X3/16"	2	$ 270.00
S10X25.4	1	$ 580.00
W6X12	2	$ 360.00
	Total	$ 1,360.00

Table 1. Cost Analysis.

The pipe gussets were made with such a sharp angle to allow for the trolley to have more travel side to side. The downside was cutting the angle with a grinder instead of a band saw but it still came out close enough to get a strong weld on it. That would be the users choice in deciding how far the trolley needs to actually travel and building simplicity. Based on their load rating, if the trolley needed to move farther the beam might be able to be longer if that does not affect the maximum beam load.

The beam was able to lift the weight it was rated for. The limiting factor for the weight rating turned out to be the casters, if the hoist was to be rated for 3tons they would not hold 125% of the rated weight along with the hoist weight. The hoist weighs 787lbs as shown in Table 2. Either bigger casters or a different wheel type would allow for a higher weight rating.

Steel Size	Weight (lb/ft)	Length (in)	Total Weight	
3" sch 40 pipe	7.35	44	27	lbs
4"X4"X1/4"	12.21	332	338	lbs
S10X25.4	25.4	120	254	lbs
W6X12	12	168	168	lbs
		Total	787	lbs

Table 2. Weight Calculation.

RECOMMENDATIONS

While building this project one major concern was matching the bolt holes on the upright and the beam. Even though the holes were drilled through the plates and the beam at the same time, and tacked together, the finish welding was done while the upright was off the beam, causing the gusset to move. This made matching up the bolt holes hard to do and required some manipulating of the upright with a pry bar to line up the holes. Drilling slightly oversized holes would make the assembly process easier and give the pattern some room to adjust. A good way to prevent this would be tack welding a piece between the plates, fully welding them, bolting it to the beam, and then knocking the piece out.

Cutting the 3in pipe gusset could have been easier by making the angles 45 degrees. The reason for the sharper angle was to have more room to move the trolley to get it out of the way or grab an item next to the hoist upright. Since one angle was much farther from 45 the angle had to be drawn with an angel finder and cut with a cutoff wheel which was harder to line up but still ended up working.

The beam mounting plates that were made could have been made longer allowing the use of washers on the 4X4 uprights. The holes are too close to allow a washer on the nut side so no washer was used. Adding 1” to the length and re-centering the upright would have allowed enough clearance for washers.

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APPENDIX A: PART DRAWINGS

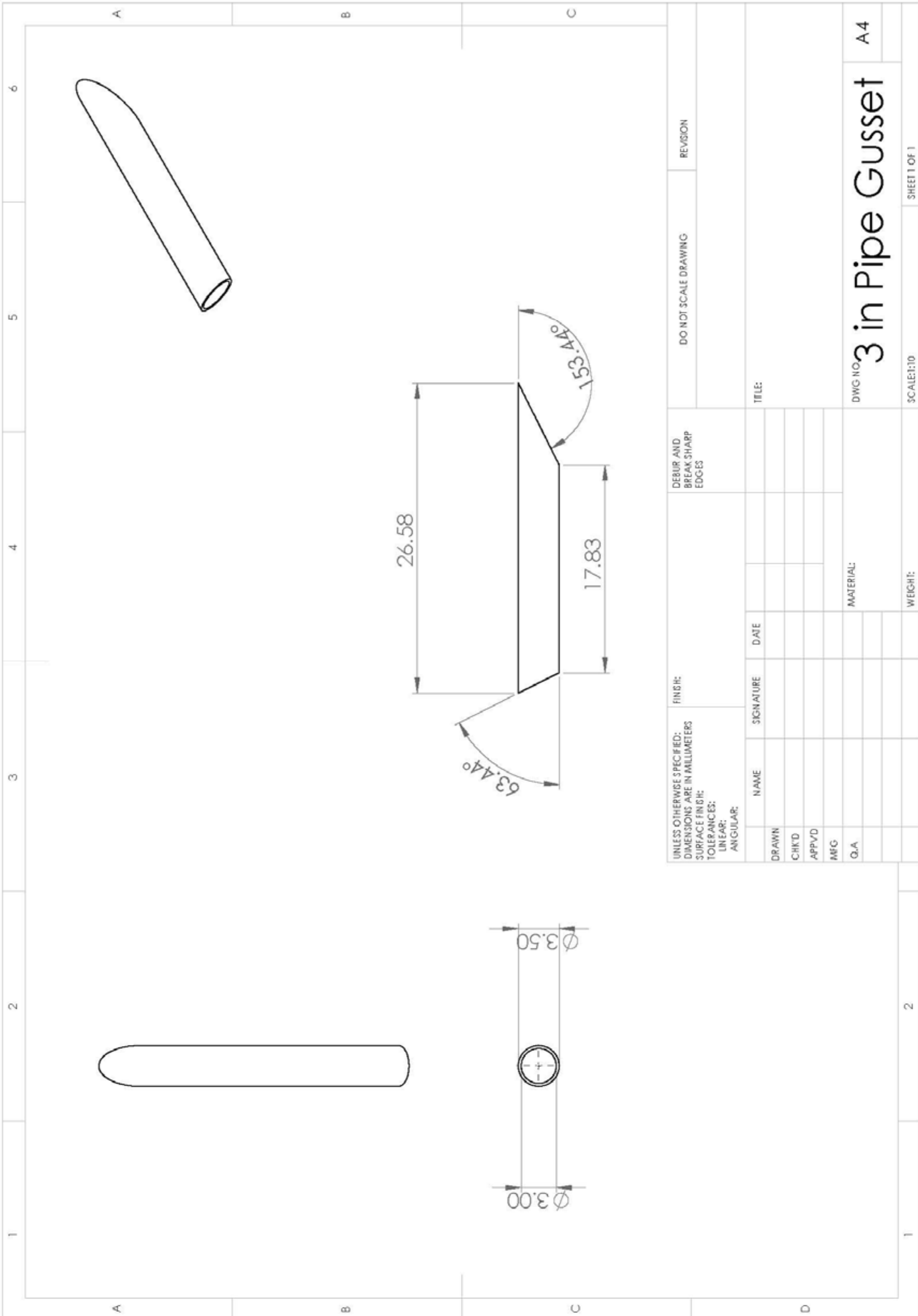

Figure 25. 3 in Pipe Gusset.

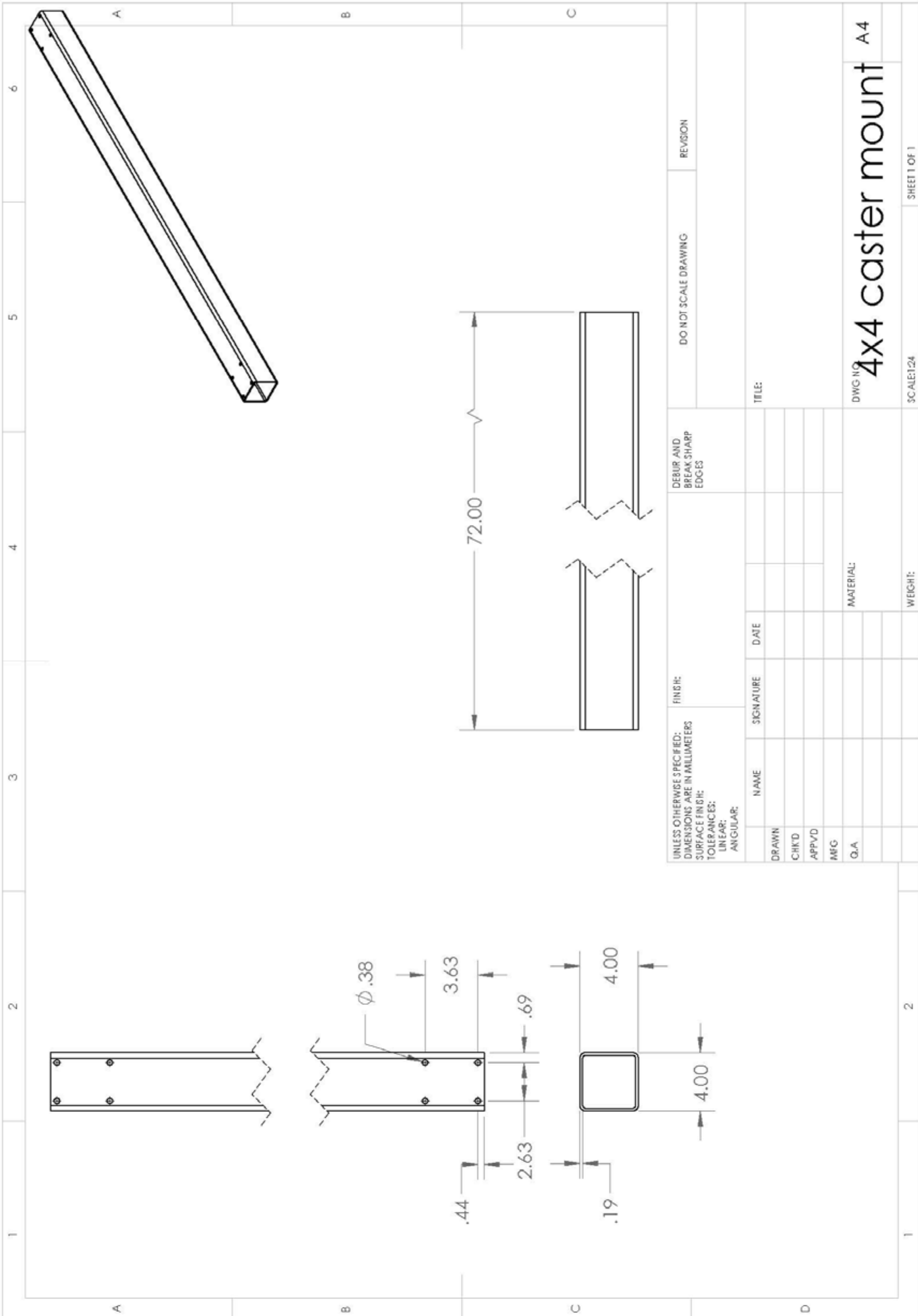

Figure 26. 4X4 Caster Mount.

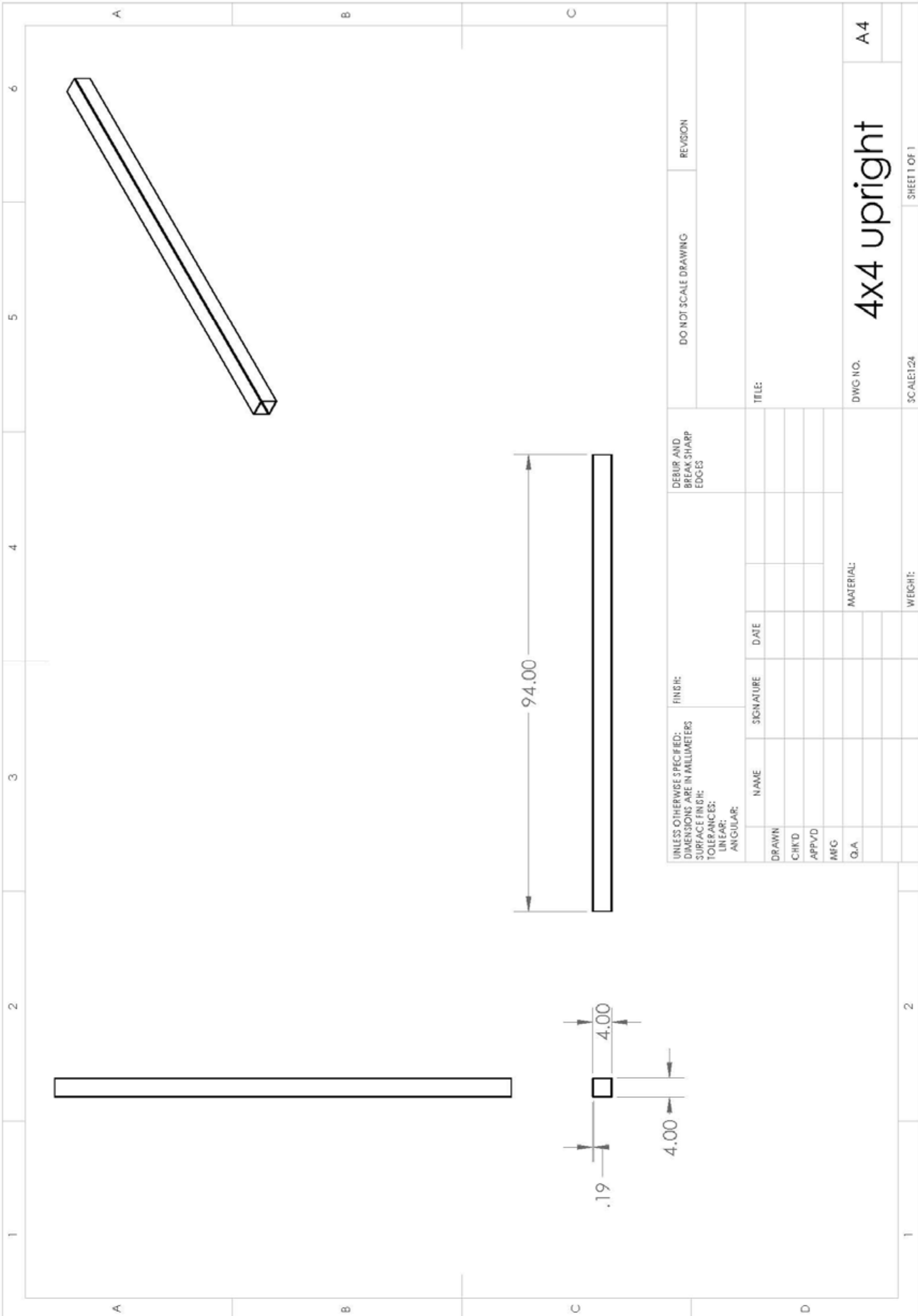

Figure 27. 4X4 Upright.

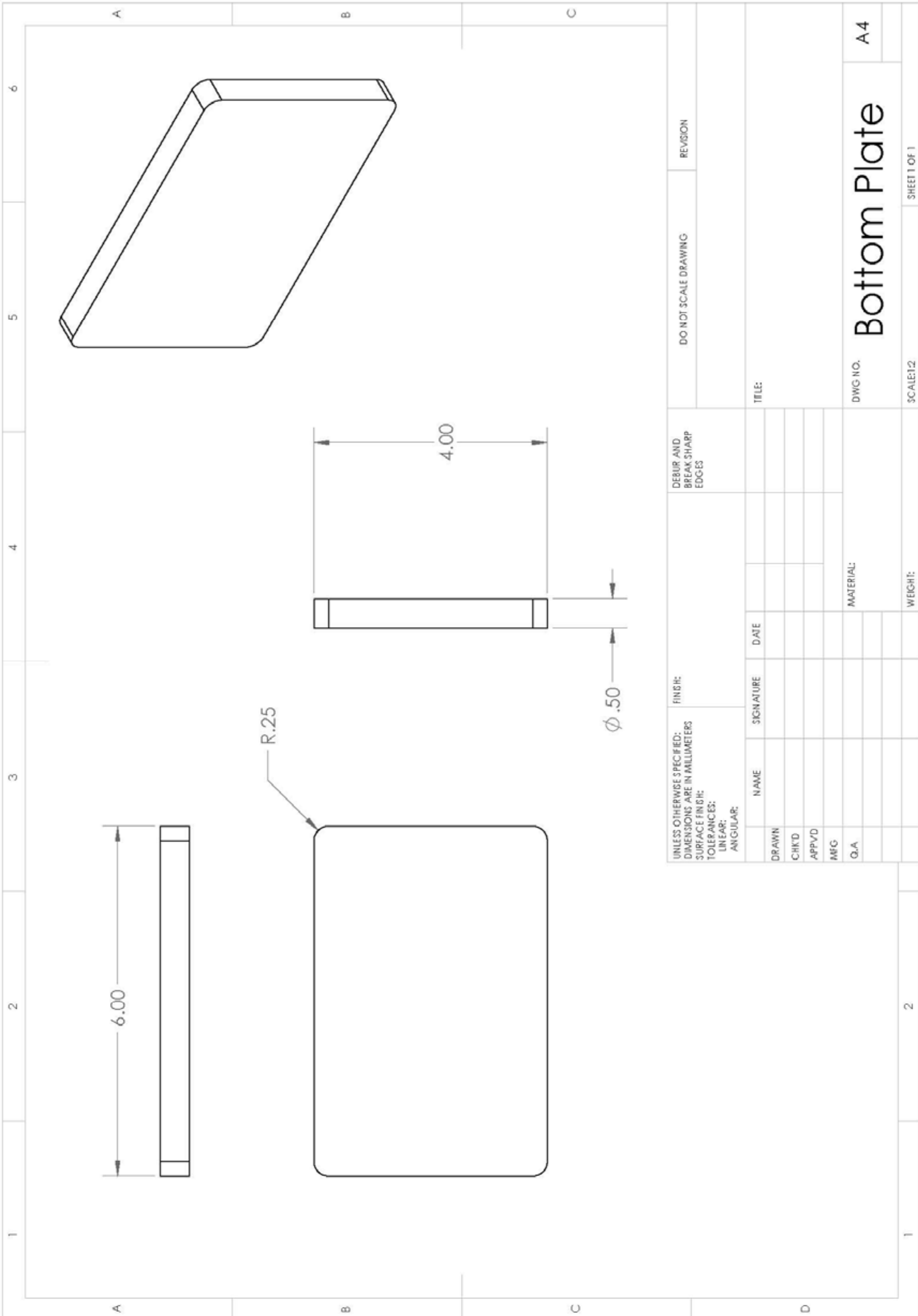

Figure 28. Bottom Plate.

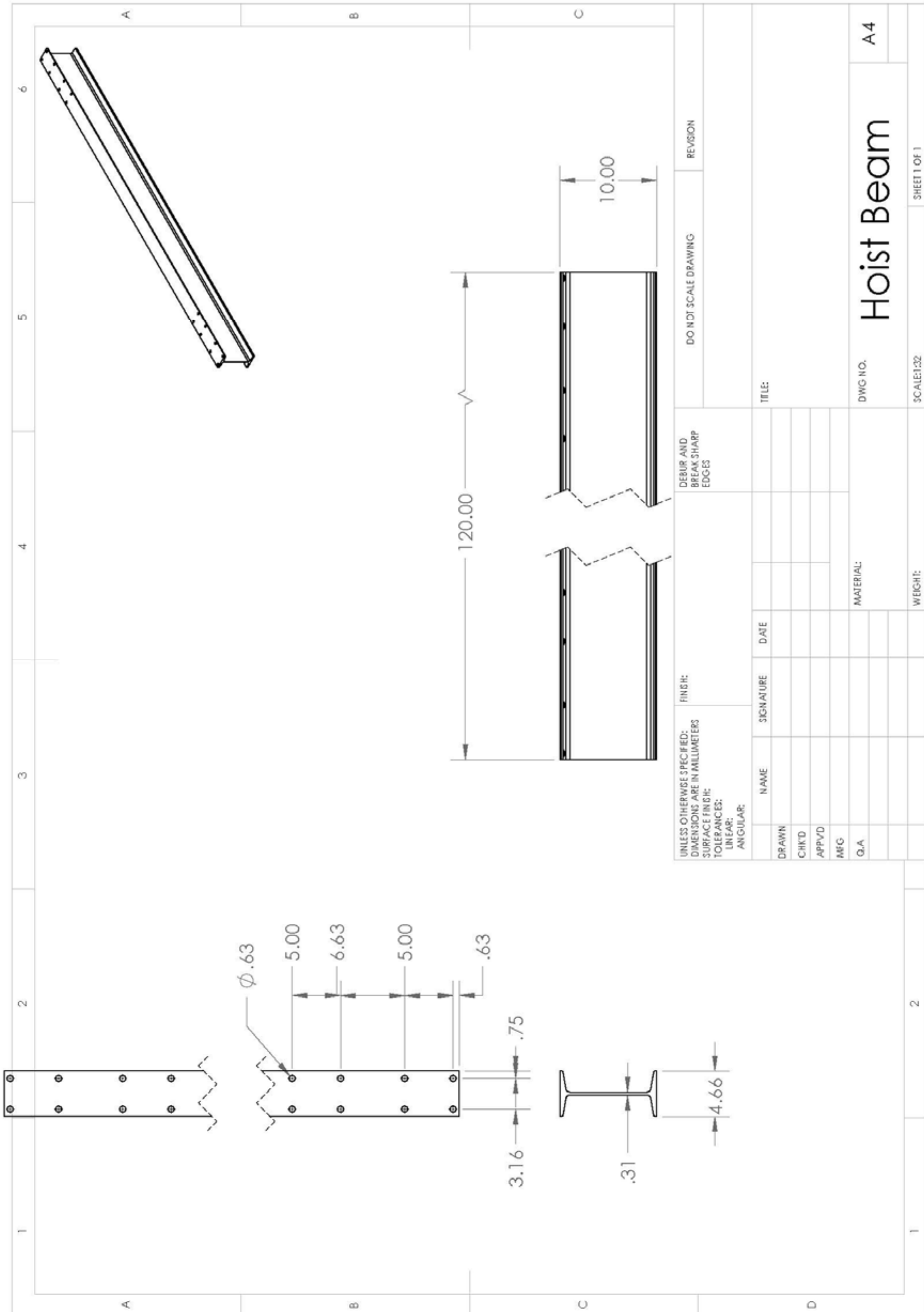

Figure 29. S10X25.4 Hoist Beam.

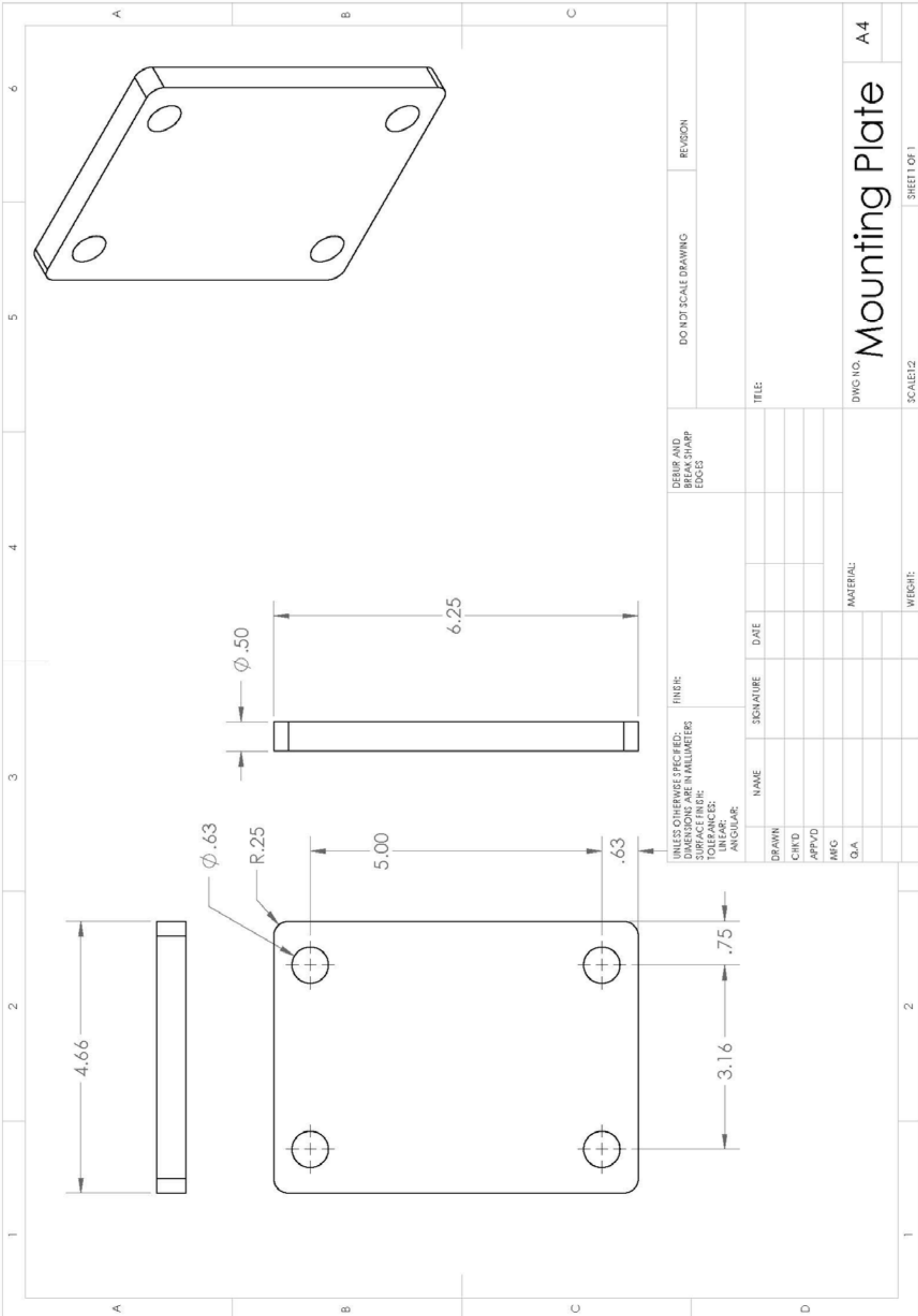

Figure 30. Beam Mounting Plate.

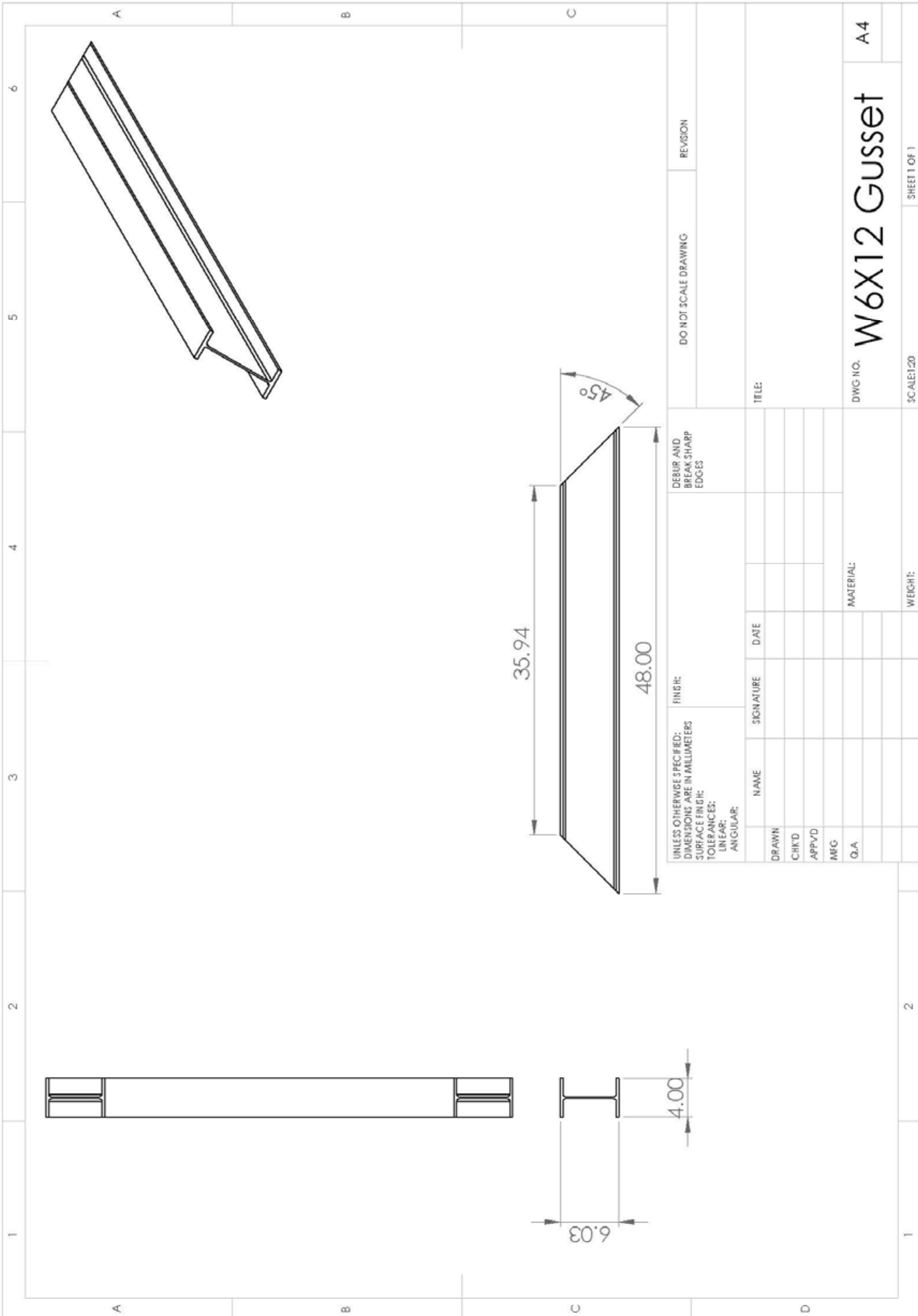

Figure 31. W6X12 Upright Gusset.

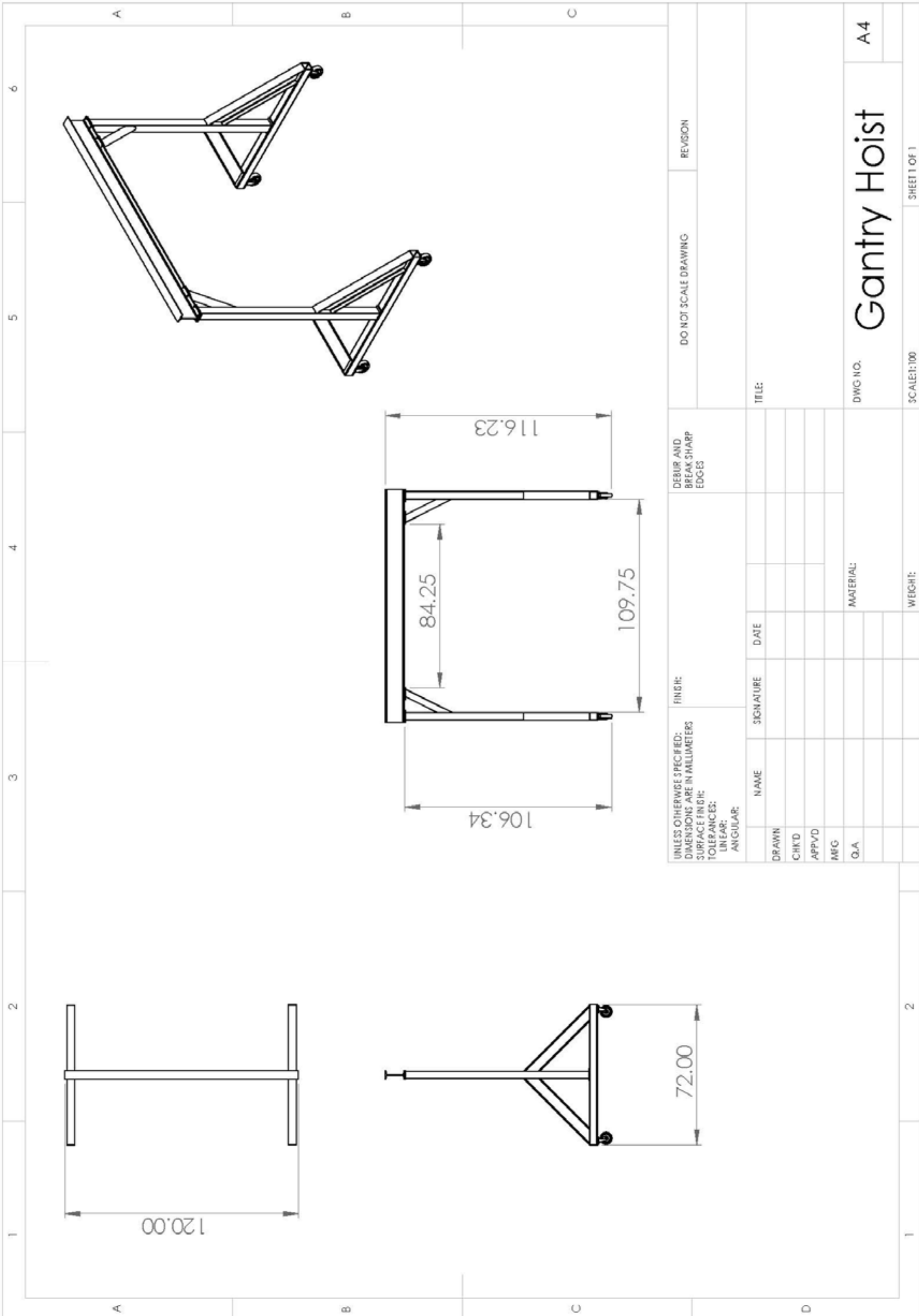

Figure 32. Gantry Hoist Dimensions.

APPENDIX B: DESIGN CALCULATIONS

Project Calculations

S10X25.4 – Main Horizontal Beam

AISC Steel Manual S10X25.4 beam with L_b=7ft and L = 10ft, (3-83):
Lp = 3.95ft, Mp = 50.8kip*ft
Lb = 7ft,
Lr = 16.5ft, Mr = 30.9kip*ft

$$M = \frac{P * L}{4} => P = \frac{M * 4}{L}$$

Pp = 20.32kips
Pb = 18.39kips (linearly interpolated)
Pr = 12.36kips

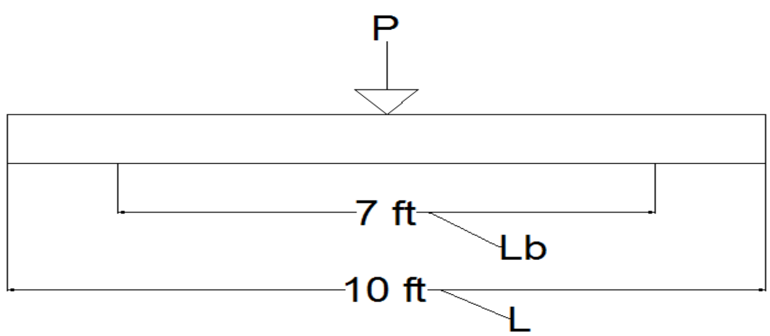

Figure 33. S10X25.4 Beam Load Calculations.

Beam will be adequate for the 2 ton rating with a F.O.S. (Factor of Safety) of 4.5 for the point load rating along with the Steel Manuals F.O.S. of 1.67.

4X4X3/16 – Main Column

AISC Steel Manual K = 2.0 for one end fixed rotation and translation, one end free translation and rotation (16.1-513).
AISC Steel Manual gives r = 1.55in, A = 2.58in^2 (4-63).

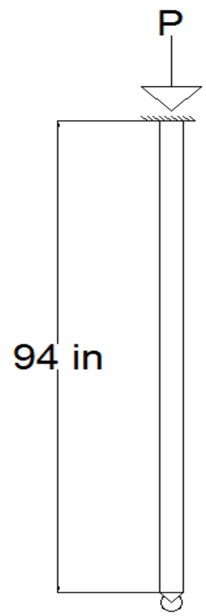

Figure 34. 4X4 Column Load.

$$KL = 2.0 * \frac{94in}{12\frac{in}{ft}} = 15.7ft => 16ft$$

AISC Steel Manual 4X4X3/16 with KL value of 16ft gives allowable load P = 25300lbs (4-63) which is 6.325 F.O.S. for the 2 ton rated load.

W6X12 – Initial Caster Mount

AISC Steel Manual W6X12 beam with L_b = 6ft gives M = lb*ft

$$M = \frac{P * L}{4} => P = \frac{M * 4}{L}$$

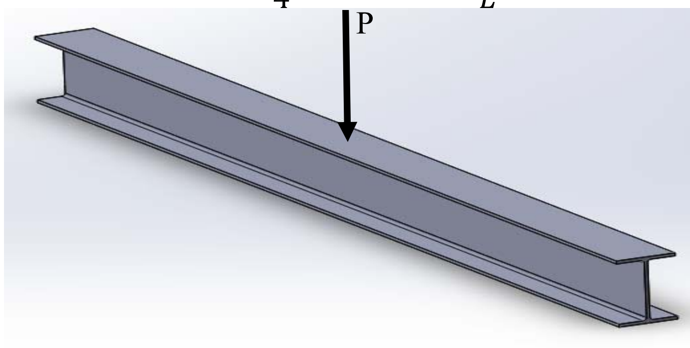

Figure 35. 6ft W6X12 Loaded Member.

Since a W6X12 is not in AISC Steel Manual, we must use equations from Manual to find Lp, Mp, Lr, Mr. (1-28, 1-29).

From Section 1 AISC:

r_y = 2.46in.
h_o = 5.75in.
c = 1
S_x = 7.31in.^{3}
J = .0903in.^{4}
E = 29,000,000psi
r_{ts} = 1.08in.
F_y = 50,000psi
Z_x = 8.3in.^{3}

Equations AISC Steel Manual (3-5).

$$M_p = F_y * Z_x = 50{,}000\frac{lbs}{in^2} * 8.3in^3 * \frac{1ft}{12in} = \mathbf{34583.3lb * ft}$$

$$L_p = 1.76 * r_y\sqrt{\frac{E}{F_y}} = 1.76 * 2.46in * \sqrt{\frac{29{,}000{,}000\frac{lbs}{in^2}}{50{,}000\frac{lbs}{in^2}}} * \frac{1ft}{12in} = \mathbf{3.24ft}$$

$$M_r = 0.7 * F_y * S_x = 0.7 * 50{,}000\frac{lbs}{in^2} * 7.31in^3 * \frac{1ft}{12in} = \mathbf{21320.8lb * ft}$$

$$L_r = 1.95 * r_{ts} * \frac{E}{0.7F_y} * \sqrt{\frac{J*c}{S_x h_o} * \sqrt{\left(\frac{J*c}{S_x h_o}\right)^2 + 6.76 * \left(\frac{0.7F_y}{E}\right)^2}} =$$

$$1.95 * 1.08in * \frac{1ft}{12in} * \frac{29{,}000{,}000\frac{lbs}{in^2}}{0.7 * 50{,}000\frac{lbs}{in^2}}$$

$$* \sqrt{\frac{.0903in^4 * 1}{7.31in^3 * 5.75in} * \sqrt{\left(\frac{.0903in^4 * 1}{7.31in^3 * 5.75in}\right)^2 + 6.76 * \left(\frac{0.7 * 50{,}000\frac{lbs}{in^2}}{29{,}000{,}000\frac{lbs}{in^2}}\right)^2}}$$

$$= \mathbf{11.2ft}$$

Lp = 3.24 ft, Mp = 34.6 kip*ft
Lb = 6 ft,
Lr = 11.2 ft, Mr = 21.3 kip*ft

$$M = \frac{P*L}{4} => P = \frac{M*4}{L}$$

Pp = 23.1 kips
Pb = 19.9 kips (linearly interpolated)
Pr = 14.2 kips

Beam will be adequate for a 2 ton point load rating. This beam will not be used however, since the caster moving out of line with the web will create a torsion about the web which is a weak point. As a general practice beams are not used in torsional loading.

4X4X3/16 – Caster Mount Member

AISC Steel Manual Flexural Strength (3-147):
F_y = 46,000psi

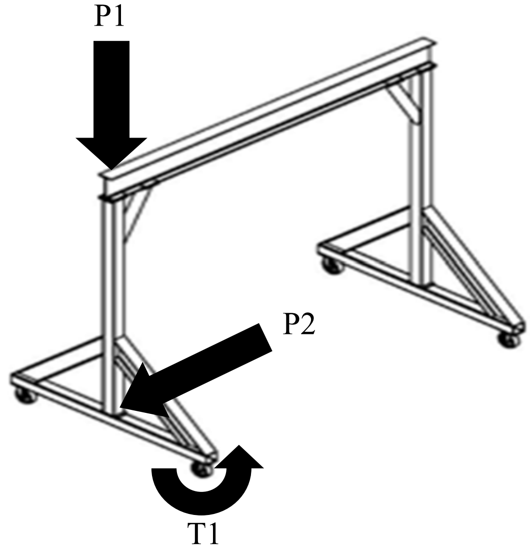

Figure 36. Forces on one side of the Gantry Hoist.

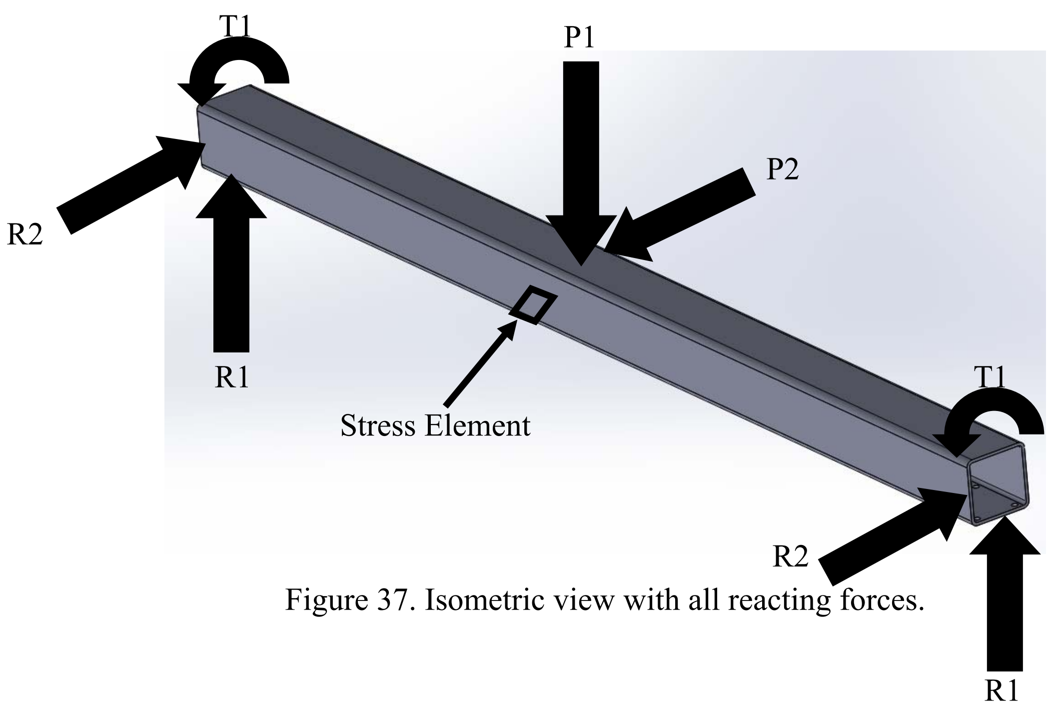

Figure 37. Isometric view with all reacting forces.

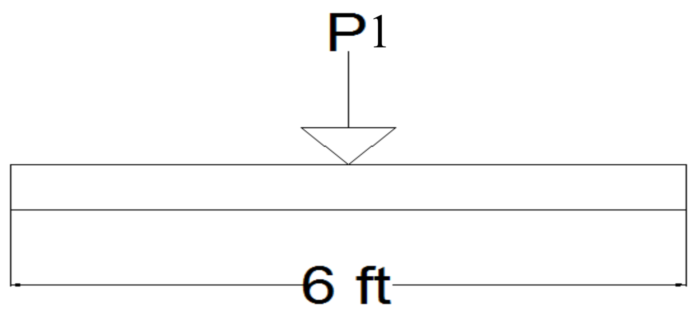

Figure 38. Side view with point load P1.

$$M = \frac{P1 * L}{4} = \frac{2{,}000lbs * 6ft * \frac{12in}{1ft}}{4} = 36{,}000in * lbs$$

$$\sigma_p = \frac{M * c}{I} = \frac{36{,}000in * lbs * 2in}{6.21in^4} = \mathbf{11{,}594.2\frac{lbs}{in^2}}$$

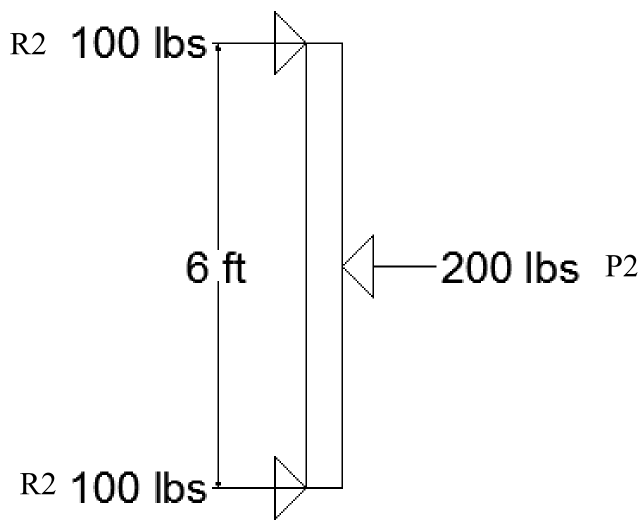

Figure 39. Top View of reaction forces if casters are being pushed against.

$$M = \frac{200lbs * 6ft * \frac{12in}{1ft}}{4} = 3{,}600in * lbs$$

$$\sigma_b = \frac{M * c}{I} = \frac{3600in * lbs * 2in}{6.21in^4} = \mathbf{1{,}159.4\frac{lbs}{in^2}}$$

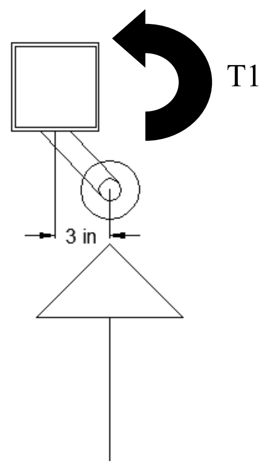

Figure 40. Side view torsional load applied by caster being off-center.

$$\tau = \frac{T1 * r}{J} = \frac{2{,}000lbs * 3in * 1.55in}{10in^4} = \mathbf{930}\,\frac{\boldsymbol{lbs}}{\boldsymbol{in^2}}$$

2-D Stress Element:

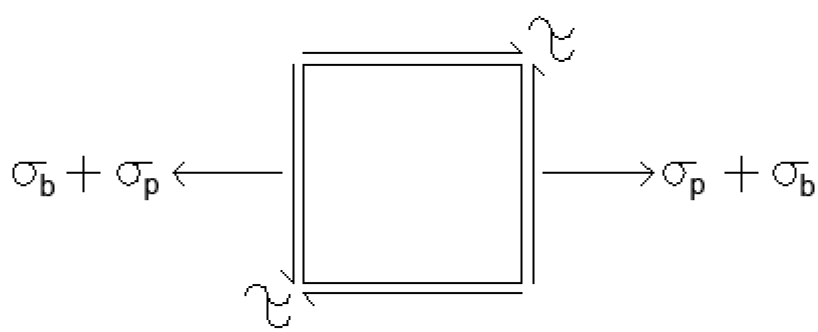

Figure 41. 2-D Stress Element.

Mohr's Circle:

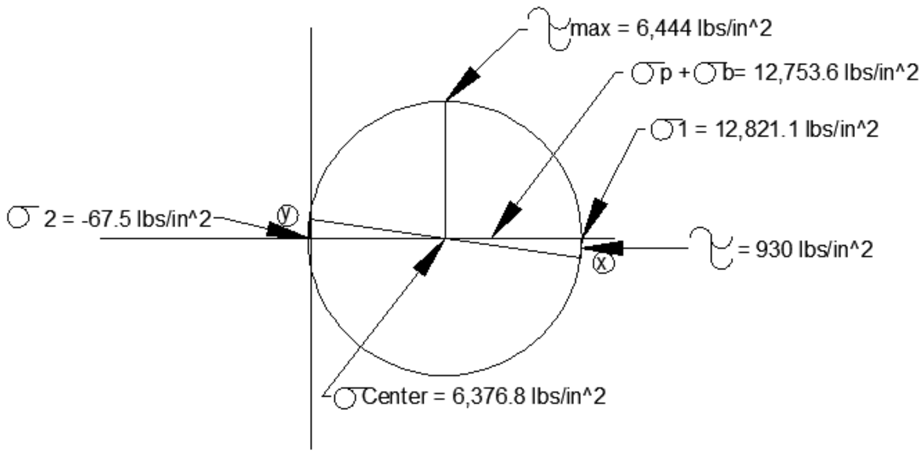

Figure 42. Mohr's Circle.

$$\sigma\ Center = \frac{\sigma x + \sigma y}{2} = \frac{11{,}594.2\frac{lbs}{in^2} + 1{,}159.4\frac{lbs}{in^2}}{2} = \mathbf{6,376.8\ \frac{lbs}{in^2}}$$

$$\tau\ Max = \sqrt{(\frac{\sigma x - \sigma y}{2})^2 + (\ \tau)^2} = \sqrt{(\frac{11{,}594.2\frac{lbs}{in^2} + 1{,}159.4\frac{lbs}{in^2}}{2})^2 + (930\frac{lbs}{in^2})^2}$$
$$= \mathbf{6,444.3\ \frac{lbs}{in^2}}$$

$$\sigma\ 1(Max) = \frac{\sigma x + \sigma y}{2} + \ \tau\ Max = \frac{11{,}594.2\frac{lbs}{in^2} + 1{,}159.4\frac{lbs}{in^2}}{2} + 6{,}444.3\ \frac{lbs}{in^2}$$
$$= \mathbf{12,821.1\frac{lbs}{in^2}}$$

$$\sigma\ 2 = \frac{\sigma x + \sigma y}{2} - \ \tau\ Max = \frac{11{,}594.2\frac{lbs}{in^2} + 1{,}159.4\frac{lbs}{in^2}}{2} - 6{,}444.3\ \frac{lbs}{in^2} = \mathbf{-67.5\frac{lbs}{in^2}}$$

τ Allowable = $0.4F_y$ = 0.4 X 46,000 psi = 18,400 psi, **τ Max is below τ Allowable.**

σ Allowable = $0.6F_y$ = 0.6 X 46,000 psi = 27,600 psi, **σ Max is below σ Allowable.**