Design Report of the Lightweight Structure

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December 12, 2017

Abstract

The goal of this project is to design a lightweight structure (crane) of minimum weight that can lift at least 260 pounds. The structure is constrained by a $250 budget for materials and overall shape dimensions. Removing material in optimized areas decreases total weight and incorporating different aluminum grades supports areas under greater or lower stresses for the lowest weight. The crane will be machined and tested with a pulley device.

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Introduction and Objective

The goal of this project is to design, simulate, and build a lightweight structure (crane) of minimum weight that can lift at least 260 pounds. The structure is constrained by several parameters. First, overall shape of the crane is limited to a given set of specifications for testing purposes. Required specifications include holes along the side of the structure to fit a pulley system with a length of 22 inches. Second, the cost of materials must be less than $250.

This project encompasses the whole process of creating, optimizing, and then building and testing the model. First, a model of the structure was constructed and tested within Creo. This includes modeling the overall shape and assembling the end plates and L-beams. Once the crane was designed, its response to stresses was analyzed using Creo. Once the design can hold 260 pounds and doesn't buckle according to the simulations, the construction of the structure will be completed strictly following the specifications of the Creo model. The crane will then be tested.

System Model Overview

Picking the Materials

Looking at the different aluminum sheet options offered on McMaster and ruling out unnecessary corrosion-resistance, certifications, and other additions, the different options available are aluminum 6061, 2024, 7075, 7050, and 6013. Eliminating those aluminums which are not offered in sheets less than ¼ inch in thickness, the options were narrowed down to aluminum 7075, 6061, and 2024. The following two figures, Figures 1 and 2, taken from CES EduPack 2016, show different specs of each aluminum, along with labels to indicate what is offered in McMaster, to help illustrate properties of the different options.

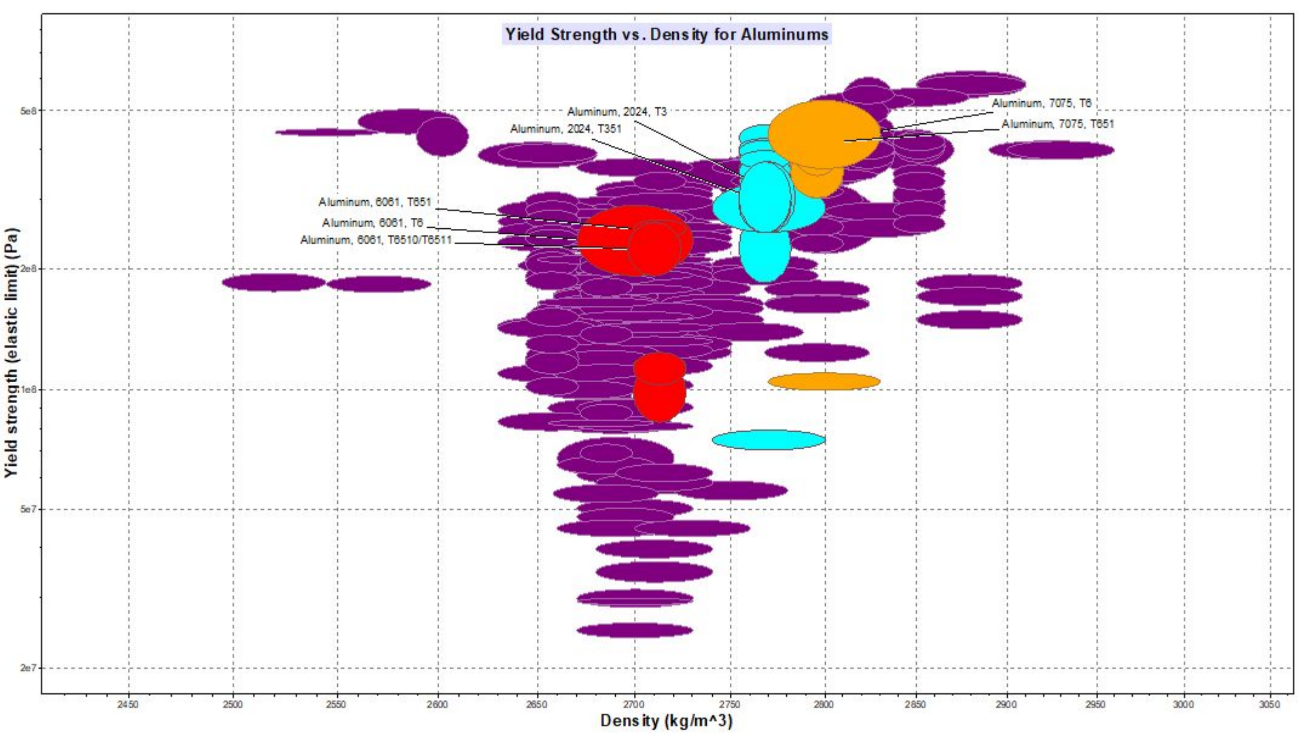


Figure 1: Yield Strength vs. Density for Aluminums

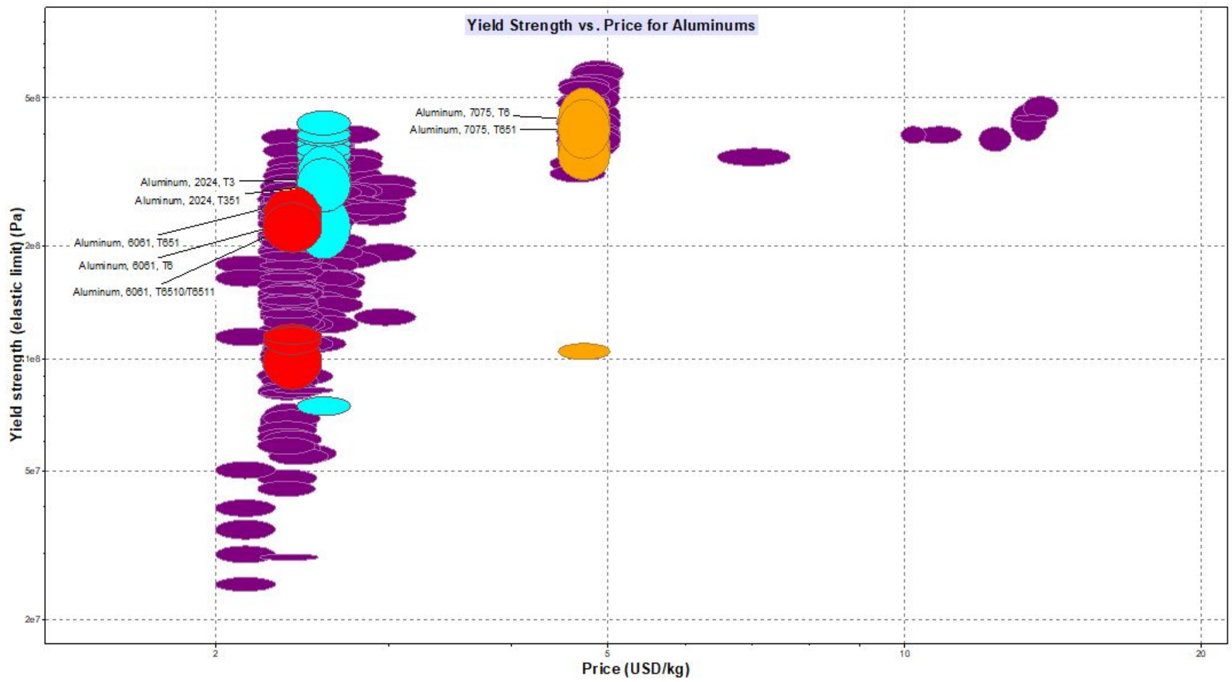


Figure 2: Yield Strength vs. Price for Aluminums

It is clear from these figures that aluminum 7075 has the highest yield strength (61,000 psi), with a not too much higher density compared to the other materials, so it is a top choice for material where yield strength is prioritized. This includes the top, sides, and bottom of the crane. Although aluminum 7075 has a higher price, purchasing the necessary number of 0.040 inch thick sheets of aluminum 7075 from McMaster is within the budget. A cost analysis is offered in the conclusion section of this report.

Because aluminum 6061 is the cheapest option, it is used for the other parts of the crane (end plates and L-beams). Since the end plates are significantly thicker (0.125 inch) than the sheets for the crane (0.040 inch), and are not under much stress, the failure of the end plates is not of concern. The same goes for the L-beams. They are thicker (0.0625 inch) than the sheets as well and their failure is also not of concern.

For the rivets, rivets of multiple sizes and materials (steel and aluminum) were purchased to allow flexibility in placing stronger, heavier rivets wherever strength is most needed, and vice versa. Because the analysis of the rivets is difficult to perform in Creo, the quantitative placement necessity of each type of rivet is unknown and will be done by intuition. It is known that steel rivets will be needed for the high stresses at the base of the crane, while aluminum rivets may be used in areas of lesser stress.

Designing the Model

The structure is essentially designed to fulfill two main objectives: to maintain structural integrity under given loads and to minimize the weight of the structure. The general model of the structure is shown in Figure 3.

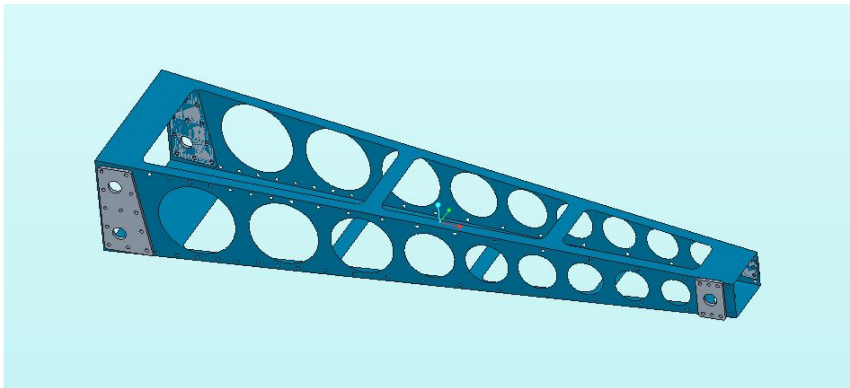


Figure 3: CAD Model of Crane

The crane is designed to comply with the given specs. The larger end has the dimensions of 4 inches minimum (height) x 5.6 inches maximum (width) while the smaller end has the dimensions of 1.5 inches minimum (height) x 2 inches minimum (width). The skeleton structure is limited to 5.6 inches width on the larger end to leave room for the plates and the thickness of the sheets while satisfying the 6 inch maximum requirement. Three holes (two at the larger end and one at the smaller end), each 0.5 inches in diameter, are cut in each side panel according to the pulley suspension geometry. The crane must be 22 inches in length.

Aluminum 7075 sheet metal of 0.040 inch thickness is used for the top, sides, and bottom of the crane. This grade of aluminum is optimal because of its relatively light weight and versatility during the machining process, along with its high yield strength of 61,000 psi, mentioned earlier.

The top, sides, and bottom of the crane are designed to minimize the amount of aluminum needed to hold up 260 pounds. On each of the side sheets (refer to Drawing 2 at the end of the report), nine circles of varying sizes are cut out, leaving sufficient space on both ends for the end plates (to be discussed later). Circle size decreases in diameter as the width of the aluminum sheet decreases. The circle sizes and the distances between each circle were decided using the Creo simulation software to optimize for minimal mass under the yield stress constraint for an aluminum 7075 sheet.

To protect the structure at the ends, 1/8 inch thick aluminum 6061 end plates are made. As shown in Drawing 4, the aluminum plate at the base of the crane is a right trapezoid to provide more support on the lower half of the crane, which will be susceptible to buckling under higher loads. It also reinforces the holes with which the pins will hold up the crane during suspension. As shown in Drawing 5, the end plates at the smaller end of the crane are made to support the pin that holds the line carrying the load. It is just a reinforcement of the circles, so it is a simple rectangular design.

As shown in Drawings 1 and 3, trapezoidal cutouts are made along the top and bottom of the structure to remove the majority of material. More material is removed along these surfaces because these surfaces will not have as much stress as the side sheets, allowing their designs to have less mass. Comparing Drawings 1 and 3, the bottom sheet has slightly smaller cutouts than the top sheet because it will be under compression and prone to buckling. The lengths and widths of the trapezoids were decided by optimizing for minimal mass with Creo simulation software. The width of remaining bordering metal is smaller on the top surface and larger on the bottom surface.

To connect the sheet metal plates, L-beams and rivets are used. The L-beams are made of aluminum 6061 with lengths of 1/2 x 1/2 inch. The thickness is 1/16 inch. The purpose of these L-beams is to hold together the overall structure as well as prevent buckling. The beams will be placed in all four corners along the entire length of the structure. These will be the only supporting structure on the inside of our structure. The idea of adding a gusset as another internal support was discarded because according to the Creo analysis, the structure was able to uphold the minimum weight without it. The gusset would only add extra material cost and weight to the structure.

Rivets are used to connect the structure. Steel rivets will be concentrated near the base of the structure and near the farthest end of the structure (at the end plates), where the compressive and tensile stresses are the highest. For the steel rivets, two types are needed: one to penetrate through the end plate and aluminum sheet, and another type to penetrate through the end plate, aluminum sheet, and the L-beam. The first type's grip range is 0.126 - 0.187 inch, and the second type's grip range is 0.188 - 0.25 inch. Both types of steel rivets will be 1/8 inch in diameter. Aluminum rivets will be used in the middle of the crane, where the stresses are lower. For the aluminum rivets, a grip range of 0.063 - 0.125 inch and diameter of 1/8 inch will be used. Drawings 4 and 5 show the placement of the rivets on the end plates.

Note: The placement of the rivets along the sheet metal has not yet been decided. These will be decided by intuition during the assembly of the crane. Tentatively, the rivets will be more concentrated at the base of the crane, and will then be spaced farther apart toward the end of the crane.

<u>The Optimizing Process</u>

The structure was first created by generally building a model of the crane in Creo, cutting circles of decreasing size for aesthetics and cutting large trapezoids in the top and bottom of the crane to decrease weight. The dimensions of these cuts were not of focus in the beginning, except for the specs that were predescribed. To optimize these cuts, a static analysis was run on the structure to locate the highest stresses. A sensitivity study was then performed on each circle diameter to identify the maximum possible diameter before the stresses would become too large. An optimization to minimize mass was then run on the circles, while subsequently making sure that the dimensions did not exceed the maximum diameter found in the sensitivity analysis. For the trapezoidal size, only the sensitivity study was used, and the dimensions were adjusted manually because Creo did not have the capability to optimize these lengths.

The end plates did not undergo the sensitivity/optimization design process as described above. The process to “optimize” the end plates was purely aesthetic, as it was assumed that the 1/8 inch thick material would not break.

Results

Simulation Results

The final results of the simulations after all optimization and changes are shown in Figures 4 and 5. Figure 4 indicates the final stress simulation of the crane with a 300 pound load at the end. As seen in the stress simulation, the highest stresses are around the circles near the edges, as expected, since these areas are where the material is the thinnest. Stresses are also highest toward the base of the structure because it is subjected to the highest torque and bending. Stresses are also prevalent toward the other end because it is where the load is applied, and the material is thinner. From this simulation, it is to be expected that the structure will withstand the load, as the highest stresses seen in the diagram 35,000 psi. This is well below the yield stress for aluminum 7075, and should not fail given our safety factor.

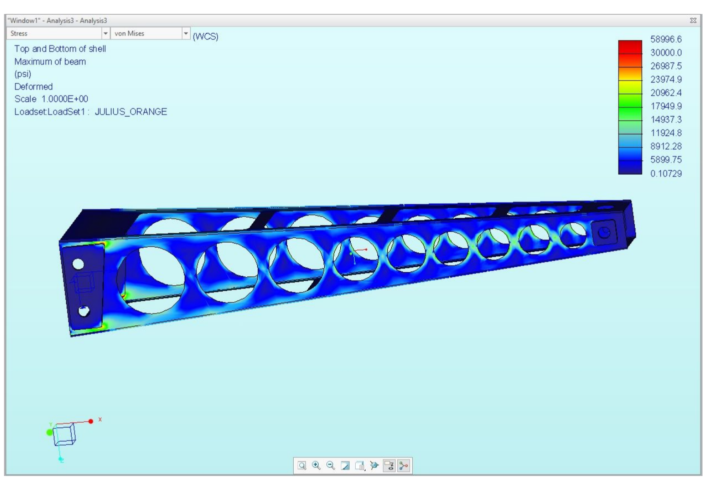


Figure 4: Stress Simulation Results of Crane

Figure 5 indicates the results of the buckling analysis. The whole structure seems to be relatively sturdy and will not buckle, as indicated by the prevalence of the dark blue. Even though the simulation results seem to show that the structure will buckle at the top of structure near the base, as indicated by the red region in the figure, this section will undergo tension, and not compression, so buckling will not occur. The red legend indicates that the max stress will be around 30,000 psi at this section.

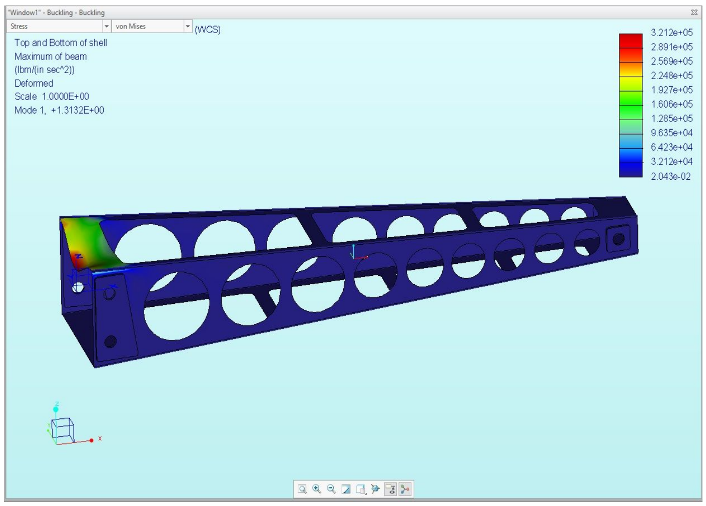


Figure 5: Buckling Analysis Results of Crane

<u>Cost Analysis</u>

The following lists the total items needed, their McMaster catalog number, and their costs:

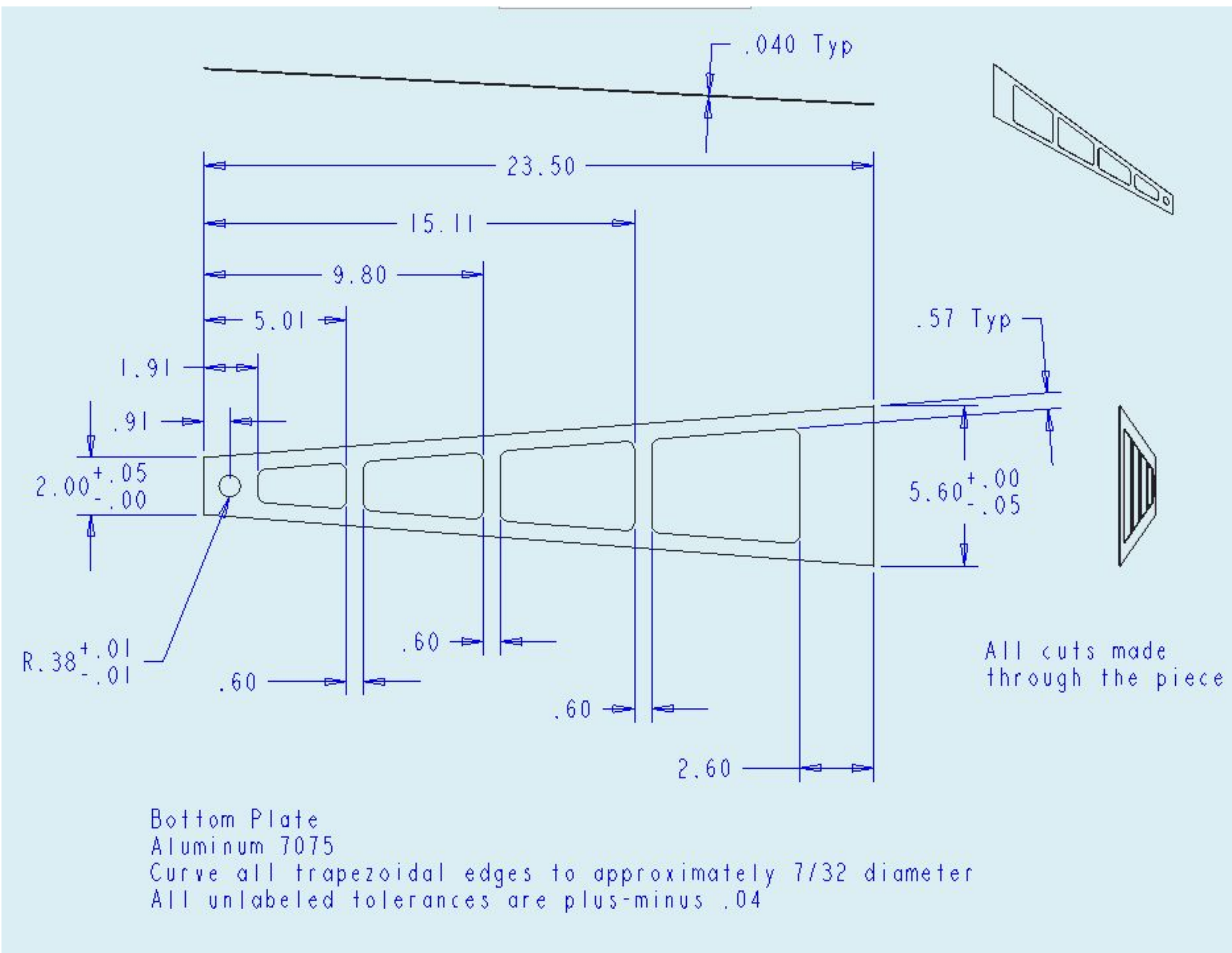
- Four 12”x24” 0.04 thick 7075 Al sheets. 888K5K8. $39.21 each.
- One 6”x6” ⅛ in thick 6061 Al sheet. 89015K235. $9.60.
- Four ½ ”x ½” 1/16 thick 6061 Al L-Beams. 8982K54. $1.55 per 2 ft.
- Aluminum rivets ⅛ dia. (0.063 - 0.125 inch) grip range. 97447A015.
- Steel rivets ⅛ dia. (0.126 - 0.187 inch) grip range. 97525A420.
- Steel rivets ⅛ dia. (0.188 - 0.25 inch) grip range. 97525A425.
- **Total Cost:** $39.21*4 + $9.60*1 + $4*1.55 = **$172.64**

Note that the total cost excludes the cost of the rivets.

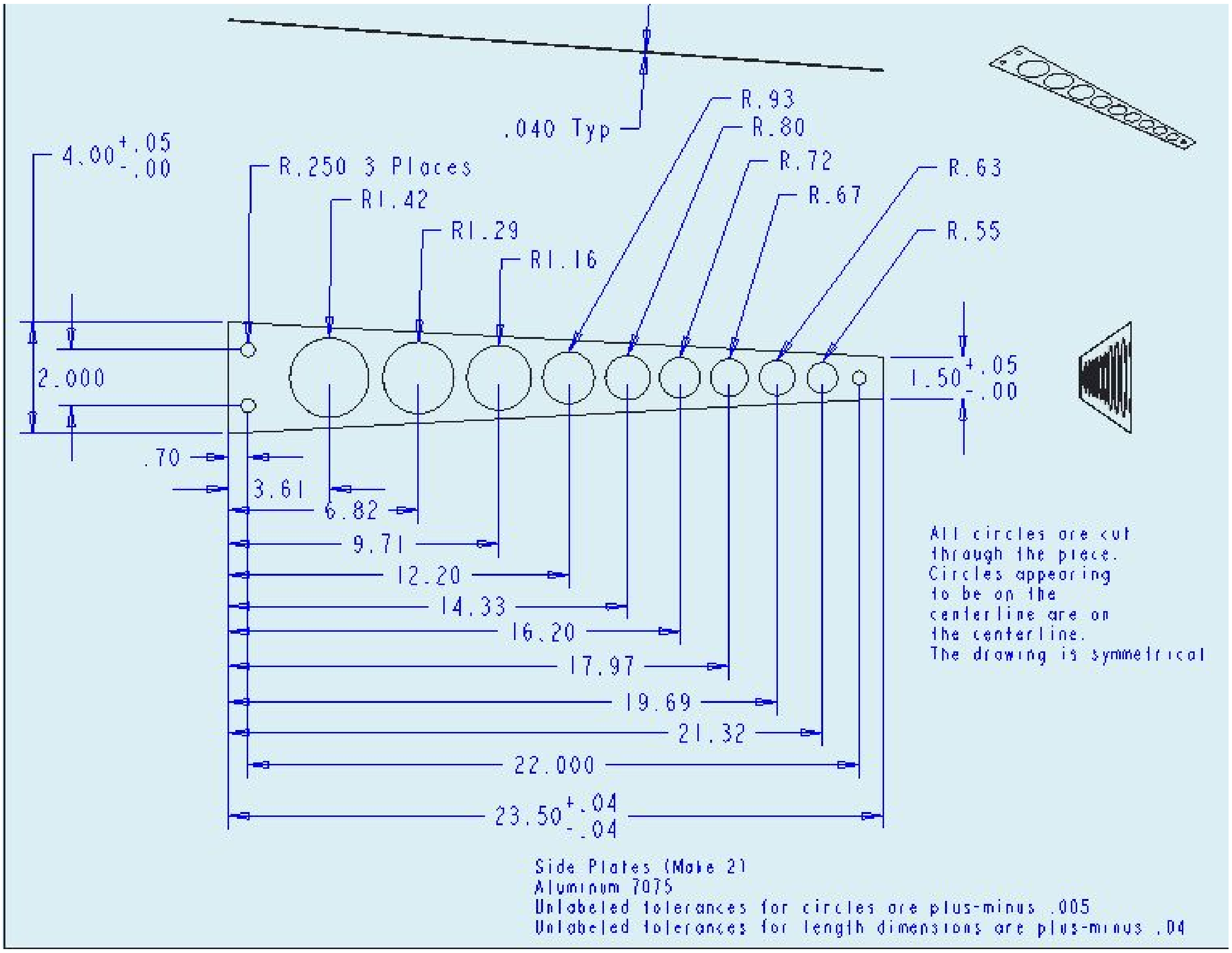
Conclusions

This project will be completed to learn the design and construction process of a lightweight structure (crane). The features of the structure are designed to decrease overall weight and to prevent yielding in areas under the highest stress. The majority of the structure will be built using aluminum 7075, steel and aluminum rivets, and aluminum 6061, placed in specific areas to reinforce the strength of the structure, particularly near the base where stresses are highest, for the minimum weight. After running a Creo analysis on the structure model, the structure is predicted to be able to lift more than the specified 260 pounds and cost $172.64.

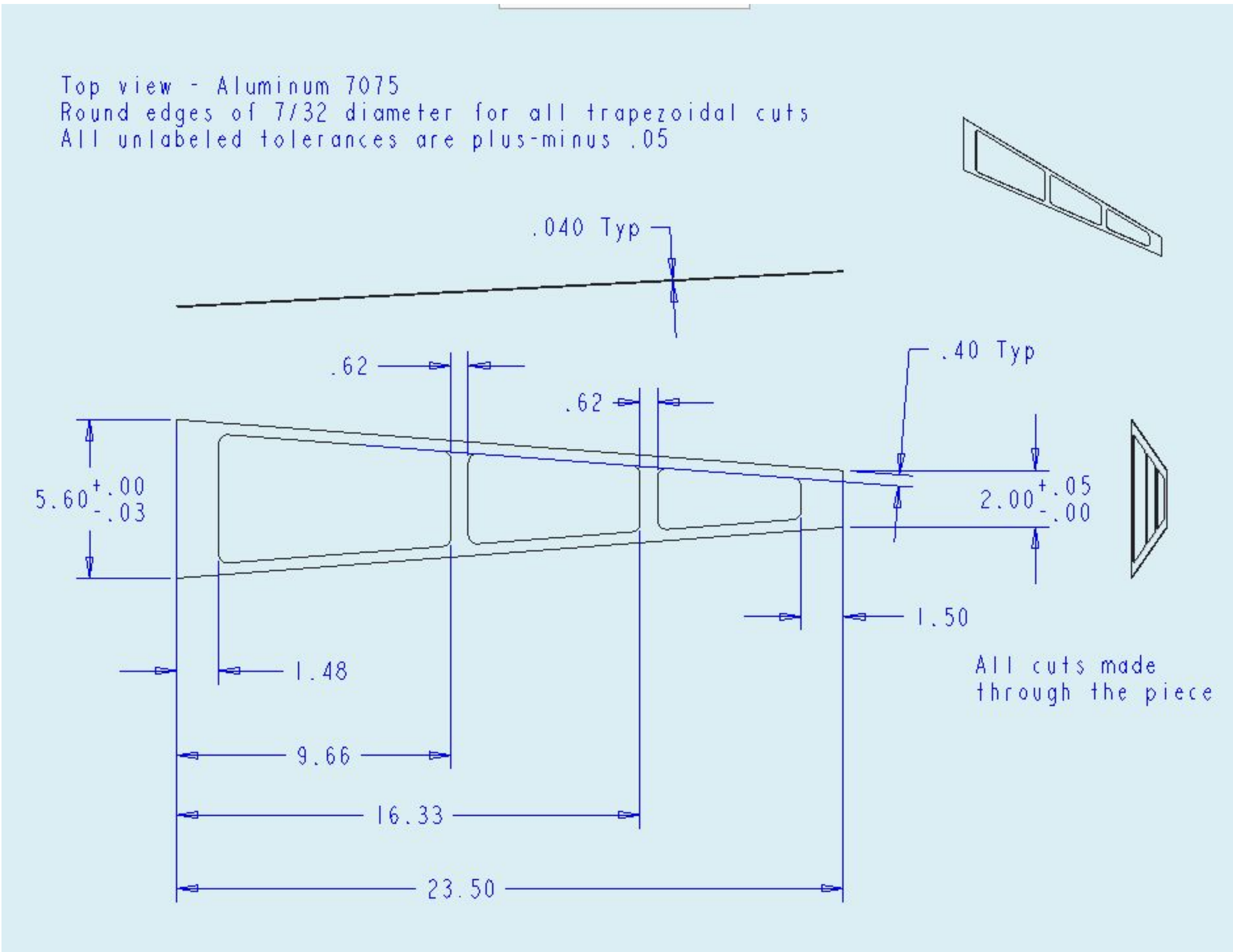
Appendix



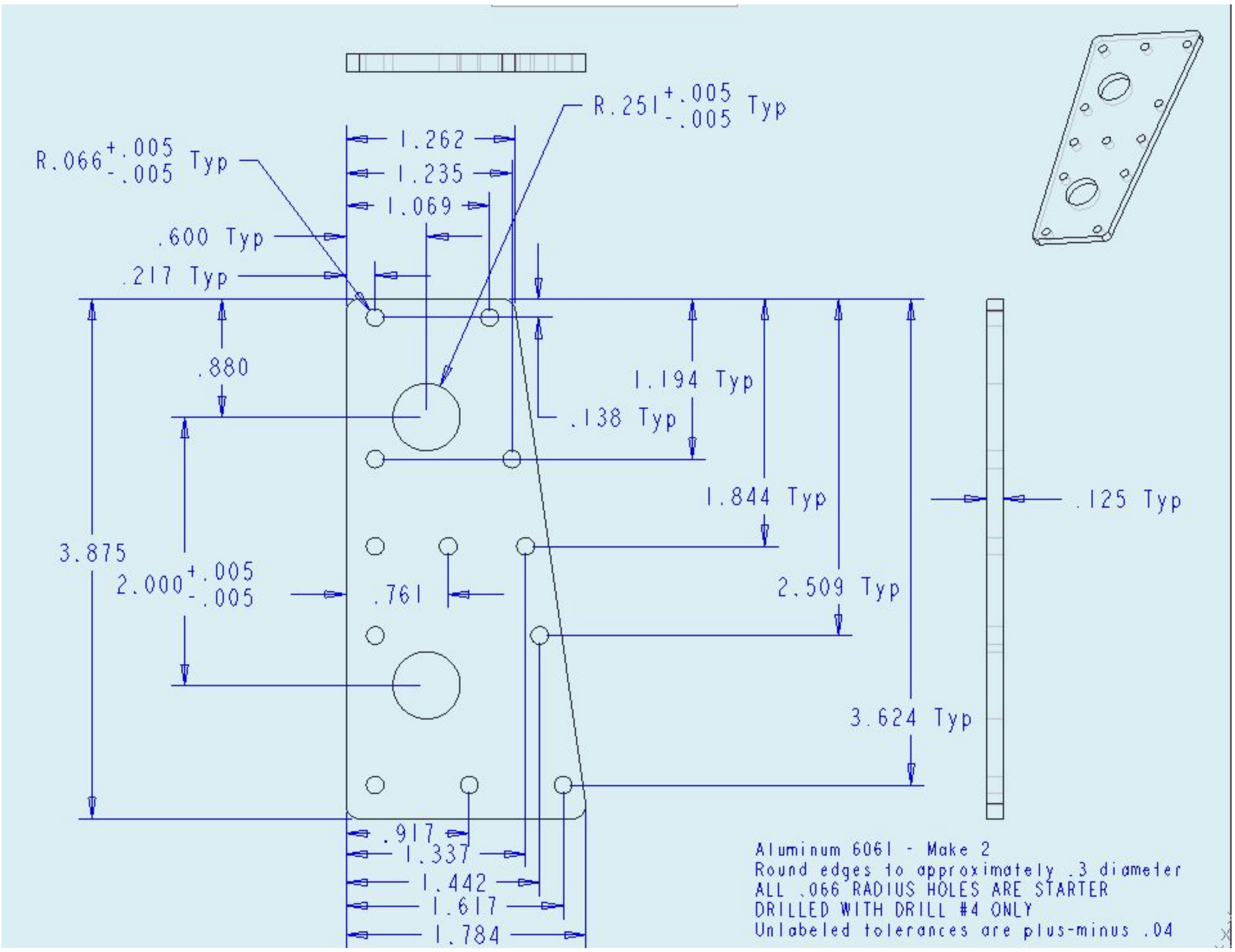
Drawing 1: Bottom of Crane



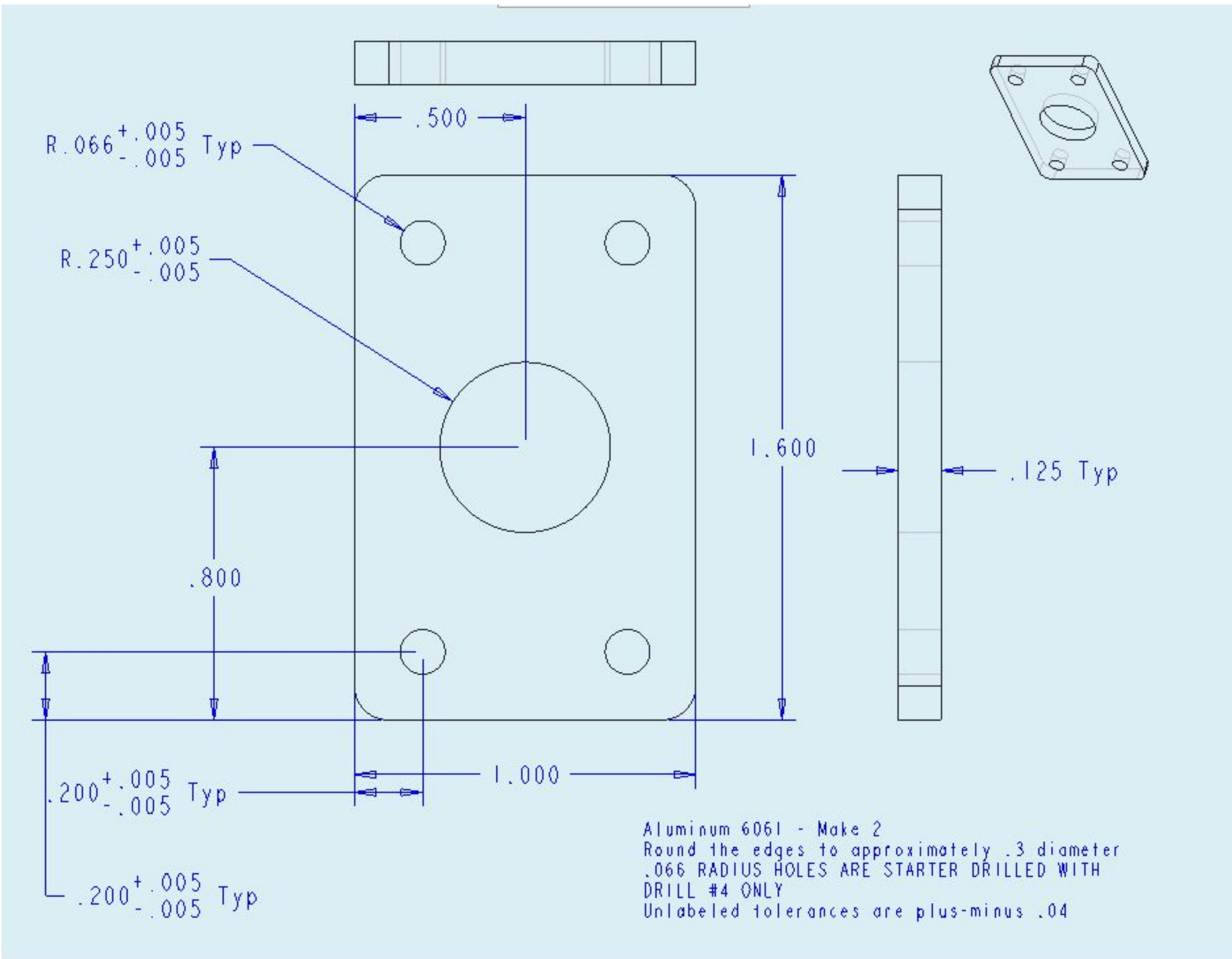
Drawing 2: Side of Crane



Drawing 3: Top of Crane



Drawing 4: End Plate of Crane Near Larger End



Drawing 5: End Plate of Crane Near Smaller End