WING IT! PROJECT

FINAL DESIGN REPORT

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Abstract:

The project goal was to design a wing that could withstand an applied load of 90 lbs at the wing tip while meeting the specified design constraints. The wing was to be as lightweight and inexpensive as possible while demonstrating quality design and craftsmanship. The initial design and analysis were accomplished using Creo Parametric software. Materials used in manufacturing the wing were chosen using a combination of the CES material library and CREO Parametric modeling. Iterative analyses using the Finite Element Method and subsequent modifications of the design were used to find a suitable final design. Once the final design was chosen, a CNC Milling Machine and a WaterJet cutter were used to manufacture the beam and bulkheads, respectively. The skin was cut out with a bandsaw, and the components were fitted together and held in place using aluminum rivets. The assembled wing, which weighed 1.61 lbs and cost $148.88, exceeded expectations by lifting up to 195 lbs and meeting all the specified design requirements. Wing deflection and buckling occurred before complete wing failure occurred, and are two constraints that could have been improved on. This report summarizes the design, analysis and manufacturing procedures of the project and records its results and findings.

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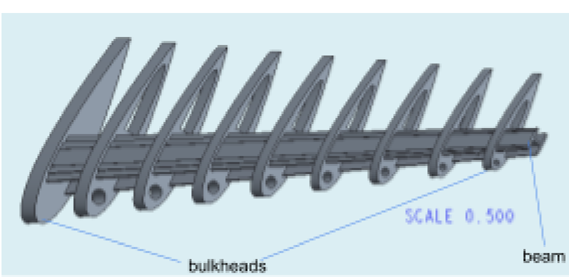
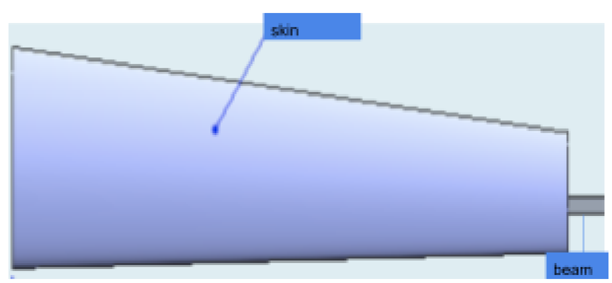
INTRODUCTION

The wing experiences the greatest force of any part of the aircraft during flight. Within the wing itself, the beam supports the majority of the load, which is partially distributed to the bulkheads and the skin. In order to simulate a wing in action, the base end of the test wing was fixed to a support via a series of bolts while a test load was applied to the wingtip. In reality, an airplane wing experiences not only vertical load but also torsional moments. However, as the project goal was only to demonstrate the ability to support a vertical load (the setup of our tests created no torsion), the effects of these moments were ignored in the design and construction.

The wing consists of a beam (or spar), bulkheads, skin, and rivets. The wing acts as a cantilever, so the stress will concentrate towards the root of the wing and will decrease moving towards the tip. Thus, an optimal wing design tapers down so that the chord length decreases towards the tip. The bulkheads are placed along the length of the beam, connecting it to the skin. They reinforce the beam by distributing stresses from the beam to the skin. Their size, shape, and placement are optimized to accomplish this task while minimizing total weight. The bulkheads are connected to the beam and the skin using rivets. Figures 1a-1c (images of previous iterations our wing) illustrate the basic structure of the wing. Major components are labeled.





Figures 1a and 1b: Illustrations of major wing components

As is visible in Figure 1a, some material has been “cut out” or strategically removed from the beam and bulkheads to reduce the weight of the wing. The locations of these cutouts are chosen where stresses are low relative to the rest of the wing. The shape is chosen based on stress profiles, the part’s geometry, and manufacturing concerns. The ideal shapes are usually circles since they often distribute stress evenly.

Therefore, accomplishing our project goal required careful consideration of various design decisions, including beam shape, bulkhead sizes and locations, material removal, and different manufacturing processes. This report explains the design and manufacturing decisions made and offers an analysis of our results.

Before beginning the design process, we built and tested a prototype wing with set specifications given to us. This wing had been designed to meet the same specifications that our design would later be required to meet. This prototype design was intended to support 65 pounds but failed at a test load of around 37 pounds. We then analyzed the method of failure of this wing in order to guide our design process.

DESIGN SPECIFICATIONS

In addition to supporting a cantilevered load of 90lbs, the wing needed to meet the following specifications:

- Constructed from Aluminum or an alloy
- Wing length of 22”
- The beam needs to extend 1 ½” past the last bulkhead
- There must be a horizontal ¼” hole 23 inches from the securing end

- The surface area of one side of the wing needs to be 92 square inches
- The design must make use of the given airfoil shape
- The securing plane uses 4-5 of 10-32 threaded holes 1” apart on the first bulkhead
- Each bulkhead must be no more than 1” in width
- The design must be able to be manufactured using the available tools

TEAM ORGANIZATION AND PROCEDURE OVERVIEW

The team was split into two sub-groups: design and manufacturing. The design team consisted of Ekin, Celine, Bethwel, and Alex (who also worked on material selection), while the manufacturing team consisted of Jacob, Sam, and Erik. In the subsequent 3 weeks, the design team worked on the first iteration of the wing. The team then wrote a preliminary design report and shared their ideas in a presentation. Afterward, the design group (Ekin, Celine, and Bethwel) improved the design by performing several new iterations while Alex worked on finalizing the material choices. During the week of 12/9/19, the wing design was finalized and the materials were ordered. As soon as the materials arrived Jacob, Sam and Erik began manufacturing the parts and assembling the beam. Sam manufactured the bulkheads and finished the beam on the belt sander. Jacob set up and manufactured the beam in the CNC. Erik drew and cut the skin. All three collaboratively made final adjustments to the pieces before the final assembly with riveting. The testing took place on 1/13/20 and the final wing lifted more than 90 lbs of weight while meeting the design specifications.

DESIGN AND ANALYSIS

Creo Parametric 6.0.2 software was used for the design and analysis of the structure. The main design decisions revolved around minimizing the weight of the structure.

Beam

The first and perhaps most important part of the design was the spar beam. In designing the beam, the main goal was to increase the moment of inertia of the beam's cross-section. This involved making sure the majority of the material was as far as possible from the beam's neutral axis. Therefore, we decided to go with an I-beam and tried to add as much material as possible in locations further away from the beam's neutral axis. To achieve this while keeping manufacturing limitations in mind, we designed a wide flange but thin web I-beam. In the first design iteration, the beam had small additional steps on the top and bottom surfaces to increase the moment of inertia of the beam's cross-section (which can be seen in Figure 2). The beam's web, which does not contribute to the moment of inertia as much, was reduced to 0.1″ thickness to decrease the weight of the structure. As discussed earlier in the Introduction section, a cantilever experiences the most stress and bending moment near its connection point. In order to distribute this maximum stress point evenly throughout the beam while decreasing the overall weight, we also tapered the beam. Finally, circular holes were placed under the web and between the bulkhead locations on the beam. These holes were strategically located in the regions where the least stress was noticed as

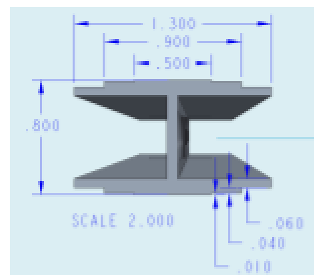


Figure 2: First iteration I-beam cross section

evidenced by the design drawings. This caused about 3% weight reduction while not adversely affecting the stress distribution on the beam.

In the second iteration, we optimized the I-beam cross-section even further by increasing the flange length and curving the top and bottom surfaces. The beam's tapering and the placements of the circular holes were kept the same while three additional holes of diameter 0.19″ were placed on protrusions along the beam. These additional holes held the beam stable during the CNC manufacturing stage. Since the prototype models that were built in-class failed due to the beam detaching from the first bulkhead, the next design decision was primarily focused on its prevention. This called for the development of a unique beam design: the intersecting region of the beam and the first bulkhead was all filled with solid material to break the I-beam pattern from the rest of the beam. As shown in Figure 3, this strengthened the beam to be able to better withstand the stress allocated in that region. It also allowed for an extra connection to be screwed from the wall of the testing mechanism directly into the beam to further improve structural support. For this connection, we had to use the standard 10-32 screws that are mentioned in the design specifications.

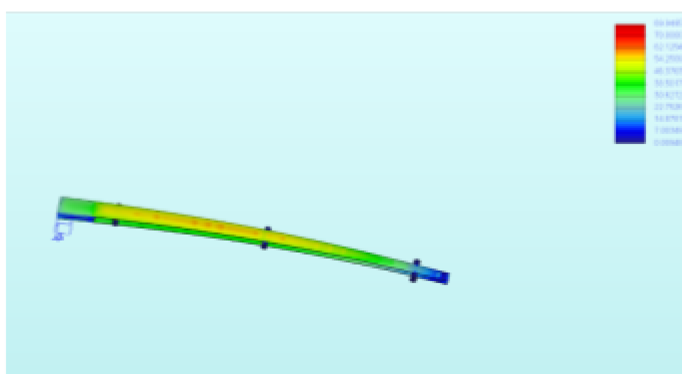


Figure 3: Simulation of the final beam under 120 lbs cantilever load

Our final design, which had AL7075 assigned to it, performed very well in the simulation analyses. Throughout the simulations, we considered a safety factor of 1.33 and applied a vertical load of 120 lbs. Stress was distributed roughly evenly throughout the beam and the maximum stress seen was about 70 KSI, which is slightly above 61 KSI, the yield strength of AL7075. The maximum stress was slightly higher than the material's yield strength, but this was fine because a lot of the stress was going to be taken on by the bulkheads and the skin as well, and this way the design was optimized around the material's limits. Based on these results, this iteration was decided to be the final beam design and the design team moved on to optimizing the bulkheads and the skin.

Bulkheads

The thickness of the airfoil-shaped bulkheads was optimized so that the maximum stress was distributed equally throughout the wing. Prior analyses revealed that while the bulkhead carried the least amount of stress -- the major potential cause of design failure -- it also contributed the greatest weight to the structure. Therefore, we decided to design the bulkheads to remove any mass not contributing to the structural strength. Several iterations were done to determine the best way to remove material without compromising the structural integrity of the wing. In the first iteration of the wing, semi-elliptical shapes and circular holes at the top were cut out from the bulkheads, as can be seen in Figure 4. It was found that removing semi-elliptical holes on the wing reduced the mass significantly without significantly increasing the maximum stress on the structure. Therefore, in the later iterations, bulkhead cut-outs were optimized by using semi-elliptical shapes. The other option that offered a similar advantage was the removal of circular-shaped blocks on the bulkheads. However, this option limited the amount of material that could be removed and attempts to

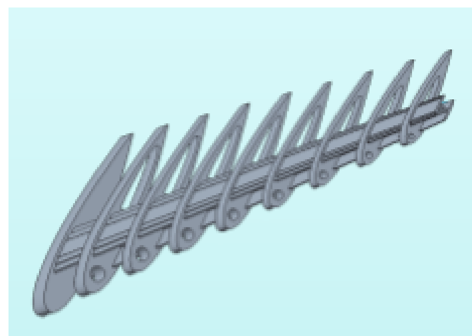


Figure 4: Beam + bulkheads in the first iteration

remove material in any other shapes resulted in concentrated points of high stress on the bulkheads and beam. After the semi-elliptical cut-outs, the end result was a mass reduction of 24%. One important exception to this mass reduction effort was the first bulkhead. No mass was removed from the first bulkhead except for the space to fit in the beam and to drill 4 10-32 holes for attaching the wing structure to the support structure during the wing testing.

Having removed material from the bulkhead, we sought to find the optimal number of bulkheads for the wing. Having performed various simulations with a different number of bulkheads, we settled on having 7 bulkheads. The last modification on the wing was to determine ideal bulkhead thickness. After testing the prototype wings mentioned in the introduction, it was revealed that the extremely high stresses in the first bulkhead could cause the rivets to tear through the bulkhead material, leading the beam to detach from this bulkhead. This caused the wing to fail. As a result, it was decided that we would overengineer the first bulkhead, doubling its width while removing only the necessary material for the required connections. It was determined, therefore, that making the first bulkhead 1 inch and rest of them 0.5 inches wide produced the best design.

Final Design Iteration

After deciding on the beam and the bulkheads, the last step to finalize our wing design was to determine the skin design, for which we decided to go forward with our preliminary choice. To reiterate from the preliminary report, our skin choice consisted of AL2024 sheet metal with a thickness of 0.032 inches, dimensioned in a similar fashion to the prototype models that were built in-class prior to this project. This marked the end of iteration #2.

After iteration #2 was completed, static analysis with 120 lbs of load was run on the entire wing, which included the design choices of the beam, bulkheads, and the skin that were just mentioned. As shown below in Figure 5, there was still a significant amount of stress focused in the region of the beam between the first and second bulkheads. Because we felt that this area of the beam was exposed to structural failure the most, we decided to increase the length of the solid section of the beam a little more, the dimensions of which can be seen in the engineering drawing of the beam in Appendix A.

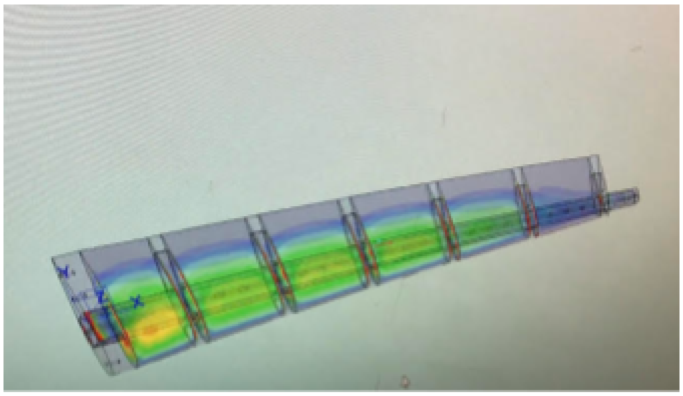


Figure 5: Simulation of the wing after iteration #2

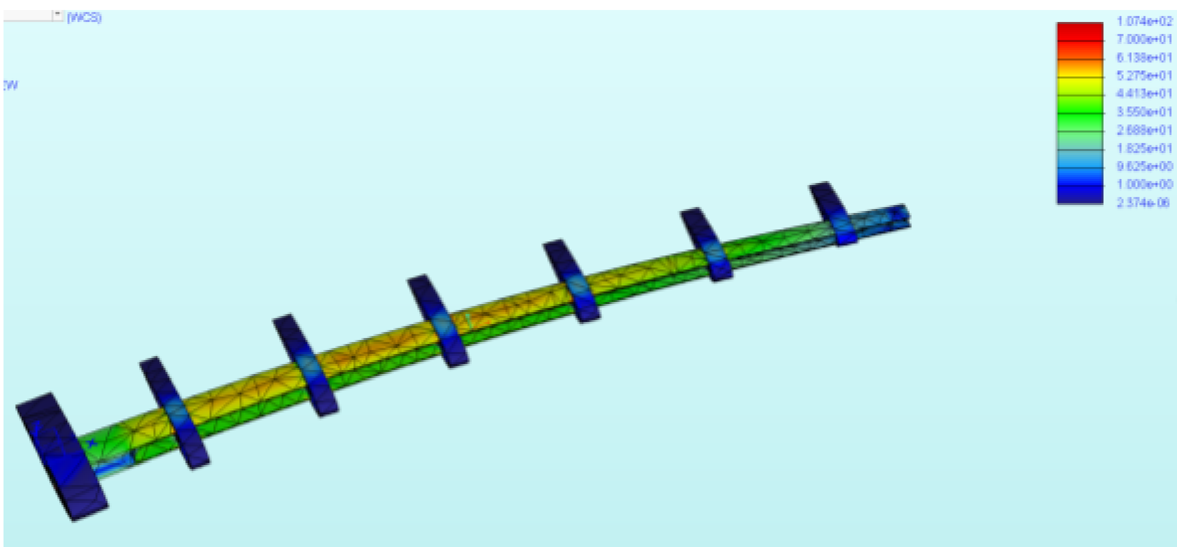


Figure 6: Simulation of the final beam + bulkheads under 120 lbs cantilever load

The simulation results of the beam after incorporating the change mentioned above is shown in Figure 6. As shown, this iteration significantly reduced the amount of stress placed in the region of the beam between the first and second bulkheads, which was the region we were most concerned about failing during the test. The maximum stress on the beam from the simulation was recorded to be near 65 KSI, which admittedly is past the yield strength of AL7075 (61 KSI). This was fine though because we wanted to optimize around the material strength, and a lot of the stress was going to be taken on by the skin as well. Something to note is that in the simulation shown in Figure 6, we did not simulate the wing with the skin; following iteration #2, we decided that the skin did not need further optimization to improve its structural attachment to the wing. Based on this last simulation, this final iteration concluded our design process.

MATERIALS

Creo's Simulate feature, as well as the CES software program, were used to make material selection decisions. CES was used to compare various materials and their properties and relevant materials were imported from CES into Creo.

The design specs required aluminum to be used as the material for the wing. The types of aluminum we considered were those available from McMaster-Carr supply company. The three products offered in the necessary dimensions and at a reasonable cost were Al2024, Al6061, and Al7075. The material qualities of these types were compared through the information available on McMaster as well as information from CES. All being varieties of aluminum, there was virtually no difference in density between them. Al7075 was a promising choice due to its very high yield strength, with Al6061 being the most economical option, while Al2024 served as a solid intermediate between the two criteria. Due to the very high simulated stresses in the beam, Al7075 was chosen as the material for this section of the wing. Al2024 was also considered as a possible option, but it was determined that the Young's Modulus was too low, causing unacceptable deformation in the wing structure.

Having previously removed as much material as possible from the bulkheads without compromising manufacturability, it was determined through further simulations that using Al6061 would not compromise their ability to withstand generated stresses. An exception was made for the first bulkhead, which we chose to manufacture from Al7075 due to the high stresses experienced by this component. Due to the skin's limited thickness, it can only resist very small compressive forces before buckling but performs much better under tension. Due to the design and forces applied to the wing, the top skin experiences mainly tensional forces while the bottom skin experiences mainly compression. Thus it was determined that the bottom skin should be made from the cheapest and most lightweight material as it does not contribute to the structural rigidity of the wing. Since the top skin is able to bear some of the load, it was determined that it should be made from a stronger material. In the interest of reducing costs, it was decided that both skins should be made from the same material. Thus Al2024 was settled on due to its ability to be shaped more easily than Al7075 and Al6061, as well as its increased strength over Al6061.

MANUFACTURING AND ASSEMBLY

Beam

The beam was cut from a 1" x 1½" x 24" bar of 7075. A single 5-stage operation was designed to cut one channel of the I-beam design, drill the holes through the web, and mill half of the curved upper and lower surfaces. First, a ½" end mill was used for a volume rough and to cut away the majority of the excess aluminum that surrounded the beam's profile. A second volume rough was then performed by a ¼" end mill to cut out most of the channel, followed by a 3/16" end mill for the holes through the web as well as the narrower sections of the beam channel. A ⅛" end mill was used to cut the three smallest holes at the far end of the beam. The final stage of the operation utilized a 3/16" ball mill to perform a surface mill on the curved top, bottom, and sides of the beam's flanges. Once done, the beam was flipped around and the operation repeated to profile the remaining left side.

To secure the beam to the CNC mill during the operation 3 housings built for 10-32 bolts were added through the sides along the length of the beam. Following the successful completion of both sides of the operation, they were removed using a belt sander.

During the manufacture of the first side, the tool holder securing the ⅛" end mill broke the clearance plane and made contact with one of the securing bolts due to its height, the short length of the ⅛" end mill, and the proximity of the smallest hole to that housing. The operation was paused, the single housing shortened with a larger end mill, and then the operation was completed. To compensate for the uneven height, a small shim was added beneath that housing to secure the beam correctly for the second operation. Aside from a busted bolt and a scuffed tool holder, ultimately this had no impact on the ability to manufacture the beam as originally designed.

Due to vibrations milling the second side of the beam, the curved surfaces did not align exactly, but the error was within an allowable margin and was further reduced by using the belt sander to even out the beam. There was negligible impact on the overall assembly process; the bulkheads still fit on the beam in their intended locations.

Bulkheads

The bulkheads were manufactured by using a waterjet to cut the bulkheads out of aluminum plates. The plate of 7075 used to cut out the first bulkhead came from the shop 1" thick and the plate used to cut out the 6 bulkheads made of 6061 came ½" thick, which was already the desired thickness for all the bulkheads so there was no need to adjust the thickness of the plates. All that had to be done was to cut out around the edge of each bulkhead from the aluminum plates. This was accomplished on CREO by creating a drawing of the bulkheads in their respective metal plates and then converting to a DXF file that the waterjet could read. After the bulkheads were cut out by the waterjet all edges of the bulkheads were deburred.

Skin

Two 2024 aluminum sheets were cut to the designed size using a bandsaw. Because the tolerancing on the skin was fairly high there was no need to use a more precise measurement. After assembling the skin on the top, it was apparent that it was too difficult to bend the front edge of the skin over the curved front of the bulkheads. As a result, it was decided to trim the front end of the bottom skin using the bandsaw to prevent the overhanging skin that existed on the top end of the wing. About ½" was removed from the front of the skin by the first bulkhead and about ⅛" was removed from the front of the skin by the smallest bulkhead.

Assembly

First, each of the bulkheads was slid into place on the beam. The skin was fastened to the bulkheads and beam using aluminum rivets from 0.160-0.164 inches in diameter. Two different grip-ranges were used depending on the size of the penetration.

The top skin was attached using five rivets in the first four bulkheads, four rivets on the fifth bulkhead and three rivets on the s. On these bulkheads, the rivet closest to the leading edge held the front of the skin down, curving it along the front of the bulkhead to mimic the airfoil shape. However, there was some overhang on the front edge due to the stiffness of Al2024. The second and third rivets from the leading edge penetrated through the skin, bulkhead and a flange of the beam on either side of the web, thereby securing the skin not only to bulkhead but to the beam itself. The fourth rivet from the leading edge was placed between the beam and the tail edge for increased strength due to the expectation of high stresses in the skin at that location. The final rivet was placed at the tail edge that penetrated through the end of bulkhead both the top and bottom layers of skin in order to form the skin to the shape of the bulkhead towards the tail edge. The other bulkheads had a similar layout of rivets except they were all missing the third rivet (the second rivet through a flange of beam) and the smallest two bulkheads were missing the fourth rivet as well. The reasons for not including these rivets on the smaller bulkheads include space constraints as well as lower expected stresses in the skin on the smaller end of the airfoil closer to the weight.

The bottom skin was secured using only three rivets in each bulkhead except for the smallest bulkhead which had only two. The rivets were located at the leading edge of bulkhead (except for the smallest bulkhead due to space constraints), through both the bulkhead and the front flange of the beam, and at the trailing edge of the bulkhead that connected both the top and bottom skin to the bulkhead. Fewer rivets were used because the bottom surface was not expected to bear much of the weight. Additionally, there was little overhang over the leading edge of the airfoil because the bottom skin was trimmed as previously mentioned.

Finally, the leading and trailing edges of airfoil were duct-taped to add some strength and to aesthetically make the wing look closed and complete.

RESULTS AND CONCLUSION

The results from our current design show that the introduction of holes in the beam resulted in a 5% weight reduction while the conical cutouts resulted in a 20% weight reduction of the wing.

The beam is evenly deflected under 155lbs load

Catastrophic failure occurred at the 2nd bulkhead

On January 13, 2020, our wing arrived at the machine shop for testing, weighing in at 1 lb, 9.8 oz at a total material cost of $148.80. First, it was subjected to 65 lbs of weight, holding this easily and experiencing only a 2 ½ inch deformation. Next came the 90 lb weight, which, to the entire team's relief was held by the wing, causing a 3 ½ inch downwards displacement of the wingtip. The beam deformed almost exactly as intended, creating a relatively uniform distribution of stress along the entire length of the wing, as seen by the smooth arching of the wing and gradual buckling in the figure.

Signs of buckling and plastic deformation escalated and became more widespread as the weight was increased, yet the wing managed to hold just under 200lbs before total structural failure. The rivets holding the skin onto the thickest bulkhead at the very base of the wing signaled the beginning of the end as they popped off like buttons. The first rivet to fail was the second one from the leading edge, which grasped one flange of the beam, followed by the fourth, followed by the third. Once the rivets popped the top skin was no longer bearing any of the weight. This dramatically increased the load on the beam leading to a catastrophic failure. The beam fractured in the middle of the second bulkhead from the base. This fracture occurred at the line of rivets that connected the skin to the bulkhead and the beam.

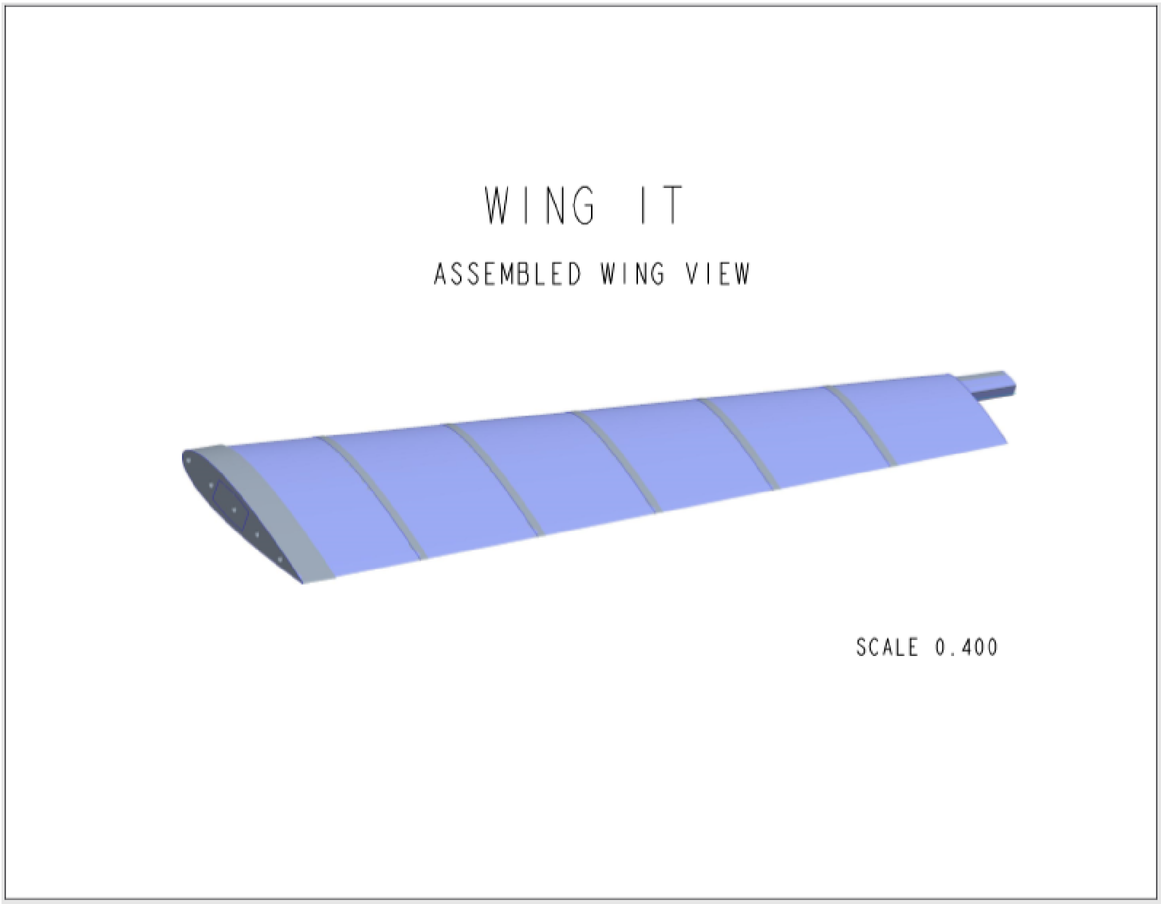
The beam failed because it simply was not designed to carry nearly 200 lbs. Even at smaller loads, the beam was failing just not catastrophically. The deflection of the beam even at lower weights was fairly large and the beam was already beginning to buckle. It would have been very risky to design the beam in a way that would decrease its strength in favor of weight because the beam was already starting to fail at our intending weight goal and had there been a significant manufacturing error the beam likely would have catastrophically failed even sooner.

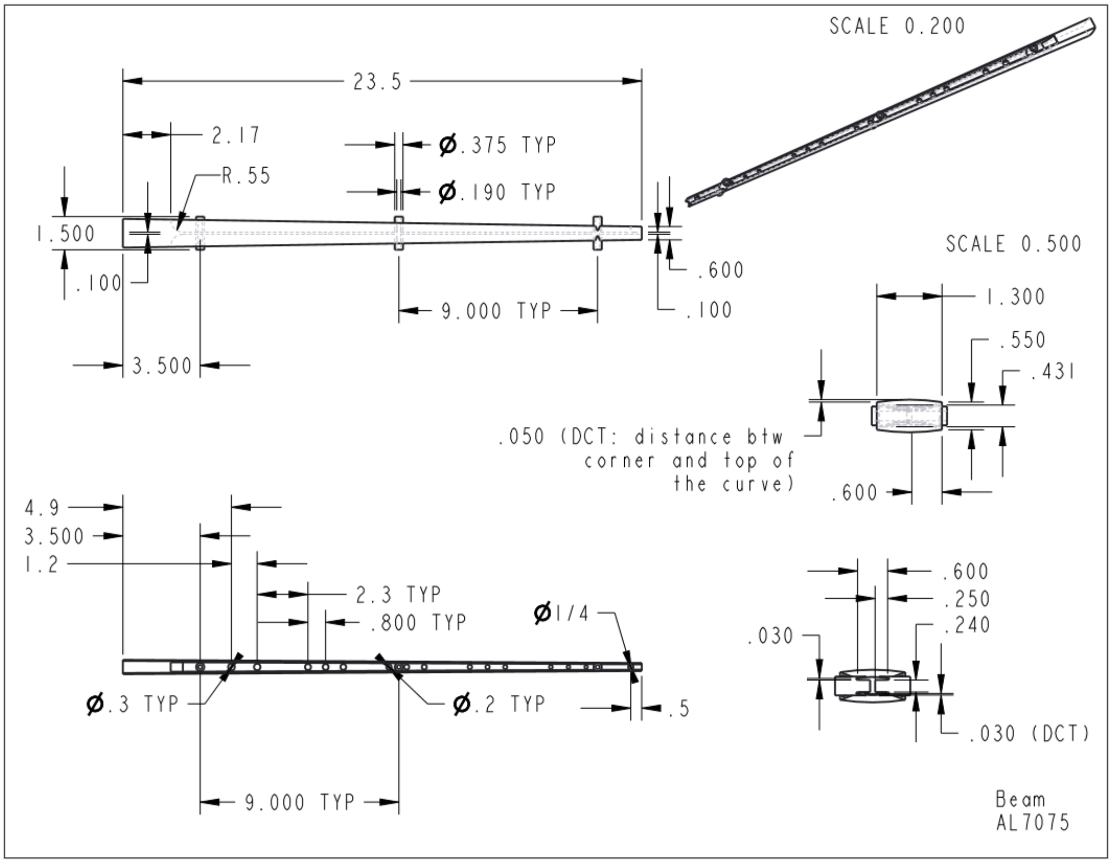
There are a couple of ways the design could have likely improved without compromising its strength too much. One method would be to create more hollow areas in the first bulkhead. This bulkhead was entirely solid and a full inch thick and made of Al7075 making it one of the strongest parts of the entire airfoil. The reason we made it that way was because in each of the example wing tests that bulkhead failed, so we made the first bulkhead as strong as reasonably possible. However, it would have been possible to maintain much of that strength while hollowing out a couple less important areas to save weight. For example, the area between the set screws likely could have been hollow without substantially compromising the strength of the bulkhead.

Another way some weight likely could have been saved would be to decrease the number of bulkheads. This would have increased the stress in the skin potentially a lot depending on the number of bulkheads removed, but it also would have saved a lot of weight because a bulkhead is quite heavy.

Finally, a lighter material could have been used as the bottom skin of the airfoil. The bottom skin supported very little of the load and was therefore mostly useless and just adding dead weight to the airfoil. The bottom surface could have been a material such as aluminum foil and the airfoil would probably have performed similarly without wasting too much weight. However, if the goal were to actually use the airfoil as a wing, you would probably still need a relatively strong material there anyway.

APPENDIX A: DRAWINGS

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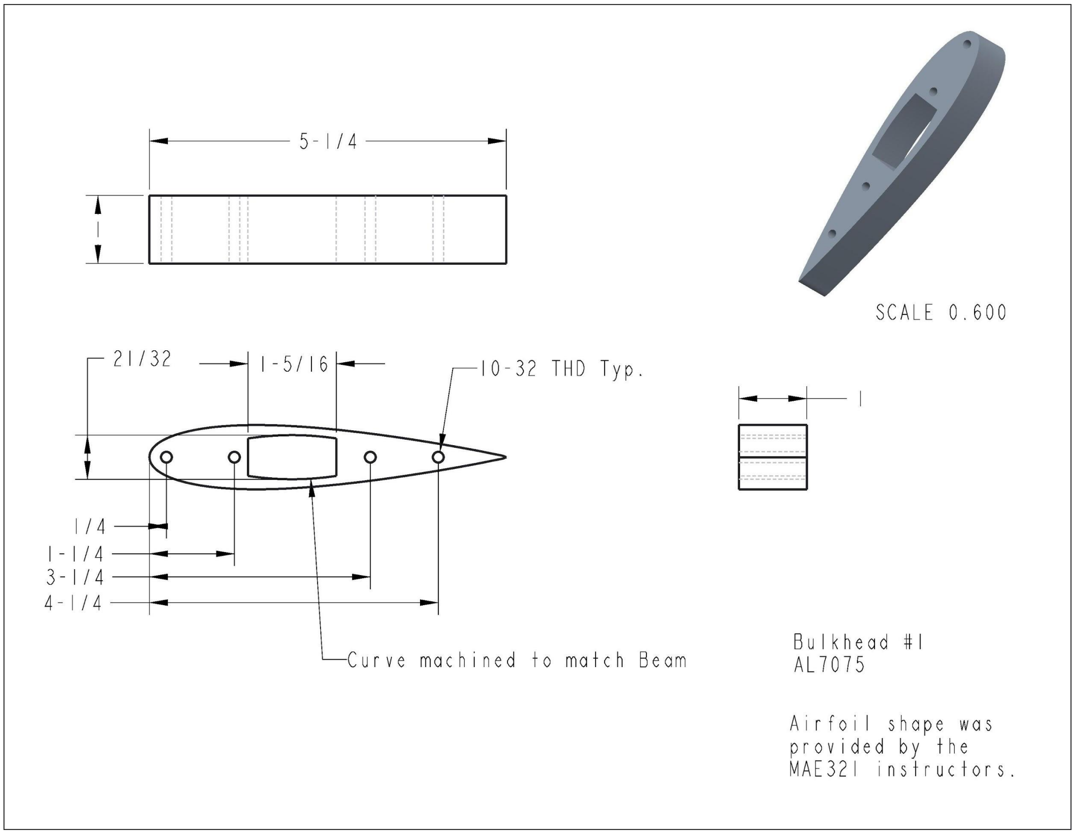
Beam
AL7075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Curve machined to match Beam
Bulkhead #1
AL7075
Airfoil shape was
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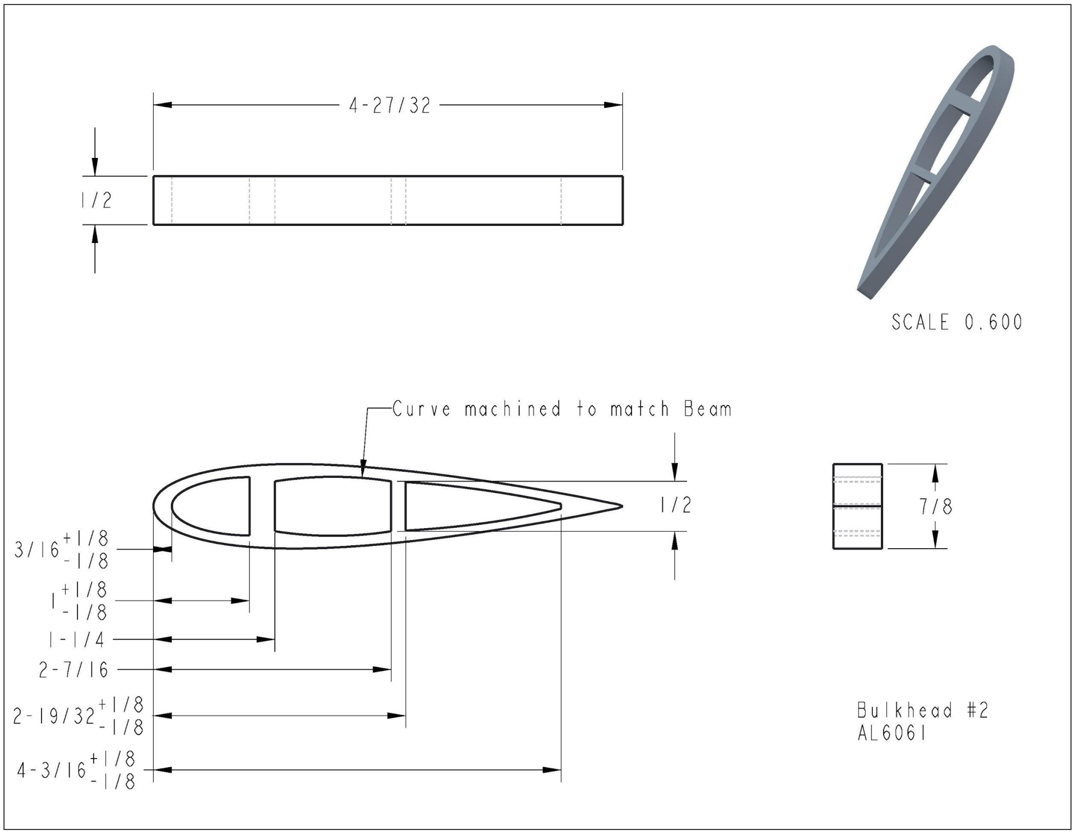
MAE321 instructors.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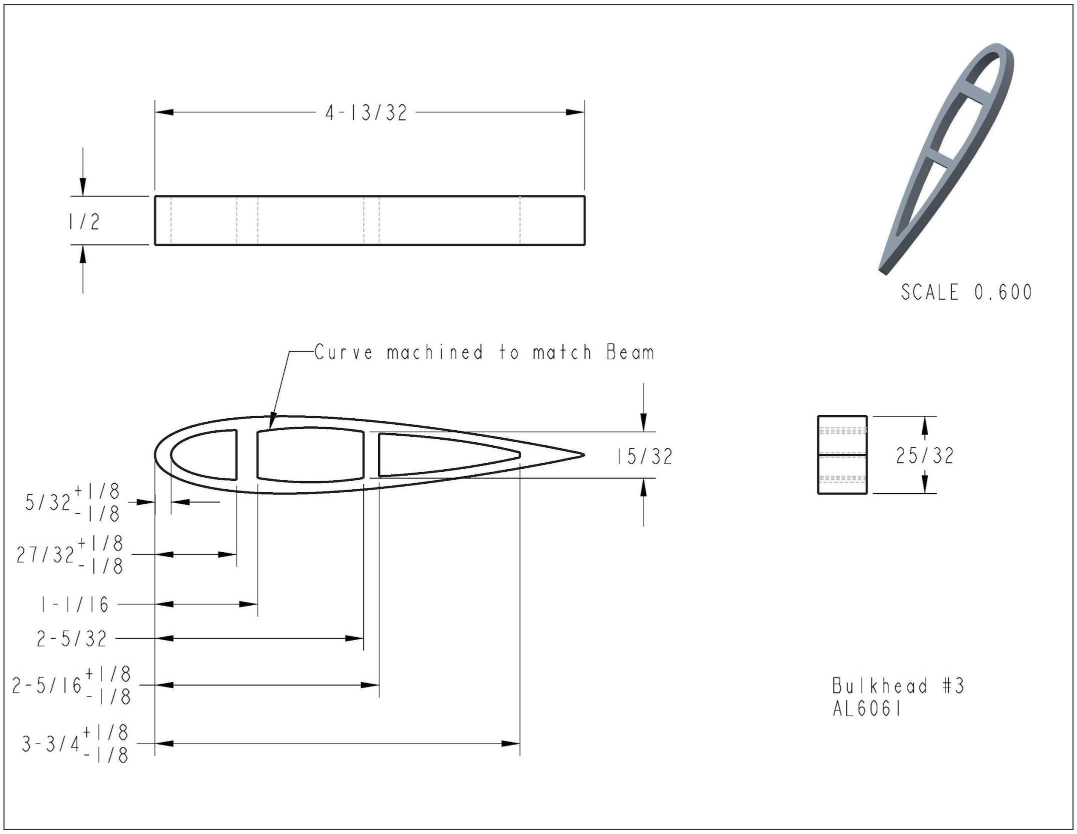
AL6061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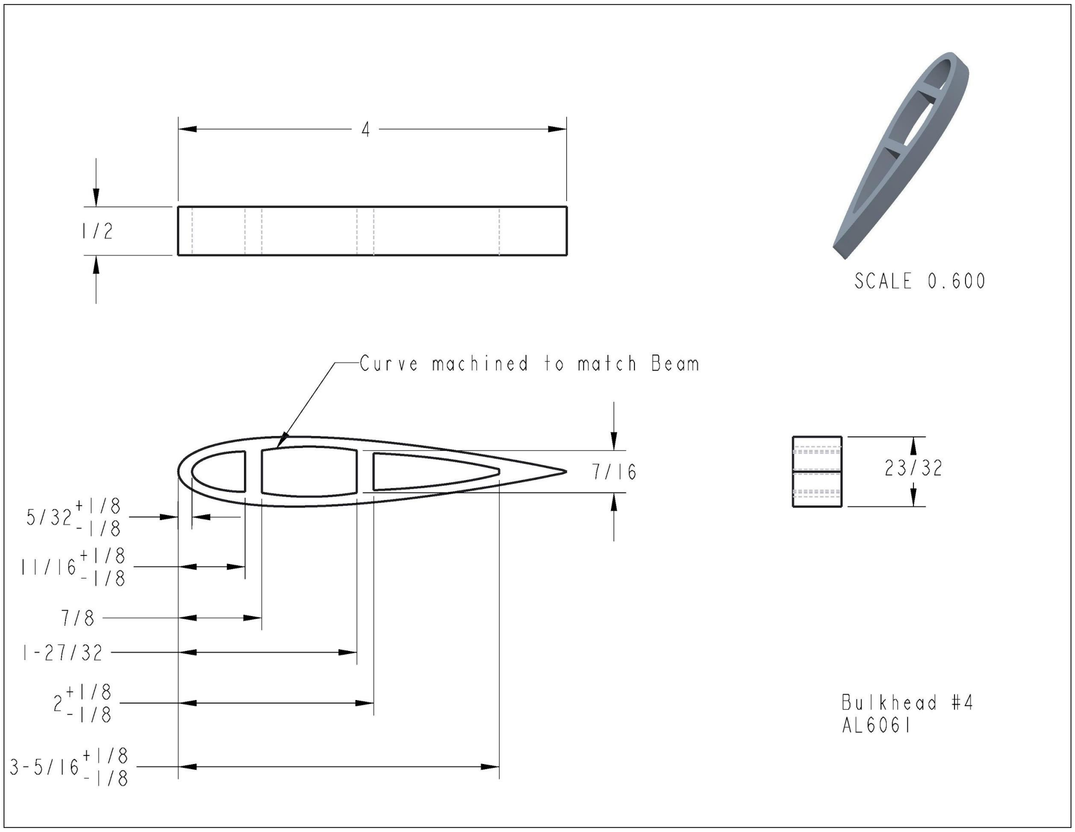
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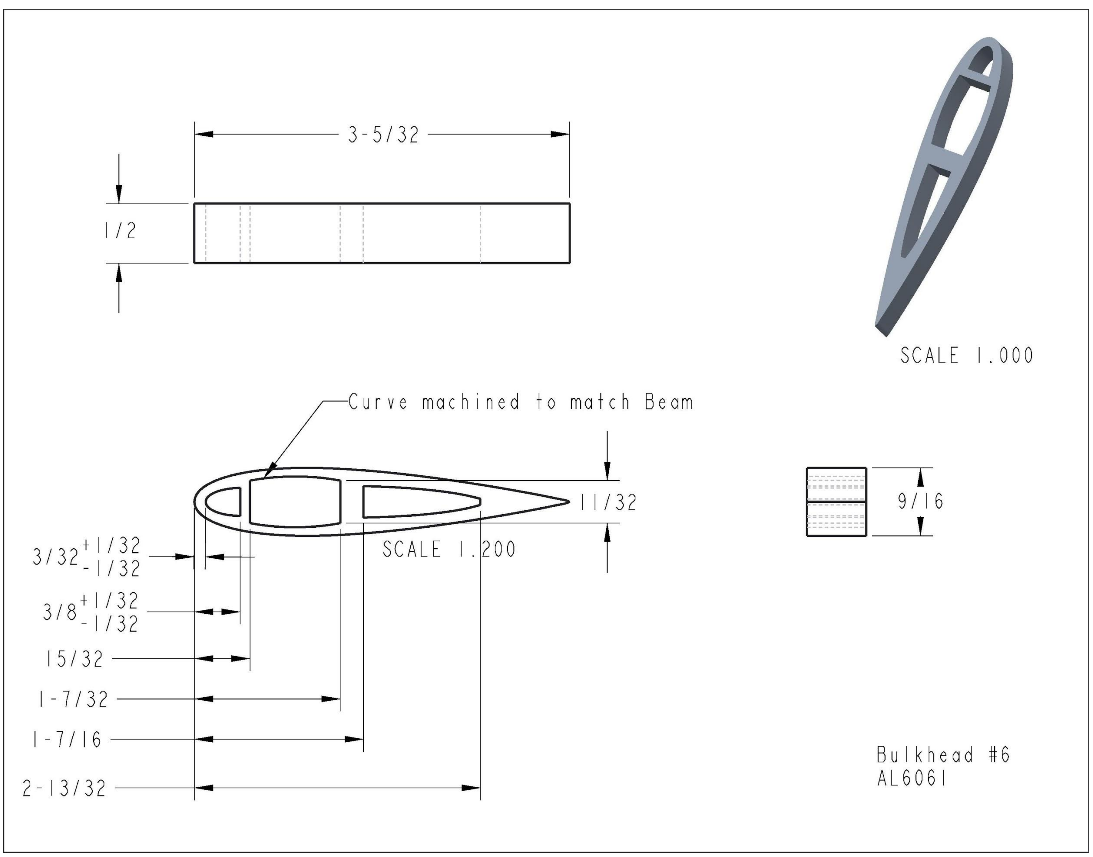
AL6061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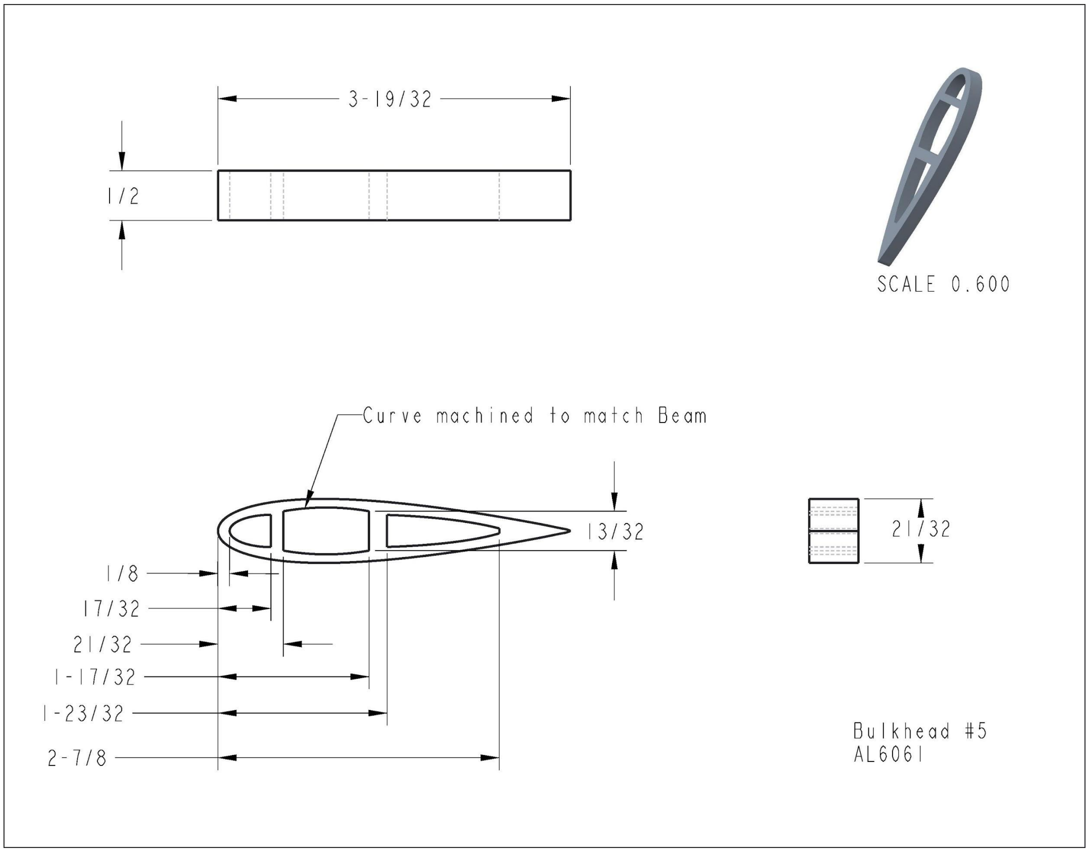
AL6061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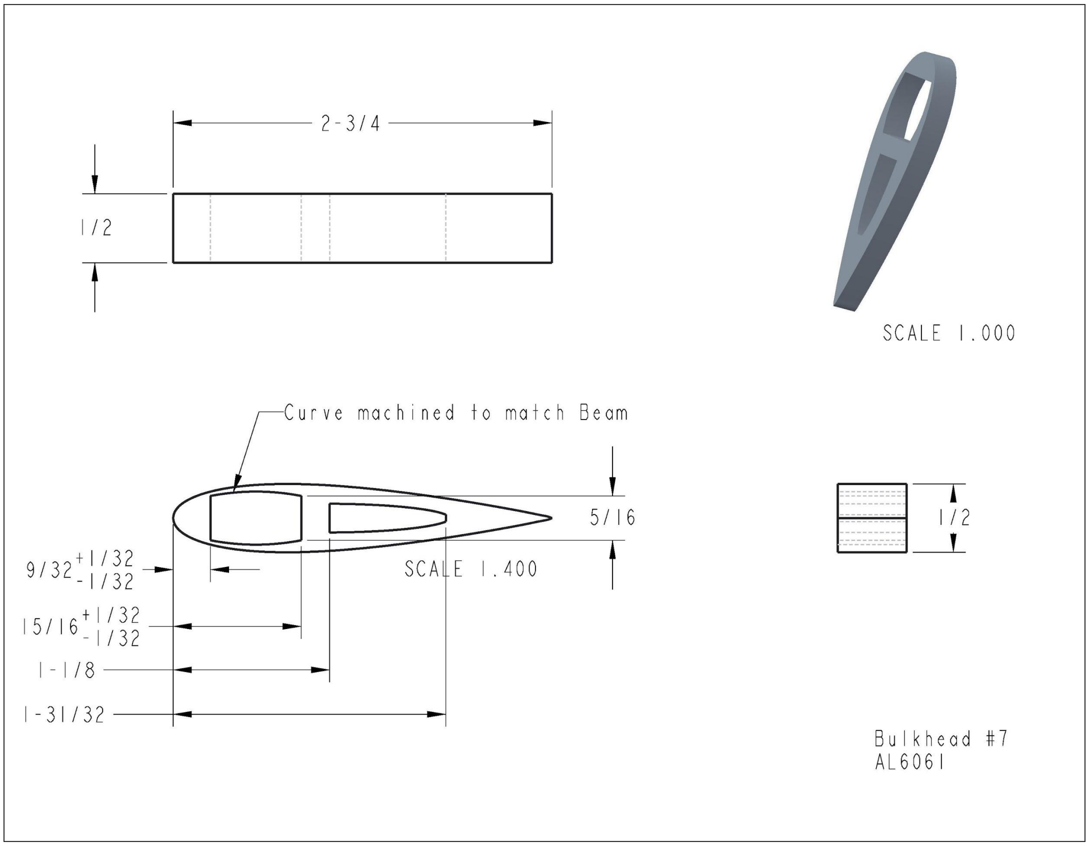
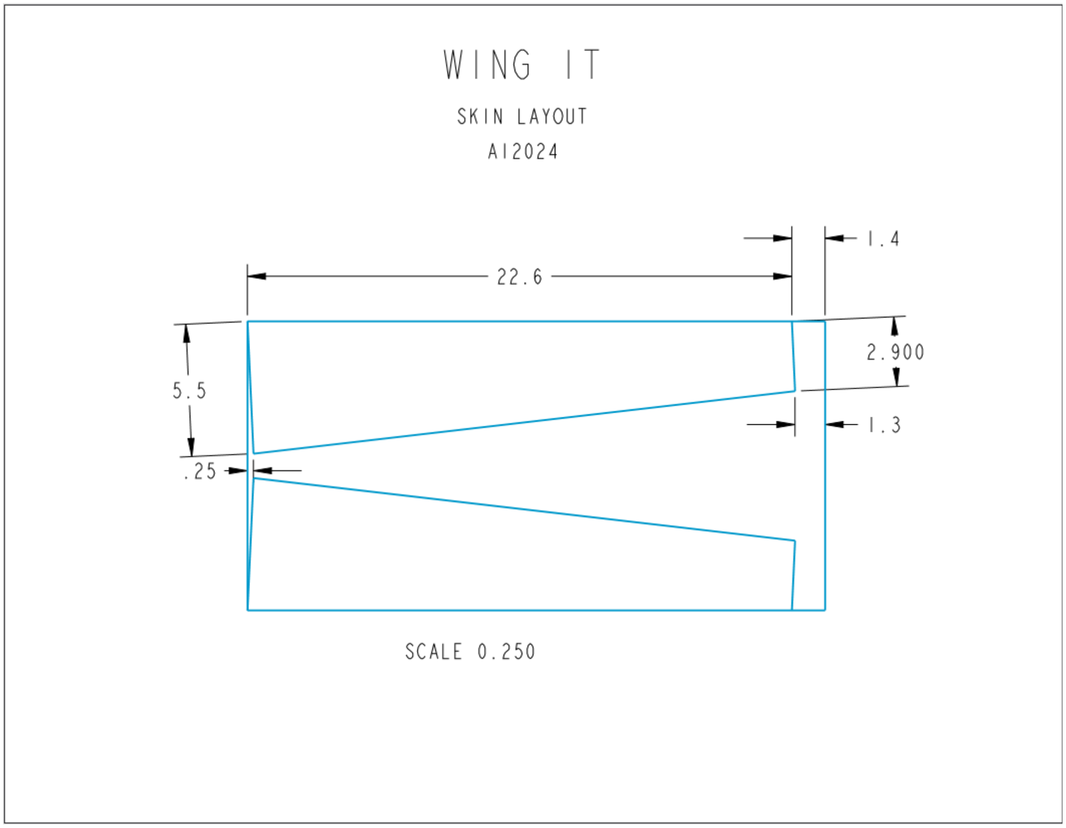
Bulkhead #5
AL6061


2-3/4
1/2
SCALE 1.000
Curve machined to match Beam
5/16
9/32 +1/32 -1/32
SCALE 1.400
15/16 +1/32 -1/32
1-1/8
1-31/32
1/2
Bulkhead #7
AL6061


WING IT
SKIN LAYOUT
Al2024
22.6
1.4
2.900
1.3
5.5
.25
SCALE 0.250

APPENDIX B: BILL OF MATERIALS

Beam

ITEM	QUANTITY	UNIT PRICE	COST
Al7075 - 1”x1.5” bar	26.5”	\$3.28/in	\$87.02

Bulkheads

ITEM	QUANTITY	UNIT PRICE	COST
Al6061 - 0.5” sheet	6”x6” (36 in^2)	\$0.517/in^2	\$18.60
Al7075 - 1”x1.5” bar	6”	\$3.28/in	\$19.70
			\$38.30

Skin

ITEM	QUANTITY	UNIT PRICE	COST
Al2024 - 0.032” sheet	24”x9” (216 in^2)	\$0.101/in^2	\$21.86

Combined Structure

ITEM	QUANTITY	UNIT PRICE	COST
Al2024 - 0.032” sheet	24”x9” (216 in^2)	\$0.101/in^2	\$21.86
Al6061 - 0.5” sheet	6”x6” (36 in^2)	\$0.517/in^2	\$18.60
Al7075 - 1”x1.5” bar	32.5”	\$3.28/in	\$106.72
Al Rivets 0.188"-0.25"	50	\$0.034/rivet	\$1.70

TOTAL COST	\$148.88

APPENDIX Z: RUBRIC

Design Report:

Complete with:		**Status**	**Delegated to**
Simulation	15 pts	Complete	Bethwel, Celine, Ekin
Engineering Drawings	20 pts	Complete	Bethwel, Celine, Ekin
Material list with cost	10 pts	Complete	Alex
Individuals input	15 pts	Complete	Everyone (Lead: Alex) *Make sure everything you did is included in "Team Organization"*
Iterations/proof of choices	10 pts	Complete	Bethwel, Celine, Ekin
CES	10 pts	Complete	Alex
Overall organization	20 pts	Complete	Alex, Jacob, Sam, Erik

Other

Manufacturing write up		Complete	Sam, Jacob
Test Results		Complete	Erik