Final Design Report

Human Powered Helicopter: Rotor Structure

Joseph Ram;Mechanical Engineering
Carlos Olvera; Mechanical Engineering

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Some material, namely the FEA Analysis, was completed by Nicholas Luzuriaga.

CHAPTER 1: INTRODUCTION

The following report encompasses the Human Powered Helicopter Rotor Team's conceptual models and ideas based on research and modeling analysis. The following gives an overview of material researched, concept generation, analyzation, manufacturing, and testing for a rotor structure to be installed in a Human Powered Helicopter.

BACKGROUND

The greatest and most sought after achievement for human powered vehicle enthusiasts is the coveted Sikorsky prize. The Sikorsky prize was introduced by the American Helicopter Society in 1980[1] and has never been attained, despite an offer of $250,000 to the first person or group that can meet the criteria. The idea is very simple; construct a controllable human powered helicopter. The algorithm, however, is very complicated. The amount of power that one man would need to produce to achieve the appropriate amount of lift is nearly equal to the amount of power a human can output. Here is a summary of the criteria:

- Must be continuous, human powered flight for 60 seconds.
- Cockpit must stay in a 10 meter by 10 meter box
- The helicopter must reach a height of 3 meters
- There may be no energy saving type device on the aircraft
- 1 non-rotating member
- No material may be jettisoned from the aircraft

The rest of the rules can be seen on the official AHS Igor I. Sikorsky Human Powered Helicopter Competition rules page.[5]

Ideas for design have largely varied; from the one rotor Cal Poly Da Vinci III design[8] to the quad rotor University of Maryland Gamera[4]. Although there has been a wide variety of ideas, not much documentation and research has been done on human powered helicopter flight. Dr. Paul Macready, the man who constructed the first human powered aircraft, put it this way when asked about constructing a human powered helicopter, "It can be done, but the task is huge, and the dollar prize not worth the time expenditure. There are many more exciting, never-been-done-before challenges that can be accomplished with much less work."[2]

While there are people that refuse to agree with this logic, data hasn't been attained and written works regarding human helicopter flight is far and few in between. In response to this, Cal Poly has decided to have Mechanical Engineering senior projects publish data pertaining to low speed helicopter flight. One of the senior project teams last year, led by Eric Behne[1], did just that: valuable data was compiled regarding varying slow rotational blade speeds at varying low heights. This data, along with data compiled this year, will greatly increase Cal Poly's chance at achieving the Sikorsky Prize.

Currently, there is only one competitive Human Powered Helicopter, which hails from University of Maryland. The largest flight time for Maryland's Gamera is 11.4 seconds, which sets the record for American flight and for flight from a woman. Other attempts have been previously recorded, most notably the Cal Poly Da Vinci III and the Yuri I. The Yuri I also utilized the quad-rotor design, and currently holds the record for flight duration and height. In 1994, it officially achieved an altitude of 0.2 m and a time of 19.46 sec with a drift of 9.95 m.[6] Though other attempts have been made, most were less successful than the previous.

The biggest advantage of low altitude flight is something called the "ground effect". The ground effect is a phenomenon that occurs when the helicopter hovers low to the ground. At extremely low altitudes, the down-wash from the blades is deflected from the ground. This deflection results in smaller wingtip vortices, thus less drag; see Figure 1[1]. A helicopter can greatly increase lift by flying extremely low to the ground, and raw data was compiled from the senior project team mentioned above.

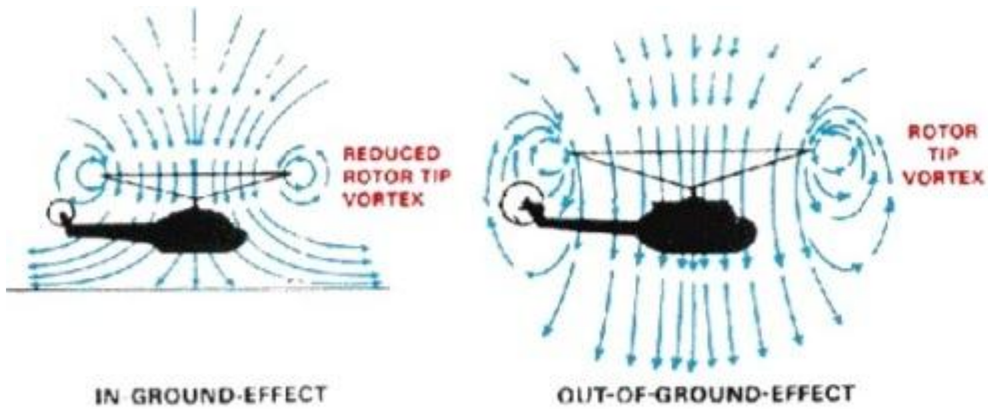


Figure 1. Visual interpretation of the ground effect for a rotor aircraft.

In terms of hub design and attachment, there are many different ways that the rotor can attach to the central hub. Each hub type has its own advantages and disadvantages, mostly in regard to weight restrictions and rigidity. A fully articulated hub is one that allows each rotor to move independently on hinges, and on modern helicopters, is controlled by the pilot[7] as demonstrated in Figure 2. While structurally it is advantageous to allow each rotor to move independently, the installed hinges will add unnecessary and unwanted weight.

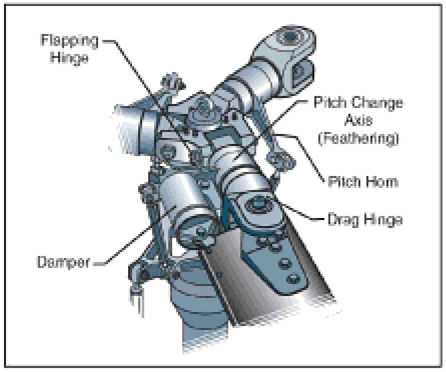


Figure 2. Drawing of a modern application for a fully articulated hub.

A rigid type hub is installed in most of the current human powered helicopters due to its lightweight design, and forces like "flapping" are absorbed into the structure itself, and result in bending. A semi-rigid hub allows for limited movement, as the hub acts somewhat as a seesaw. If flapping is induced into the rotor system, the blades flap together: one blade flaps up as the other flaps down,[7] discernible in Figure 3. This type of rotor hub is applicable to an even number of blades.

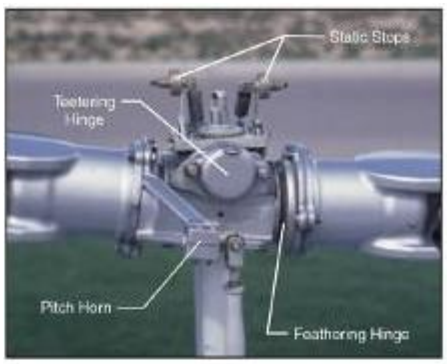


Figure 3. Annotated drawing for a semi-rigid rotor.

The fly-bar system attempts to "balance" the rotors by introducing hanging weights perpendicular to the rotors in a 2 part rotor system. While this system does have its advantages, extra weight is a major concern on a human powered helicopter and the system will typically be inadequate for the application.

One of the most major concerns for helicopters is the issue of coning. Coning is induced on the rotor blades when lift forces are applied to the airfoil, and the rotor itself will bend under these forces[7] , see Figure 4. The lift vector that is applied to the rotor blades is perpendicular to the blades itself, therefore, when coning is induced, lift is lost in the system. Since the person flying the helicopter barely produces enough lift to lift the whole system, losing lift is the most detrimental occurrence to the human powered helicopter. Lastly for the human powered helicopter, since the rotor blades move very slowly, most of the lift is produced in the furthest third of the blade itself. This is also where coning of the rotor blades is most affected, thus drastically reducing lift.

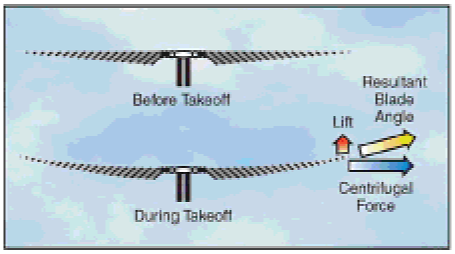


Figure 4. Induced coning on a rotor blade system.

The problem concerning coning can be approached multiple ways, but can be difficult to approach due to the weight requirements. One idea is to make the blades out of a very rigid material, that way there is less bending toward the wing tips. This approach will take great knowledge in understanding composites, and Dr. Joe Mello has volunteered to assist with understanding composite rigidity. Another approach is to install an anhedral wing as seen in Figure 5[9], so that way when forces are applied to the rotor blades, the blades bend up to horizontal position.

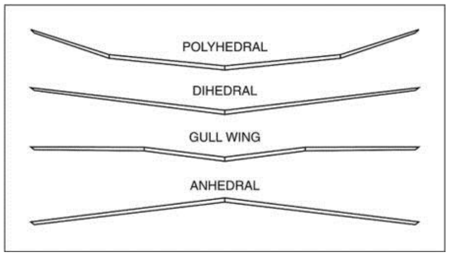


Figure 5. Example of different types of wing orientation.

REQUIREMENTS

Table 1. Current Requirements.

REQUIREMENTS	VALUE	UNITS /NOTES
Lift Load per Rotor	55	lbf
Static Weight per Rotor	10	blm
Solidity	10	%
Budget	2000	dollars
NACA-4418 Airfoil	n/a	n/a
Scale	1/3	n/a
One-Piece Rotor	n/a	n/a
Truss-Like Spar	n/a	n/a

Rectangular Planform	n/a	n/a
No Twist	n/a	n/a
Max Vertical Displacement	12	inches
Hub Diameter	12	inches
Outer Diameter, 10’Inner Diameter	40-10	feet
Chord	3.927	feet
Thickness	8.47	inches
Area in Lift Plane	117.81	ft sqr
Natural Frequency Calculations – Vertical	n/a	Hz
Natural Frequency Calculations – Lateral	n/a	Hz
Natural Frequency Calculations – Rotational	n/a	Hz
Rotor Speed	20	rpm
Rib Thickness	.5	in

Project Deliverables

- Incorporating predicted forces to create a structural model of the rotor.
- Generating alternative spar designs and performing a trade study to select the best alternative.
- Building multiple rotors
- Performing structural tests to verify the structural model.
- Integrating the rotor set with the fuselage being developed concurrently.
- Generating alternative hub integration and performing a trade study to select the best alternative.

Table 2. Discarded and unnecessary requirements.

DISCARDED AS REQUIREMENTS	VALUE	UNITS /NOTES
¼” flight height above ground	1/4	inches
90-100RPM Cadence	90-100	rpm

CHAPTER 2: CURRENT DESIGNS

Da Vinci 3

The Da Vinci 3 had an interesting concept that is no longer implemented in current HPH attempts. The span was 50ft radius with a 2 ft radius hub. The spar was made of 0° and 45° wrapped 4inch diameter carbon graphite cylindrical beam, wrapped at 8° to withstand the 6000ft-lb moment applied to the hub.

The airfoil was a Liebeck Design, serial code fx63-137. Determining the chord was difficult, as there were conflicting dimensions from different sources. The most credible source gave the dimensions of 6ft chord at tip, 8ft chord at the root. There was a 6° twist to the chord. The ribs were compose of divinycell and were placed every 2 ft. The skin was made of heat shrunk Melinex, a type of thin polyester film. The speed of the rotor was 8.5-9 rpm.

The Da Vinci had many problems, and one of them was their inability to utilize the ground effect. The wing could not withstand the static loading of its own weight, so the wing was lifted higher and a guy wire was attached to give it structural integrity.

The simple tube spar was not the optimum design, but was simple to make. This spar design may have been reason why the Da Vinci had problems with its inability to withstand static loading, as well as its major problem with coning.

The Da Vinci was designed with a dihedral wing, which is unfavorable when power efficiency is a concern. The projected current wing will be preloaded with a tension member to give an anhedral wing to address the issue of coning.

Yuri I

The Yuri I currently owns the record for longest flight, as well as highest flight. The total diameter of the quadrotor system was 10m (each rotor). From a Youtube[11] video, the following analysis was made:

- Ribs were made of foam
- Each blade only weighed 4.4 pounds (8.8 pounds total rotor)
- Blades look to be made of:
    - Wood
    - Melinex
    - Foam

The spacing for each individual rib was .5m. The chord was .882m, with a thickness of .27 meters. These dimensions were determined from photo analysis. The airfoil type was the DAE-11. The structural spar looked to be made solely of foam, with the leading edge being made entirely of foam**.** It is worth noting that a cross-sectional picture of the blades could not be found, so there may be unseen spar in the foams leading edge.

The Yuri flew very well, and was well designed. It was lightweight, and only weighed just over 100 pounds. Even though the Yuri I did well, it still had its issues. The Yuri I had problems with vibration analysis. From the video, it looks like the blades and the fuselage hit an undesired frequency, and the blade tips hit each other. This caused total destruction to the hph. This problem needs to be monitored and addressed in the spar and wing analysis. Also, from simply viewing the video, it seemed that the Yuri I had issues with the pulsing from the rider. The blades seem to move out of sequence, and don't seem to be in perfect frequency with the other blades. Lastly, the Yuri I also experiences coning, which is crucial when most of the lift comes from the last 1/3 length of the wing nearest to the tip.

Gamera

The Gamera is the current competitive HPH today, and hails from University of Maryland. The Gamera has a 6.5m blade, with a 1m chord. The leading edge is made of hollowed foam, with foam ribs every 2m. Inside the foam's leading edge is a truss spar, in the shape of a triangle. The trusses make repeated x shape on each side, (i.e. XXXXXXXX). The aft-section is made of foam and balsa wood ribs. Each balsa wood rib has .4643m spacing (determined by photo analysis). The blade used is reported to be the DAE-11 foil, and has a 1m chord.

The Gamera was built nearly the same as the Yuri, except made out of composites. The Gamera has a HUGE problem with coning, which could have to do with the spar design. The truss spars are made of carbon fiber, and due to the orientation of the triangle, two members are under tension, while only one is under compression. Due to carbon fiber's composition, the plastic resin would take nearly all of the compressive force, which is very undesirable. From simple estimation of video analysis, the maximum vertical displacement at the wingtips of the Gamera range from 2.5 to 3 feet.

CHAPTER 3: DESIGN DEVELOPMENT

CONCEPT GENERATION

During the concept generation phase of this project, many different designs were proposed and considered. Initially, many glider designs were considered, which included simple I-beams and multi-composite layered spars as seen in Figure 6. While these designs are successful and applicable to gliders, they cannot be applied to a human-powered-helicopter due to rigidity and weight constraints.

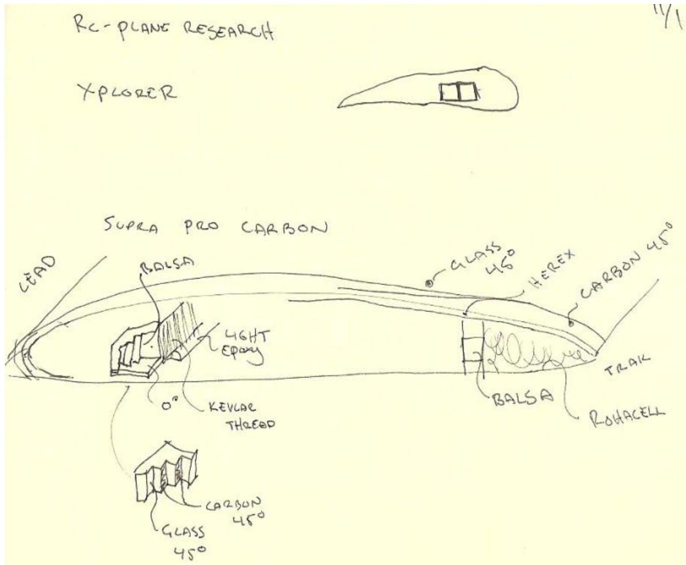


Figure 6. Cross-sectional wing of RC glider (Xplorer)

Along with truss type designs, the strongest design that was considered was a design that used a large sheet or ribbon of carbon fiber that would act as the entire bottom of the wing. To take the compressive force of the applied moments, aluminum or composite honeycomb would be installed into the wing as seen in Figure 7. That way, the sheet of carbon fiber would be nearly all in tension, while the honeycomb would absorb the compressive force. While this idea seemed to be a strong design, the sponsors determined it was too abstract, and decided to constrain the project to trusses only. In doing this, the project could be more focused and could be simplified.

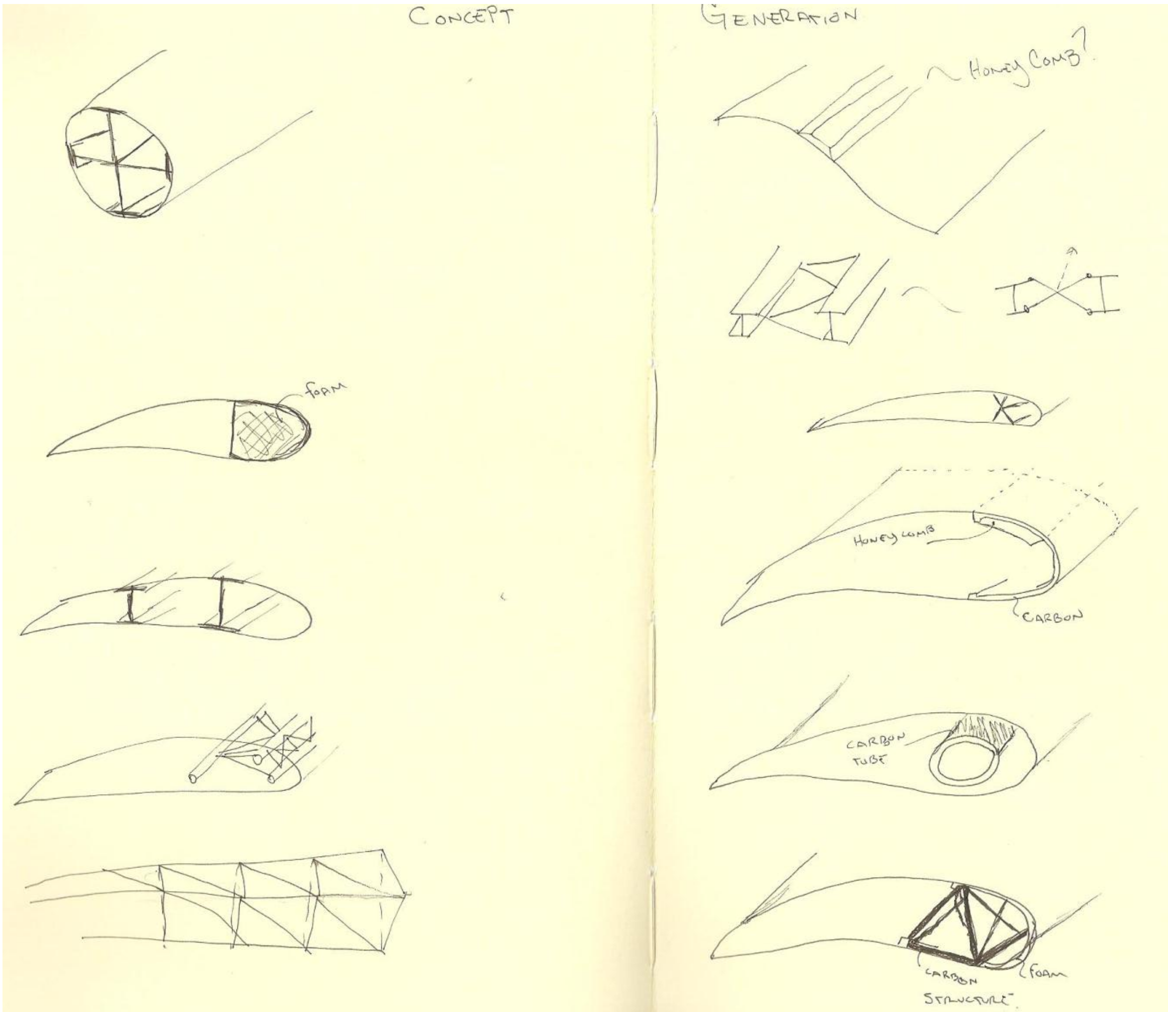


Figure 7. Concept Generation. Boxed solutions are the most promising designs mentioned above.

CONCPETUAL DESIGN ANALYSIS

Truss Design

In previous triangular wing truss designs, primarily noting the Gamera, the truss has been oriented in a fashion where the base of the triangle is on the bottom of the wing. This would be undesirable for carbon-fiber trusses because the bottom of the triangular truss is under pure tension, while the top is in compression. Instead, with the triangle is oriented with the "peak" at the bottom of the triangle, two carbon tube runners are able to absorb the compression created due to bending, while only one member is in tension (Figure 11). This is most desirable, since carbon-fiber is very strong in tension, and relatively weak in compression. As stated previously, it is believed that the Gamera greatly suffered in wing deflection due to their improper orientation, which resulted in a great amount of coning, and ultimately, loss in lift.

Through brainstorming and collaboration, three trusses were determined to be adequate for this senior project. The first design, as designed by Carlos Olvera, features a repeating "N" type pattern, with an “X” pattern on the top of the truss. The second pattern, as designed by Joseph Ram, is known as the Warren Truss. The last pattern, as designed by Joseph Ram, is known as Pitt’s Truss. All three of these trusses have their own strengths and weaknesses, which ranges different constraints such as weight, strength, tip displacement, and construction feasibility. All of the proposed designs were compared against each other using FEA Analysis program Abaqus. The following trusses were designed at full scale with similar dimensions and composites, and will be scaled down to 1/3 for testing.

Along with each simple three carbon tube spar design is an additional design; a design constructed with the bottom member made of a type of wire, as designed by Carlos Olvera. The bottom wire will be strictly under tension during bending, which negates the issue of buckling for that member. By adding a wire instead of a carbon tube, a considerable amount of weight is saved.

In addition to weight reduction, the wing can now be preloaded with tension to give anhedral to the wing. This is desirable because the wingtip displaces a considerable amount, and this simple solution can keep the wing from coning. The alternative method to produce anhedral would be to set the truss in an anhedral mold during construction. While this is feasible, the difficulty of molding proper anhedral for a wing would be extreme and would be hard to replicate if multiple wings were made. While this option is still a strong possible solution, a considerable amount of valuable resources, such as time and budget, would be spent solely on producing this anhedral.

Warren (Lenticular) Truss

This truss design is desirable when weight is needed to be at a minimum. This truss is identified by its repeated angled bars along the main spars. The entire truss would be entirely constructed from carbon tubes, with the exception of the bottom point of the triangle being made of a type of wire composite for an optional design. A main weight concern when dealing with composites is with the joints. The joints themselves can weigh a considerable amount if not constructed properly. This design minimizes the amount of joints needed to complete the 40 ft. length, while maintaining proper structure.

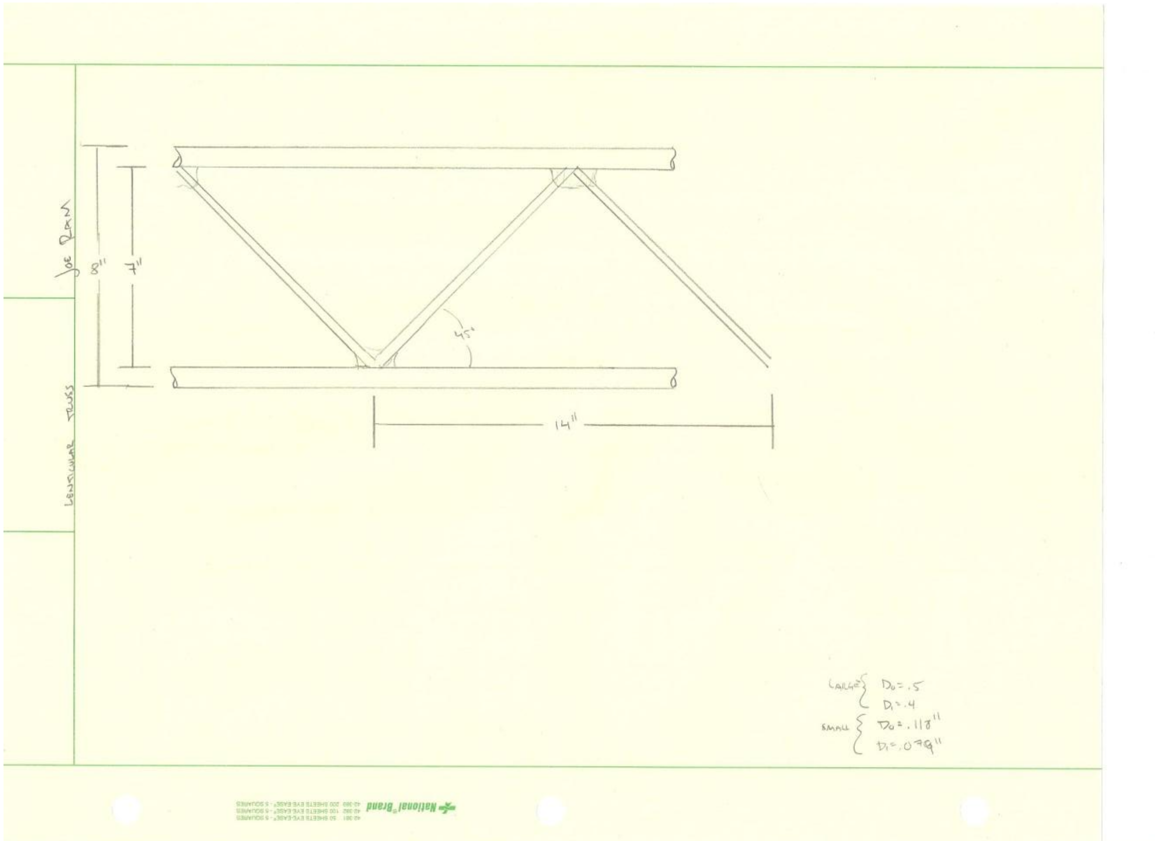


Figure 8. 2-dimensional drawing of Warren Truss (*Note: dimensions are outdated).

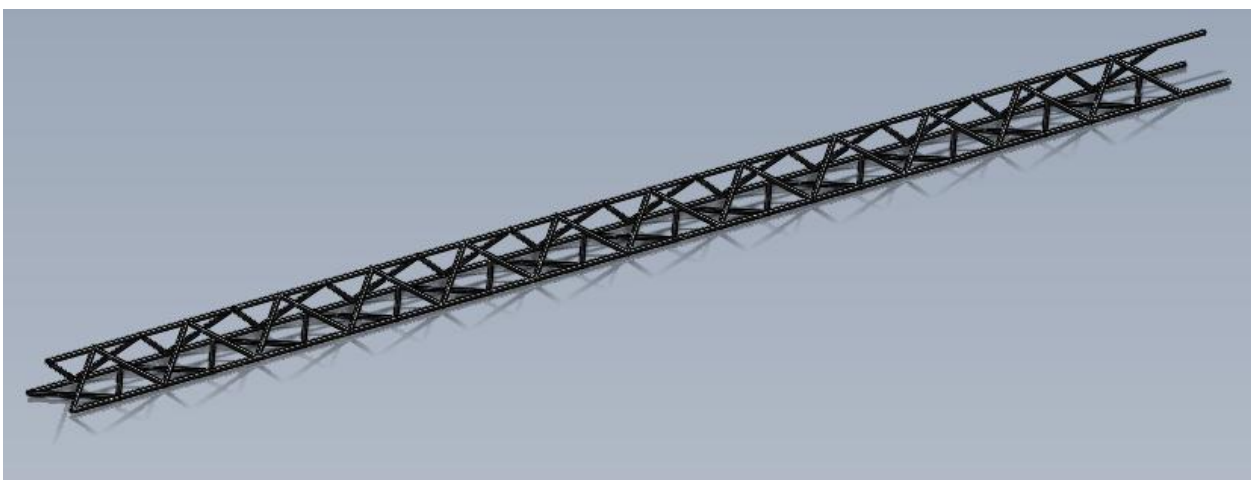


Figure 9. Solid Model of Warren Truss.

Pitt's Truss

Pitt's truss was the chosen truss design by the competing Gamera team. The 2-dimensional view of one leg of the truss displays a pattern similar to a series of "X's". While the structural integrity of this truss would be strong, there is a big concern with weight and manufacturability. There are twice as many joints in this truss when similarly compared with the Warren Truss above. The “X” itself is tough to construct, whether constructed with one long diagonal piece with two small opposite diagonal pieces, molded as one piece. If the piece is molded, then the team will approach budget simply on the molds, while if the “X” is constructed of smaller, half size tubes would triple the weight contributed from the joints when compared against the Warren Truss. This truss will be analyzed as a comparable design and will give insight about Gamera’s wing truss.

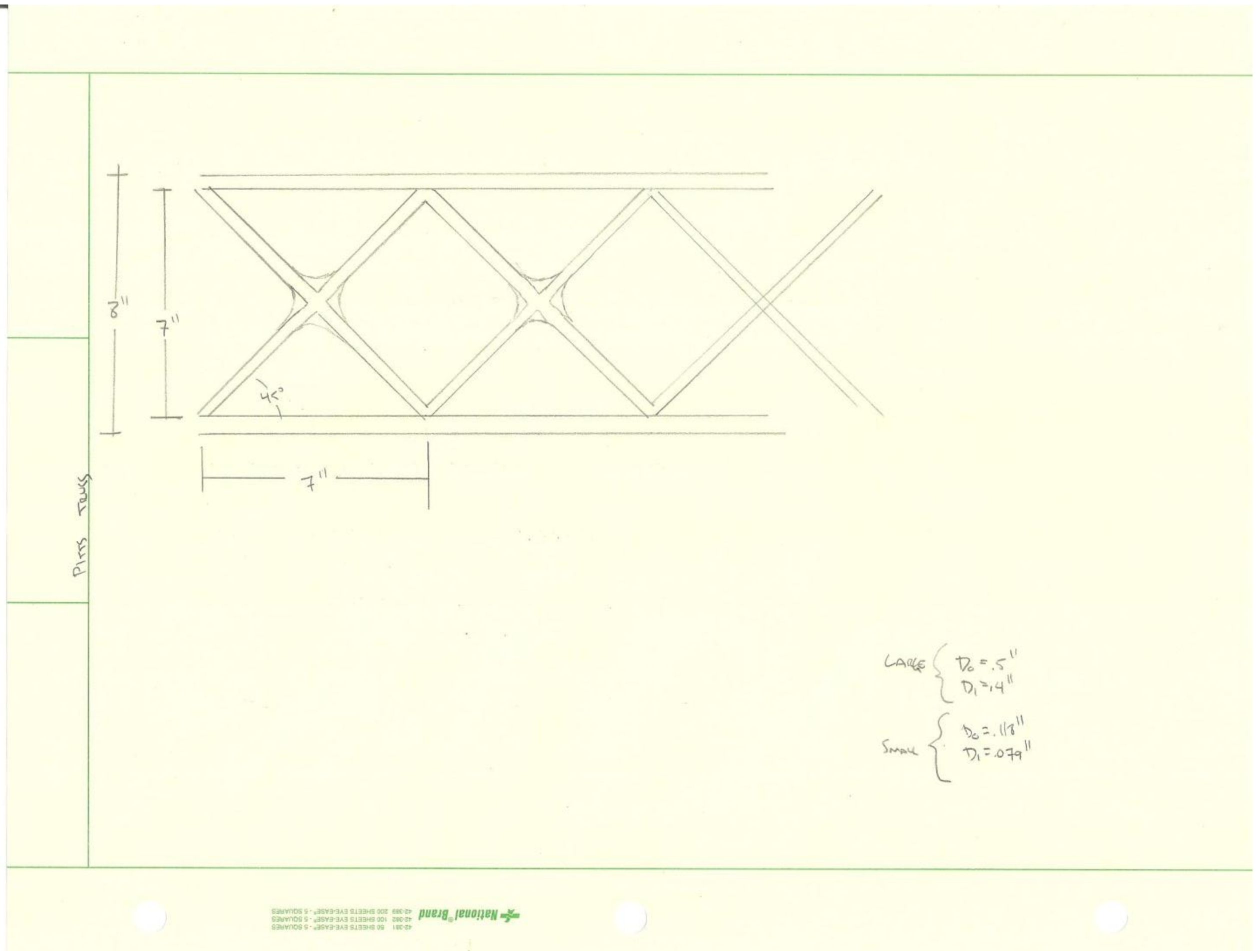


Figure 10. 2-dimensional drawing of Pitt's Truss

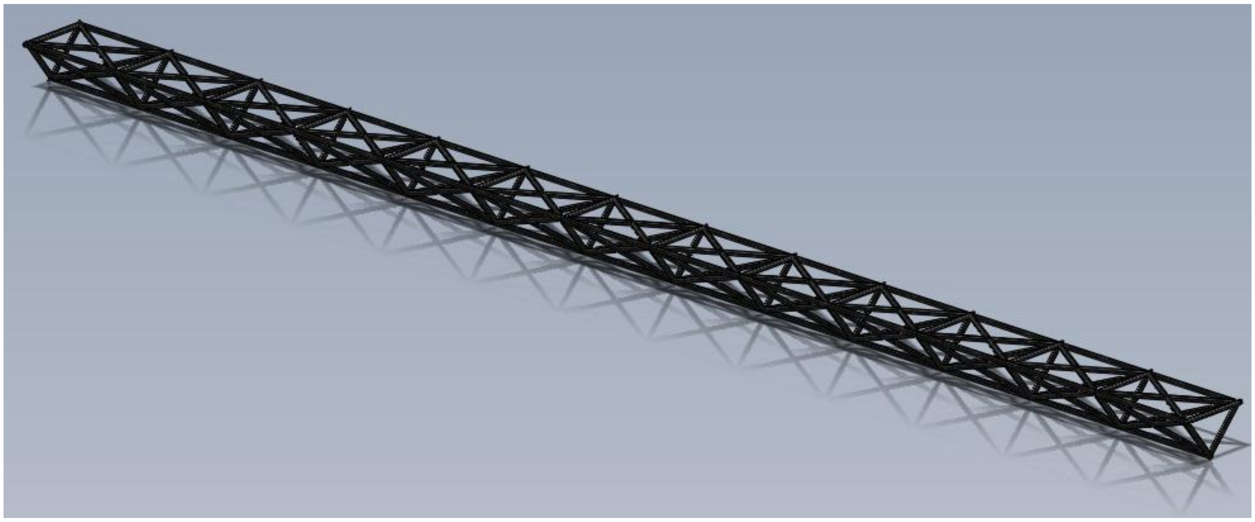


Figure 11. Solid Model of Gamera's truss

"N" type Truss

During initial idea generation, the one competitive truss idea was the "N" type truss (Figure 12) with the tension wire. This adjustable member would be used to set the member in pretension to counteract the deflection problem seen in most of the HPH rotor designs. It also was determine that an anhedral angle was desired so that when the rotor was in full speed the deflection would result in a horizontal rotor. The adjustable member takes care of this desired feature wished by the sponsor. The issue of coning, however, cannot be completely eliminated, as mention by DR. Mello, so an approximation will be acceptable for this senior project.

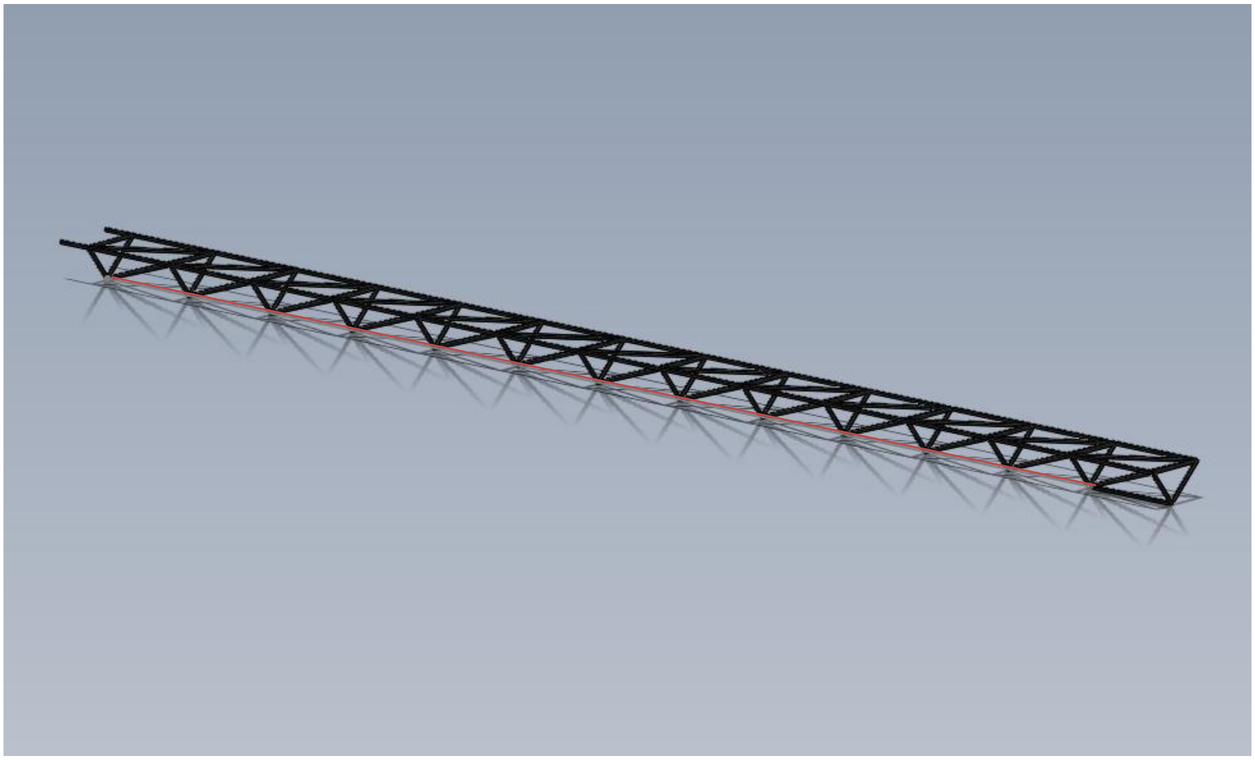


Figure 12. Approximated shape of the spar design. The red line represents the lower member flexible wire.

Hub Design

One of the key components of the rotor is the hub that will integrate to the fuselage. Although the hub has no effect on the performance of the spar structure, it is important that the hub can withstand the large moments applied by the lift load. During one of The Team's meetings with the sponsor, the group collaborated and decided that optimization of the hub was outside of the dynamic of this senior project, but a hub would still need to be designed for testing purposes. Ideally, the proposed hub will also be able to be integrated into the future full scale design. Whether or not the proposed hub (shown in Figure 13) will be included in the final wing weight is still under discussion with the sponsor. Regardless of the decision, the hub still needs to undergo weight reduction.

The hub design only needs to meet a few requirements, which are minimizing weight and integrating with the Fuselage Team. Based on these requirements, carbon fiber was chosen to be the best material to use. This hub can be constructed using a custom injection mold that would accommodate the spar carbon tubes. This method was chosen because the hub would not be structurally sound if composed simply of carbon tubes. Also, those tubes (in the hub) would somehow integrate together along with the wing spar, and would create many more joints. The injection molding of the proposed hub will avoid the need for joins. In conclusion, the proposed hub design not only gives a light weight option to hub integration, but also gives strength to the most critical part of the wing.

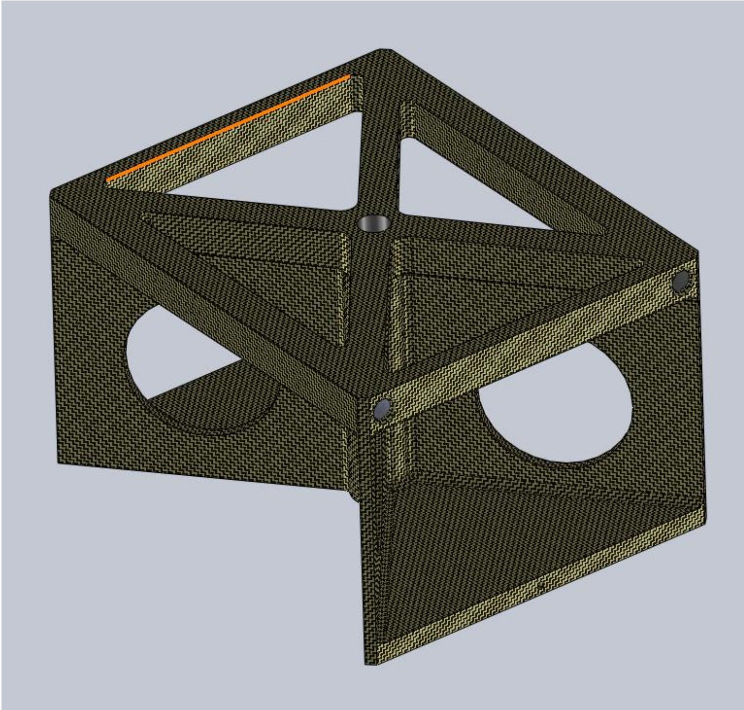


Figure 13. The figure above is an approximation of how the hub will look once built. The hub will be manufactured from carbon fiber composites.

Wing Design

The initial proposed design of the spar structure was done to the specifications of the airfoil DAE-11, the same airfoil used by the Yuri 1. When further analysis was done, the projected full scale wing thickness equated to be approximately 6 inches. This issue was discussed during a team meeting with the sponsors, and it was determined that the strongest structure could be made with a larger foil, so the NACA-4418 was chosen. Using this new foil, there is now nearly 8.5 inches to design the truss in, which can pay dividends when calculating wingtip displacement.

In addition to the truss itself, the ribs, leading edge, and wing skin need to be analyzed. The ribs, leading edge, and skin add many problems to the analysis, particularly when analyzing the natural frequency. This issue was discussed with the sponsor during team meetings, and an agreement was met that analyzing the natural frequency of the entire wing was outside the scope of this project, and will need to be done by another team or by testing the full scale model.

The ribs are made of ½ inch thick foam, with a density of about .8 lbs/ft^3, lined on the edge with a ribbon of carbon fiber. The purpose of the ribs is to keep the skin in place, and transfer the applied lifting load to the truss. The ribs are not meant to take much loading, therefore, can be slimmed down to help with weight reduction if needed. The ribs are spaced at consistent distances along the wing, and those distances are dependent on the truss chosen. The optimum way to space the ribs would be according to the lift distribution on the wing, but this optimization was determined to be outside the scope of this senior project. On average, the total weight added due to the foam ribs will total just less than 2 pounds.

In addition to the foam ribs will most likely be a thin foam leading edge. While this aspect of the project still has yet to be decided with the sponsor, the leading edge will probably be constructed out of hollow foam, similar to the Gamera design. This leading edge will provide strength to the wing in the event of hitting an object, and will maintain the leading airfoil shape as it begins to fly. While providing some strength, the leading edge will be detrimental to the weight limit, and therefore, will limit our final truss weight.

The skin on the wings is made of Mylar, which is a very thin plastic(.005 in). This skin is made by heat-shrinking it over the ribs, and produces a beautifully produced, flat and lightweight foil. During production, this Mylar must be carefully monitored to ensure there is no bowing in between ribs, particularly in the trailing edge. The Mylar film will add on average just over 2 pounds to the total weight of the wing.

Table 3. Properties of wing materials.

Material	Density
Mylar	.0505 lbs/in cube
Expanded Foam	.75-.85 lbs/ft cube

FINITE ELEMENT ANALYSIS

Intent for Abaqus

It is the intention of utilizing Abaqus to iterate through several models of trusses to understand the effects of changing loading conditions and truss structure and how these relate to the airfoil tip deflection, modal characteristics, max stress, and weight. By importing models into Abaqus from Solidworks, the analysis predicted that there could be a higher throughput of models to analyze.

Model Development

As discussed prior, an entire rotor consists of two identical blades. Each blade is formed by a Mylar sheet, which holds its form from the ribs. The ribs are then held by a truss structure that is cantilevered from the center of the hub for the rotor. Fortunately, this means that all distributed loading onto the wing is transferred to the ribs, then onto the truss as point loads. As the truss structure within the rotor only undergoes point loads, this allows for the analysis of the truss to be done purely with truss member elements.

There are three types of sections within the structure: big tubes, small tubes, and guy wires. Most truss structures analyzed are in the form of two “running rails” along the top and bottom rail that form a triangular prism that is webbed together by interior rails. The big tubes are used for the two running rails, the small tubes for the webbing, and guy wire for the bottom rail. Otherwise, models were constructed purely from big tubes. (the single and double rod models). Both the tubes and wire were made out of carbon fiber with the following properties:

- 0.06 density(lbs/in^3)
- 17e6 Young’s Modules(psi)

Five preliminary models were analyzed for this concept analysis and they are as follows:

- Carlos: X-top with N-side truss structure.
- Gamera: For comparison, a model of the structure used within the Gamera.
- Lenticular: Angled webbing between three carbon tubes
- Single Rod: The first club concept for an internal wing structure, a single rod.
- Double Rod: The second club concept, two rods running in parallel in the blade.
- Elongated: One elongated section of a V truss with X top for comparison.

One of the largest challenges was finding a way to import a wireframe model of the truss. It is most ideal for the wireframe to be composed as a sketch in Solidworks so as to allow for a parametric table to rapidly generate several different models that vary by web spacing. Eventually it was found that the best way to import a wireframe model is as follows:
In Solidworks:

- Using the 3D Sketch Feature, draw the truss.
- File->Save As
    - Save as Type: *.igs
    - Options
        - Check everything except “IGES solid/surfaces entities”
        - It is imperative to have at least the following two options checked:
            - IGES wireframe(3D curves)
            - Export Sketch Entities

Each model was pinned on one end, by the three nodes that support it. The ribs were decided to start one section away from the boundary condition and repeat every 2 sections. The ribs always connect to the structure through the joints; therefore, the distributed load of 27.5lbs that would be on one blade was equally divided among the 7 ribs, and then further divided by the three joints that the rib connects to. Therefore, 1.31lbs was enacted on each joint in the upward direction(y-axis). Similarly, there was a 0.1333lb load on each joint for the lateral loading conditions, in the direction along the chord(z-axis). See figure 14 below for an example of vertical loading conditions.

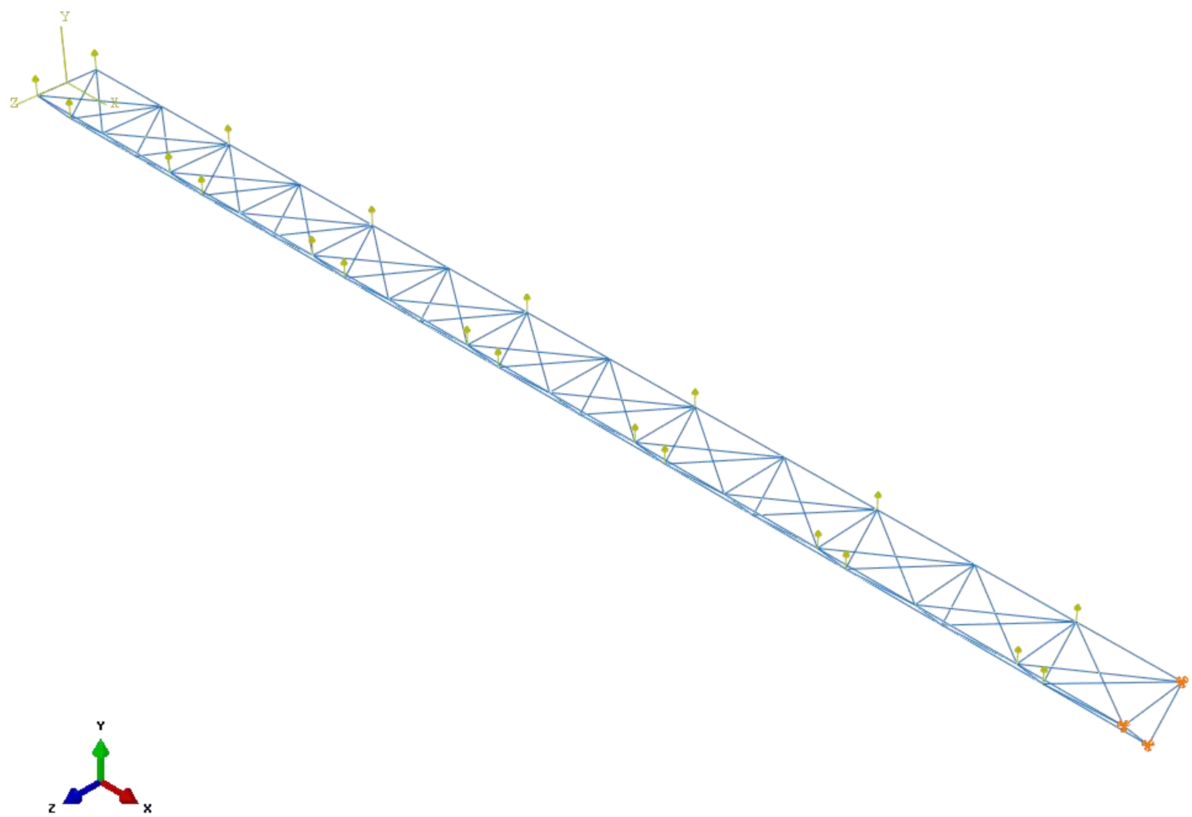


Figure 14. Vertical Loading and Boundary Conditions.

Mesh Development

As analysis was done for a truss structure, the model was formulated with a seed size by number of 1. The element types used were Standard Linear Truss elements.

Analysis

For the single and double rod models, it was necessary to use an encastre boundary condition and beam analysis; otherwise the model would be unconstrained. A common error in analysis was the existence of singularities, which helped demonstrate instability in some of the conceived structures.

It can be seen in the Figures below that certain members of the truss “buckle out” under loading; however, this is a consequence of using truss members, which imply a pinned connection. These members that deflect outwards are demonstrating unloaded members which are free to displace. These obtuse members can be seen in the Gamera Lateral loading(Figure 18) and Gamera Vertical loading(Figure 17) as having the most deflection making it appears that the entirety of the truss is stationary; however, it is imperative to note that this is not the case.

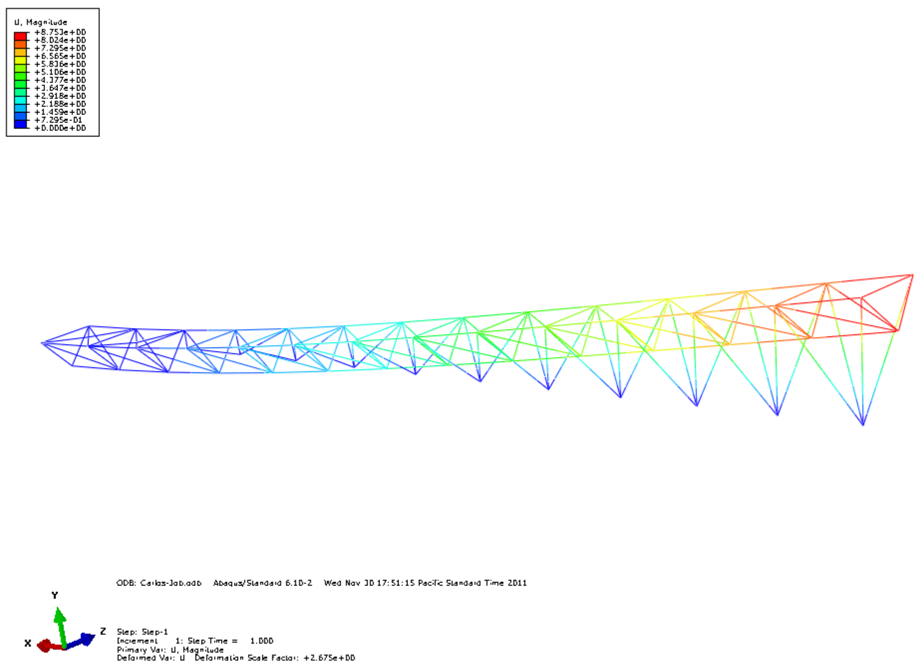


Figure 15. Carlos Vertical.

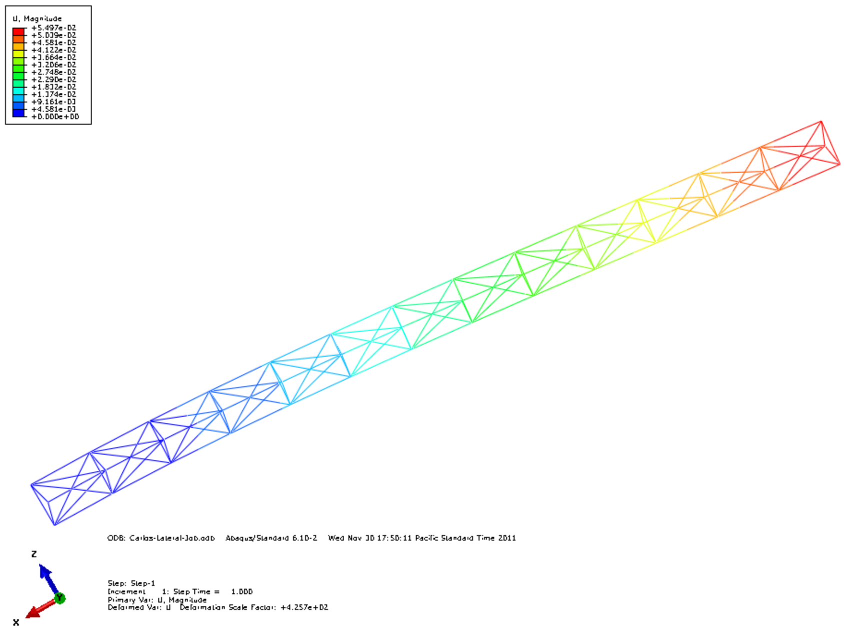


Figure 16. Carlos Lateral.

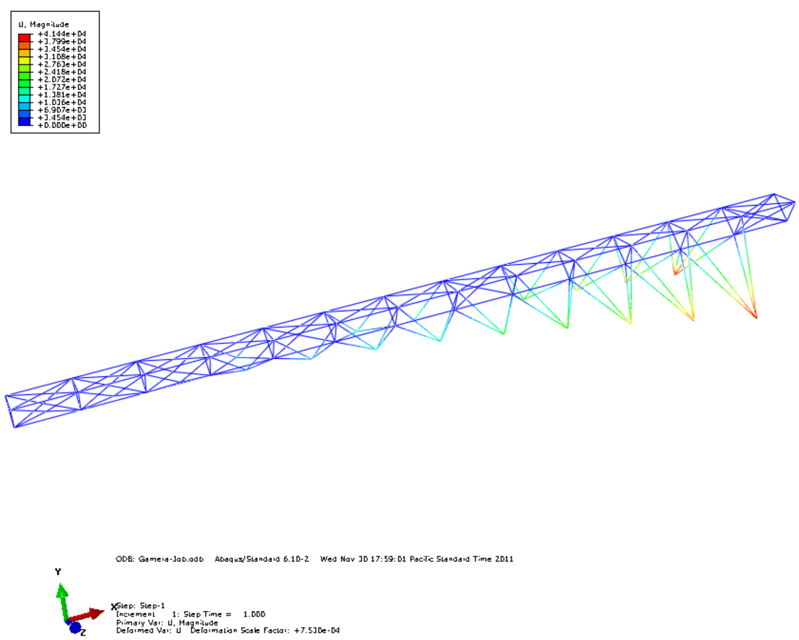


Figure 17. Gamera Vertical.

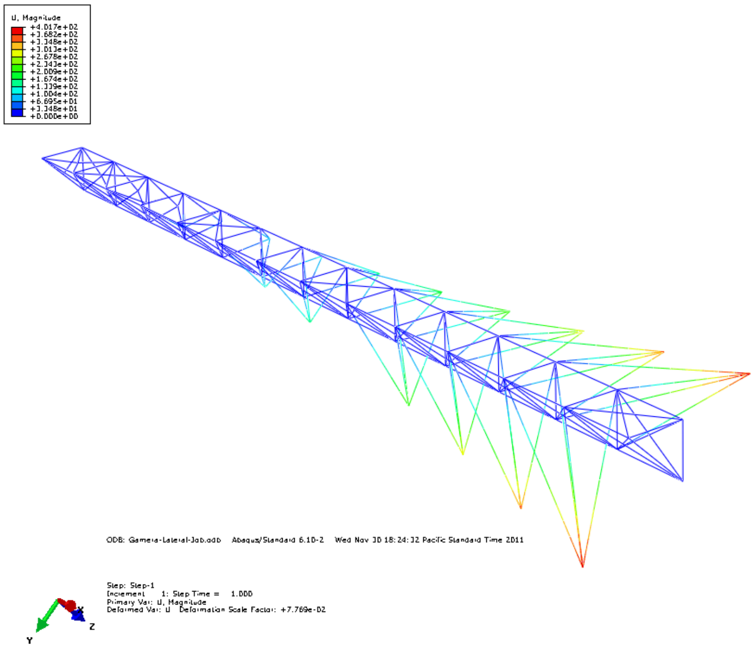


Figure 18. Gamera Lateral.

Mesh Convergence

By using a Matlab algorithm that solves for the tip deflection of the Carlos Truss, it was determined that the Abaqus model follows within 5% of the predicted value of the Matlab script. Moreover, this validation was used to validate the process of importing models and applying loads and constraints so that other models could be analyzed.

Results

Table 4- Comparison of Different Tested Models

Truss	Max Stress[psi]	Tip Deflection[in]	Lateral deflection[in]	First Mode[cyc/s]	Mass[lb]	Number of Nodes
Carlos	122573	8.746	-0.055	3.6	2.656	110
Gamera	76367	5.67	-0.055	8.8	5.72	164
Single Rod	809214	8160	-	-	0.99	2
Double Rod	404607	4080	-	-	1.98	4
Elongated	170665	51.4	-	-	-	8

Discussions

Lateral deflection and modal analysis of single rod, double rod and elongated model where not computed as these models were found to have extreme tip deflections.

Carlos truss and Gamera truss have the same lateral deflection because the members that support that loading are the same in both(the top members and running rails). The difference between the two models is in the side webbing; however, these members are not affected under lateral loading for a truss system. Lenticular truss was not analyzed because the truss was found to be unstable due to the design.

The team decided to prioritize weight over wingtip deflection since the Abaqus analysis is highly conservative. The Abaqus analysis is completed by treating each member as a two force member and pinned joints. It is obvious that the joints will not be pinned and in fact fixed; therefore, there will be stiffness in the joints themselves to help reduce tip deflection. Furthermore, it is necessary to prioritize weight since the joints will significantly contribute to the total weight of the wing.

Conclusion of Initial FEA

From this analysis, it was determined that the Carlos truss would be optimal as it weighs the least out of all structures. Furthermore, its tip deflection is within the 12 inch limit even with the conservative estimate of a truss analysis. With real joints, it can be expected that total deflection would be less since they provide more stiffness to the truss. Though the natural frequency for the Carlos truss is the lowest, it is still within that of the requirements which state a rotor operation of 20rpm, or 0.33cycles per second. Lastly, if there is still believed to be a problem with tip deflection, it would still be possible to have an anhedral angle by adjusting the guy wire through the hub.

Further FEA of Carlos' Model

Having chosen Carlos' Model, we felt it necessary to readdress the skewed FEA models. By remodeling the truss structure as beams within Abaqus, we were able to eliminate the jutting of truss members. The loading applied to the truss can be seen below.

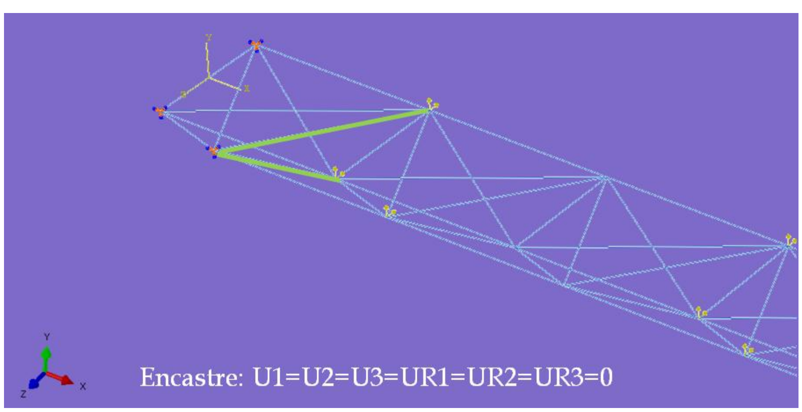


Figure 19. Boundary Conditions on Carlos Truss Structure.

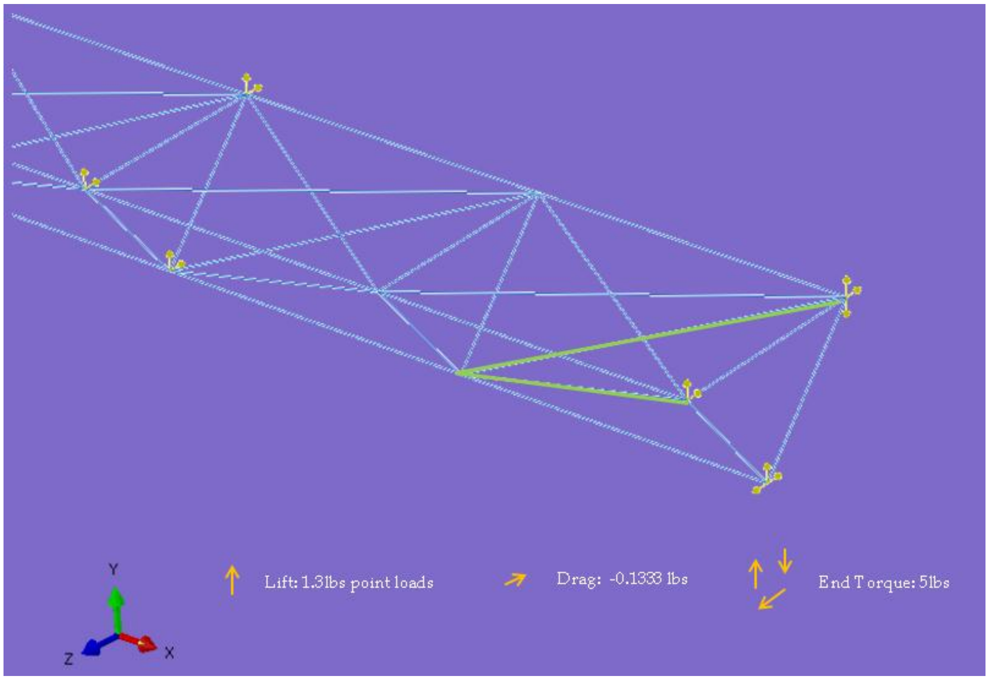


Figure 20. Combined Loading on Carlos Truss Structure.

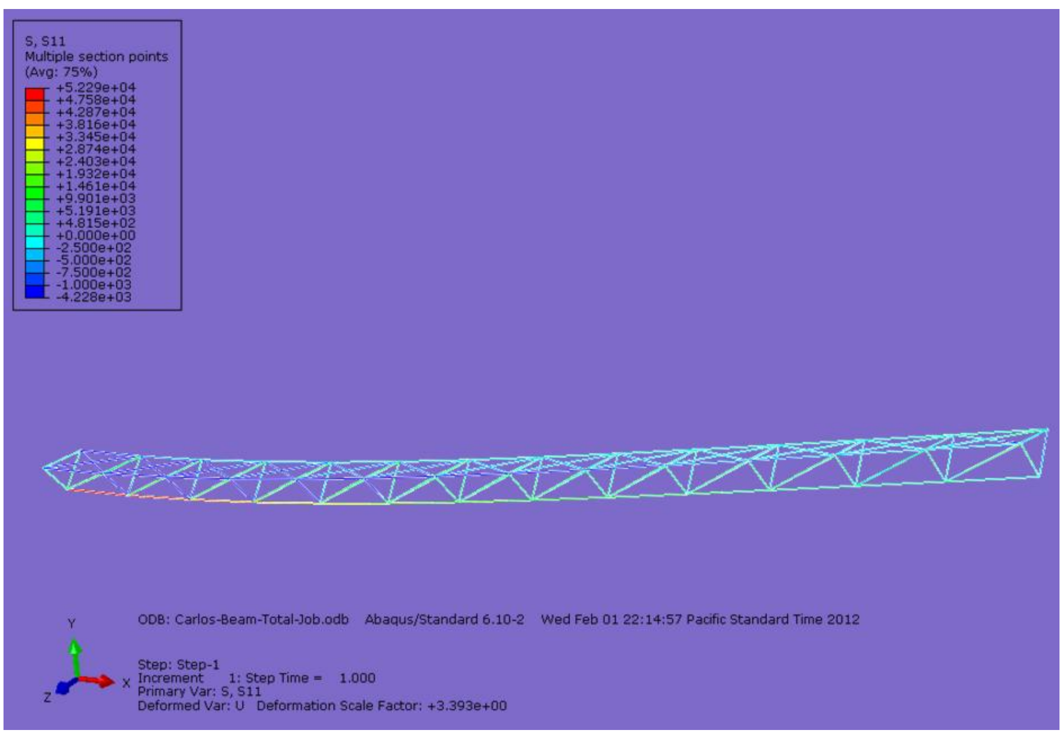


Figure 21. Axial Stress of Combined Loading.

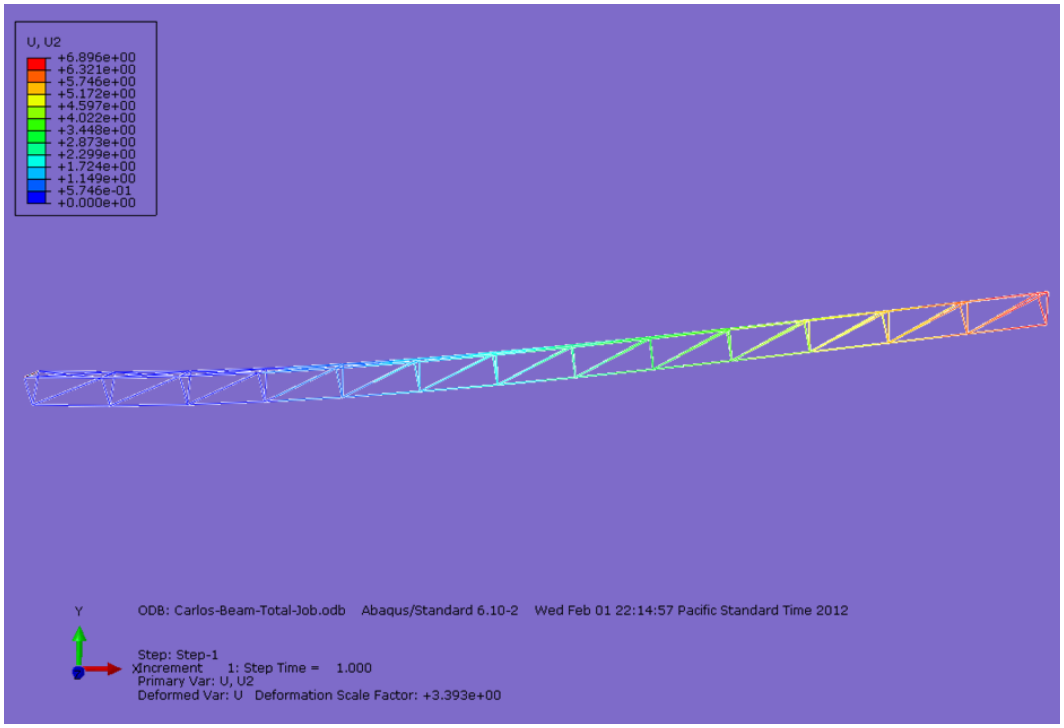


Figure 22. Vertical Displacement of Combined Loading.

From the Abaqus models we can conclude that the vertical displacement meets the design requirements, and the maximum axial loading applied to the truss members is allowable for the material purchased. Therefore, the truss is a sound design according to Abaqus and testing will be needed to compare against the proposed models. Hand calculations for tube buckling can be seen in Appendix E. The max axial loading determined from Abaqus, can be seen in Table 4. When compared with hand calculations, the axial loadings are underneath the rating loadings for each tube. A sample calculation can be seen in Appendix E.

Table 5-Max Axial Loading Determined From Abaqus Models

		Max	
		Compression[psi]	Tension[psi]
Large Tubes	Runners	3549	175
Small tubes	Triangles	4228	1872
	N-bars	2777	11259
	Top Cross	3629	1415
Carbon Toe	Guy Wire	N/A	52290

CHAPTER 4: FINAL DESIGN

Wing Design

Upon further sponsor discussion, investigation, and considerations, the final wing design was altered and finalized. The issue of proper scaling was addressed and the conclusion was to build a conceptual 1/3 scale model for manufacturability and visual purposes only. The final build of the rotor will be a great feat in itself, and will help the next generation of engineering students that will be basing their work on this final design. In addition to the 1/3 scaled model, a small section of the full scale design will be built, and from this full scale section raw data will gathered. It is important to note that all designs were designed according to full scale loading and weight, and was scaled down to a 1/3 model to the best of the ability of the team.

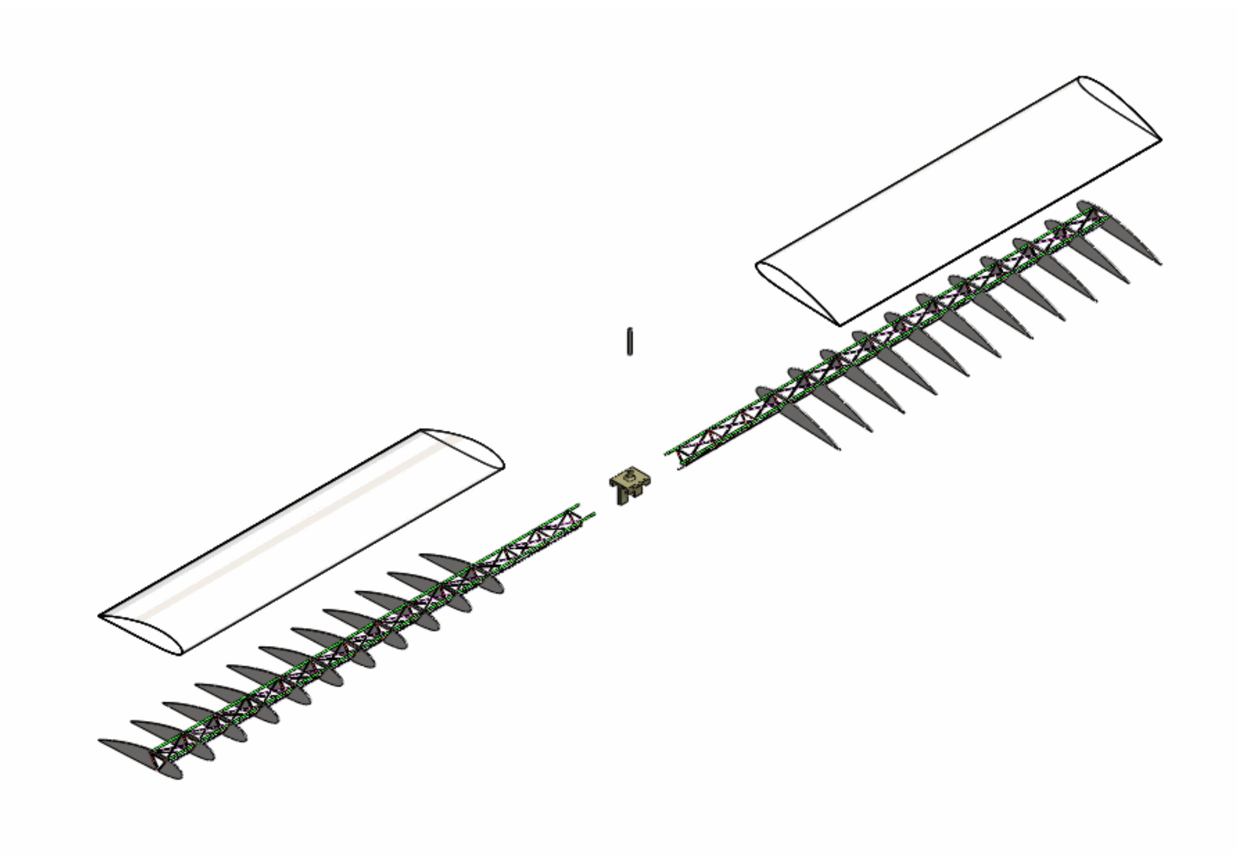


Figure 23-Exploded Isometric of Full Scale Rotor.

The application of the wing's main components are described on page 16. In addition, the application of the guy wire concept is applied to the final concept, and it is believed that this will aid in the issue of wing tip deflection. The guy wire is adjustable, and can be tightened and pulled through the hub to induce an anhedral on the wing. The guy wire is attached to the truss through a series of eyelets, and will be fixed at the wingtip. The idea of the eyelet application is intended to apply similarly to a fishing pole; the guy wire isn't attached to each individual eyelet, but when tightened, will slightly collapse the wing, thus inducing an anhedral type effect.

Hub Design

The initial hub design, as seen in Figure 13, needed revision due to its inability to meet the specified requirements; the truss structure needed to be one continuous piece. The hub above does not allow for one continuous truss, but instead is design for to individual trusses to piece together into a hub. In addition, the proposed hub would require expensive molds to build, which easily exceeded the proposed budget. A new hub, as seen in Figure 24 was designed, and fully meets all requirements. It was proposed with success to the sponsors, and is understood to be a non-optimized, easily manufactured component.

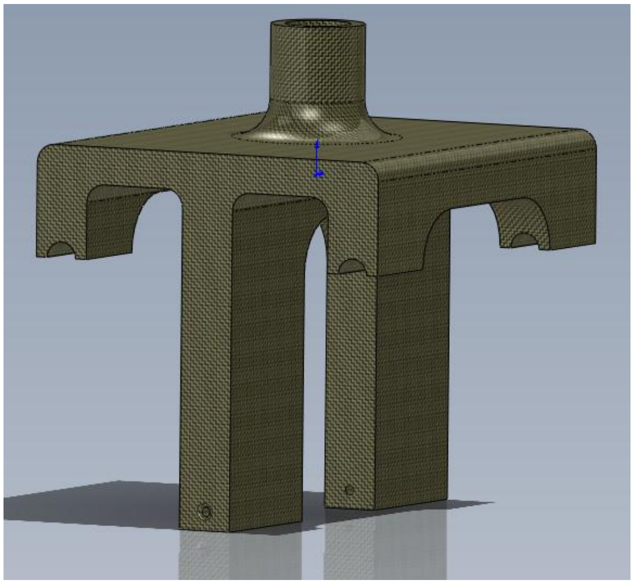


Figure 24-Full Scale Hub Prototype

CHAPTER 5: FABRICATION AND ASSEMBLY

Everything purchased underwent strict and careful assembly. The wing, truss, and hub were all assembled and built from the bare materials purchased. After each individual part was built, all of the components were assembled to complete the rotor.

1/3rd Scale Model

The sponsor has decided on a 1/3rd scale model for the sole purpose of testing the manufacturability of a full scale model. As such, only length will be scaled; however, even with only scaling length, the 1/3rd scale model will be unable to support itself with such members as the ribs. The ribs for the scaled model will need to be comprised of balsa wood to have the structural stability and thickness the 1/3rd scale model needs. Had foam been used as for the full-

scale model, the foam would need to be of thickness less than 0.08” with carbon fiber; however, foam at that thickness would not be able to support itself; instead, a sheet of balsa wood will be used without carbon fiber. Though the full scale model does not benefit from using spectra thread, the scaled model benefits greatly due to the reduced width of tow that would be required; therefore, for the 1/3rd scale model spectra thread will be used as a guy wire.
Unlike the ribs, the hub will be manufactured in the same way as the full-scale model which will consist of using hot-wire cutting to cut out a foam mold which will then be laid up with carbon fiber.

Once the truss and hub are assembled, the ribs will need to be cut to exact dimensions for the NACA-4418 airfoil, as seen in Appendix B. Also, the ribs will need to have a triangular hole cut out to fit the truss inside. After the ribs are cut to dimension, the rotor is ready for full assembly. The truss fits inside the cut hole of the ribs; the ribs are spaced evenly so its loading is applied at a truss junction. The skeleton fixture is then fitted into the hub, and the guy wires are pulled through the small holes at the bottom of the hub. Lastly, the Mylar is wrapped and heat shrunk around the wing; it is absolutely essential to rotor performance that there are no sags or folds in the Mylar. A full assembly can be seen in Figure 23.

Full Scale Section

As a 1/3rd scale model is being built to test the manufacturability of the wing, the sponsor has also requested the simultaneous build of a section of the full-scale model to test the structural design of the proposed truss structure. This section will model the truss structure only. For this section model, all joints and materials will be built according to what has been proposed prior for a full-scale complete wing. This means carbon-tubes will be utilized for their low density and high yield strength. Carbon tow will be used as the bottom guy wire as this member is always in tension during operation of the wing and allows the team to save weight from using excessive tubing that is necessary for compressive conditions, and induce the anhedral intended for the design. It has been considered that in place of carbon tow spectra thread will be used for the guy wire; however, with the marginal increase in weight savings as compared to the significant decrease in tensile strength from carbon tow, spectra thread was deemed unnecessary for the full scale design.

Truss Assembly

Epoxy/Resin Tow Mixture

It was found when applying epoxy to the joints, the low viscosity and slow cure time would cause the epoxy to drip out of the joints during the cure process which would both be aesthetically unappealing and weaken the integrity of the joint. It was hypothesized to increase the viscosity of the joints small segments of carbon tow would be added to the epoxy mixture. By mixing in segments of tow after mixing the hardener and resin, it was found that not only were the joints significantly more viscous, but that they held significantly higher loads than pure epoxied joints.

It should first be noted that carbon tow should be added only after thoroughly mixing the resin and hardener, so as not to hinder the mixing process. It was found that when adding the hardener, resin and toe at the same time as opposed to adding the tow after mixing resin and hardener, that the joints would be weaker.

It was found that a sufficient consistency of epoxy can be arrived by cutting 6" of carbon tow into 1/8" segments, and the total of this tow would be mixed into a thoroughly mixed epoxy resin solution with 0.5 fl. oz. West-Systems 105 epoxy and 0.1 fl. oz. of West-Systems 206 hardener. Not much testing was done on optimizing the ratio of tow to epoxy; however, one test was done in comparing 6" of tow to 3" and it was found that 3" of tow would still drip away from the joints during the cure process, which is unfavorable for our purposes. Furthermore, testing was done between 1/8" segments of tow as compared to ½" segments, where it was found that the later was too long. The ½" tow would form together like hair, and would not clump as desired. Instead, it stuck together like spaghetti and would form ribbons when one would try to apply to the joints.

An alternative solution to having more viscous applications of epoxy, was to use the Pro-Set 175/275 Epoxy/Hardener gel mixture. Using syringes 20cc of Epoxy and 10cc of hardener were measured and mixed with again 6" of 1/8" segments of tow. Without adding tow, the Pro-Set mixture was significantly more viscous than tow-less West-Systems mixture, which made it more favorable for the application process. Furthermore, by adding the tow to the Pro-Set mixture, the joints were able to withstand higher loads.

One major flaw found in the West-System with tow mixture, was an inconsistency with the mixture itself when applying to the joints. For some mixtures, the toe would wrap around the joints neatly; however, for other mixtures, the tow would spread out and away from the joints during application, and not wrap around causing a weakened joint. With the initially high viscosity for the Pro-Set gel mixture, tow would not spread away from the joint during application. This final criterion is what has guided the team to use the Pro-Set mixture with tow for making the joints.

Tube Joining

The manufacturing process of the spar structure consisted of: tube preparation, which included sanding and cutting, tacking with super glue, and epoxy application.

The sanding consisted of sanding the runners with 150-grid-sandpaper, only at the joint area which it covered about 1½" length of the tubes at every 18" along the tube. It also included sanding the web tubes with 220-grid-sandpapaer about 1" into the tube length on each side of the tube. The web tubes required using finer sandpaper because they are much less thinner than the runner tubes. It is important that the sanding only goes as far as removing the shine of the area in question, sanding more than that would result in the weakening of the tubes.

The cutting consisted of cutting the tubes to proper size, with allowing ½" tolerance for error. Some of the issues cutting the tubes were that the upper cross web tubes had to be offset height because they are not joined at the cross center, rather, one is on top of the other. As a result complex angles needed to be cut for these tubes. If the angles were to be cut with a machine, it would be a very complex setup; therefore, all the upper tubes need to be cut manually with band saw to approximately a 23 degree angle at one end and the same at the other end but rotated 180° so it is opposite to the other end.

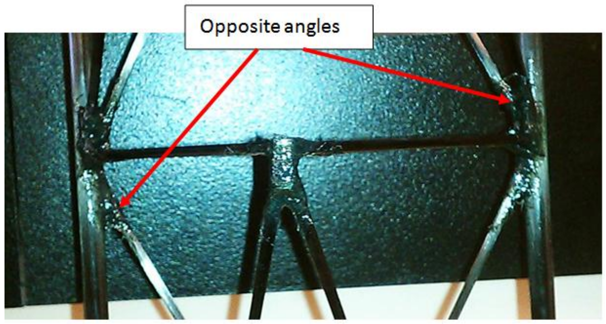


Figure 25 The upper cross tubes of the structure which have opposite angles.

Fixing the tubes with super glue is a process that became simple and very convenient when building the spar structure. The glue dried in 5 minutes and was sprayed with an accelerator to instantly cure. The tubes were joined to the runner member at the top of the truss, and were joined at small aluminum eyelets at the bottom. These eyelets were lightweight and allowed the team to install the tension member after the truss was completed. Once the tubes were installed super glue was applied at both ends and set in placed. Right after the accelerator was applied. Some of the issues encountered with super glue was that it coated the sanded area of the tube, making a smooth and shiny coating where the resin mixture was going to be applied. This coating needed to be re-sanded to allow proper bonding between the epoxy and the tubes. See figure 26 below.

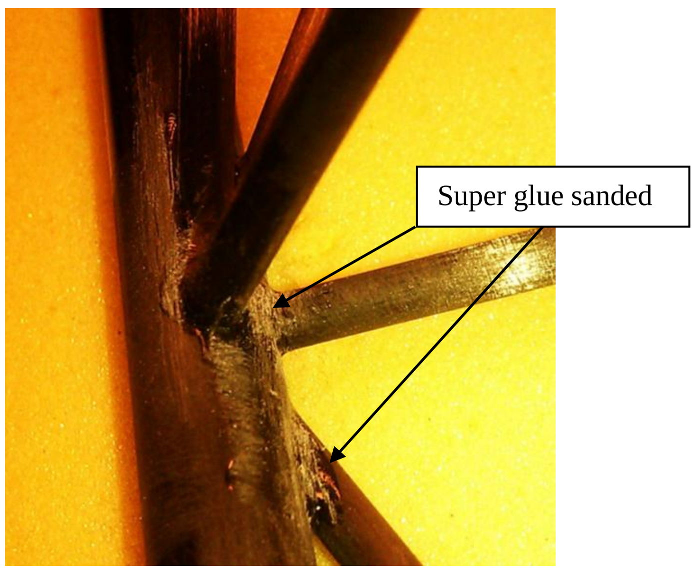


Figure 26-the joint after it was fixed with super glue and the super glue sanded to promote joint mixture adhesion.

Wooden Mold

The Jig, or wooden mold, was a modeling system used to aid in the manufacturing process of the truss spar. The jig was not specifically a requirement, however, greatly reduced time and human error. This is very important in manufacturing due to the potential variation tube angles due to human error. The truss needs to be as similar as the design as possible (since it is confirmed by the FEA model), and errors in angles may increase the amount of force on each member due to the force induced from lift.

The shape of the spar is a triangular one that consists of two runners on top, one flexible member on the bottom, and the web that would give the necessary strength to withstand the force required to for lift off which is about 50 lb per rotor. See Fig. 27 below for details.

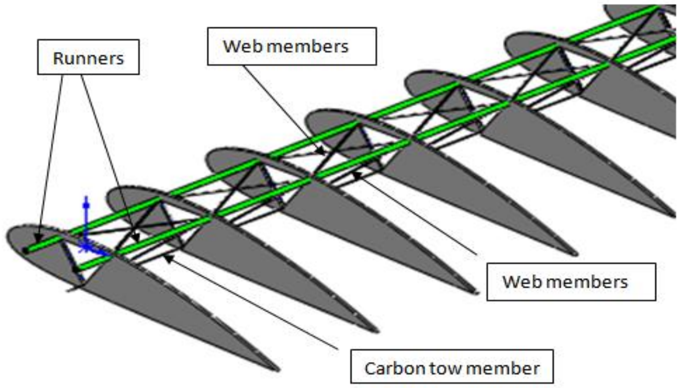


Figure 27-The spar structure along with the ribs.

The material chosen to build the jig was regular wood; the initial reasoning for this choice was due to its workability, low price, and availability. 2X4" wood members were used to form the inner and outer members of the jig and were the ones that would have the mold of the joins. The mold would be carved in the members along with the guided holes at the specific angle required by the spar structure. See Fig. 28 below for details.

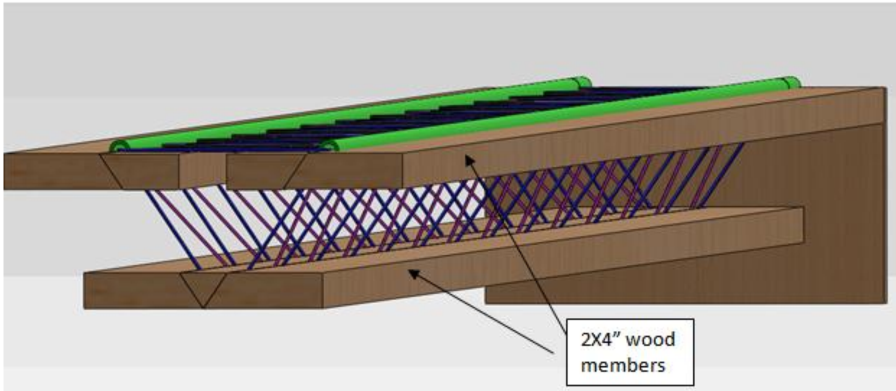


Figure 28- Conceptual wood mold, designed in Solidworks.

The jig has some holes that needed to be drilled at specific angle. The triangle members have an angle of 34 degrees from the vertical, and the diagonals members had a 20 degrees angle from the horizontal in addition to the 34 degrees from the vertical. See Fig. 29 below for details.

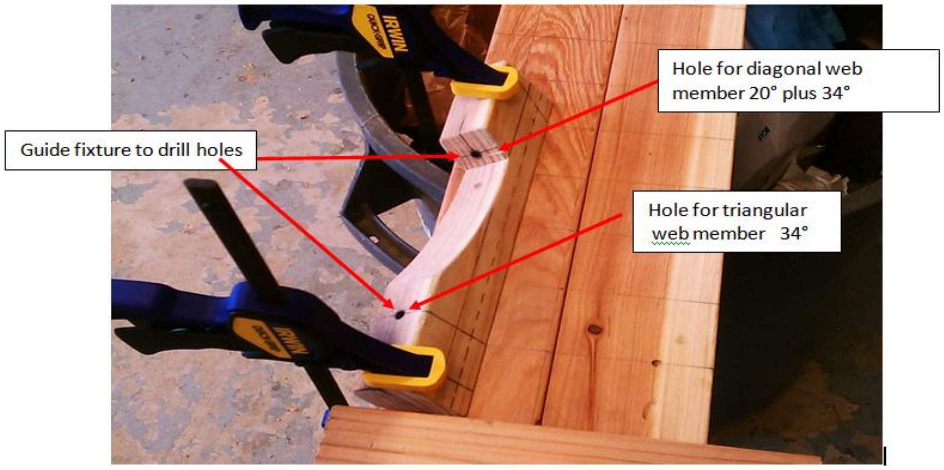


Figure 29. 2X4" members are being drilled with a guide fixture that has predetermine angles required to build the spar structure.

During testing of the manufacturing process, the team realized the complexity of the fixture. There had to be a release mechanism for the wood and joints if the jig was going to succeed. A release method for the wood need to be used since the joint's had to be built with a two part epoxy and carbon tow mixture. The joint mixture would stick to the wood as glue would, and it would be impossible to take the wood apart after the epoxy dried. As a result, some release agents were considered: wet silicon, dry silicon, and Teflon tape were considered and tested, as discussed in the testing portion of this report. As a result of all of the above release agents failing, Duratec high build primer was considered. This process would involve painting, polishing, waxing, and applying a special release agent. The team determined that there was not enough time or budget to pursue this method, and determined that the jig would need to be redesigned.

This issue was presented to the sponsor, and upon further discussion, a resolution was determined. The sponsor suggested we use the 2x4" member to hold the carbon tubes away from the joint to allow the joint to harden without contact to the wood. This way, instead of the initial injection idea, the epoxy/resin mixture would be applied by hand. The jig was modified by lowering the 2x4 members with the guide holes, and by removing the lower support.

Some of the issues encountered once the team started building the jig were that the holes did not have the exact angles, and it would be impossible to make tubes meet at the joint on the bottom. Upon investigation, it was concluded that the main problem was that the drill bit was traveling as it was drilling. Another issue related to the incorrect angles was that accuracy of the tools being used, i.e. the drill press and the band saw. In addition, the holes on the guide fixture needed a bushing that could hold the drill bit on course. The team considered all the issues encountered and concluded that the jig would play a less significant role in the building of the spar structure. Only the inner members and the side wood plates would be the only members to use in the building process. see Fig. 30 below.

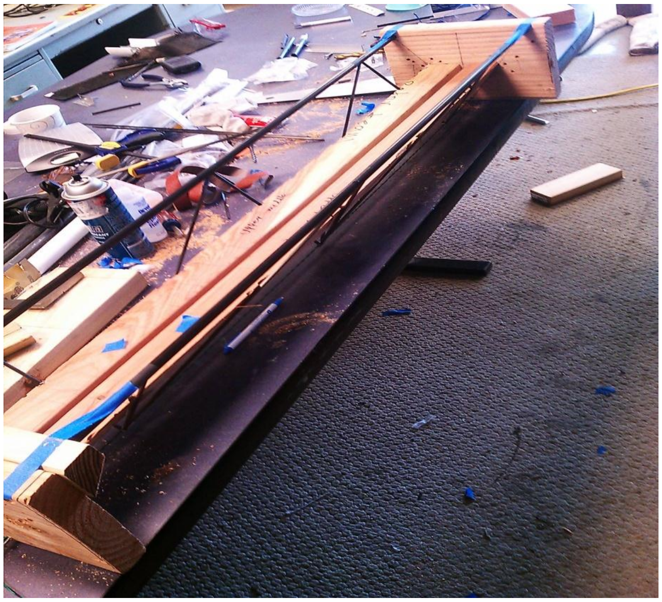


Figure 30-final form of the jig after consideration of the issues encountered

The final design of the jig served well in building the spar structure. One of the products that helped in the process was C-A glue, or more commonly known as super glue. C-A glue was used to tack the joints together while in the jig, and once dried, the truss spar was removed from the jig. The wooden mold provided a consistent way of installing the tubes at the necessary angles. See Fig. 31 below.

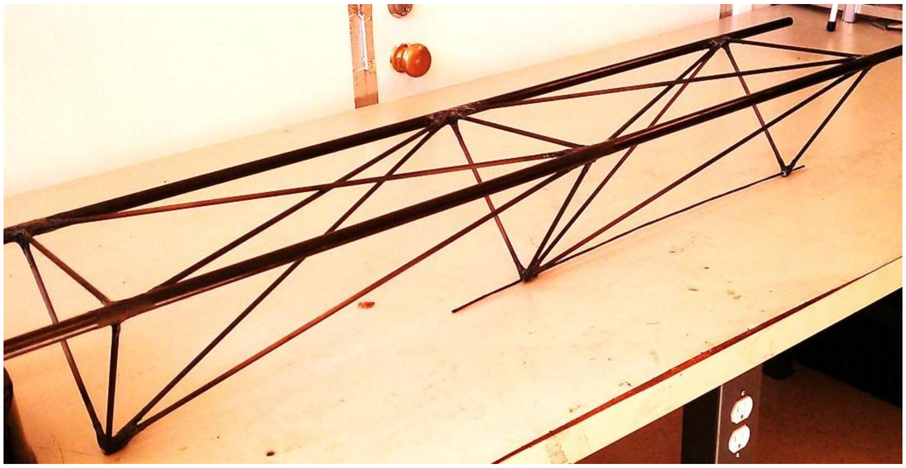


Figure 31-the spar structure after the tubes were fixed with super glue.

1/3 Scale Hub Assembly

The hub was carved out of a foam block according to the dimensions proposed to Appendix B. After, the foam block was laid over with one layer of carbon fiber. Being that this hub is merely a prototype, it was not optimized and will need composite analysis to determine exactly how many layers of carbon cloth it will need to maintain its rigidity under lift loads. In addition, according to the request of our sponsor, the hub was installed with a tension system.

The tensioning system as originally intended for the full scale was to incorporate a mechanism in the hub to tighten the bottom wire to induce anhedral to the wing. A screw tensioning system was developed and integrated to the third scale hub; some reinforcements in the hub were necessary to support the tensioning screws as seen in Figure 32. The tension system is comprised of an inner threaded cylinder, a screw with a radial hole drilled into it, and angle aluminum pieces to fit on the hub. The spectra thread is woven through the drilled hole of the screw, and the screw is tightened into the aluminum cylinder. If one wishes to tighten the wire, a thin flathead screwdriver is used to hold the screw in place, and the cylinder is turned.

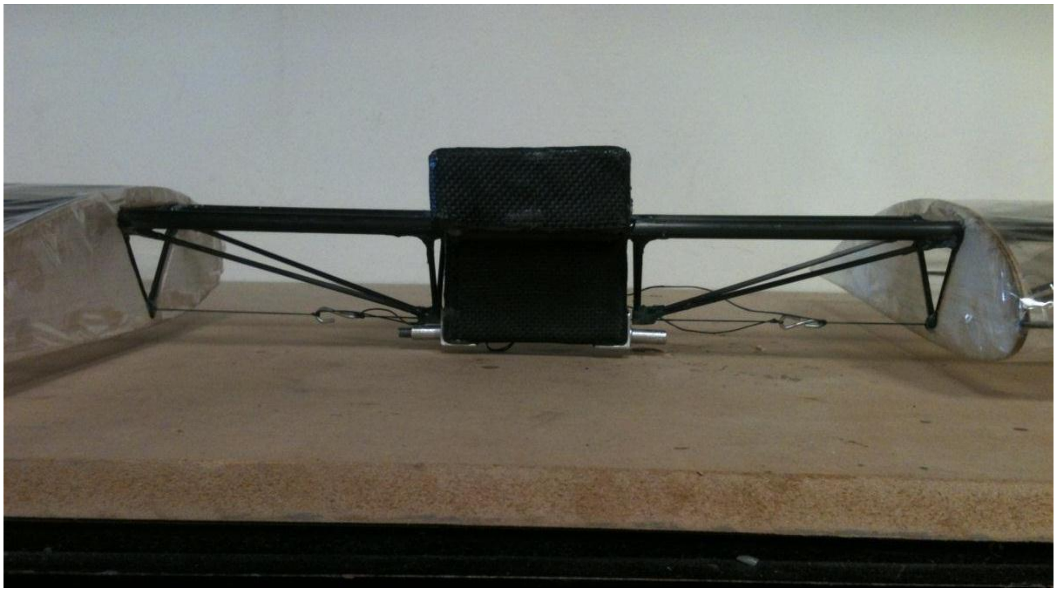


Figure 32-Installed Hub with Tension System

Ribs Installation

The Ribs were designed in Solidworks and saved as an Adobe file for proper formatting for laser cutting. The balsa wood used for the ribs was too thin to stand alone (was only 1/16”) so 2 pieces of balsa were glued together using 3M Super 77 spray. After, the ribs were installed on the completed truss, and the initial installation procedure was to slide them from the end of the truss to the desired position along the truss. This became an issue since the tolerances along the truss were too small to slide, so the team began sanding the inside triangle of the ribs to better fit the truss. Upon further deliberation, the team determined that the best course of action was to make cuts at the top of the ribs, and fit them to the position they needed to be in (Figure 33). This installation worked fine and upon inspection, didn’t seem to add weakness to the structure. To prep for the Mylar skin, each rib was sprayed with the 3M Super 77 spray, then the edges were wrapped with double sided tape to ensure a good bond to the Mylar.

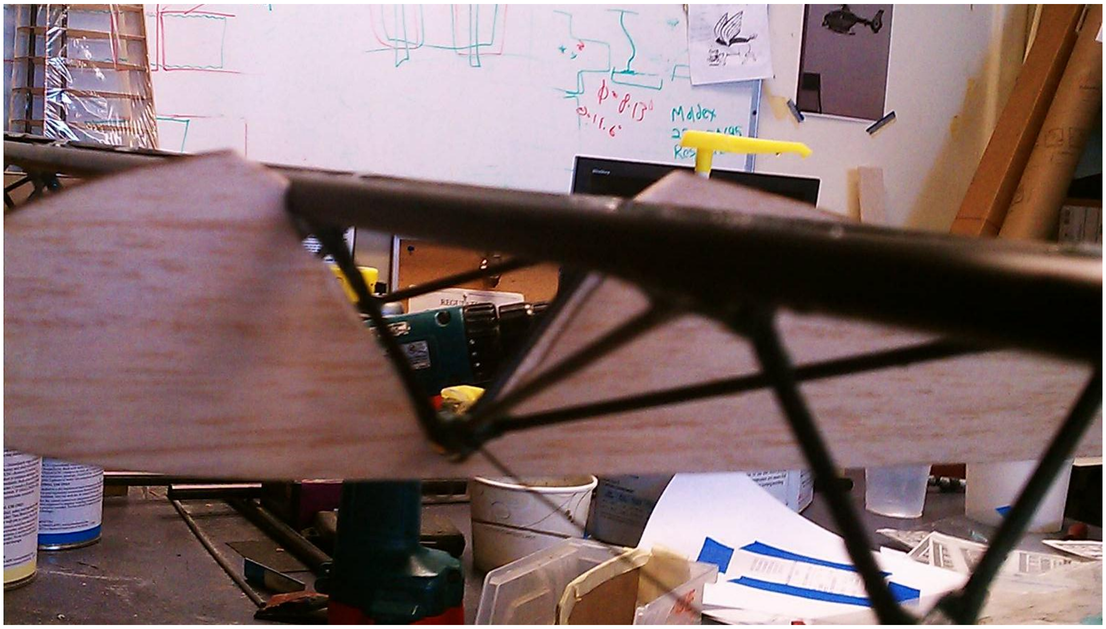


Figure 33- Rib during installation without top edge

Mylar Installation

For the skin of the rotor, .005” thick Mylar was used. This skin was chosen due to its lightweight properties. The sheet was applied in 3 different ways; the first installation was a rolling technique. Mylar was laid flat on a table, and the trailing edge of the truss/rib spar was lined up with the edge of the Mylar. The top edges of the ribs simultaneously were rolled onto the Mylar sheet, and the spar was rolled continuously till the whole sheet of Mylar was stuck to the spar. This process was very difficult, and caused a lot of wrinkles in the skin (Figure 34). Wrinkles are very undesirable, since they can disrupt the boundary layer and create drag. In addition, the skin was not very tight. This is also undesirable, since the high pressure zone of the wing will most certainly deflect under operation, thus reducing lift/increasing drag.

Figure 34-First Completed Wing using 1st Mylar Installation Procedure

For the second truss spar, a carbon tube edge was installed to aid in manufacturing and to give the wing more structural rigidity. This time, the edge of the Mylar sheet was lined up with the leading edge of the wing, and was pulled back over the top and bottom of the wing. This procedure produced similar results as the first installation: many wrinkles, with a loose skin.

Figure 35-Installation of Mylar using second procedure, with help from Team Icarus.

Figure 36-Finished wing from procedure 2. Note the wrinkles and leading edge.

Only two spars were built, so there were only two chances for Mylar installation. Because the second installation was somewhat disappointing, it was scrapped and redone. This time, the Mylar was stretched over the top, and laid down over the top of the wing (Figure 38). This produced a tighter skin, with very little wrinkles.

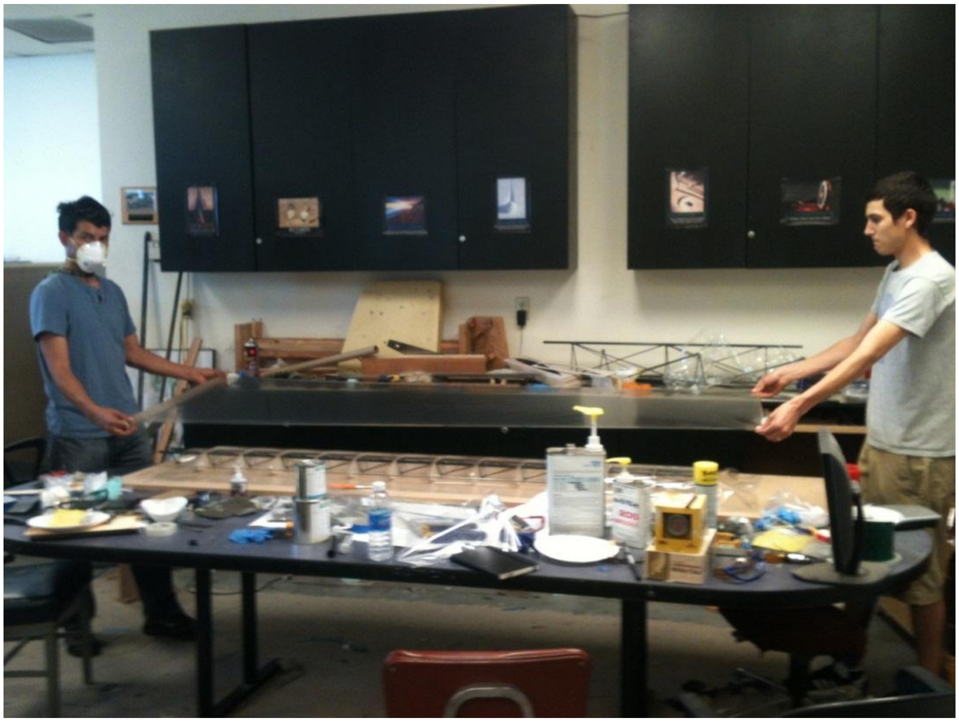


Figure 37-Proper Installation of Mylar

Figure 38-Finished wing using procedure 3

Assembly Summary

There were a few modifications done to the initial design during the manufacturing process of the 1/3 scale and full scale. On the truss, more members opposite of the “N” type members were installed to help with the moment applied to the end of the truss due to the tension member. This addition didn’t add too much weight, but added necessary strength to the truss. Another modification to the truss was the addition to small aluminum eyelets. These eyelets allowed the bottom guide wire to be installed after the truss was completed, while still allowing the truss members to be joined at the bottom.

After the ribs were installed, leading and trailing edges were installed (made of a simple carbon tube). These edges aided in the manufacturing process, and helped keep the rear tips of the ribs in line. This was important to ensure the proper airfoil shape was constant along the length of the wing.

The joints initially were designed to be epoxy/resin only, but testing proved that adding chopped tow improved strength considerably and eased manufacturing while negligibly increasing weight. This was important since the joints of composite structures can be the weakest part of the structure, and through research done by Team Icarus, showed that other joint methods would not be sufficient for operation.

The initial requirement as proposed by the sponsor was to have a symmetric airfoil for the inner quartile of the wing. This proved very difficult for 1/3 scale construction, and upon further discussion with the sponsor, was deemed unnecessary for 1/3 scale construction. This may be a design used in the final full scale design, but was not used in this project.

Lastly, a tension system was installed in the 1/3 scale hub. Being a prototype, the tension system wasn’t optimized, but did allow for one to simply tighten the guy wire by twisting a screw using a flathead screwdriver. This tension system worked great and is recommended for future use.

See Chapter 6: Conclusions and Recommendations for summary and critical review.

CHAPTER 5: DESIGN VERICATION PLAN (TESTING)

Abstract

The following is the testing procedures executed in Winter 2012 and Spring 2012 for the human Powered Helicopter Rotor Team. These various tests were executed to determine ease of manufacturability, to verify FEA models, and to verify manufacturer’s strength claims.

Experiment I. Joint Testing Procedure

Objective

The objective of the joint test is to construct and test various joints to failure. This data will be compared against proposed stresses determined from FEA.

Background

To verify and achieve the strongest bond at the joining of carbon tubes, several tests must be performed. The following test will verify strength in sanding the tubes, using different types of resin/hardener brands, and different amounts of carbon tow. These tests will give results that will point the team into a better understanding of manufacturability, and will assure the team that the bonds between the carbon tubes will not fail under lift loads.

Materials

- For Carbon Tube Construction:
    - Epoxy/Hardener (For this experiment, West-Systems 105/206 and Pro-Set 175/275 will be used)
    - Carbon Tow-0.1" diameter; multi-strand
    - Sand paper
    - Scissors
    - Stir sticks
    - Paper cups
    - Carbon Tubes
        - OD=0.197", ID=0.157", 10 foot length
        - OD=.5", ID=.4", 5 foot length
    - 12 open eye bolts-OD=0.197" (threaded diameter must be equal to carbon tube inner diameter)
    - Protractor
    - Dremmel-0.5" fitting
    - Two syringes
    - acetone

- For Test Fixture Construction:
    - 2 X 6 X 12" plank of MDF
    - 2 X 4 X 12" block of wood
    - C-A Glue
    - Wood screws
    - 2" height 4" length square aluminum angle
    - Protractor
    - Level
    - 16" hose clamp
    - Bucket
    - Sand

Procedure

Carbon Tube Construction:

1. Using a protractor, draw out the prospective carbon tube joint orientation (i.e. draw lines to ensure proper angles for tube orientation). The joint carbon tube will be constructed of one 0.5" OD tube and two 0.197" OD tube. One 0.197" tube will be joined perpendicularly to the 0.5"

tube, while the other will be joined at a 20° from the horizontal. See Figure 42 for example of finished joined tubes.

2. Cut carbon tubes to 5" length each using a band saw. *Note: careful to execute a clean cut to allow proper bonding.
3. Dremmel the ends of the 0.197" tubes with a 0.5" fitting to allow more surface area to be in contact between the joined tubes. *Health hazard: If sanding for long periods of time, be sure to use proper face mask care to prevent inhalation of particulates.
4. To get variation of test data, sand several sets of tubes to compare against un-sanded tube joining. Record which runs are sanded and which aren't. There will be 12 runs total from the sections: therefore, six sets of tubes will need to be sanded, six sets will not.

Epoxy/Hardener with tow mixing:

5. Mix 0.5 fl oz West-Systems 105 epoxy with 0.1 fl oz of West-Systems 206 hardener. The amount mixed may vary due to varying test sizes, but the mixture **must be 5:1.** Make 2 different batches for varying tow ratio.

   *Note: To mix epoxy and hardener with carbon tow, the Epoxy and hardener **must** be mixed **first**. If tow is mixed with the epoxy before the hardener is added, it may cause unequal distribution of hardener into the epoxy.
6. After the epoxy/hardener is mixed, cut 6" of carbon tow to 1/8" stubble; add to one batch. Cut 3" of carbon tow to 1/8" stubble, add to other batch.
7. With a stir stick, mix the fiber and epoxy mixture to a uniform consistency. Separate any clumps of tow to allow mixture to be more uniform.

Figure 39: 1.2oz of Epoxy/Hardener mixture with 6" of epoxy.

8. For the Pro-Set 175/275 Epoxy/Hardener, measure 20cc of Epoxy and 10cc of hardener using two syringes. The amount mixed may vary due to varying test sizes, but the mixture **must be 2:1.** Make 2 different batches for varying tow ratio.

Figure 40: Pro-set Epoxy/Hardener with application syringes.

*Note: To mix epoxy and hardener with carbon tow, the Epoxy and hardener **must** be mixed **first**. If tow is mixed with the epoxy before the hardener is added, it may cause unequal distribution of hardener into the epoxy.

Figure 41: Pro-set epoxy/hardener mixture.

9. Repeat steps 6 & 7, then clean one of the syringes with acetone. Fill up syringe with acetone for easier application.

Mixture Application:

10. Carefully apply mixtures to set tubes. The mixture must be applied properly to prevent bubbles and to fill voids due to clearances in the tube joining. Apply West-Systems: minimum tow to two tubes: one sanded, one unsanded. Apply West-Systems: maximum tow to four tubes: two sanded, two unsanded.
11. Apply a small amount of the mixture inside the smaller tubes, then press fit an eyebolt into the hole. These eyebolts will allow mass to hang during testing. See Figure 42 for clarification.
12. Repeat process with Pro-set mixtures.
13. Allow 24 hours for mixtures to dry.


Figure 42: Completed Joined Tubes.

Building Test Fixture:

14. Cut 2 X 4 into four pieces
15. Using a band saw and a drill press, carve the blocks until they resemble a “U” shape. This will allow for quick exchange of tests. See Figure 43. *NOTE: the block numbered “2” in the picture must not be drilled completely through: there needs to be a normal force to hold the tubes in place while a weight pulls it down.
16. Using a protractor, draw a horizontal line on the bottom of the 2 X 6, and draw a 20° angle from the vertical in the center of the block.
17. With C-A, Glue the four small blocks in the same fashion shown in Figure 43. The blocks **must be 4” apart** to allow for clearances. Glue these pieces on the lines drawn in step 16.
18. Cut the aluminum angle into two 2” pieces. Orient them as circled in Figure 43, drill them into the wood using wood screws. *Note: If you drill too high, you will crack the wood, and ruin the structural integrity of the test block.

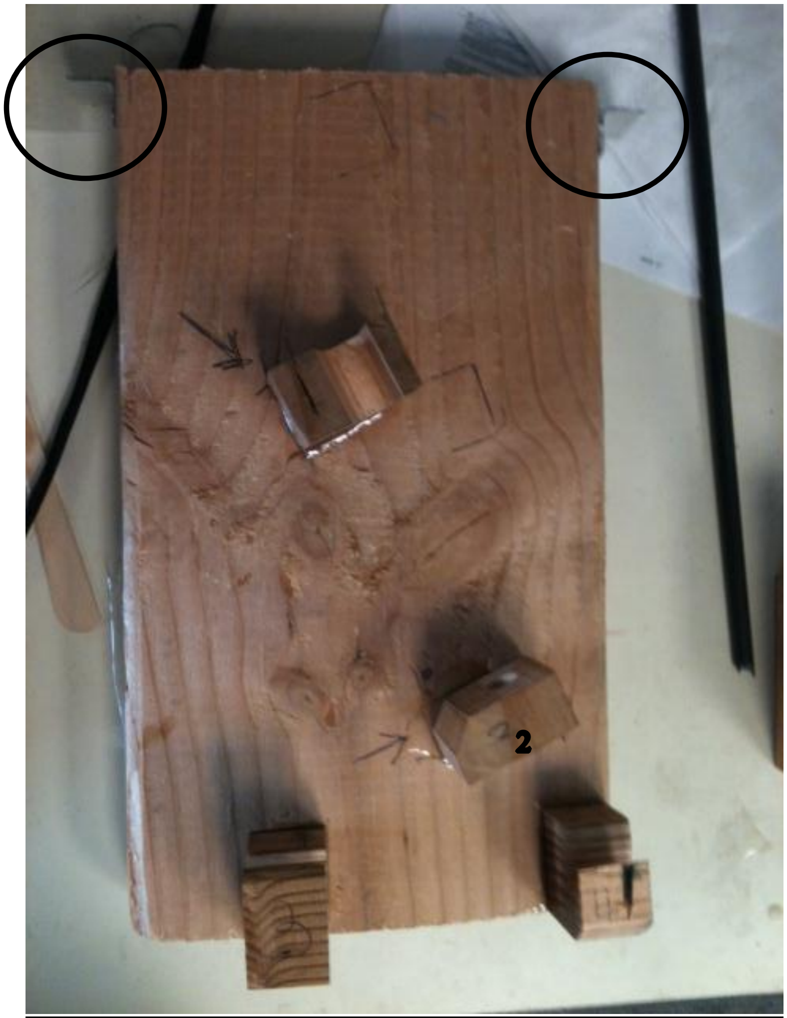


Figure 43. Completed Test Fixture. Note the two aluminum angles at the top.

Testing

19. Attach the test fixture to a rigid object by clamps. See Figure 44.
20. Place a tube to be tested into the test fixture. Since the 20° tube will be in tension during flight, run eight trials in the 20° position, and four in the horizontal position (West-Systems: max tow-sanded, West-Systems: max tow-unsanded, Pro-Set: max tow-sanded, Pro-Set: max tow-unsanded). When attaching tube for 20° position, wrap the hose clamp around the tube and the fixture to prevent a moment from being created.
21. Using the eyebolts glued into the inside of the tubes, hang a large bucket to the fixture. Fill the bucket with sand or known mass till failure. Repeat for various trials, record results.


Figure 44: Test Fixture with loaded tubes, oriented in horizontal position. Bucket is filled with sand and known masses.

Results and Analysis

Key concepts integrated into the current design were taken from this procedure and testing. The team learned that it was very important to sand the joints before applying the mixture; many of the joints failed simply by lightly handling them due to the weak bond formed to the slick tube surface. Upon loading, the sanded joints were able to withstand more than 115 pounds of weight. This is significant because it roughly equates to be 91.5 KSI, which is well over the predicted stress of 11.2 KSI determined from our FEA analysis. This gives a safety factor of just over 8 for the most at risk joints, which is more than sufficient for flight.

In comparing the two mixture types, both were able to withstand the same loading. This is proved in the manufacturing analysis, which gives a tensile strength of 7.25 KSI for Pro-Set, and 7.3 KSI for West-Systems. A qualitative study found that the Pro-Set mixture was much easier to apply due to its viscosity, and was more consistent in mixing with tow. The West-Systems viscosity varied greatly due to the amount of tow added, and was difficult to replicate exact viscosity through different trials of batches produced.

Lastly, through different trials of batch making, the team determined that using carbon tow "stubble" was the greatest way of applying the tow. In the early phases of development, we kept the carbon tow length to be under ½", which was too long. The strands would form together like hair, and would not clump as desired. Instead, it stuck together like spaghetti and would form ribbons when one would try to apply to the joints. Upon multiple iterations, the team determined that the best way to apply the epoxy/tow mixture was by using strands of tow approximately 1/8" long.

Experiment II. Joint Release Agent Testing

Background

The joint release agent objective is to test whether it is possible to use the wood structure (JIG), as seen in Figure 45 below, to hold the spar structure of the human powered helicopter and build the joints at the same time. The joints molds are to be carved in to the wood, and the carbon fiber tubing is going to be introduced into the wood joint mold which will have the needed angles that project the tubing toward the join location. And finally the wood is to be taken apart leaving the joint formed. The products that are going to be used in the test are Teflon tape (plumbers tape), dry silicon spray, and wet silicon spray. The objects to test are carbon fiber tubes of .5", wood blocks, and resin-hardener-tow mixture.

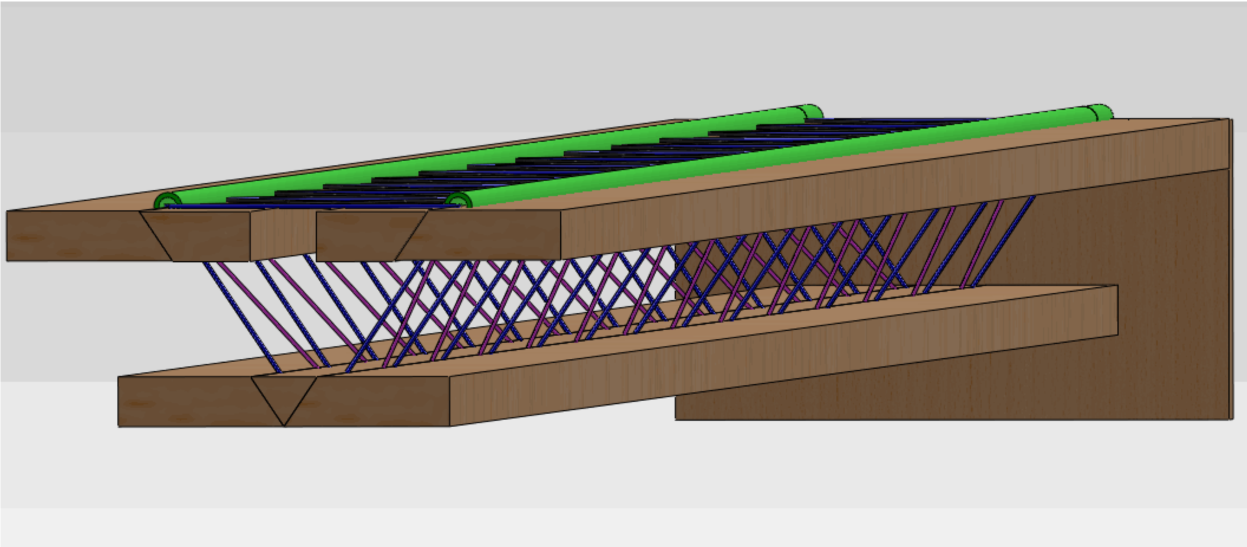


Figure 45-Proposed design of the JIG to build the Spar structure.

Joint Release Test Procedure:

Wood Cutting:

1. Cut a 2x4" piece of wood five inches long.
2. Drill through the center of the wood block with a 5/8 inch drill bit in a direction perpendicular to the 4" plane.
3. Cut the wood block in half along the length of the member and perpendicular to the 4" plane, making sure the cut goes through the drilled hole, half way.

4. Clean the block from any wood rough edges or wood fragment left by the drill bit using 80-grid-sandpaper.
5. Repeat step 1-4 four times.

Release agent application:

6. Apply wet silicon to both halves of block #1 directly at the area of the hole, and let it set for 10 minutes.
7. After 10 minutes had passed clean block #1 from any excess silicon that has not been absorbed by the wood block. Note: is Ok if silicon is sprayed outside the area of the hole, it will not affect the test.
8. Apply wet silicon to both halves of block #2 directly at the area of the hole, and let it set for 10 minutes. Note: there is no need to clean excess since it is dry silicon.
9. Wrap Teflon tape around each half of block #3 making sure the area of the hole is covered completely, in addition cover one inch along the length of the block extending on each side of the area of the hole.
10. Block #4 will be a control subject. No release agent is to be applied to this block.

Tube Cutting

11. Cut four .5 OD x.4 ID" carbon tubes four inches long. Note the carbon tubes do not need to be sanded.
12.

Resin-Hardener-carbon tow mixture:

Figure 46-West Systems Resin/Hardener-tow mixture

13. Cut 6 cm long of carbon tow into 1/8 inch pieces.
14. Mix .5 oz of West System - 105 Resin and 0.1 oz of West System - 206 Hardener Slow Cure in a cup.
15. After the resin/ hardener mixture is thoroughly mixed, add the chapped carbon tow, and mix it thoroughly with the resin/hardener mixture.

Resin-Hardener-carbon tow mixture application:

Figure 47-Joint test fixture and materials. This image is to be used as a reference not as a template for the test; the test follows the procedure specified in this document.

16. Apply the resin-hardener-tow mixture to about 1 ½ inches along the length and about .1 inches thick around the circumference of the carbon fiber tube.
17. Sandwich the tube/mixture along the drilled hole with the wood block halves, making sure the tube is as concentric with the hole as possible.
18. Once the tube and the block are aligned, apply tape around the wood block to fasten the tube/block fixture.
19. Repeat steps 15-17 for the other three tubes.
20. Let the four tube/block fixtures dry for about 24 hours.

Results and Analysis

This test demonstrated that a redesign was necessary, because there was no good release agent that could be used consistently on the same jig. The dry silicon test failed because it didn't release the tube from the wood (Figure 48). The Wet silicon test failed because it mixed with the epoxy, then upon separation, it allows the epoxy to bond to the rougher surface (the wood) and debond from the smoother surface (the tube). The Teflon Tape proved to be most promising, as it allowed the carbon tube to bond to the epoxy, but unfortunately, was inconsistent: if epoxy seeped through the cracks of the tape, then the epoxy bonded the tube to the glue. Also, this method proved in efficient since it made the joint very messy, since the epoxy bonded to the tape itself.

There are a few release agents that may have worked, i.e. the release paint and wax that the Supermileage Team used for their monocock, or release cloth commonly used in composite application. The issue with using these methods were that they were either too expensive, or they created tolerance issues within the jig, and would be tough to replicate. The team decided the best action was to redesign the jig, so that was the joints could dry without touching any part of the jig (see Figure 28).

Figure 48-Experimental Joint release agents, using Dry Silicon, Wet Silicon, Teflon Tape, and a Control. All failed the test.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Favorable Results

Tension Member for Induced Anhedral

While initially seemingly a risky design, the design proved to be somewhat successful on the 1/3 scale model. The team was able to induce a few inches of anhedral on the 1/3 scale model, which was impressive due to the elasticity of the spectra thread and the strength of the 1/3 scale wing (reminder: the 1/3 scale wasn't properly scaled due to scaling issues, therefore was stronger than what the 1/3 scale wing was supposed to be). For projected full scale application, a carbon tow tension member was constructed using West Systems resin/epoxy. The constructed tension member demonstrated the desired stiffness and strength upon quick inspection. To ensure that the carbon tow member can be properly installed and used for full scale application, a good manufacturing process needs to be implemented to ensure proper fiber volume, and the member should be tested at estimated loading and tensioning.

The tension system prototype also performed great; not only was it able to induce the desired anhedral, but was able to do it easily. In addition, the tension system was made from aluminum, which sufficed in strength while adding minimal weight to the rotor.

Strength of Joints

The joints were tested and were able to be constructed quickly and efficiently. For full scale section construction, each joint added less than half an ounce of weight, while still providing the proper strength to the joint. Through the process, the team learned that surface preparation is extremely important; each joint needs to be sanded and cleaned before joining: otherwise, the bond will fail prematurely.

Manufacturing Process

The introduction of the wood jig was great for the ease of manufacturing. The team wanted a process that allowed quick construction while minimizing human error. This was achieved with the jig: to construct the truss, one needed to only place the carbon tubes in the proper grooves lined in the wood mold, then tack-glue the carbon tube to the runners of the truss. This jig produced accurate, repeatable building for the truss.

Under Budget

By the end of the year, the team was well under the required budget. The proposed budget was $2000, and by the end of the year the team was under $1000. Further budget analysis can be viewed in Appendix C.

Under Weight

According to calculations done in Appendix C, the full scale truss would be under the required weight of 10 lb. There is some variance in this calculation, since it doesn't include the hub weight, tension system weight, and assumes consistent joint weight through each node. The total weight of the wing equated to be approximately 2.5 lbs.

Improvement Potentials

Scaling and Natural Frequency

Determining the natural frequency is a complicated matter because the hand calculations are not only tedious, but there are many opportunities for mistakes. Dr. Wu, an expert mechanical engineering professor in vibration analysis, proposed it was better to use a finite element analysis (FEA) program like Abaqus to do vibration analysis; Abaqus is proven to work and gives reasonable results. As a result, the team was able to obtain the natural frequency as required. In addition to the Abaqus analysis, the team will try to gain accesses to the vibration lab to do physical testing using Fourier Transforms. This will give more insightful analysis of the properties of the truss structure.

In addition to the difficulty of scaling natural frequency, determining the truss natural frequency may not be an accurate estimate to determining the wing's natural frequency. The addition of Mylar, foam ribs, and the leading edge will drastically change the natural frequency, and may be only obtained by testing. As stated above, this analysis is outside the span of this project.

Furthermore, when it comes to the calculation of the natural frequency of a structure, the weight is the most important factor. When addressing issues with different proposed requirements, the proper scaling of weight was determined to be nearly impossible. The proper scaling for a 1/3 scale model would need to be 1/27 of the total weight, which results in .37 lbs. This scaling is defined by reducing all the 3-dimensional lengths by one third, which results in a cubic root of the initial scaling (i.e. (1/3)^3). As a result, the sponsor and the team determined that the natural frequency of the scaled model would be of no benefit other than for future reference.

Truss Structure

A major issue that still needs to be optimized is the proper joining of the carbon tubes. Due to weight constraints, it may be too much weight to simply join the tubes with an epoxy and resin compound, so other methods should be considered for future use.

One method takes a composite string, such as Spectra thread or carbon tow, and wraps the joint. Using this method, a much smaller amount of epoxy is used on the wrapped joint, while maintaining the structural integrity of the truss. This idea is simple and lightweight, but may have issues during fabrication. Each joint will need to be meticulously and carefully wrapped to provide consistency: an unbalance of the wing can occur if different nodes are significantly heavier than others. As a result, the amount of time required to construct only one 40 ft rotor may become a colossal undertaking.

Another technique, proposed by Quattro Composites, uses a silicon mold to press a small patch of carbon fiber around each individual joint. The carbon fiber would solidify, and the mold would be removed. After solidification, the excess resin is trimmed, leaving the joint wrapped in carbon fiber. This technique would be optimum for manufacturability and consistency, since the same mold would be used on each joint to produce consistent results. Unfortunately, the mold required to press the joints could be upward of a couple thousand, which would consume nearly the entire allowed budget. If the mold could be machined in one of the shops here at Cal Poly, hundreds of dollars could potentially be saved.

The final idea, as proposed by Dr. Mello, would be to make a small "ball" of carbon fiber, and drill small holes into the ball. The individual carbon tubes would then press fit into the holes, with a small amount of epoxy added. This idea is the simplest idea, but may be difficult to construct. It is very difficult to drill into carbon fiber, since the fibrous weave tends to fray and tear. This technique may also weigh more than the above proposed solutions.

On the topic of truss member optimization, the angles for the proposed designs were chosen to be simple angles, such as 60 and 45 degrees. This became a problem when trying to optimize the pattern along the 20 feet of the wing. At these angles, the pattern would not be able to finish soon enough for hub integration, or finish too soon and leave too much of the central part of the truss without truss members. For future applications or analysis, it would be beneficial to the HPH club to optimize the proper angles in the truss members to better reduce bending caused by the lifting force. This can be done using parametric tables in Solidworks, by varying the nodal distances, and searching for a proper weight-to-safety factor ratio.

Leading Edge

On the second wing, a leading edge was installed, and while it was only a thin carbon tube, it helped significantly with the rigidity of the ribs and with the Mylar application. On the other hand, the team noticed that it still allowed loose skin in the high pressure zones of the wing, which is highly undesirable. The reasoning behind not installing a D structure (or have the entire leading edge made of foam) was to see if Mylar would suffice, which it didn't. A leading edge made of foam or hard plastic will need to be installed, similar to that of the Yuri I seen in figure 49.

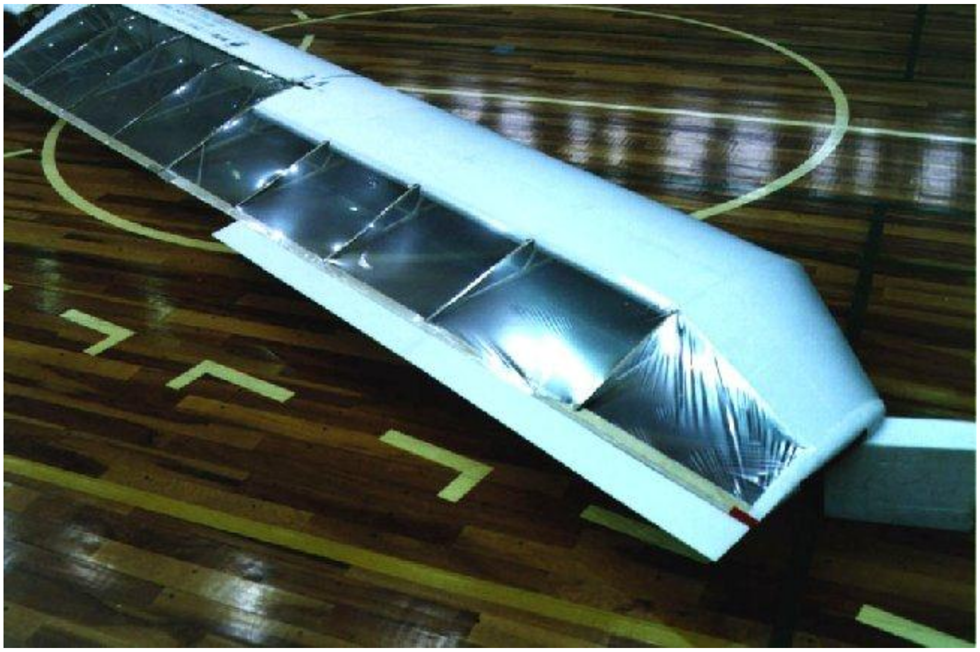


Figure 49-Wing of the Yuri I. Note the foam leading edge.

Wing Skin

While the last application of Mylar produced minimal wrinkles, there were still wrinkles in the skin, which is highly undesirable. Wrinkles can disrupt the boundary layer and flow, which will induce drag. It was great that the Mylar was able to be so lightweight and relatively strong, but for future teams, some type of shrinkable skin will need to be used, like Ultracoat or Monocoat. While more expensive and significantly heavier, these skins will give the wing a nice tight skin, which will prevent the skin from deflecting due to high/low pressure zones.

Moment-Bend Test

To prove the FEA done through Abaqus, moment testing on the full scale sections needed to be done. Unfortunately, due to time constraints, that testing was unable to be completed before the end of the year. The team has set up a procedure for the test, and hopes that the HPH club will be able to test and evaluate the moment-bend test to ensure a good truss design. It is important to test bending moment as opposed to force loading only on the sections because the sections would experience very little bending and very high shear at the ends. The bending test could not be implemented on the 1/3 scale because it's not a true 1/3 scale as mentioned above.

Carbon Tow Test

In addition to the Moment-Bend Test, a tensile carbon tow test should be executed to ensure the tow can take the loading forces in flight. The tow should be able to take the forces suggested in Abaqus, multiplied by 1.5 as a safety factor for fluttering and vibration the wing may see.

Strength of joints

The strength of the joints needs to be optimized, since there can be great weight reduction potential. Although each joint weighs under an ounce; this weight quickly adds up when considering how many joints there are on the entire wing: 84 joints. If the joints are optimized by how much volume of material is needed per joint, weight can be saved. If the joint volume is not carefully monitored and measured, then the truss can easily go over the 10 lb weight requirement.

Hub Redesign

The hub prototype was built for concept only, and was not optimized to take the loading from the tension wire or the moment induced from rotor operation. Composite analysis will need to be done through hand calculations and Abaqus to determine how many layers of carbon cloth is needed to ensure structural rigidity and to ensure there is no failure in flight. In addition, the tension system will need to be optimized as well to ensure no slippage occurs during flight, and to ensure the forces acting on the system doesn't collapse the hub.

Tension Wire

Even though we were able to induce anhedral in the third scale model, the spectra thread stretched after a few hours and the induced anhedral was lost. The intent of the team is to use carbon tow for the full scale, and it is not expected to undergo elastic deformation due to the induced tension.

Another major modification to design to be introduced into the full scale rotor is the fixing of the lower member at each eyelet node. Through Abaqus the team learned that if the lower member is not fixed at each node, then the integrity of the truss is lost due to its inability to transfer forces through all the members of the truss. Therefore, after the initial desired anhedral is induced, the tension wire will need to be permanently fixed at each node.

Maintenance and Repair

Due to the fragility of the structure and components, the rotor will eventually fail and break. This is done by design; ideally the aircraft will fly once, win the prize, and then break right after. In addition to fragile components, the estimated safety factor is also low: around 1.5. If the rotor does fail, an assessment will need to be done to determine what the best course of action needs to be done: if the hub cracks or fails, the wings can be salvaged and a new hub will need to be built, and visa-versa. If there is any doubt in the team's mind about the strength of the repair or the wings structural integrity, it is advised that the team builds a new rotor.

Final Thoughts

Although the team was unable to test the full scale sections that were built, much was accomplished through the manufacturing process and joint testing that was done. The trial and error method of Mylar application gives the HPH great direction of what kind of skin needs to be installed and gives insight to what kind of leading edge is needed to maintain the integrity of the airfoil. This team is confident that the tension wire design to induce anhedral will aid the HPH club in building a great rotor, and hopes that in a few years' time Cal Poly at San Luis Obispo will build another successful Human Powered Helicopter.

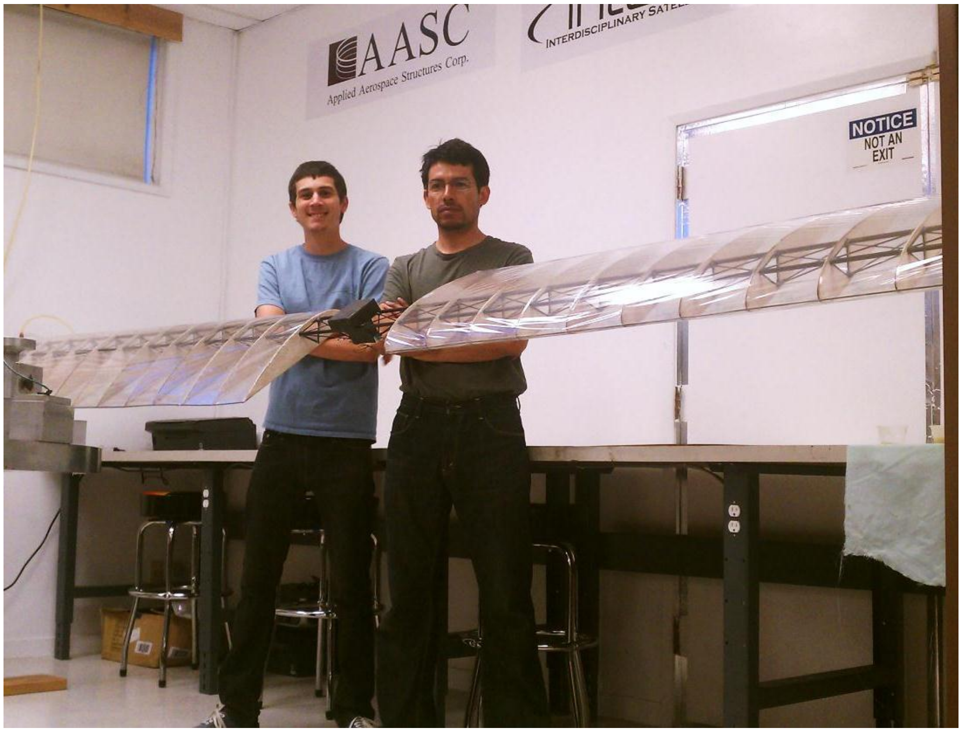
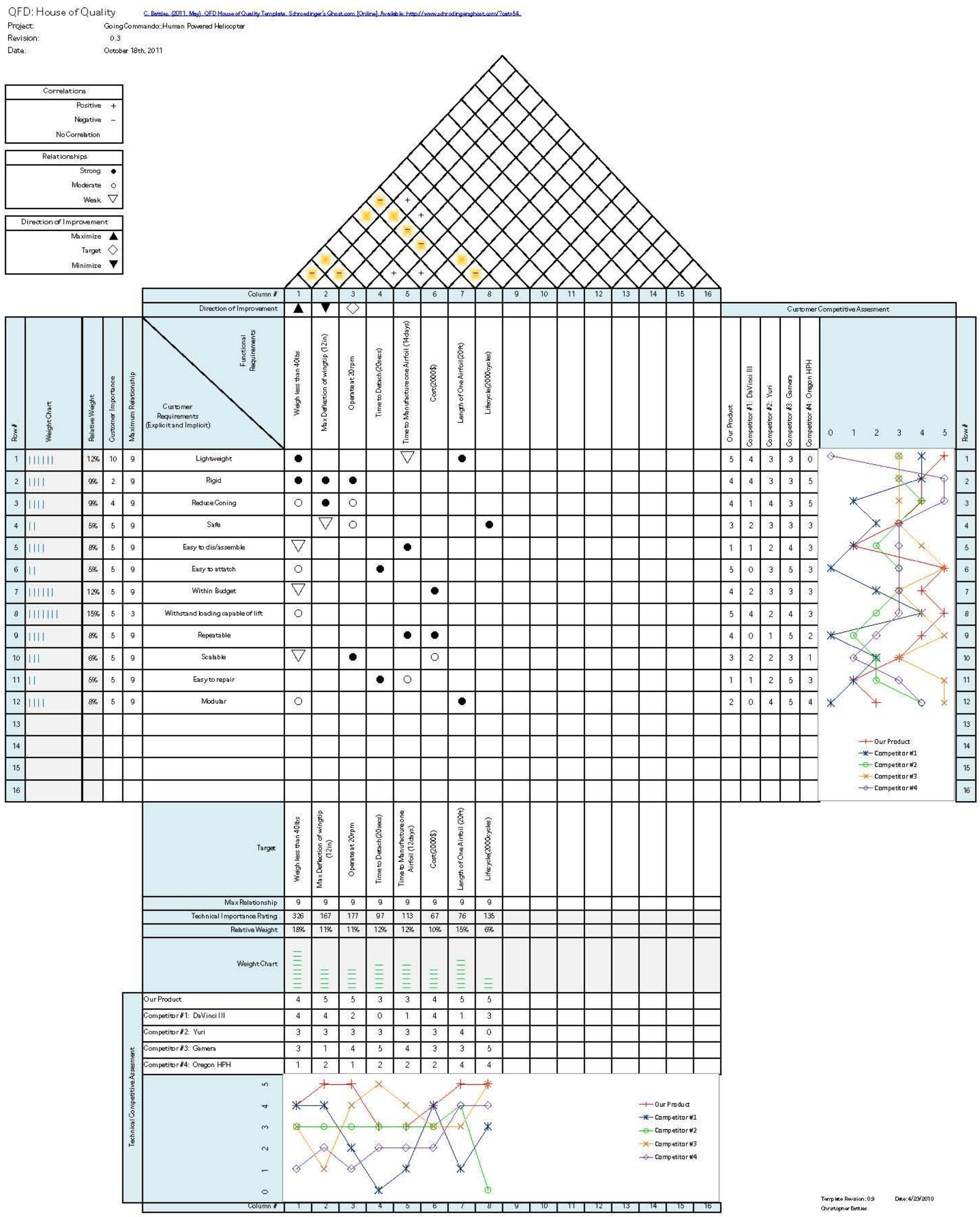
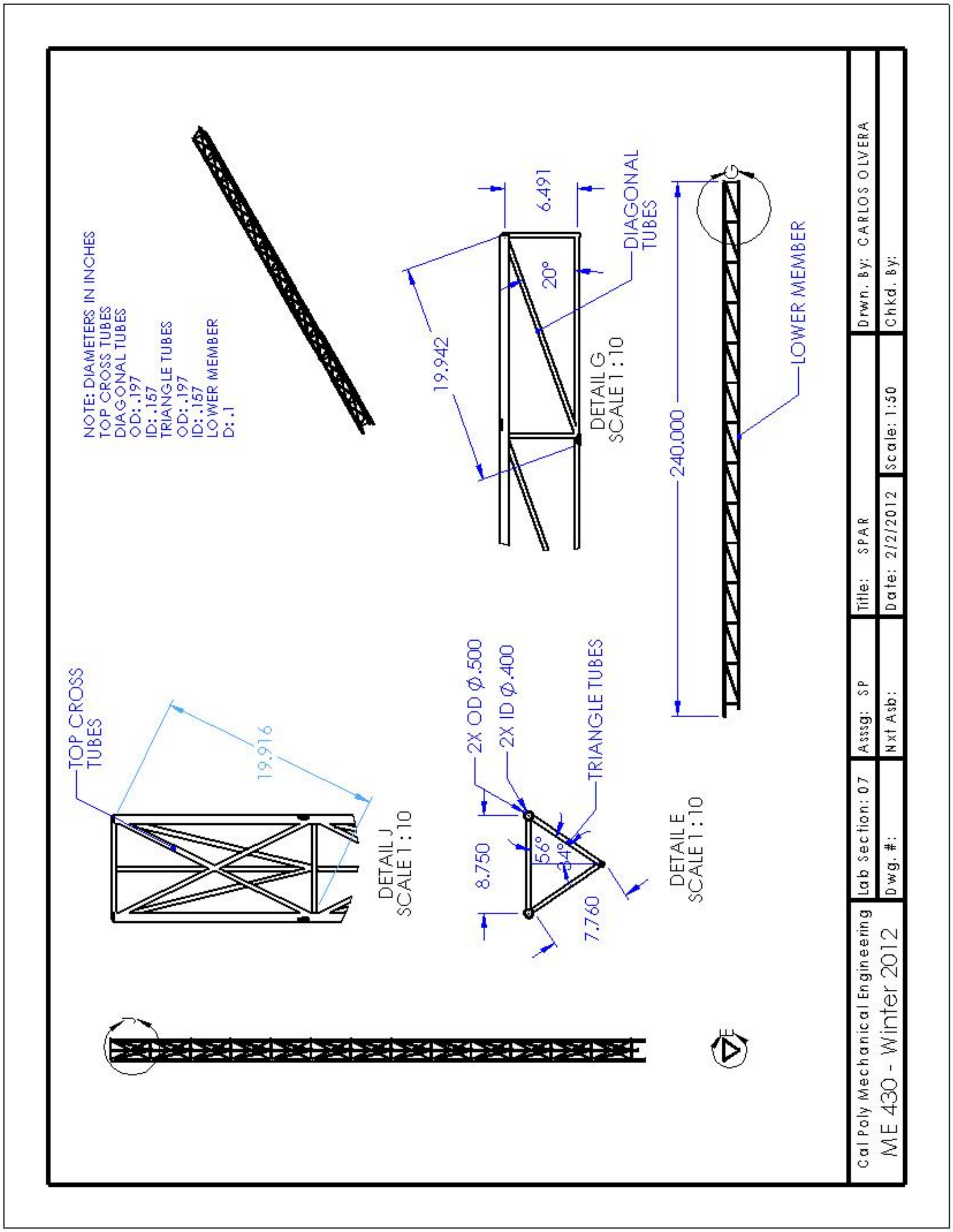


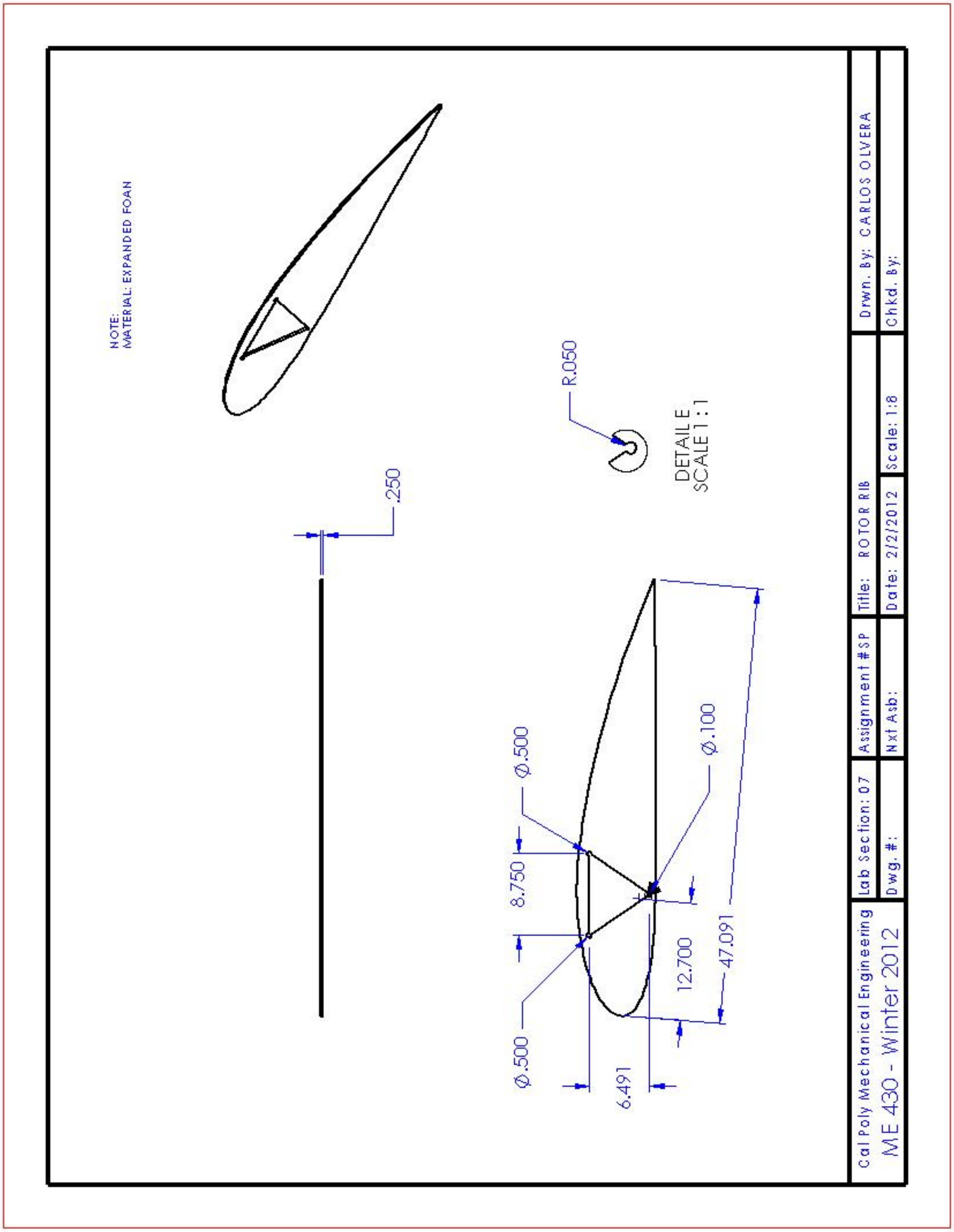
Figure 50-Human Powered Rotor Team with the finished 1/3 scale rotor.

APPENDIX A: QFD



APPENDIX B: DRAWINGS

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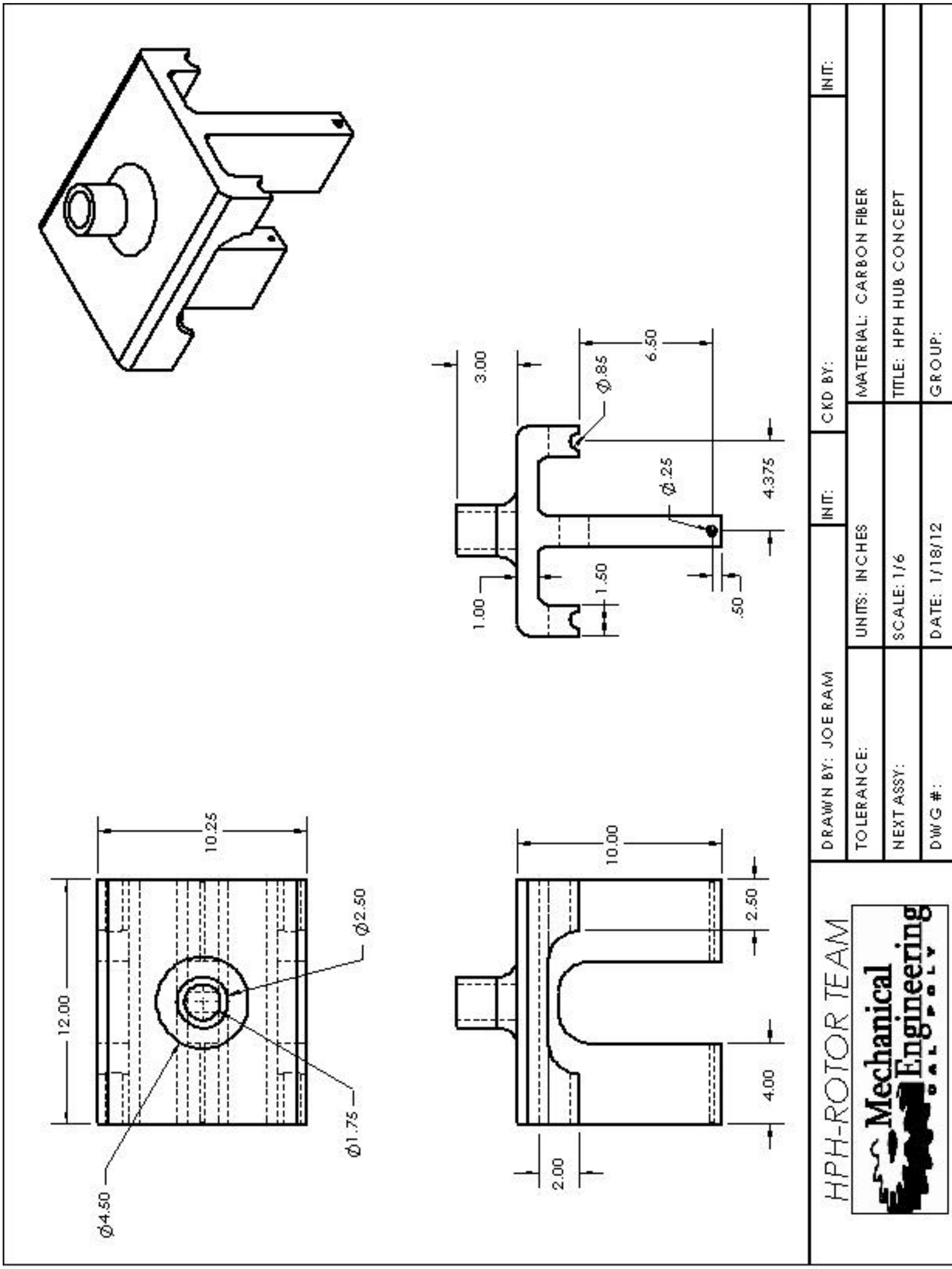
Cal Poly Mechanical Engineering
ME 430 - Winter 2012
Lab Section: 07
Dwg. #:
Assignment #SP
Nxt Asb:
Title: ROTOR RIB
Date: 2/2/2012
Scale: 1:8
Drwn. By: CARLOS OLVERA
Chkd. By:



HPH-ROTOR TEAM
Mechanical Engineering
CAL POLY
DRAWN BY: JOE RAM
INIT:
CKD BY:
INIT:
TOLERANCE:
UNITS: INCHES
MATERIAL: CARBON FIBER
NEXT ASSY:
SCALE: 1/6
TITLE: HPH HUB CONCEPT
DWG #:
DATE: 1/18/12
GROUP:
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10.25
Ø2.50
Ø1.75
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4.375
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APPENDIX C: PRICING and WEIGHT

Tubing Info full scale

tubes	tube OD	tube	price	weight (g)	length (in)	ID number	weight density (lb/in
diagonal,cross top	0.197	0.157	6.40	11.1	39.37	T509Lm	0.00062
triangle	0.197	0.157	6.40	11.1	39.37	T509Lm	0.00062
runners	0.5	0.4	14.25	98.6	48.00	T530L4	0.00453

Tubing Info Third Scale

tubes (1/3) scal	tube OD	tube	price	weight (g)	length (in)	ID number	weight density (g/in
diagonal,cross top	0.118	0.079	3.65	5.6	39.37	T507Lm	0.00031
triangle	0.125	0.118	2.00	5.1	39.37	T512L4	0.00029
runners	0.375	0.29	8.50	55.5	48.00	T524L4	0.00255

Total weight

segments	length (in)	length (1/3)	number	total length	total weight	total length (1/3)	total weight (1/3)
runnerstop cross	240.0	80.0	4	960.0	4.35	320.0	0.82
top cross	19.6	6.5	52	1020.3	0.63	340.1	0.11
side diagonals	19.0	6.3	52	986.4	0.61	328.8	0.09
side triangles	7.8	2.6	56	438.8	0.27	146.3	0.09
top triangles	8.3	2.8	28	231.0	0.14	77.0	0.05
wing total weigth				**full scale**	6.01	**third scale**	1.16

Number of tubes

tubes	# tubes full	price	# tubes (1/3)	price2
diagonal,cross top	51.0	326.22	17.0	108.74
triangle	17.0	108.88	5.7	36.29
runners	20.0	285.00	6.7	56.67
wing		720.10		201.70

Mylar

Mylar	perimeter (in)	length (in)	thickness (in)	volume in cub	price (dlls)	weight density (lb/in cub)	total weight
full scale	98.1	360	0.0005	17.66	69.03	0.051	1.8
(1/3) scale	32.7	120	0.0005	1.96	24.5	0.051	0.2

Ribs

Ribs	area of rib (in-sq	thickness (in)	# ribs	price (dlls) shet	weight density lb/ft-cu	total weight (lb)
full scale	245.18	0.25	22	2	0.85	0.66
third scale	27.24	0.125	22	50	8	0.35

sumary	total weight	total price	Actual Weight
full scale	8.46	791.13	-
third scale	1.70	276.20	2.4

Joint Weight/Node
0.0077

APPENDIX D: DVPR

Report Date		3/8/2012	Sponsor	DR. COLVIN						Component/Assembly	TRUSS SEC	REPORTING ENGINEER	JOSEPH RAM
TEST PLAN										TEST REPORT			
						SAMPLES		TIMING			TEST RESULTS		
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsi	Test Stage	Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	NOTES
1	WEIGHT<10 LB/EASE OF MANUFACTURING	JOINT TESTING	MIN WEIGHT/EASE OF MANUFACT./STRENGTH	NL	CV	6	A	2/18/2012	2/19/2012	PASS	3	3	RESULTS- SAFETY FACTOR OF 8
2	PROOF OF FEA	JOINT LOADING	TEST TO FAILURE	JR	CV	6	A	2/18/2012	2/24/2012	PASS	3	3	
3	EASE OF MANUFACTURABILITY	WOOD MOLD ASSEMBLY	ACCURACY BY .1" TOLERANCE	CO	PV	1	C	1/16/2012	2/26/2012	FAIL	0	1	PASS AFTER REMODEL
4	PROOF OF CONCEPT	GUY WIRE MANUFACTURING	RIGIDITY/STRENGTH	JR	CV	2	A	2/24/2012	2/27/2012	PASS	2	0	
5	EASE OF MANUFACTURABILITY	JOINT RELEASE AGENT	NO ADHESION TO WOOD/TUBES	JR	PV	4	C	2/7/2012	2/8/2012	FAIL	0	4	RESULTED IN WOOD MOLD REMODELING
6	EASE OF MANUFACTURABILITY	CARBON TOW ANALYSIS	PROPER ADHEASION TO TUBES	CO	PV	3	C	2/18/2012	3/6/2012	PASS	2	8	FAILED APPLICATION WITH LONG STRANDS
7	MUST BE ABLE TO UNDERGO LOADING=55 LB PER ROTOR	MYLAR APPLICATION	NO FOLDS/ TEARS	NL	CV	2	A	4/27/012	5/4/2012				
8	PROOF OF FEA	COMPRESSION LOADING	MIN=4700PSI	NL	PV	3	C	3/1/2012	4/1/2012				
9	PROOF OF FEA	TENSILE LOADING	MIN=52290 PSI	CO	PV	3	C	3/1/2012	4/1/2012				
10	-	WIND TUNNEL	MIN DRAG	JR	CV	1	A	3/1/2012	4/1/2012				OPERATE AT VARIOUS SPEEDS UP TO 7 MPH
11	PROOF OF FEA	DEFLECTION	12"	NL	DV	1	B	3/1/2012	4/1/2012				

APPENDIX E: SUPPORTING ANALYSIS

Mesh Convergence Matlab Script

```
clear all
clc
E=17e6; % elastic modulus of carbon fiber
t=.706*12; % the thickness of the spar in the vertical direction
w=1.5*t; % the length of the chord of the rotor
h=.85*t; % the corrected thickness to fit the air foil used as the
L=18; % the length of one segment of the spar
od1=.5; % outside diameter of the upper tube
id1=.4; % inside diameter of the upper tube
od2=.118;% outside diameter of the diagonal members tube
id2=.079; % inside diameter of the diagonal members tube
f=55/2; % the force applied to the spar at end of the spar furthest from the
hub
A_1=(pi/4)*(od1^2-id1^2); % area of the upper tube
A_2=(pi/4)*(od2^2-id2^2); % are of the diagonal tubes

B=(h^2+L^2)^.5;         % length of the diagonal member

r1=f*L/h; % reaction force at the upper members

r2=-f*L/h; % reaction force at the lower member

R_B=(r2^2+f^2)^.5; %reaction force seen by the diagonal member

delta_Lu=r1*L/(2*A_1*E); % the change of length on the upper tubes

L_new=L-delta_Lu; % the new length of the upper members

delta_L_B=R_B*B/(2*A_2*E); % the change in length of the lower member

L_B_new=B+delta_L_B % new length of the lower member

theta=acos((L_new^2-h^2-L_B_new^2)/(-2*h*L_B_new)); % law of cosines to
calculate the new angle
% of the new triangle

delta_Lb=abs((r2)*18/(.1^2*(pi/4)*E));

theta2=atan(delta_Lu/h)+atan(delta_Lb/h);

H_new=L_B_new*(sin((pi/2)-theta)+theta2); % the new height of the end of the
segment

delta_h=H_new-h % the change in height at the particular segment

str=('delta_h');
disp(str)
```

```
%%
for i=2:13  %loop to iterate the delta_h at every segment of the truss
r1=f*i*L/h;

r2=-f*i*L/h;

R_B=(r2^2+f^2)^.5;

delta_Lu=r1*L/(2*A_1*E);

L_new=L-delta_Lu;

delta_L_B=R_B*B/(2*A_2*E);

L_B_new=B+delta_L_B;

delta_Lb=abs((r2)*18/(.1^2*(pi/4)*E)); %change in length lower member

theta=acos((L_new^2-h^2-L_B_new^2)/(-2*h*L_B_new));

theta2=atan(delta_Lu/h)+atan(delta_Lb/h);

H_new=L_B_new*(sin((pi/2)-theta)+theta2);

delta_h=H_new-h;

str=num2str(delta_h);
disp(str)

end

figure(1)
plot(R_B,delta_h,'c+:')
```

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