Design of a Human Powered Helicopter Airframe

Final Design Report

Team Icarus

Cal Poly Mechanical Engineer Senior Project

June 8th, 2012

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Dear Dr. Noori,

Attached is one copy of our senior project final report: Design of a Human Powered Helicopter-Airframe; a project in conjunction with the Cal Poly Human Powered Helicopter Club and the Mechanical Engineering Department.

Sincerely,

Sheen Kao, Daniel Layton, Philip Sobol

Statement of Disclaimer

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Abstract

In 1989 Cal Poly's Da Vinci III was the first human powered helicopter (HPH) to achieve flight; our goal is to research and develop a new airframe for the next generation Da Vinci. This report outlines a brief history of human powered flight and details a method of constructing for the airframe. An optimized airframe geometry was also researched and is explained in detail.

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Introduction

The Sikorsky Prize was established in 1975 to be awarded to the first team to maintain a steady hover with a helicopter powered by humans. The two biggest obstacles to overcome in the challenge are to hover for a minute and reach a max altitude of 3 meters. No team has yet accomplished either of those tasks. The most successful helicopter designs have four rotors at the bottom of the craft to exploit ground effects. This method forgoes the altitude challenge and aims to create the longest hover at ground level. Cal Poly's next iteration of human powered helicopters will follow this design.

Since the beginning of the Sikorsky prize many schools have researched and built human powered helicopter prototypes. While some designs have done fairly well, others have failed right out of the gate. Historically, there have only been three to achieve flight.

The first one to fly was Cal Poly's Da Vinci III in 1989. The craft used one overhead rotor that was 100 feet in diameter.

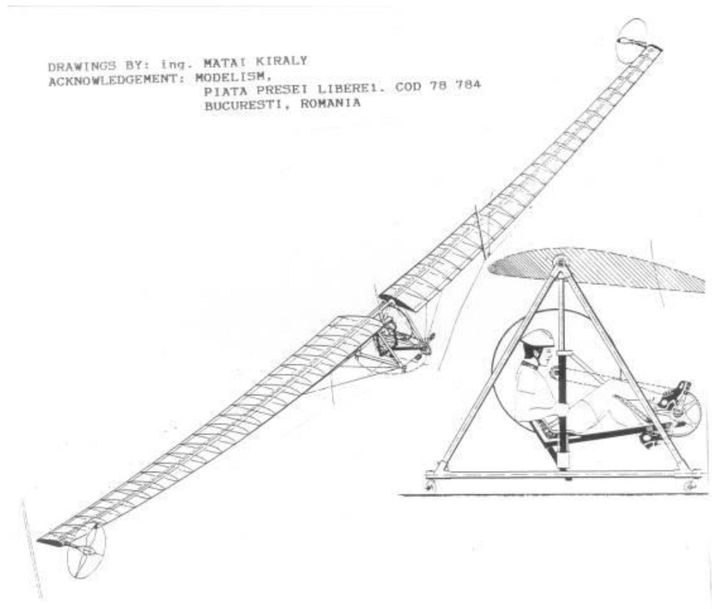

Figure 1 Da Vinci III (Cal Poly)

The second and most successful craft to date is the Yuri 1, designed by Dr. Naito from Nihon University. In 1993, the largely wooden Yuri I flew for 19.46 seconds before it was destroyed by a rotor collision. This showed the effectiveness of the four rotor design and the importance of ground effects.

Figure 2 YURI I (Nihon University)

In May 2011, the University of Maryland tried to improve on the YURI concept with the Gamera. It was also a four-rotor ground effects machine but experimented with different components like the frame, rotors, and drive system. While the Gamera did achieve liftoff, it was too unstable and could not surpass the YURI.

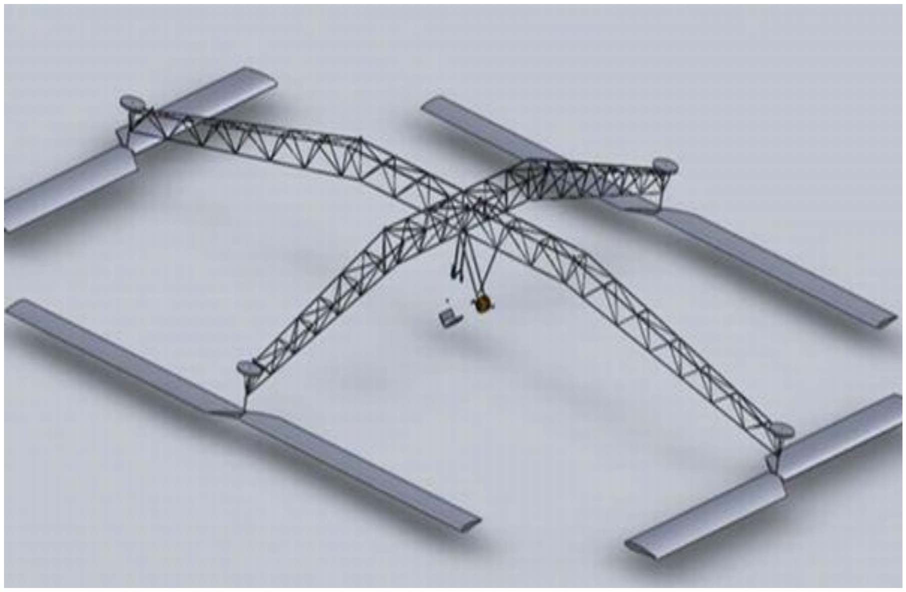

Figure 3 Gamera (University of Maryland)

As part of the large scale effort to create a human powered helicopter, our team will focus on designing and testing a scaled fuselage. Since weight is the most important factor in the helicopter, our primary goal is to create a frame that can support the weight of the pilot while keeping overall weight to a minimum. This project is being directed by Dr. Colvin and the end result is to have a working scaled prototype of the fuselage that future teams can learn from. This will consist of a series of research, design, and testing iterations for each subsection.

Prior Projects and Research

Airframe

The airframe refers to the structure that supports the rotors and transmits loading from rotor lift to lifting the pilot. Typical designs utilize truss type geometry. Both the University of Maryland and Nihon University have implemented truss structure design. The Yuri I uses four 'arms' with the rotor drive shafts mounted furthest outboard (1). Near the root of the Yuri I arms the trusses come together with slight triangulation to mitigate the internal bending moment on the wooden tubes. Contrasting to Yuri I, the Gamera's four arms meet on a straight beam resembling a horizontal trussed bridge. The lateral stiffness of the Gamera's airframe

appeared to be a problem in the video (7). Trusses work well because most the members are in pure tension or compression and each member can be optimized for the strength required. This allows us to keep the airframe as light as possible by mitigating excess material where it is not desired. Typical materials used are balsa wood, bass wood, carbon fiber, fiberglass, and aluminum. Carbon fiber tubes, though expensive, offer the best strength to weight ratio that is predictable and easy to manipulate by adding/subtracting plies. Joining carbon tubes has been an area of concern, however, since maintaining strength while keeping weight minimized is a challenge.

We decided to utilize a truss type structure similar to the Yuri I and Gamera. The overall concept of a four-arm truss structure has been proven most effective so far, and we attempted to optimize this design using numerical methods.

Fuselage

The fuselage refers to the seat and drivetrain integration where the pilot controls the aircraft. In 2009 the Cal Poly HPH team designed and built a full-scale fuselage. The team used molded carbon fiber as a “saddle” for the rider with lightweight bike parts mounted in a recumbent position (3). Gamera, Yuri I, and Da Vinci rotorcraft also used a recumbent position for the rider, suggesting research done by the 2009-2010 Cal Poly HPH team converged on a similar rider position for peak power transmission efficiency. The use of a molded carbon fuselage versus a miniature truss -like that used in Gamera- may not weigh any less, however, the ease of building and reduction of parts is desirable (3).

Our team did not re-visit the design and analysis of the fuselage. We still possess the 2009-2010 Cal Poly HPH fuselage prototype and considered it for incorporation with the new airframe design.

Rotor Layout

Teams have experimented with a varied of rotor types and configurations. The original Da Vinci III used a single 100’ rotor to generate lift. Other rotorcraft like the Yuir I and Gamera used a four rotor layout with each rotation point at the corner of square layout. University of Oregon utilized a twin rotor designed that had multi-blades per rotor similar to a turbine (8). Currently, two different rotor designs have been proven to work. The single rotor Da Vinci III was the simplest design; however the pilot rotated as a result of the single rotor. Both the Yuri I and Gamera combated the stability and pilot rotation phenomena by using four rotors with pairs rotating in opposing directions. Testing performed by the 2010-2011 Cal Poly HPH team proved that a four rotor design with intermeshing was yet another viable solution (4). Intermeshing

refers to the overlapping of adjacent rotor paths; however the rotors do not collide when they're timed correctly.

Our airframe geometry was designed around the use of a four rotor with intermeshing layout. Using intermeshing rotors, we were able to reduce the size of overall HPH and thus save weight and increase stiffness. Intermeshing along with the implementation of the promising four rotor layout should yield the most efficient HPH to date when the full scale version is built.

Drivetrain

The drivetrain consists of all the components necessary to transmit power from the pilot to the rotor spars. Based on the 2009-2010 Cal Poly HPH team research, an ultra-lightweight bicycle drive train can be partially used to convert the pilot's pedaling action into rotational energy (3). Typically the drive shaft being powered by the rider has a pulley attached to it that unwinds a string wound around another pulley attached to the rotor shaft. Da Vinci III and Gamera used the same type of design. Cal Poly utilized aluminum gears with lightening holes. While they were able to reduce the weight of the gears removing material, use of polymer gears was not explored.

Dr. Naito researched elliptical drive gears to smooth out the torque input from the oscillating pedaling motion of the pilot (1). He concluded the elliptical gears were not worth implementing because they do not add power to the dead spots in the pedaling cycle. However, he did discover that utilizing a flywheel with an elliptical rotor helped to smooth out the power input, and thus aided in the flight of Yuri I.

While the rider and drivetrain were kept in mind during the airframe design, we did not research or test rider input this year. For the purpose of the scale test model, we hope that later teams can retrofit an electric motor as the power source and develop a drivetrain that keeps content tension on the drive cable. It is understood that at any point if the cable driving the rotors goes slack, the slack will have to be taken up before power is transmitted to the rotors again. Past drivetrain may be improved by reducing the amount of backlash created when the torque input is in the 'resting' phase between power strokes. Therefore, a tensioning device will be explored with future teams.

Design

The current design of the airframe has been optimized for the specific design requirements provided in Appendix A. We began with 1/18 scale models, however we quickly realized we could not scale down the properties of the aircraft to $1/18^{th}$ scale, therefore, we were unable to obtain meaningful data from these models. We chose to optimize the geometry through numerical analysis using MATLAB and Abaqus. We constructed a $1/3^{rd}$ scale model of one of the plausible designs using similar materials and build methods as the full scale HPH as a proof of concept and to gather information about necessary fabrication processes.

Balsa Wood Models

Since our end goal was to create a scale model of the HPH, we wanted to understand how the mass properties and stresses would change from the full size to scale size. Initially, we concluded that performing a strictly numerical analysis of a scaled HPH airframe would be unfeasible. The dimensions of the carbon fiber tubes do not scale down in such a way that scale tubes would still be easily constructed or handled. Therefore, the weight and stiffness of any scale model would not accurately reflect the values of its full size counterpart.

1/18th scale models of Yuri I and Gamera airframes were partially constructed from balsa wood to better understand how the two designs compare to each other. It was useful to see how the two airframes appear side-by-side; however, the models do not offer relevant data on their relative strengths, since balsa wood does not have consistent density.

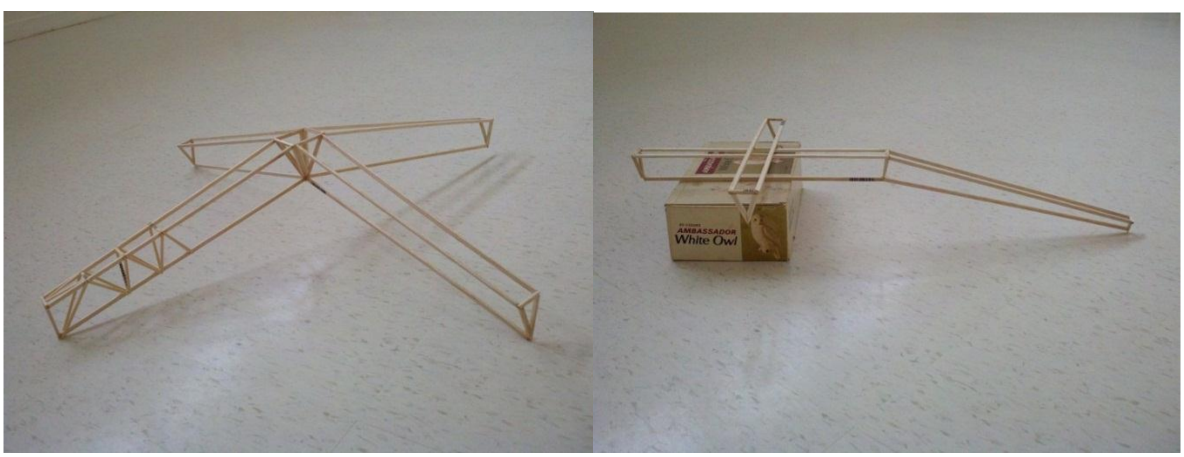

Figure 4: Partially completed 1/18th scale models of the Yuri I (left) and the Gamera (right) airframes

The Gamera airframe has longer arms than the Yuri, which makes sense since it also used larger rotors. However, the Gamera's arms are significantly thinner, i.e. there is less vertical separation between the two top spars and the single bottom spar. Also, the center portion of the Gamera's truss is parallel to the ground, which we believe would be more susceptible to

bending than the Yuri, in which the main spars never parallel the ground. We do not know what constraints the designers of the Gamera were under which lead them to this design, but videos of their respective flights suggest that the Yuri airframe performed better, especially in terms of stability. During flight, the rotor hubs of the Gamera appear to deflect vertically relative to the pilot, which suggests inadequate stiffness in the truss.

Both scale models seem to be especially susceptible to torsion along the axes of their arms, but there is not enough data to conclude that this will be a problem. Neither of the full scale craft appeared to have issues during flight due to torsion.

Due to balsa wood's varying density and consistent bonding difficulty we decided to abandon the balsa models. Inconsistency in model construction lead to poor data on how their respective strengths compare to one another.

The models reinforced our theory that the truss design of the Yuri I is more resistant to bending due to lift than the Gamera's. The shortfalls of smaller vertical separation and horizontal centerpiece became more apparent with the models sitting next to each other. Also, because of the scaling difficulties and differences in materials, we believe any additional scale models should be constructed with materials and methods more similar to those used in the full scale in order to more accurately represent how the airframe will perform.

The experience of building a small 3D truss suggested that constructing a large truss with adequate precision would be extremely difficult, especially with regards to positioning the truss members. We developed a fixture to aid the scale manufacturing process.

Analysis

In order to optimize strength while keeping weight low, we chose to simulate the numerically. We used MATLAB and Abaqus to simulate a variety of truss geometries while varying certain parameters. Our first approach was to perform a static analysis on the truss using MATLAB. We chose to use MATLAB for three reasons:

- The truss geometry could be easily generated using a set of parameters
- MATLAB could determine the static forces in all the members for a given geometry, assuming a constant load
- MATLAB could subsequently iterate by varying parameters to find the optimum design.

The statics analysis works by applying Newton's 2nd Law at each node in each dimension. This results in a system of linear equations, which MATLAB can convert them all into one large

matrix and take the inverse of it to find the forces in each member. Since this is a purely statics analysis, there are two major concerns:

- It assumes everything is a two-force member so it cannot account for bending
- It cannot solve statically indeterminate trusses.

The truss will be statically indeterminate if the degrees of freedom (# of beams) are greater than the number of static equations (three per node). Fortunately, almost all the designs we tested were statically determinate.

Our first test for the simulation was to generate the YURI truss and see how it would perform if it were made of carbon fiber. We were able to approximate the geometry in MATLAB by studying their limited available media, but the YURI is statically indeterminate, so we turned to FEA.

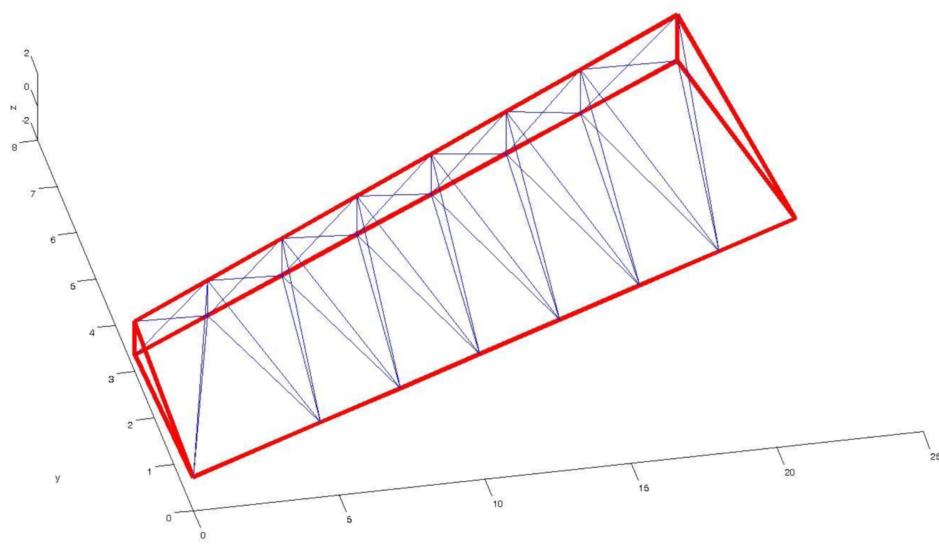

Figure 5: ***YURI generated using MATLAB.***

Abaqus Simulations

With the help of Dr. Garrett Hall, we were able to take the truss generated in MATLAB and turn it into an input file for Abaqus. After we could successfully simulate the truss, we began tweaking the YURI design to see if we could reduce the weight.

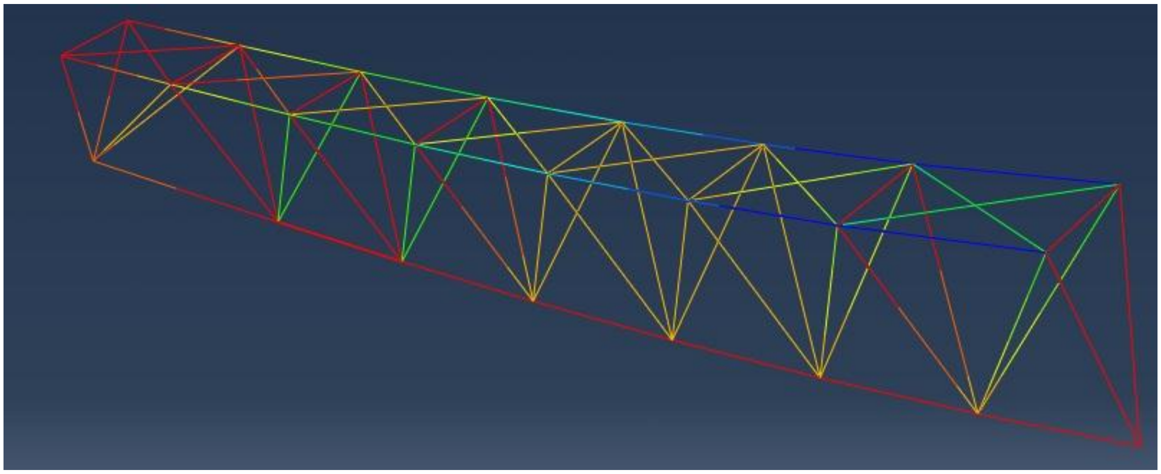

Figure 6: *YURI stress analysis simulated using Abaqus.*

After removing some beams to save weight, we realized that the truss was no longer statically indeterminate. When we compared Abaqus's results to MATLAB's results, we found that they were almost identical (<1% difference) for all our different designs. Based on our findings, we decided that it would be best to just use the statics analysis so we could do the entire iterative design process in MATLAB.

MATLAB Iterations

With MATLAB, we have the flexibility of being able to vary parameters and run loops to generate a variety of different trusses. Some of the parameters we varied were tube diameter, number of support beams, and distance between nodes. We believe the two most important parts of a truss design are safety factor and weight. For every permutation of truss we generated, we plotted it on a universal graph of safety factor vs. weight as seen in Figure 7.

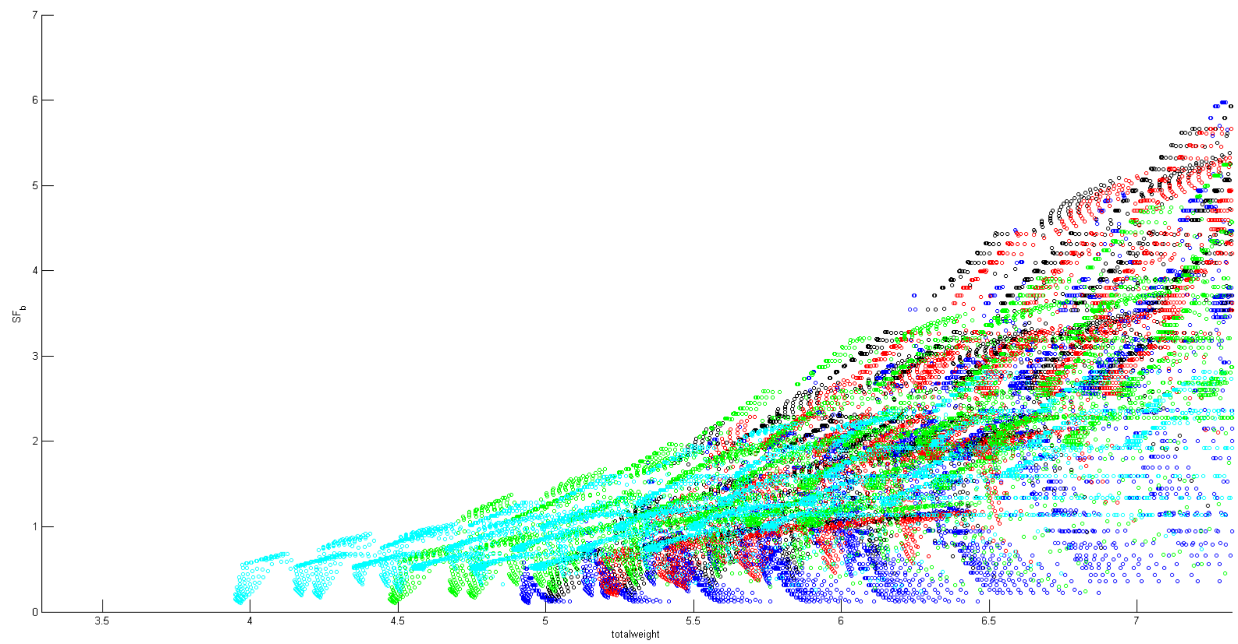

Figure 7: *Universal plot showing safety factor versus weight for various truss geometries.*

This model is based on a few critical assumptions:

- The primary failure method is Euler Buckling (pin-pin), which is expected for long, narrow tubes
- The vertical load is 50 lbs applied vertically at the tip
- There is a horizontal load perpendicular to the arm of each truss set at 15 lbs (which was estimated to be a reasonable expected force)
- All beams are two-force members
- Inverted triangular truss geometry
- Separation of the main spars at the tip is fixed.

In the interest of saving weight, we have chosen a safety factor of 2.0 as the bare minimum to account for dynamic loading. Since all our calculations are based off the static loads (50 lbs vertically and 15 lbs horizontally), we should expect that the dynamic loads at any instantaneous point to be no more than double the static loads. This also assumes that the final construction of the helicopter will be made exactly to specification, especially the lengthwise modulus and second moment of area of the main spars.

Simulated Design Conclusions

Based on our simulations, we have reached the following conclusions on the truss geometry:

- Having the smallest possible wall thickness (~0.025”) is optimal for maximizing the

moment of inertia while minimizing weight; however, they are more susceptible to radial crushing.

- Having the truss taper down to a smaller cross-section at the wing tip greatly reduces the probability of buckling since the supporting members near the end undergo the most compression.
- The X-members on the top face of the truss are required to prevent the truss from twisting due to horizontal forces.

Final Truss Design

The final design has a weight of 6.9 lbs and a buckling safety factor of 2.0. Information about the truss geometry can be accessed in Appendix B. The m file used to generate the truss is located in the Cal Poly HPH Dropbox called "FinalDesign.m".

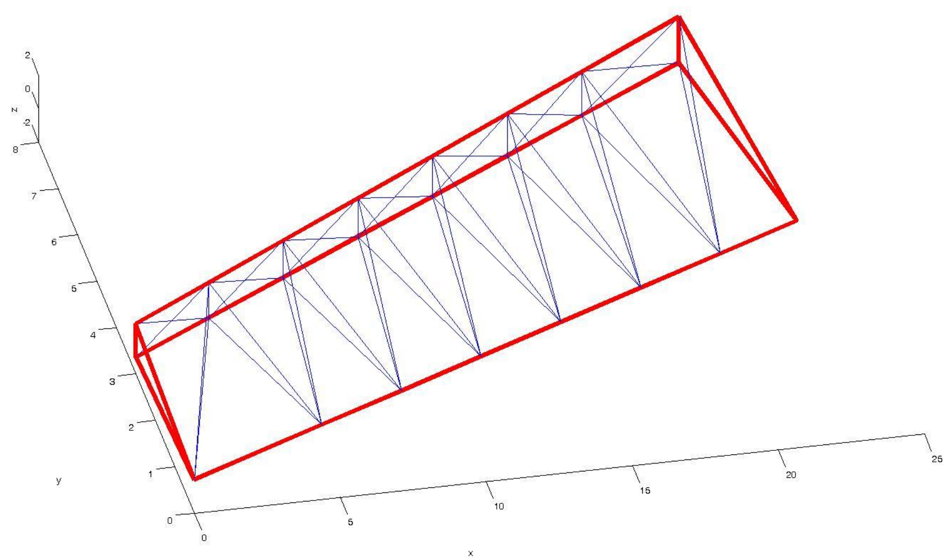

Figure 8: Final truss geometry plotted in MATLAB.

Failure Modes

The airframe geometry described earlier in this report explains the boundary conditions to which it should be designed. Of the failure modes possible, Euler Buckling and joint failures appear to be the failure mode which will occur first. Other failure modes considered were deflection and vibrational responses.

Euler Buckling

Euler buckling is described as the bending of a column due to an applied axial load. As seen in equation (1), the maximum axial force a column can withstand before buckling is a function of the beam's modulus of elasticity, area moment of inertia, length, and end-condition (denoted as K).

$$F = \frac{\pi^2 EI}{(KL)^2} \tag{1}$$

We verified Euler buckling could be used in our application by testing a few long sections (~79" in length) of 0.236" carbon tube. We assumed 'pinned-pinned' end conditions, the most conservative case. The results from testing can be seen in table 1.

Table 1: ***Experimental results from Euler Buckling tests.***

Length	End Condition	Buckling Load (theoretical)	Bucking Load (experimental)
79"	Pinned-Pinned	2.2 lbs	2.25 lbs
66"	Pinned-Pinned	3.2 lbs	3.25 lbs

In industry, it is typical practice to add a safety factor of 2.0 to account for imperfections in the tubes. However, the actual end conditions are closer to 'fixed-fixed' due to the epoxy joints at both ends. Therefore, it would be too conservative to add a safety factor of 2.0 on top of the conservative estimation that our beams are being supported by pinned-pinned connections. After verifying the use of Euler buckling to analyze our tubes, we were able to proceed with the buckling analysis of the truss. In our MATLAB program, we determine the maximum force required to buckle each tube. The program then determines a safety factor for each member if the load applied is less than the minimum allowable load to cause buckling.

Figure 9: Calfee Designs bike frame us cross-weave carbon cloth to reinforce the joint location of multiple tubes.

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Joint Separation

Joint failure was another area of concern. The airframe contains hundreds of tubes that must connect by strong and easy-to-manufacture joints. Each joint in the airframe must be as lightweight as possible without sacrificing strength for weight. Similarly, in the cycling industry, many companies opt to make their chassis from carbon fiber tubes and desire similar strengths joints. From this, we discovered carbon tubes could be joined a variety of ways.

One method of joining tubes requires the use of aluminum or compressed short-fiber carbon 'nodes'. These molded nodes are manufactured to specific details, guarantying each tube connects at the exact specified angles. These nodes also offer superior manufacturing reproducibility to other methods, resulting in very controlled strength and repeatable properties. The aluminum molds are created by either casting or machining their shape, while the compressed short-fiber nodes are created by compressing a slurry of resin and carbon in a mold. Both methods require exact dimensions to be provided. Unfortunately, the HPH airframe utilizes trusses that taper in both the horizontal and vertical directions; because of this, each joint requires the tubes meet at different angles. Due to the necessity to machine or mold each of these nodes, the cost and weight associate with making hundreds of custom nodes outweighs their benefits of strength. Therefore, creating and testing aluminum and compressed short-fiber nodes have not been explored at this time.

Carbon tubes can also be joined by molding cross-weave carbon cloth over the joint, similar to the bike frames manufactured by Calfee Designs as seen in Figure 9. This method requires notching each tube so it fits flush against the surface of the adjacent tube. A single ply of carbon cross-weave is then fitted around the joint and wet epoxy resin in used to bond the components together. This joining method creates very lightweight and strong joint. Applying this method to HPH construction seemed like a plausible solution, however we later discovered the joints were heavier than desired with strength far exceeding what was necessary. If we had a way to remove the excess resin, this method may still provide useful in joints where we expect high amounts of stress.

Figure 10: Epoxy resin failure in shear for a carbon tow wrapped joint.

Carbon tow wrapped joints similar to Figure 10 provided similar results to joints used with cross-weave wrapping. Again, the carbon tow added a significant amount of strength, however due to the excess resin; the weight of each joint far exceeded other plausible options.

The joint methods previously mentioned all require additional materials at the joint location. Aside from these methods, we also researched using resins/epoxy exclusively at the joint location. Previous designs used a special layup technique or required separate manufacturing methods to create the joint. Using cyanoacrylate (CA/super glue), epoxy resin, or resin mixed with chopped carbon fiber as a bonding agent, we discovered we could eliminate the need for additional manufacturing processes. These methods still require the user to notch each tube to create the correct joint geometry. The bonding agent can then be applied to hold everything in place. Testing was performed to verify the effectiveness of various bonding agents, as discussed in the joint fabrication section of this report.

Deflection

During the fall quarter we discovered that truss deflection has caused failures in past human powered helicopter projects. The Yuri HPH experienced a catastrophic failure when two of the airframe trusses deflected horizontally, allowing the rotor tips to collide. This collision could have been avoided if each arm of the truss was stiffer in the horizontal plane. We took both horizontal and vertical stiffness into account with the MATLAB program used for analysis. Also, the airframe was designed so that adjacent rotors can be 90° out of phase from each other. This reduces the chance of rotor collision in the event of unforeseen arm deflection, although it introduces a new chance of collision if the rotors change phase. Our 1/3 scale model allows us to test the differences in stiffness between the vertical and horizontal planes. While we recognize the 1/3 scale model strength does not scale to the full size airframe, we can still compare horizontal stiffness to vertical stiffness qualitatively. This should provide better insight when choosing full size truss geometry.

Vibration

The vibrational response of the airframe has been considered as well. While we have not been able to test a completed structure, we recognize that 1/3 scale testing will not help to determine the natural frequencies of the full size airframe. Using Abaqus, we can estimate the first few natural frequencies of any given truss geometry. These values should be compared to the gait of the rider. If a rider typically pedals at a frequency of 90 rpm and for each revolution there are two power strokes (one power stroke for each leg), then the natural frequency we need to avoid is near 3 Hz. This was considered when the final geometry of the truss was chosen.

Joints

An important part of optimizing the truss airframe involves the joints which connect the carbon fiber tubes together. Since there are upwards of 30 nodes per arm, keeping each individual joint lightweight becomes a critical factor. Also, the simulations done in MATLAB and Abaqus do not analyze joint connections. Thus, we wanted to develop an adequate joint design for the scale model, and recommendations for developing fully optimized joint for the full scale craft. There are three types of joints we needed to design: permanent joints connecting supporting members to the main spars, permanent joints used to connect the main spars end-to-end, and non-permanent joints connecting main spars which can be dismantled to transport the helicopter in manageable pieces.

Support Joints Preliminary Testing

Our first series of tests were to gauge the relative strength of the resin we were using: West System 105 epoxy resin with 206 slow hardener (picked exclusively due to convenience). The first series of testing was performed on 7/8" diameter unidirectional carbon tubes joined at 45° angles. These tubes were larger and thicker than the tubes we planned on using for 1/3 scale construction, and were again chosen due to convenience. Four tube connections were created; two with resin only, one with carbon cross-weave and resin, and one with uni-directional carbon tow wrap and covered with resin. We constructed a fixture which allowed us to load one end of the tube in tension, and hung weights from that end via an aluminum slug bonded to the inside of the tube (see Figure 11 below).

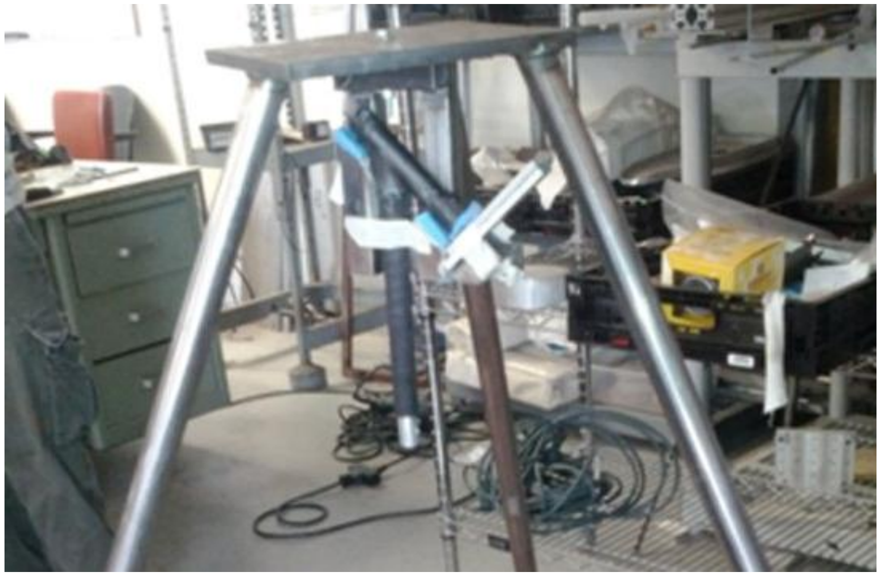

Figure 11: Fixture and joint holder used for testing

These tubes required far more weight to break than we anticipated: the weakest joint (resin only) failed at 112 lbs, and the strongest (carbon tow wrap) failed at 512 lbs. From this test, we decided that resin alone or even CA glue could possibly be strong enough for 1/3 scale construction.

Support Joints 1/3 Scale Testing

Further testing was performed on 1/3 scale tubes measuring .520” and .236” diameter. We constructed similar joints to the preliminary test, varying only the bonding composition and the surface preparation. As seen in the table below, a joint using carbon tow (similar to the carbon tow wrap from the preliminary test) and resin can support the highest loads in tension. However, we recognize this joint may be stronger than necessary as well as heavier than desired.

When comparing the sanded/unsanded joint strengths of CA glue, it appeared that sanding the surface of the tube prior to applying adhesive added significant strength. Also, upon inspection of the joints after failure, the unsanded joints all broke cleanly; the epoxy or glue peeled off in one piece, whereas the unsanded joints had a much rougher break, with adhesive remaining on both tubes. From this, we decided to further examine CA glue on a sanded surface with another round of tests (results can be seen in Figure 12).

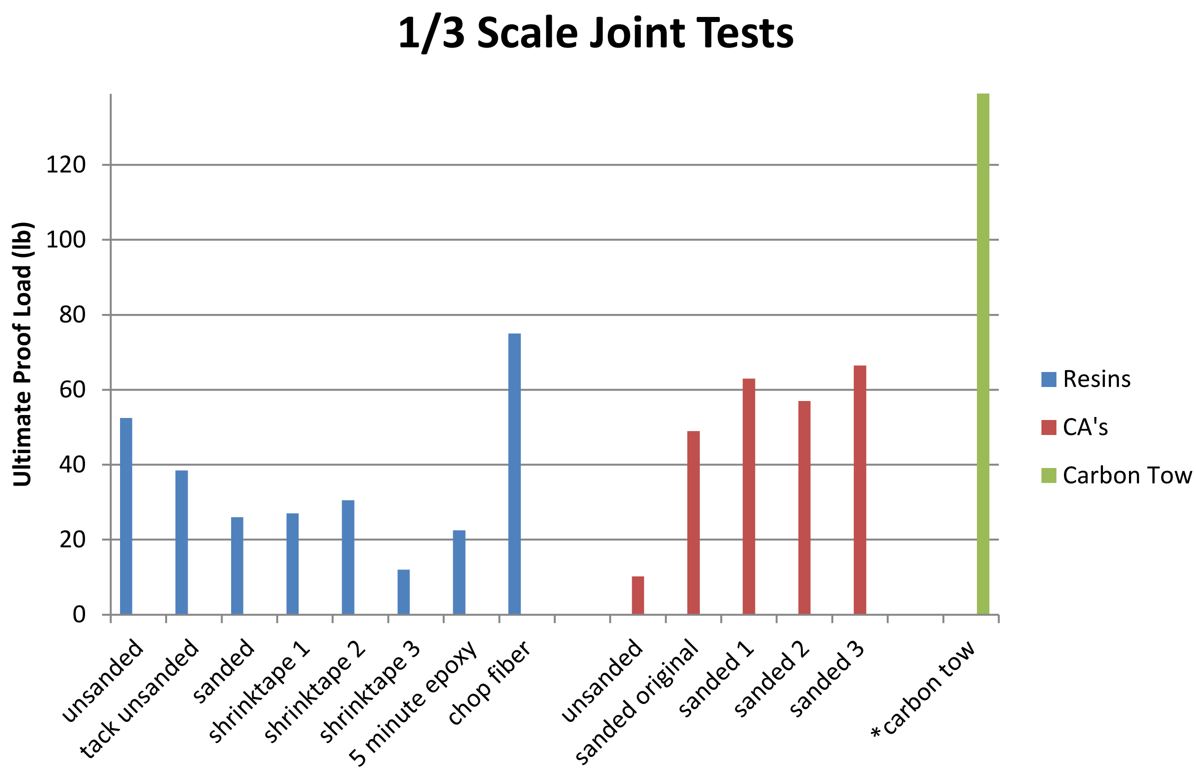

Figure 12: Results of 1/3 scale joint testing *carbon tow failed at 294lb.

In addition to the CA glue testing, we wanted to develop a consistent method of applying the correct amount of resin and removing air bubbles. To further investigate this, we conducted a joint test on four 1/3 scale joints consisting of resin-only with a shrink tape wrap. Our theory was that the shrink tape would cleanly peel off after the resin had hardened, and the pressure it exerted during shrinking would squeeze out excess resin and air bubbles. Unfortunately, our results indicate that the tests with shrink tape were not any more consistent than before, and the tape was difficult to remove the afterwards (results can be seen in Figure 12). Since the joint area is very non-uniform, it is impossible to apply the shrink tape without creating creases. When heat is applied and the tape constricts, epoxy is forced up into the creases, effectively bonding the tape to the joint while not effectively removing bubbles.

Based on our final round of tests, we concluded that CA glue on a sanded surface would be adequate for 1/3 scale construction. We were able to successfully test three different joints to an ultimate proof load within 5lb of 60lb, which we consider to be acceptably consistent. However, we also believe that CA glue alone is not strong enough and too brittle to be used for the full scale airframe.

Over the course of the joint testing, the joints which utilized a carbon tow wrap or chopped tow performed exceptionally well. However, the carbon tow is difficult to hold in place to apply

resin, and appears to absorb more resin than other joints. Because of this, we think that joints of this type are not suitable for mass production on the full scale. The chopped fiber joint is easier to manufacture; the epoxy and fiber can be mixed prior to use, or a pre-mixed resin can be purchased. These are applied the similarly to regular resin. Our tests indicated that this joint was stronger than resin only, which coincides with data obtained from the Rotor Team. From this, we currently believe this type of joint merits investigation for the full scale.

Permanent Main Spar Joints

Since the tubes we purchased for the main spars are not long enough to build the entire 1/3rd scale arm, we needed a method to join them together without affecting the surface of the tubes. To do this, we inserted a 7/16” hollow aluminum rod covered in resin. To make up for the clearance between the tube ID and the insert, we wrapped the insert with a paper towel. While this does not add any strength, it absorbs the resin and pads the rod so it stays in the center of the tube, allowing for a straighter connection.

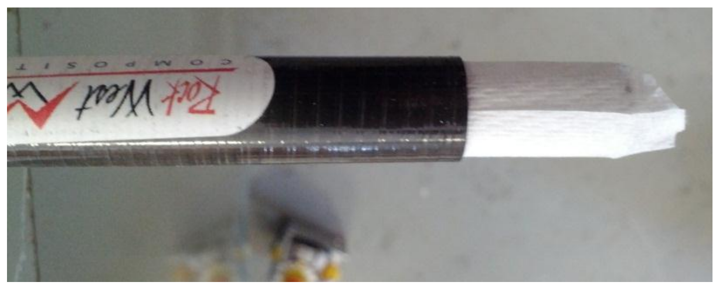

Figure 13: Permanent Joint Insert

After the resin was applied, the tubes were wrapped with shrink tape and placed in a trough made from 80/20 aluminum beams. This made sure that the tubes were parallel and concentric when they cured.

It is important to note that this type of permanent joint may not be necessary for full scale construction. If the main spars are built at Cal Poly, they can be manufactured up to twenty feet long, which makes it possible that that the only break in the main spars will be a non-permanent joint. These joints are discussed in the next section.

Figure 14: Curing Fixture of the Permanent Joints

Non-permanent Joints

Due to the size of the full scale model, transportation and storage could be quite difficult. To combat this, we attempted to design non-permanent joints in the truss. Therefore, the truss could be quickly disassembled into smaller portions which fit in a standard trailer. While this might not be completely necessary for a scaled model, we wanted to include non-permanent joints to indicate feasibility and proof-of-concept.

The airframe model features several different designs of non-permanent joints with varying degrees of stiffness and weight. The following table shows each type of joint and its advantages and disadvantages.

Name	Picture	Description	Pros	Cons
Flange Joint		The flange joint is created from a solid aluminum tube, milled down on one end to fit inside the carbon fiber spar. It is bonded via epoxy to the inside of the spar and attached to the opposing flange with 3 bolts.	Strong Works in tension and compression Keeps main spars straight	Very Heavy (each joint increases the weight of the arm by 17%) Forces significant separation between the supporting spars
Threaded Joint		Two threaded inserts are bonded to the inside of each carbon fiber spar. The threaded rod is righ-hand only, so it must first be threaded into one side, then partly backed out to be threaded into the other.	Simple Good in tensile loading	Heavy (threaded portion is solid steel)
Pin Joint		A hollow aluminum tube is bonded into either side of the joint for reinforcement. A solid aluminum tube fits inside of that and is held in place with the pins.	Allows tubes to butt up against one another	Difficult to reduce clearances and play in tubes

Discarded Non-Permanent Joint

Our first non-permanent joint design was very similar to the existing threaded rod joint, but used both right and left-handed threads. As can be seen in Figure 15, the double-threaded rod had a hole through the middle by which it could be turned with an small rod. This allowed tightening/loosening into both tubes simultaneously.

Figure 15: Discarded design for a non-permanent joint. The joint is shown with the threaded inserts attached to the ends and a sample piece of carbon fiber spar over one insert. The area around the center hole is too small and doesn't provide adequate strength.

Due to the small tube diameters of the 1/3 scale model, the double-threaded rod was deemed too weak for use. The area where the hole is drilled is quite small and susceptible to bending, making difficult to produce a straight connection.

It is important to note this discarded joint may still be adequate for full scale, where larger diameter main spars allow for a stiffer and stronger threaded rod. This type of connection is similar to the threaded joint discussed earlier, however, the benefits of this joint could be greater than the current model if acceptable left/right hand threaded rods could be manufactured or purchased. For example, it becomes easier to vary the amount of separation between the spars than with right-hand only. Also, threading the right-hand only joint requires clamping the threads to turn them, which slowly damages them. Turning the double hand thread would not have this issue.

Conclusions for Non-permanent Joints

After comparing the different non-permanent joint designs, we decided on pin joints for the spars in compression and the threaded joint for the tension spar. While the flange joints were some of the strongest, they were too heavy for use. The pin joints were chosen for the compressive spars because their design allows the tubes to contact each other, reducing separation between the supporting nodes and allowing stresses to transmit directly along the spar instead of through the pins. Ideally, the only function of the pins is to hold the truss arm in place while it is unloaded.

We felt the pin joints would not suffice in tension, since they would put large shear stresses on the pins. Instead, we used the threaded joint, which appeared to perform very well in tension, comparable to the flange joints.

1/3 Scale Construction

Part of the design phase for this year's team was to develop a build process that would be practical for building the full scale HPH. We therefore explored fixtures and build techniques that should be passed on to future teams. While this report does not cover all possible building methods, it provides useful techniques with validation of said techniques.

Fixtures

In order to produce consistent trusses for each arm of the truss, we explored a couple different fixtures. Quick and accurate building of each truss demanded a simple fixture that provided consistent results. We considered assembling each supporting member 'triangle' first, then adding in the three main tubes afterward. Figure 16 shows (in concept) how we could use a base plate with magnets to position each leg of the triangle to pre-drawn dimensions on the base plate. Due to the arm's taper, each triangle must be re-drawn with new dimensions, creating a considerable amount of work for the builder, along with a high probability for mistakes. Also, each tube connection of the triangle would have to be at the exact specified location in order for the main tubes to line up straight with each triangle. Because of this, this method of construction was abandoned for simpler approach.

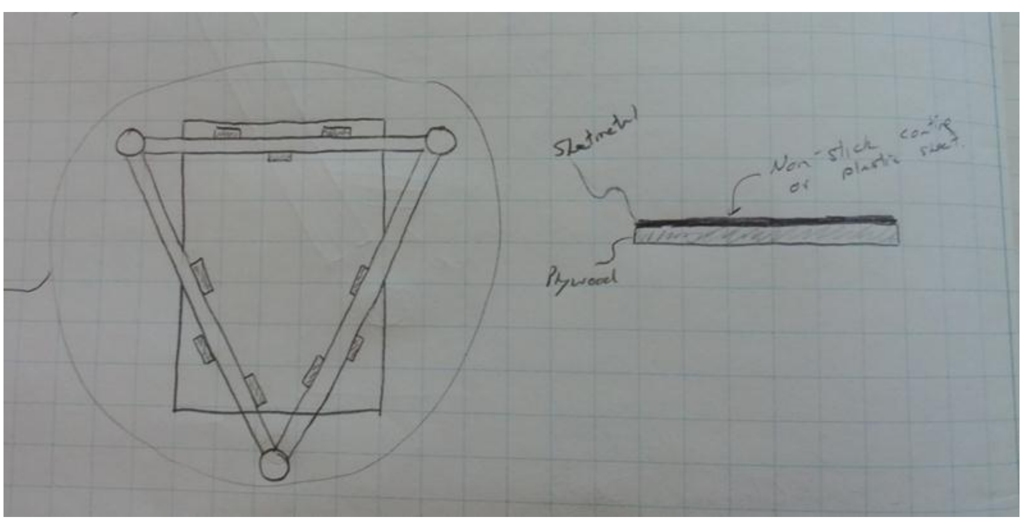

Figure 16: Fixture design using a steel plate with magnets to hold supporting tubes in place.

The fixture design we settled on can be seen in Figure 18. This fixture supports each end of the three main tubes and orients them in the correct position so that smaller connecting tubes can be fit in place. The main tube ends are held in place with removable aluminum inserts for installation and dismantling (Figure 18). The holes for the aluminum inserts were drilled at the precise angle to orient the last triangle (the tip triangle) vertically. Also, we recommend building the truss in place upside down. By constructing it upside down, any deflection due to the weight of the unsupported section adds a upward curvature to the arm, thus helping to minimize vertical deflection when loaded for flight. For the 1/3 scale fixture, we used 80/20 aluminum and medium density fiber (MDF) board for construction. These materials allowed us to make adjustments quickly and easily. For the full scale HPH, additional vertical supports may be necessary to minimize sagging of the main tubes. These can easily be added to our fixture as well if necessary.

Figure 17: Final 1/3rd scale fixture used to create each arm of the truss.

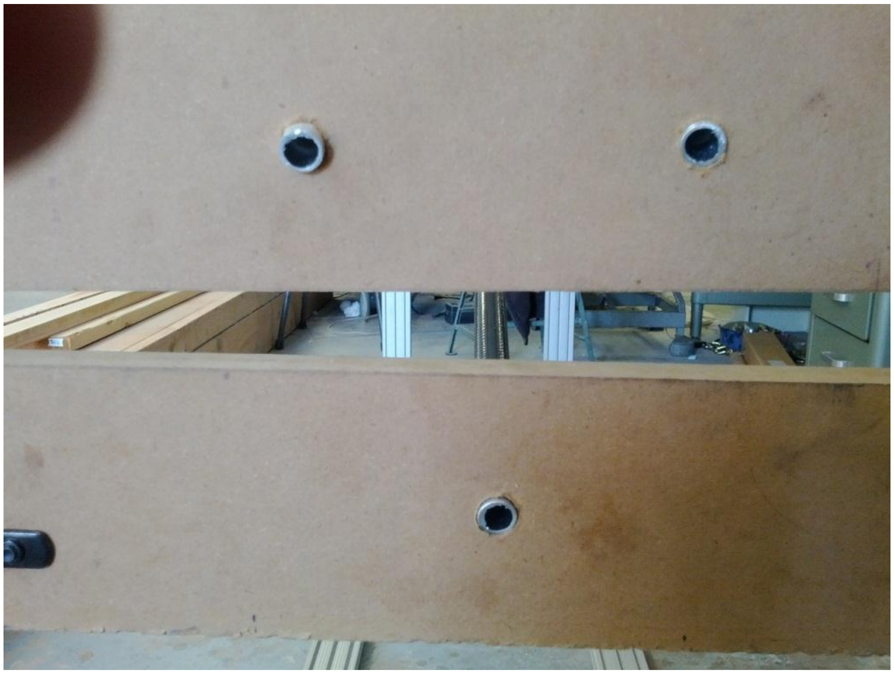

Figure 18: Aluminum inserts are used to hold the main tubes in place.

Construction Procedure

1. Inspect tubes for manufacturing defects.
    a. Cracks
    b. Bumps/dimples
    c. Flaking
    d. Bending
    e. Dryness
2. Joint tubes together to create full length main tubes.
    a. Use permanent/non-permanent connections where specified
    b. Sand the inside of each tube to the depth of the joint to be installed. Inspect after sanding, no glossy regions.
    c. Sand the outside of each joint where in contact with resin.
    d. Prepare joining surfaces with acetone.
    e. Apply epoxy resin to joint and insert into tubes.
    f. Rest tubes in a channel (i.e. 80/20, long v-block, angle iron) and secure in place for the duration of resin cure time. (See Appendix C Figure 1)
    g. Once cured, inspect tube for joint straightness. If applicable, check non-permanent joints for ease of removal/installation.
3. Install main tubes in fixture
    a. Cut each tube to length.

    b. Grind/sand tube ends to match desired angle.
    c. Support main tubes along the span if sagging occurs.
4. Prepare node locations of top and bottom tubes.
    a. Mark each node location starting at arm tip and measure towards the center of the airframe.
    b. Thoroughly sand each node location where supporting members contact the main tubes. Remark node locations if necessary after sanding.
5. Fit supporting members in place.
    a. Cut supporting members to length, leave ~0.250" extra for grinding into place.
    b. Grind supporting tubes to length using a sanding drum with the same diameter as the main tubes. Match the angle of intersection between the supporting members and the main tube. Check for joint flushness, no gaps should be present.

       Note:

       When grinding supporting members, a slightly dull sanding drum has a tendency to fray the end of the tube. This fraying creates loose fibers which appear to provide additional bond area. Do not grind away frayed fibers before gluing into place.

    c. Clean the ends of the supporting members and the bonding location on the main tubes with a rag or paper towel wetted with acetone.
    d. Place the ends of the supporting members carefully in place, being sure to account for other tubes that meet in the same location. Using cyanoacrylate glue, carefully bond each supporting member between the main tubes. If necessary, spray Insta-Set catalyst onto joint.

       Note:
       It may be easier to assemble the 'X' sections of the arm first i.e. join the top two main tubes together before connecting the 3rd tube. Also, consider building the tip triangle early in the build phase; it helps keep all three tubes together while placing the supporting members.
6. Epoxy supporting members in place.
    a. Chop carbon tow into very small lengths (approximately 1/8") to be mixed with epoxy resin slurry. 1 cup unpacked carbon tow mixes with approximately 6 ounces (by weight) of Pro-Set 175/275 epoxy resin. Too much carbon tow makes it difficult to apply, too little doesn't add very much strength to the joint. Exact amounts can be experimented with for optimal joint performance.

b. Thoroughly mix chopped carbon tow and epoxy resin together ensuring complete mixing of resin and hardener.
c. Pack a large syringe with the mixture. The syringe helps apply the mixture directly to the joint location.
d. Apply resin mixture to all supporting member joints. The goal is to fill any gaps and to create small fillets where tubes meet each other. Fillets should be at most double the diameter of the supporting members to ensure strong light weight connections while reducing stress concentrations.
e. Once cured, sand the epoxied joints to prevent carbon splinters when handling.

7. Construct the center section.

   Note:
   It is worth mentioning the center section was constructed upside down. This puts the square section of the center on the bottom while each arm attaches at an upward angle.

   a. Mark out the square dimension of the center section on a flat board. This will help when lining up the center tube and the angled tubes that connect to each arm.
   b. Place the center tube in the middle of the center section, elevated to the location where all four arms meet at one point as seen in Appendix C Figure 3.
   c. Cut and grind the four lengths of tube that bond to the center section that each arm will connect to.
   d. Sand the center tube and prepare with acetone
   e. Using CA glue, bond the four angled tubes to the center tube.
   f. Orient the arms of the HPH to the angle specified by the design. Match the top two ends of each arm to the corners of the square as seen in Appendix C Figure 4
   g. While making sure the arms are square and the correct finish length, grind the main tubes to match the radius of the center section and the angled tubes. When done correctly, all four arms should fit flush against the center tube and the angled tubes simultaneously while the arm ends are off the ground the specified height.
   h. Prepare and bond all four arms into place using CA glue.
   i. Cut and bond in any additional tubes to finish the center section.
   j. Finish bonding the center sections with carbon tow and resin mixture similar to step 6.

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