DESIGN AND FABRICATION OF ULTRA-LIGHTWEIGHT COMPOSITE STRUCTURES FOR THE *GAMERA* HUMAN-POWERED HELICOPTERS

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ABSTRACT

Motivated by the Sikorsky Prize offered by the American Helicopter Society International for the first successful human powered helicopter, a team of students from the Alfred Gessow Rotorcraft Center at the University of Maryland designed and built *Gamera I*. Utilizing novel, ultra-efficient composite structures, *Gamera I* weighed only 48.6 kg empty and was able to hover for 11.4 seconds in July of 2011, setting the Fédération Aéronautique Internationale (FAI) record for flight duration of a human powered helicopter. Since their successful flight the team has proceeded to design and begin construction of *Gamera II*, which is expected to be 33 % lighter and capable of hovering for 60 seconds. This paper will present some of the structural innovations that lead to their success.

1. INTRODUCTION

This paper explores the innovative structural design of the *Gamera* human powered helicopters from the University of Maryland. It is intended to highlight only the most important structural technologies for those interested in how the team accomplished this feat. An extensive knowledge of rotorcraft is not assumed of the reader. The paper will begin by introducing the project and its motivation. It will then proceed to look at the construction of the rotor blades of both *Gamera I* and *Gamera II*, with a focus on the development of a unique wound truss spar and its testing. After this, discussion will shift to the airframe of the vehicle, its configuration and optimization as well as novel micro-trusses used to bear the highest compression loading in *Gamera I* and further implemented in *Gamera II*.

The Igor Sikorsky Human Powered Helicopter (HPH) prize was first offered in 1980 by the American Helicopter Society International. The prize is for the first human powered helicopter to hover for at least 60 seconds and momentarily reach an altitude of at least 3 meters, while not drifting out of a 10 meter square [1]. Since its inception there have been many attempts at constructing such a vehicle. The first successful liftoff came from the Cal Poly *Da Vinci III* in 1989, which maintained hover for 6.8 seconds. Their accomplishment was followed up in 1994 by Nihon University with *Yuri-I* and its 19.5 second flight. Neither of these vehicles was capable of hovering for 60 seconds or approaching the 3 m altitude requirement.

After over a decade without any further success, a team of students from the Alfred Gessow Rotorcraft Center at the University of Maryland designed and constructed *Gamera I*. During two rounds of flight testing in the summer of 2011 the team managed several short flights, the longest of which was certified at 11.4 seconds by the Fédération Aéronautique Internationale (FAI) as the official world record for human powered rotorcraft in both the general and feminine categories, depicted in Figure 1. Since the initial success of *Gamera I,* the team has been working on its successor, *Gamera II*, a significantly improved design which is both lighter and more efficient.

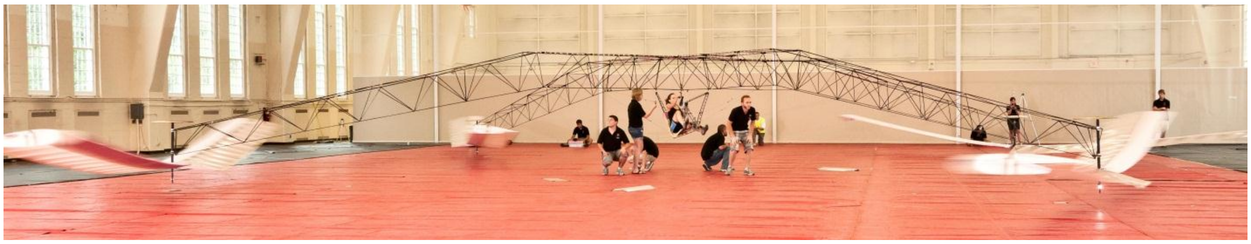

Figure 1. *Gamera I* during its FAI record setting 11.4 second flight, July 13, 2011

1.1 The *Gamera* Project

The Team Gamera from the University of Maryland began work in the fall of 2008. The first vehicle, *Gamera I*, was a quadrotor design completed in the spring of 2011 (Figure 2). Four rotors, each 13 m in diameter, were positioned at the end of large truss arms which formed the main structure of the vehicle. Although the quadrotor configuration tends to be heavier than more conventional layouts due to the large structure required to connect the four rotors it was chosen for its improved stability characteristics. *Gamera I* was flown for the first time in May of 2011 by pilot Judy Wexler. The empty weight for the whole vehicle was 48.6 kg and total weight with the pilot was 98.6 kg. After several improvements it underwent a second round of flight tests in July, 2011. Immediately following these successful tests the team began designing a successor vehicle, *Gamera II*. Similar in design and scale, but offering improved aerodynamic performance and even lighter structures, the new helicopter is under construction at the time of writing and expected to be completed for flight tests in the summer of 2012.

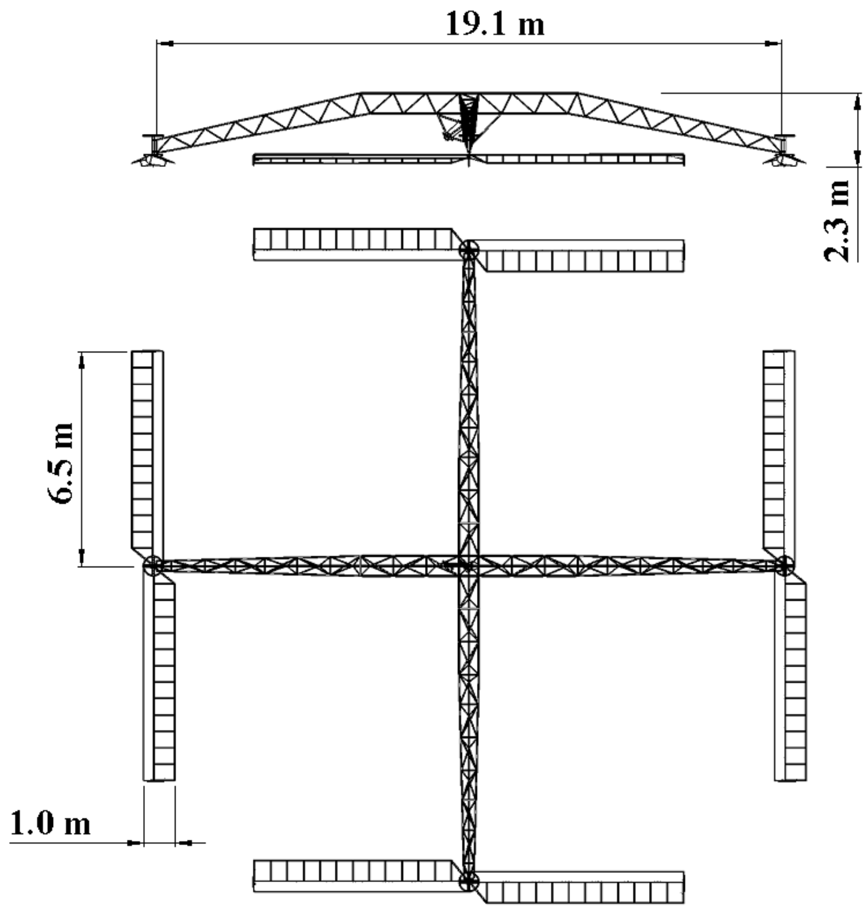

Figure 2. Two views of *Gamera I* HPH

1.2 Unique Challenges

While human powered airplanes have been flying for decades, human powered helicopters present a unique challenge which requires much greater attention be paid to vehicle weight. Whereas a fixed wing vehicle needs to generate only enough thrust to overcome drag and move the vehicle forward, a rotorcraft must have enough thrust to lift itself vertically off the ground. The power required by the rotors scales up with this thrust, resulting in

$$C_P \propto C_W^{\frac{3}{2}}, \quad [1]$$

where C_P is the non-dimensional power required to generate the thrust and C_W is non-dimensional weight [2]. This relationship demands the vehicle must be as light as possible in order to keep the power requirements in line with what a human can provide. In conflict with this goal is the fact that a helicopter with lower disk loading, the ratio of vehicle weight to its rotor disc area, is more efficient. Therefore a large, but lightweight, aircraft needs to be designed. Figure 3 demonstrates that the largest contributors to vehicle weight are the main airframe structure truss arms and the rotor blade spars. As such these components saw the most intense efforts to save weight.

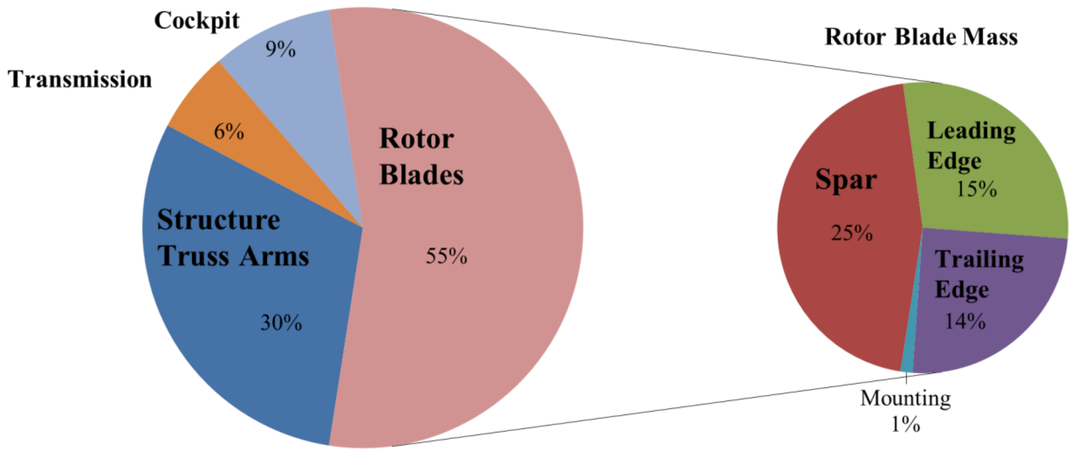

Figure 3. Gamera I mass breakdown. Total mass: 48.6 kg

Minimizing weight, however, could not come at the expense of stiffness due to the importance of ground effect to a human powered helicopter. Ground effect is the reduction in power required to produce a given thrust for a rotor operating near the ground plane. The *Gamera* human powered helicopters operate with their blades at a low height so as to maximize ground effect and any upward tip deflections will negate these benefits. The impact of ground effect is described in terms of the ratio of the rotor height off the ground (Z) to the rotor radius (R). Figure 4 shows the percentage improvement in power required as the rotor is lowered; over 60 % for operating with a 0.1 Z/R. It can be seen that the curve in the region where *Gamera I* operates is quite steep and as such any upward deflection of the rotor blades will come at a penalty in the form of extra power required.

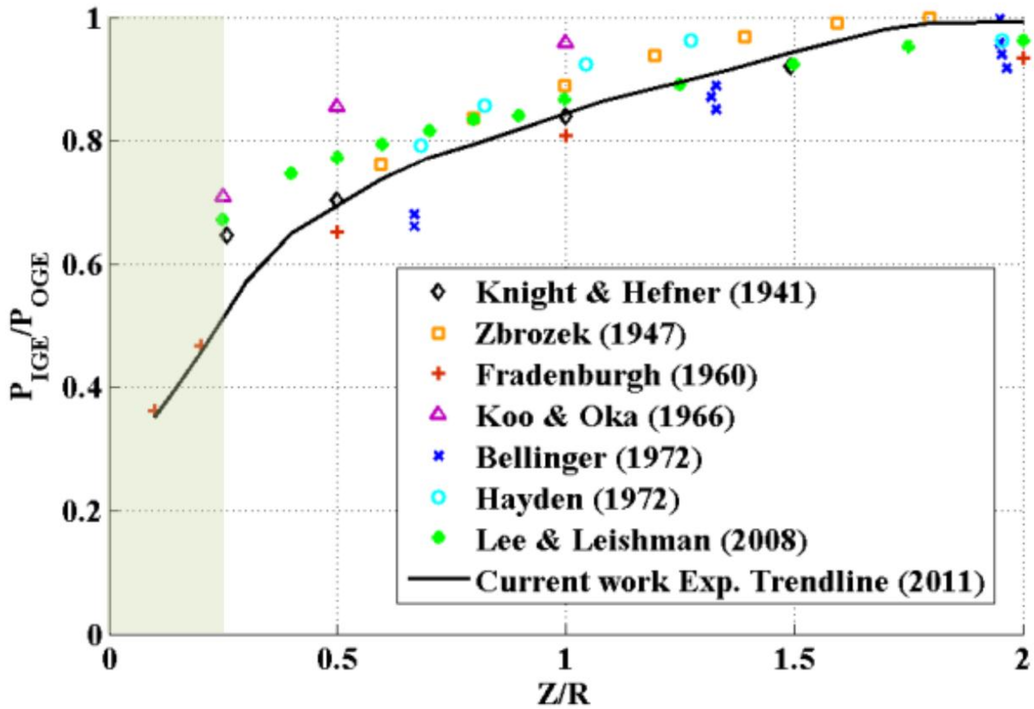

Figure 4. Power reduction from ground effect with HPH operational region shaded [3]

2. BLADE DESIGN

The rotor blade design for *Gamera I* was inspired, in part, by construction techniques used on model airplanes and previous human powered aircraft. An Eppler E387 airfoil was used for the cross section. Each blade was 6.5 m in radius and had a 1 m chord, a rectangular planform, and no twist (Figure 5). The design philosophy was to wrap a minimal weight airfoil surface around an ultra-efficient spar. The role of the airfoil surface was to maintain the desired shape and to transfer the local pressure loads into the spar, which then carried the global bending and torsion loads into the rotor hub.

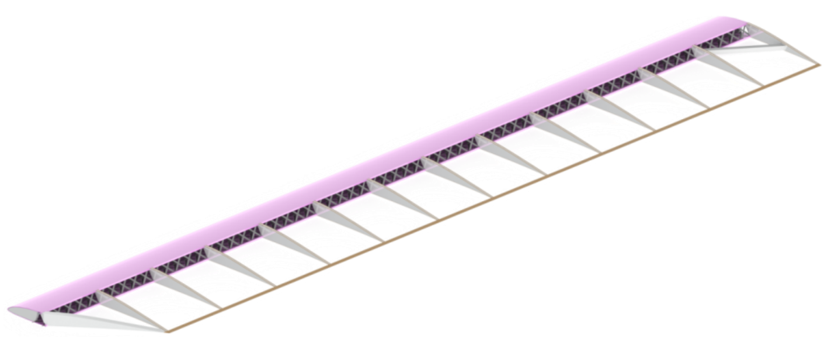

Figure 5. Render of *Gamera I* blade

2.1 Blade Construction

A main spar ran the length of each rotor blade. Extending rearward from the spar was a series of trailing edge ribs, spaced 0.5 m apart for a total of 13 ribs. Cut from 16 kg/m^3 expanded polystyrene (EPS) foam using a CNC hot wire machine, these ribs connected the spar to a balsa wood trailing edge piece. Balsa wood strips were also fixed as caps along the top and bottom of each trailing edge rib, effectively creating a tapered foam core sandwich structure. This significantly increased chordwise and spanwise bending stiffness over a solid foam rib with minimal added weight. Additionally, the tapered shape was well matched to the tapered pressure loading over the trailing edge of the airfoil.

Similarly, EPS leading edge ribs extended forward from the spar. The leading edge of the blade was a monolithic shell of extruded polystyrene foam (XPS) cut using the same CNC hot wire. These leading edge shells were bonded to the forward ribs and wrapped around the spar, where they were shaped with mechanical locking features designed to fit around the profile of the spar, as shown in Figure 6. The trailing edge skin was a single layer of 0.0254 mm (0.001 in.) thick Microlite Mylar film with an areal density of 20 g/m^2.

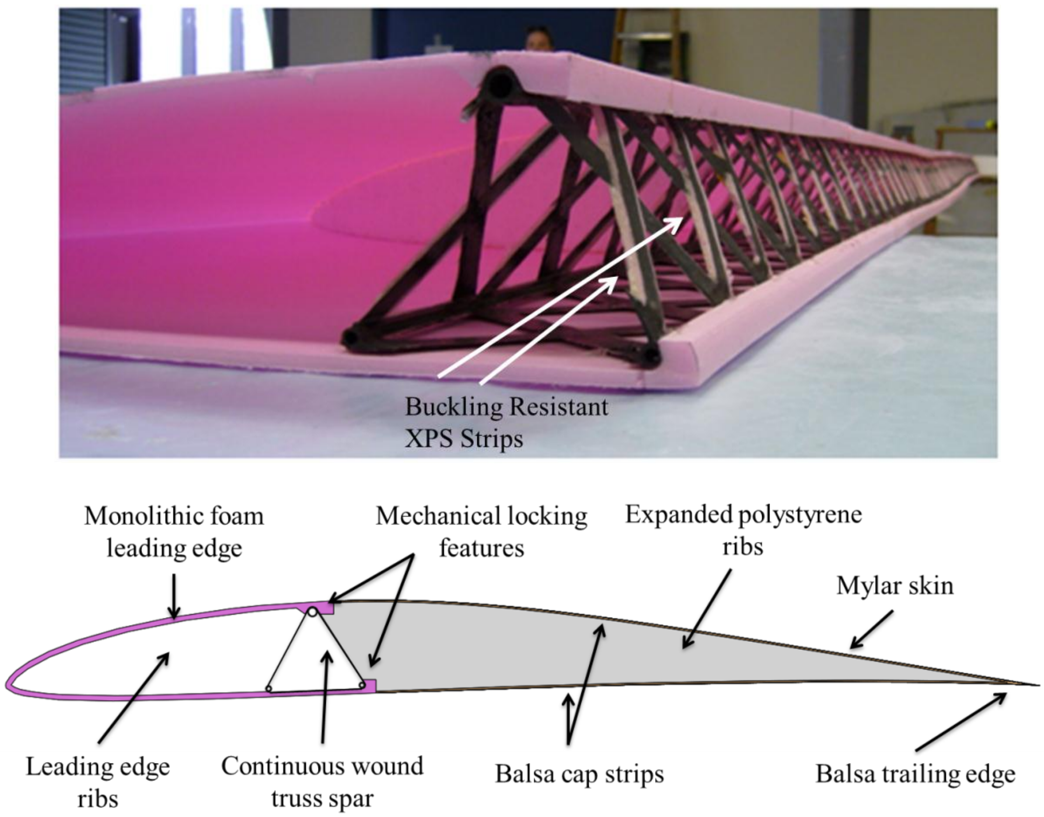

Figure 6. Photo and schematic of *Gamera I* rotor blade

2.2 Spar Design

Traditional composite rotor spar designs including circular tubes, box beams, and I-beams, were initially considered for use in the blades of *Gamera I*, but were found to be heavier than desired. Due to their continuous section geometries, these options all have high surface areas requiring a large amount of composite material. The thickness around the cross section contour of these components is usually varied, making the shear webs as thin possible and increasing thickness at the areas of high stress. Such broad, thin shear webs, however, have poor local buckling resistance, which significantly limits the strength of the spar.

The design philosophy that led to the development of the truss based structures used as rotor blade spars, and throughout the vehicle, was that the nonlinear impact of thickness on buckling could be used to the designer’s advantage if the structural material were concentrated in discrete members instead of being dispersed evenly over the surface of the beam. Locally increasing the thickness would give a highly nonlinear increase in compressive strength. Furthermore, this grouping of material could be accomplished in a manner creating highly optimized substructures.

In the spar design developed, the longitudinal members were made from commercially available pultruded unidirectional carbon fiber-vinyl ester composite tubes. This provided optimized stiffness and strength for the global bending loads and significantly increased local buckling strength. Similarly, the shear web of the beam was constructed from unidirectional carbon fiber-epoxy composites arranged in bundles with a ±45° angle, optimal for carrying both shear loads and the torsion loads induced by aerodynamic moments. Use of a triangular spar cross section provided maximum stability. The triangular cross section (Figure 6) was aligned such that all of the carbon fibers which take the global compression loading were grouped into a single tube (as opposed to the tension material which is split in two). Once again, this was done to take advantage of the nonlinearities of buckling resistance.

The use of truss based structures lead to significant weight reductions. The primary problem with traditional built-up truss structures is the large number of components; the need to manufacture and then assemble all of these parts typically leads to long construction times and labor intensive manufacturing operations. A novel fabrication process was developed for this truss spar which allowed for large scale truss structures with hundreds of “members” to be built in only a few hours. A sacrificial extruded polystyrene foam core was used to align the longitudinal members and provide support for the shear web which was wound around them, a standard modulus carbon fiber tow impregnated with epoxy. The completed continuous composite trusses had no discrete joints or individual members, reducing labor, stress concentrations, and weight while eliminating the need for fasteners or secondary bonding. Buckling prone truss members were built into sandwich structures with the addition of XPS foam reinforcing strips between the layers of carbon fiber tow during construction, as can be seen in Figure 6.

2.3 Spar Testing

The rotor blade spars were statically tested by cantilevering the root with the spar upside down and hanging masses from the structure. Simulation of the distributed upward load experienced by the blade was achieved by using distributed discrete weights, the mass of each selected based on analytical rotor thrust predictions. The static tests proved that the spars permitted an acceptable degree of vertical deflection. Just as importantly, they revealed that the spars for all eight blades were of comparable stiffness with a standard deviation of 5 % from the average (Figure 7). Uniformity among the spars was critical to ensure that all blades behaved the same during flight testing.

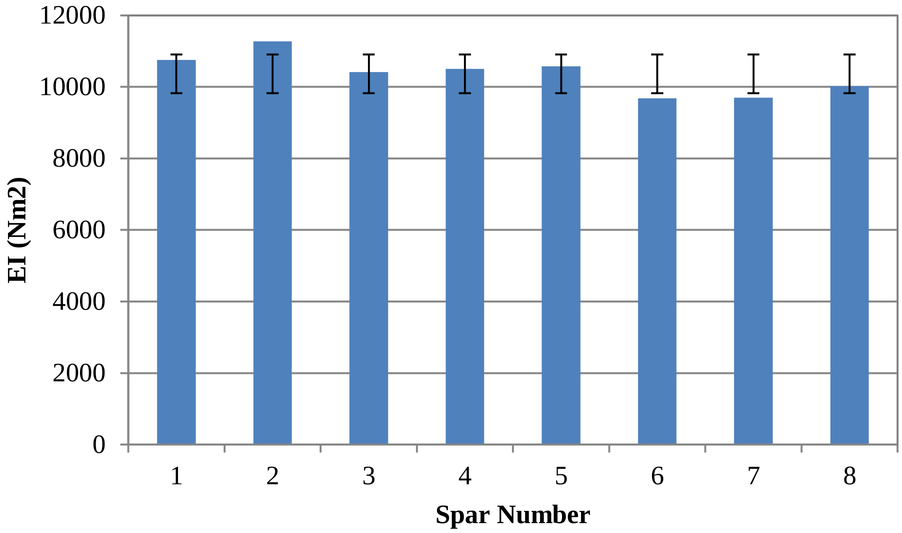

Figure 7. *Gamera I* spar bending stiffness

Upon completion of static testing, the blades were built around the spars. These blades were then placed upon a full scale rotor test stand, instrumented for measuring thrust and power, which was constructed for the project. Testing on the hover stand was done at full thrust and demonstrated the ability of the blades to survive dynamic flight conditions.

2.4 *Gamera II* Blade Design

Following the successful flights of *Gamera I* the team began development of *Gamera II*. One of the most important improvements for the new vehicle was a change in rotor blade design. The new blades utilize a thicker airfoil, the Selig S8037. Increased thickness allows for a taller spar, improving bending stiffness which keeps the blade tips down, increasing ground effect and thereby decreasing power. Furthermore, the blades are tapered. Taper not only provides an aerodynamic benefit but it also allows the spar to get larger towards the root, again increasing bending stiffness. Finally, the blades utilize lighter construction techniques, including applying lower fiber count tow for the shear web, exchanging XPS with lighter EPS foam for the leading edge shell, and using smaller diameter tubes for the longitudinal members of the spar toward the tip where bending moments are lower. Overall, these changes result in more than 39 % weight savings per blade (10 % vehicle weight savings) while simultaneously decreasing tip deflection during hover testing from approximately 100 cm to 30 cm.

3. AIRFRAME DESIGN

The airframe of *Gamera I* was designed to support the thrust of four widely spaced rotors. It was critical to maximize the efficiency of this structure to minimize vehicle weight. To this end, an X-shaped airframe composed of four structural truss arms which met at the center, and supported the rotors at their ends, was adopted. Each arm was 9.6 m long to give about half a meter of clearance between the tips of the 6.5 m radius rotors. An upward sloping angle was given to each of the arms to allow for upwards deflection of the rotor blades in flight (Figure 8). At 6.5 m, once clear of the blade tips, the slope of the structure was halted, resulting in a horizontal center section which reduced the height at the center where the pilot was accommodated. To facilitate construction and transportation of the enormous structure, several joints were modified so they could be separated for transportation, allowing the structure to be dismantled into several sections as shown in Figure 9.

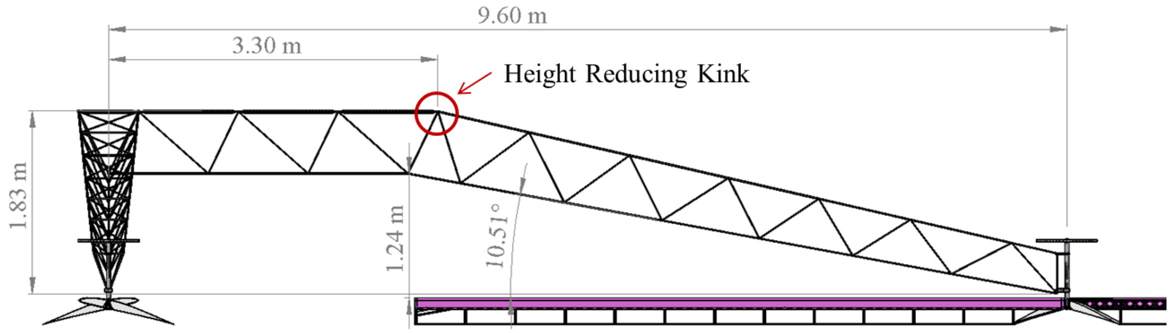

Figure 8. Profile of *Gamera I* truss arm

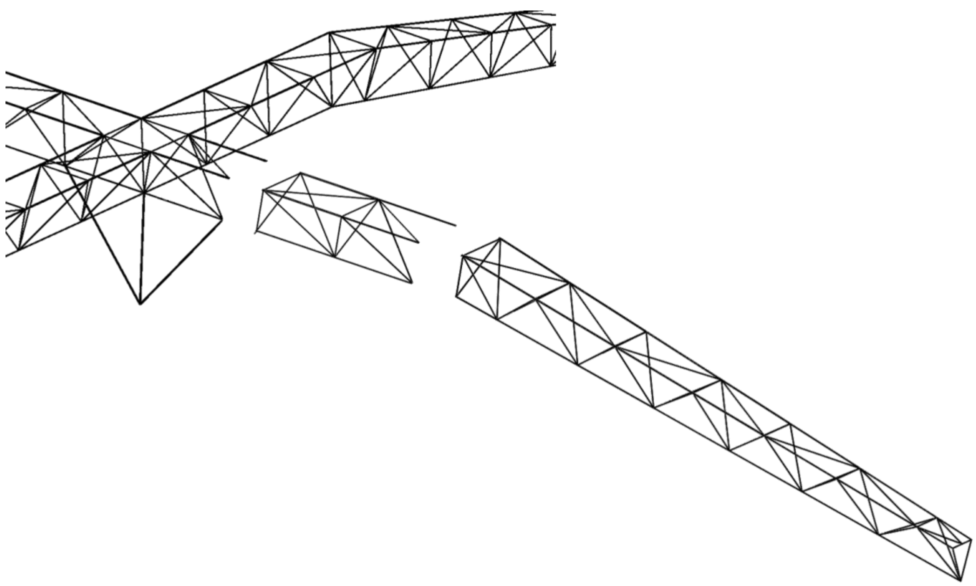

Figure 9. Schematic of *Gamera I* disassembled at separable transport joints

3.1 Truss Construction

The truss arm itself was made of pultruded carbon fiber-vinyl ester composite tubes, similar to the ones used as longitudinal members in the blade spar. Shear carrying truss members connected two main compression members on the top to a tension member on the bottom, forming an inverted triangle profile. Reinforcing members braced the nodes across the top of the truss. The junctions between the tubes at the nodes were formed by cutting the tubes to form a coped (fish mouth) joint. Adjacent tubes were then connected with strips of unidirectional carbon fiber tape before being lashed with epoxy wetted carbon fiber tow to form a strong but lightweight composite joint. Using this method allowed robust joints to be quickly created between several tubes at a variety of angles.

3.2 Truss Optimization

For design purposes, the four identical arms were modeled as simple, cantilevered, triangular trusses with an upward tip load equal to the thrust of the rotor. In addition to the thrust load, experience with the rotor blades during testing showed that any aerodynamic dissimilarity between a pair of rotor blades would introduce a periodic moment. To account for this a tip torque, taking on various directions, was added to the model. The magnitude of this torque was determined by hover testing of a full scale isolated rotor. Finally, to model the tension in the string that transmitted the pilot pedal power to the rotor, a force was added in plane with the rotor and applied to the tip of the truss. These loads are summarized in Figure 10.

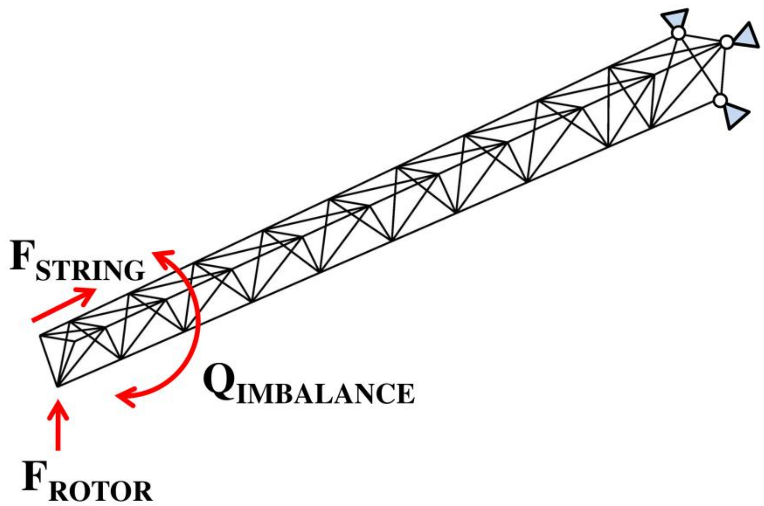

Figure 10. Loading for analysis of *Gamera I* truss arms

Although the total length, height, and slope of the truss were constrained by the blade sizing and design, several degrees of freedom still existed in the truss design. The height and taper of the truss were unconstrained, as well as the number and distribution of the truss nodes, presenting an infinite number of combinations. Further, a variety of composite tubes were available for use, adding more unknowns. To select the most efficient truss design from among all of the possible variations, a genetic algorithm targeting minimum weight while ensuring sufficient stiffness was utilized.

The genetic algorithm searched for a minimum weight truss by mimicking an evolutionary process. The algorithm generated a random population of possible truss solutions, known as chromosomes, with varying heights, tube diameters, and number and distribution of nodes. The fitness of each truss was evaluated by comparing weight while pass/fail criteria ensured that material strength limits were not exceeded and the stiffness, in terms of tip deflection and rotation, met design requirements.

Once the various trusses in the population had been scored, processes known as selection, cross-over, and mutation were used to create a new generation containing the best traits from the old. It is important to make the distinction that this process does not necessarily generate more fit children, but if a sufficient number of children are generated, and if the process is repeated for a sufficient number of generations, then the average fitness of the population should increase and so should the fitness of the best performing truss candidate. Though incapable of guaranteeing a true minimum, a genetic algorithm deals with large design spaces and mixtures of discrete and continuous variables well, making it an attractive tool for the truss optimization.

3.3 Development and Testing of "Micro-Trusses"

The optimization results showed that buckling of slender members under compressive loads was always the limiting failure mode for the truss. Buckling was modeled using the Euler buckling formula,

$$F = \frac{\pi^2 EI}{(KL)^2}, \quad [2]$$

where each truss member was treated as a beam of length L under axial compression with second area moment I, and stiffness E. The end conditions were defined by K, where $K = 1.0$ indicates pinned-pinned end conditions and $K = 0.5$ indicates fixed-fixed end conditions. Through the testing of joints on an MTS machine, a conservative value of K = 0.8 was determined to approximate the near fixed-fixed end conditions of the truss members.

Initially, only commercial off-the-shelf composite tubes were used for the airframe structure of *Gamera I*. Although of high quality, these tubes were only available in certain diameters and thicknesses. Such discrete size changes allowed only limited tailoring of the structure. This proved especially problematic in the members along the top of the arms in the centermost section; these experience the largest bending moments and therefore the highest compressive loads. The tubes used at first were not sufficient and the next step up in size came at a large weight penalty.

With the aim of achieving adequate buckling resistance without the increase in mass associated with using a thicker member, the team developed custom "micro-trusses", shown in Figure 11. Manufactured using the wound truss technology developed for the blade spars, these smaller trusses were made with three equal diameter pultruded composite rods arranged in a triangle. A shear web of intermediate modulus carbon fiber tow impregnated with epoxy was wound around the structure at ±45° angles. By placing the majority of the material in the three longitudinal members at the corners of a triangle, a larger second moment of area could be achieved than with tubes of a similar cross sectional area. During compression testing in an MTS machine (Figure 11) the micro-trusses proved to carry significantly higher loads before buckling than the tubes they were designed to replace while also being lighter. The combined impact of higher strength and lower weight can be seen by considering the buckling efficiency metric *EI*/mass. For a given length and boundary conditions, the buckling strength of a member is directly related to the *EI* of its cross section, as in Equation 2. Dividing the *EI* by the linear mass (in grams/meter) shows how efficiently the buckling resistance is obtained. Figure 12 shows this buckling efficiency metric for two sizes of micro-truss compared to commercially available pultruded carbon fiber-vinyl ester composite tubes. It can be seen that the micro-truss geometry used in

Gamera I provides a 620 % increase in buckling efficiency over a single tube of equivalent weight.

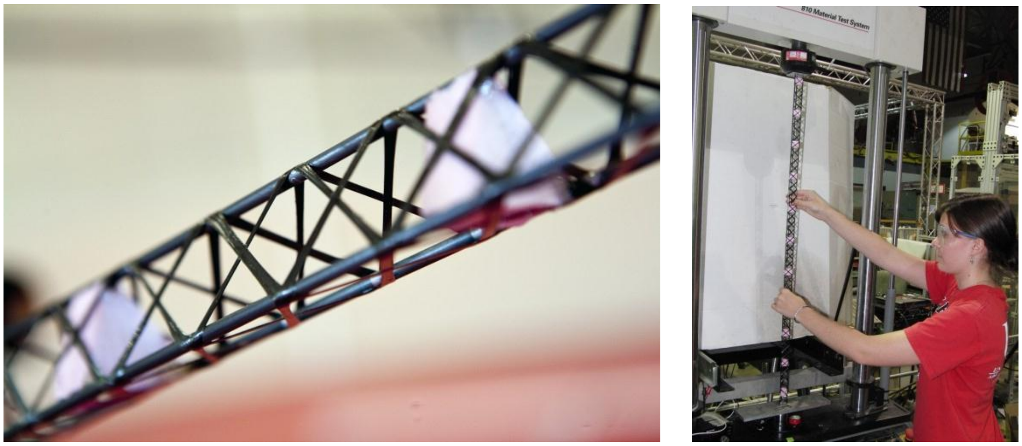

Figure 11. Detail of micro-truss and micro truss under compression testing

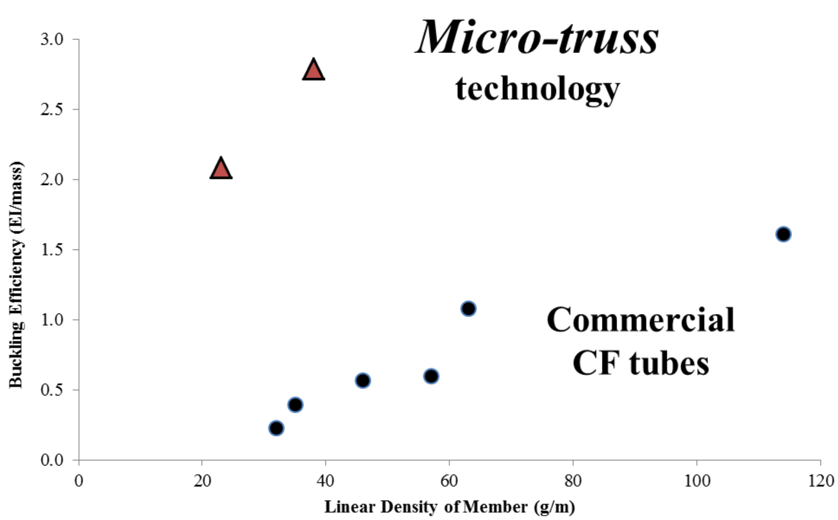

Figure 12. Buckling efficiency of micro-trusses and COTS composite tubes

3.4 *Gamera II* Airframe Design

When designing the structure for *Gamera II* the same genetic algorithm was employed, though this time micro-trusses of various sizes were included alongside the off-the-shelf pultruded tubes. The results of the optimization showed that micro-trusses were preferred for most members, with only the axial tension members along the bottom of each arm selected as individual tubes. To streamline the manufacturing process only two different sizes of micro-truss were used in the final design for *Gamera II*. Utilizing the micro-trusses more extensively in *Gamera II* resulted in a weight reduction of approximately 40 % compared to an all tube design. Combined with the blade weight reductions, the new vehicle weighs 34 % less than its predecessor.

In addition to the implementation of micro-trusses for most members, the structure of *Gamera II* is also appreciably shorter than the original helicopter. This height reduction comes about as a result of the increased spar stiffness mentioned previously. With less deflection from the blades the new structure has a similarly decreased slope, obviating the need for the kink present in *Gamera I* (Figure 13).

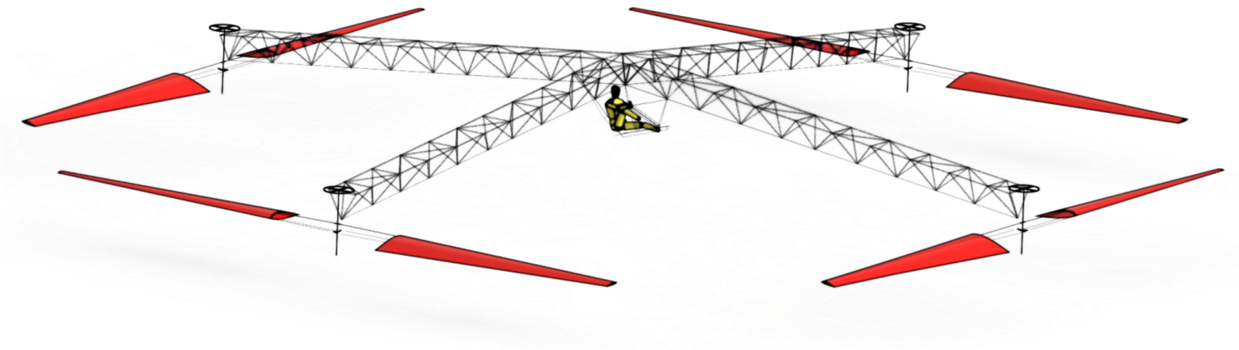

Figure 13. Model of *Gamera II* HPH

4. SUMMARY

Through thoughtful and innovative composite structural design, a team of students from the University of Maryland was able to build *Gamera I*, a human powered helicopter which set the FAI record for flight duration of a human powered rotorcraft at 11.4 seconds during its first ever round of vehicle testing. With a final mass of 48.6 kg, the vehicle weighed less than its 50 kg pilot. The low weight of this very large aircraft was the direct result of the implementation of novel ultra-lightweight construction techniques. Chief among these was a wound truss technology developed specifically for the *Gamera* project which allowed for the production of highly optimized carbon fiber truss structures quickly and cheaply. These structures significantly outperformed traditional composite tubes and were used for the most highly loaded primary structures, including the blade spars and airframe root compression members. There is potential for these structures to be employed in a wide range of applications that demand high structural efficiency including aircraft (manned and unmanned), wind turbines, high performance automobiles, and space structures.

Taking account of lessons learned during the development and flight testing of their first vehicle, the team designed a second, improved helicopter. By manufacturing stiffer, lighter blade spars and implementing a greater number and variety of micro-trusses, *Gamera II* weighs only 32.1 kg, 66 % the mass of the first vehicle. With decreased weight and increased aerodynamic efficiency, it is expected that the new vehicle will be able to hover for over sixty seconds. Construction is currently proceeding and is scheduled to be finished by the beginning of June, 2012.

5. ACKNOWLEDGEMENTS

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