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Student Research Through the JPL Adapter Design Competition

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Abstract

The Jet Propulsion Laboratory (JPL) initiated a new program in 1993 called the Pluto Fast Flyby (PFF) mission to send a probe to the last unexplored planet in our solar system. Tight budgets have caused NASA to look at non-traditional methods of funding, such as student design competitions, for the initial design and prototype manufacturing of some parts. As a first trial, JPL sponsored the Adapter Design Competition for all universities world-wide to design and fabricate, if possible, a prototype light weight adapter, supporting the design loads. The spacecraft adapter will connect the PFF spacecraft to a Thiokol Star 27 kick motor. The JPL baseline design had a mass-to-beat of 12.5 kg. At Georgia Tech, a student team was organized to participate in the competition. This paper describes the student research performed in preparing the Georgia Tech chapter of Students for the Exploration and development of Space (SEDS) entry in the JPL spacecraft adapter design competition. The activity was both a successful student research program and a successful design competition experience. The Georgia Tech Team's prototype adapter, measuring in at just under 2 kgs, won first place and was awarded $5,000.

The reason this activity was successful is that the students were working on something that if successful, would be used in a real space mission and was innovative. The design was innovative for two reasons: 1) it may never have been used before on a U.S. space mission and 2) several original ideas were added to the work of Japanese researchers.

I. The Pluto Fast Flyby Mission

The purpose of the Pluto Fast Flyby Mission is to study Pluto's atmosphere. In the year 2015, the atmosphere of the furthest planet in our solar system will collapse unto its' surface giving this mission the opportunity to study the planet's activity before it freezes. JPL plans to send two lightweight spacecraft to the planet on a fast trajectory, that is a direct route, a hyperbolic orbit, as opposed to an elliptical orbit, to reach the planet in 6 - 8 years.

The main structure of the spacecraft, as described in the competition announcement, was a hexagonal shell which houses the electronics and the power systems. Subsystems such as UV spectrometer and IR/visible camera are mounted on top of the main structure. The high gain communications antenna will sit above the main structure and cameras. Below this main structure is a 42 cm diameter fuel tank. The total weight of the spacecraft including fuel is to be 164.14 kg, thus the adapter must support this static load as well as dynamic loads encountered during the launch and orbit insertion.

Obviously, in this day and age it is very important to keep the costs of the mission down. Therefore, JPL, as mandated in the PFF mission statement, vied for student participation. This resulted in the Pluto Fast Flyby Spacecraft Adapter Design Competition.

II. The Adapter Design Competition

The competition began on May 31, 1993, with a letter of intent. Final specifications from JPL were received on June 5, 1993. A preliminary abstract and design was due on June 28, 1993. The deliverables included a report and a prototype of the adapter, due at JPL in Pasadena by August 16, 1993. The report would be a full write-up of the design, including reasons for selecting a particular material, a study of loading cases, methods of design, a description of the prototype fabrication, and lessons learned. Loading cases included static, dynamic, single, and combined loads. A full disclosure of the techniques and time required for prototype fabrication was requested. As an option, if time allowed, JPL asked for testing of the adapter. JPL wanted a verification that the adapter could support the static and dynamic loads as well as a write-up of the testing procedures.

The last stage of the vehicle was specified as a Thiokol STAR 27 solid rocket motor.. The adapter was constrained to attach to the hard points of the spacecraft via pyro-bolts. Bolt hole placement on the kick motor was also given. The adapter also had to be designed to accommodate the explosion of the pyro-bolts during the separation phase of the mission. In general, the adapter had to: support all loads, connect between the STAR 27 kick motor and the PFF spacecraft itself, have a minimum natural frequency of 40 Hz, have a mass less than 12.5 kg, have a minimum part count, and be compatible with fuel and electrical cabling requirements and the pyro-bolts.

The top 5 entries would receive $1,000 and if the design was found useful, this could be increased by as much as $4,000. The award would represent JPL's offer to buy the rights to use the design in the PFF mission.

III. The Georgia Tech Entry

This paper details, to a moderate degree, the design process and philosophy used to prepare the Georgia Tech Entry. Generally, design competitions are not looking primarily for innovation or creativity.[1] However, here was an instance to the contrary; moreover, the winners of the competition may get to see their design used. With this motivation students willing to show off what they learned and attempt creative solutions quickly rose to the challenge.

By the end of May, the Georgia Tech Chapter of SEDS had formed a design team with undergraduate and graduate members. Work on the Georgia Tech Entry began in early June. A look at current work on spacecraft adapters lead to consideration of the Japanese design[2]. It is Georgia Tech's variation on their design that is presented herein.

III.1. Material Selection

Composites were an integral part of our conceptual design. Graphite epoxy has the advantage of being very strong but lightweight. The decision to use a prepreg was due to the ease of manufacturing. Filament winding was ruled out of the manufacturing process since the adapter design was too complex to use a filament winder. By using prepreg, the design team was able to hand lay-up the adapter with a minimum of difficulty. ICI Fiberite Corporation in Tempe Arizona donated 25.7 lbs of prepreg.

III.2. Concurrent Engineering

As a result of the extremely short timeline, our design team was forced to practice at least some form of concurrent engineering if the design process was to be successful. Essentially, no iterations between conceptual design and manufacturing were allowed. Therefore, conceptual design and manufacturing decisions had to be made concurrently. The objective was to design a composite lattice cone. However, knowing the manufacturing constraints at the forefront, a true cone was unreasonable. A trade off between manufacturablity and approximating the desired conceptual design was made, resulting in a twelve-sided conical shape. Each side of the adapter would have two diagonal, crossing members and two lateral members, see Figure 1. The lateral members of each side connect forming twelve-sided circular bands around the trunk of the design. A short vertical band at the top of the adapter connects the trunk to the upper flange and allows room for the pyro-bolts which would separate the structure from the spacecraft during flight.

III.3. Analysis of Design

III.3.1 Loading Cases

To identify the worst-case, a study of loading cases supplied by JPL was made. The loading conditions for this adapter design were calculated based on the load requirements described by JPL. The following table, Table I, gives the results of the load calculations. MAC stands for mass acceleration curve, referring to loading data from JPL. The MAC provided a method for calculating loads induced by accelerating the spacecraft. All loads and moments calculated for loading cases included a safety factor of 1.5.

From this study of the loading cases it was determined that the critical load was indeed the axial load during launch and thus, buckling would, as expected, be the critical failure mode.

	Single load cases
1	MAC-Axial
2	MAC-Bending
	Combined load cases
3	Angular Acceleration
4	MAC-Axial + 18g compression load
5	MAC-Bending + 18g compression load
6	Axial Force + Spin Rate
7	Spin Rate

Table I. Loading Conditions

It should be noted that both S.I. and U.S. units are used throughout this paper. JPL used mixed units in the writing of the design specifications. Most data directly from JPL was given in metric units but most data from Thiokol was in U.S. units. There was no specification as to what units should be used in the report. As a result, there is a mix of units in this paper.

III.3.2. Preliminary Analysis

The main load-carrying members were truss beams elastically constrained by two lateral rings. The elastic constraints were approximated by simply supported conditions to provide conservative values. This paved the way for analysis via Euler buckling equations:

$$P_{cr} = \frac{\pi^2 EI}{L^2} \quad \text{for simply supported beams}$$

$$P_{cr} = \frac{(4.49)^2 EI}{L^2} \quad \text{for fixed-hinged conditions}$$

where P_{cr} is the critical load, E is Young's modulus, L is the length of the longest beam segment, and I is the moment of inertia. Using the ultimate compressive load as the design load, the critical load was determined for the beam members of the design. Using this value as the Euler buckling load, the required moment of inertia was determined to be $2.4076\text{x}10^{-11}\ m^4$. It should be noted that use of this moment of inertia would result in a conservative buckling load since the design exhibits elastic restraint on the end rotations. With a value for moment of inertia the cross sectional dimensions can be determined. For ease of manufacturing, we selected a rectangular cross section with a width of 0.8 cm which results in a thickness of 0.334 cm. The choice of dimensions was such that the adapter would prefer to buckle out-of-plane.

III.3.3. Finite-Element Analysis

A full analysis of the design was made using the finite element program COSMOS. The finite element model is shown in Figure 1. The COSMOS model consisted of 348 beam elements. Due to the nature of the design, it was assumed that accurate results could be obtained using a linear beam approximation with an elastic modulus equal to the modulus obtained from a 0 degree uniaxial tensile test of the composite material. After this test, buckling analysis was performed to compare the theoretical hand calculations with the full finite-element model. The buckling loads by both hand calculation and finite-element modeling are shown in Table II.

Method	Buckling Load
Euler	73179 N
Finite Element	126180 N

Table II. Buckling Loads

It should be noted that the hand calculations resulted in conservative values since a pinned-pinned boundary condition was used. The conservative figure was intentional to ensure that the manufactured specimen will withstand the maximum loading. The beam members of the finite element model were elastically constrained at each end. This provided a more realistic condition for design.

The buckling mode as predicted by the finite-element model was well above the worst-case loading. The model exhibited a natural frequency of approximately 839 Hz. This was well above the minimum, 40 Hz, as required by JPL.

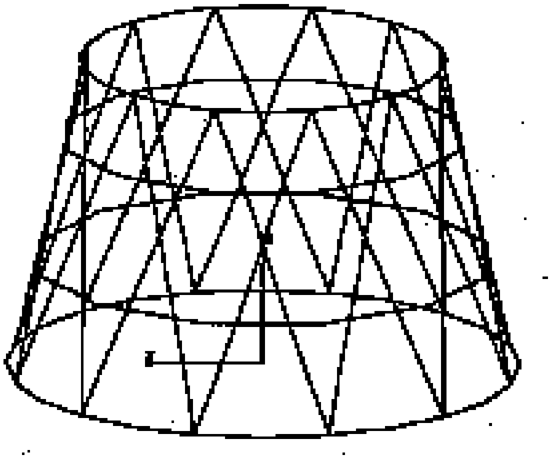

Figure 1 Graphic Representation of COSMOS Finite-Element Model.

III.4. Manufacturing Plan

The manufacturing process for the prototype included the construction of a mold, lay-up of the composite material, curing of the composite and the removal of the specimen from the mold. The mold facilitates the lay-up of composite material as well as maintains the shape of the adapter during the heated cure. The mold became a major design driver. Ideally, a true cone shape would have been desired for the adapter. However, a mold for this would be difficult to fabricate. A twelve-sided approximation of the cone was adopted. An AutoCAD drawing of the mold is shown in Figure 2.

The mold was manufactured as 26 sections of aluminum. Two of these, the upper and lower flanges, were molded from singular sections. The upper cylindrical band around the top of the adapter was molded from twelve identical pieces that were attached to each other, the upper flange mold, and a conical lower band. This conical lower band was also made of twelve identical pieces. These slanted pieces had grooves machined into them for laying-up the cross members of the lattice. The conical band was attached at the bottom flange mold.

Each component of the mold, including the upper and lower flanges, was machined for a smooth surface wherever composite material would be laid down. As each component was machined, they were fitted and marked because each component fit best to a unique neighboring component. The grooves in the plates were also machined for the best fit with neighboring components. All pieces of the mold were attached together with simple aluminum brackets and bolts. The bolts were driven in from the inside of the mold and ground down on the outside so that they did not protrude into the composite material.

To facilitate mold removal after cure, a piece of shim stock was placed between two of the slanted plates of the conical band. The idea was that this would ease removal of one of the plates with the rest of the mold to be removed piece by piece.

III.5. Description of Prototype Fabrication

III..5.1. Fabrication Methods

The spacecraft adapter structure was designed to fit a mold by cutting pieces of prepreg for a custom fit. Beam members were of unidirectional design with fibers in the longitudinal direction. For buckling, the beam dimensions were the critical design parameters. The beam width was chosen to be 0.8 centimeter for ease of manufacturing which corresponds to a thickness of 0.334 centimeters so that desired buckling characteristics were maintained. Given the thickness per ply of the sample specimen, this corresponds to 25 plies of composite.

Both flanges as well as the top band were laid up in units for ease of manufacturing and maintaining symmetry. The top flange and band consisted of four units of $[90/0_3/90]$ to combine for 20 layers. The bottom flange lay-up was as follows $[(90/0/15/0/90)_3/(90_2/0_2/15_2/0_2/90_2)]_T$. The last two units were doubled up in the interest of lay-up time; though manifested in the prototype it was not part of the design. Although the doubling took the total laminate out of symmetry with respect to the center ply, the number of ply orientations remained balanced with respect to the center ply; thus, laminate warping during cure was avoided. The top flange lay-up consisted of four units of $([90/0_3/90])$. The 90° layers of the flange were continuous with the 90° plies of the band.

The top band was a cross ply shell of four $[90/0_3/90]$ units with an extra ply of 0° on the outside for a better finish. The fibers in the 90° direction were continuous onto the top flange. This provided a desirable load transfer through the turn onto the flange. The 90° plies were cut into 12 sections while the 0° plies are continuous except for one discontinuity around the perimeter. The break was positioned so that the sections did not overlap. The units used for the horizontal rings were also continuous with one break and had the same sequence for breaks as the band.

The joints between the beam members and the flanges were designed in such a way as to reduce buildup at overlapping areas and to efficiently transfer load. The build up of material was reduced at the center beam joint by widening the channel in the mold to allow for the extra material. The joint to the flanges was reinforced with material extending into the upper band. The material at the joint to the top flange was frayed to allow a better distribution of the load.

The adapter was cured in a Thermal Equipment Corporation (TEC) 4 foot diameter autoclave provided by Lockheed Aeronautical Systems Company in Marietta, Georgia. The cure cycle used was the standard Fiberite Cure Cycle C-6. The structure was allowed to bleed freely during cure. A significant amount of resin was lost during cure in both the upper band and flange as well as the bottom flange.

III.6. Mass and Cost Estimate

III.6.1. Mass Estimate

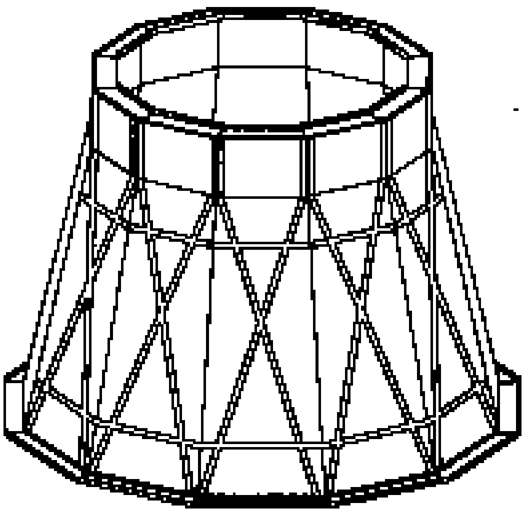

Figure 2 CADKey Representation of Mold

The amount of prepreg required to construct the adapter was calculated by determining the volume and multiplying by the density. The density of the composite was determined using the anticipated volume fraction with fiber and matrix densities using material properties obtained from Fiberite. The calculated volume of the adapter was 1201.5 cm^3 resulting in a precure mass of 1.91 kg. The post cure weight was 1.79 kg with the weight reduction from the bleeding of the epoxy during cure.

III.6.2. Cost Estimate

The cost for the Pluto Fast Flyby adapter can be separated into that of the mold and that of the adapter. These costs can be further broken down into material and labor costs. Overall material costs include aluminum for the mold, composite material for the adapter, and the materials required to prepare the adapter for curing in the autoclave. The latter materials, referred to as the vacuum bag buildup, included the vacuum bag, Frekote release agent, and Teflon, etc. The aluminum required to make the mold for the adapter was 48" by 96" of quarter inch aluminum, costing approximately $300. The composite material, Toray T1000G prepreg, amounted to 7 lbs, assuming roughly 50% waste material and the adapter mass. Composite costs were about $75 per pound, amounting to $525 for composite materials. The materials required to prepare the adapter for curing in the autoclave cost under $20.

Labor represented the largest portion of the adapter cost estimate. Mold construction required approximately 200 man hours. The lay-up of the composite material also required a considerable amount of time, approximately 150 man hours. Finally, curing the adapter required two Lockheed workers for a seven hour shift .

Adding the costs of these individual component costs gives a one time cost for initial setup (manufacturing the mold) of $9,300. The cost for the adapter itself comes to

$10,595.00.per adapter The total cost estimate for manufacture of three adapters comes to $41,085.

This cost estimate is based on information from the Georgia Tech School of Aerospace Engineering Machine Shop; Lockheed Aeronautical Systems Company, Marietta, Georgia; Fiberite in Tempe, Arizona; and ALCOA, an aluminum supplier. This cost estimate did not include any overhead or equipment use charges, other than the autoclave.

III.7. Prototype Testing

III.7.1. Test Setup

The axial test was performed on a Baldwin Testing Machine. The Baldwin Testing Machine has a test section of 31 inches with a flat lower platform and an upper cross head with two built in load cells. As the loading was applied, a Keithley Data Acquisition system combined with an IBM PC took real time readings from the load cells. A solid steel plate on top of the adapter ensured an even load distribution. A rubber padding was placed inbetween the steel plate and the adapter so that stress concentration did not occur on the adapter surface. The weight of the plate (100 lbs) was included in the test loading. Two Linearly Variable Differential Transducers (LVDTs) were used in the set-up to measure displacement. Both LVDTs were zeroed at zero load. One LVDT was used to measure the displacement of the cross head while the other measured the displacement of the upper band. The compression of the solid upper band was assumed to be negligible relative to those of the truss structure. In the interest of time, the bending and applied torque tests were deemed secondary and were not performed.

III.7.2. Test Results

The first test load was to reach a maximum load of 74,798 Newtons or 16,814 lbs, corresponding to a safety factor of 1.05 on top of the conservative figures. Upon reaching a load of 6752 lbs, the beam members were noticed to have begun buckling. The load-deflection data from this test are shown graphically in Figure 4.

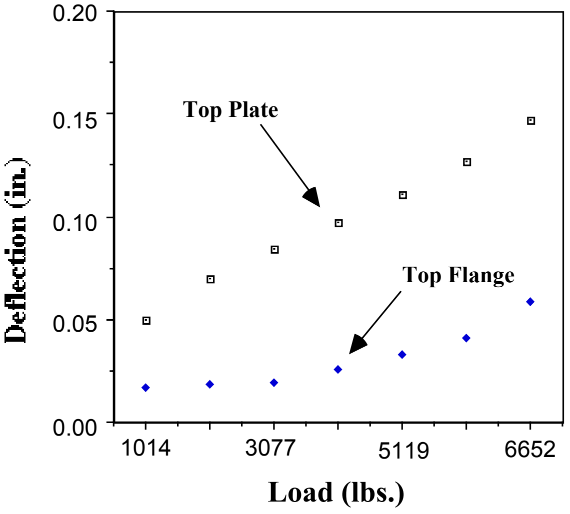

Figure 4 Test Results: Deflection Data

The early appearance of the buckling mode can be attributed to two causes. The effective length of the buckling member was underestimated by assuming the length of the longest beam segment instead of the entire length of the beam. The assumed effective length caused the first buckling mode in the out-of-plane direction for the entire side instead of the designed first mode buckling of the beam segments. Another factor was the post-cure dimensions of the beam cross-section.. Pressure plates were not used during the cure, thus resulting in a parabolic surface. The average thickness of the beams at the low point of the cross section was 0.252 cm as opposed to the design thickness of 0.334 cm. This gave a relative error from the design thickness of 24.12%.

III.7.3. A Testing-Design Iteration

At this point, a decision was made to reinforce the center joint for out-of-plane buckling: a third ring was added to the structure. The new ring was made with 14 strands of 12K tow IM7 fiber. Ten strands of fibers were wrapped around the structure. The other four were wrapped around the structure and wrapped around the joints to secure the fibers. A room temperature cure Bondo brand epoxy was used. The epoxy was allowed a twenty hour cure time. The structure was again tested in axial compression. The Load-Deflection data from this test are shown graphically in Figure 5. This time, the loading reached 7079 lbs before the second beam buckling was noticed. This time the buckling was different. The low ring of the adapter was noticed to have buckled inward and the upper ring buckled outward. A photograph of the adapter, with the modification, is shown in Figure 6.

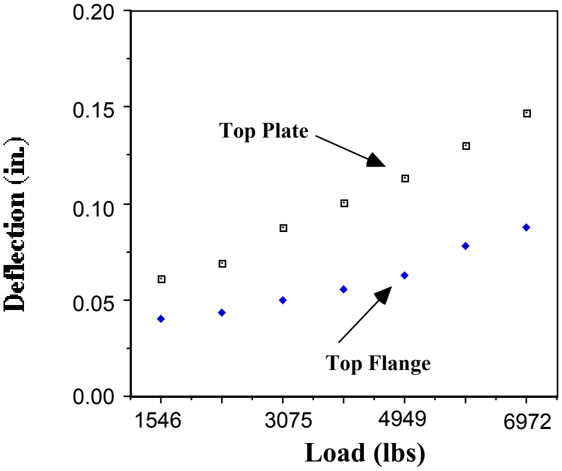

Figure 5 *Deflection Data for Modification*

III.8. Remarks on the Prototype

The primary problem we encountered was an unexpected buckling mode. The beam members were designed to buckle inward and outward (radially) because the widths of the beams were designed greater than the thickness. In this design, an assumption was made that the intersection between beam members would exhibit an elastic restraint. Although this was true in the plane of the mold, it is not true in the buckling direction. For this reason, the buckling modes came much sooner than predicted. A simple solution to this design flaw is to design the beam members to buckled sideward. In this case, the joints between beams would act as an elastic constraint, and the buckling load should increase respectively.

The thermal stresses that the mold exerted were underestimated. The thermal expansion of the mold in the radial direction was considered, but not the expansion of aluminum around the grooves. After the cure, it was very difficult to remove the composite from the mold, even though release agents were applied. The composite had taken the shape of the mold when the aluminum expanded during cure. During the cool down stage of the cure, the aluminum contracted, “clamping” onto the composite. Thus, the mold should also be slightly redesigned to allow for an easier separation of the adapter from the mold. There are two options available for modification of the mold. The first involves modifying the channels cut for the adapter beams. In this first prototype, the channels were machined with straight edges. The grooves could be angled to ease removal from the adapter by decreasing the clamping force on the members. A second possibility involves changing from the solid aluminum panels used in the first prototype to panels resembling the design itself. These could be easily created by cutting out the large sections of aluminum on each plate in the original mold design. This will reduce the thermal stresses and ease removal from the mold.

Figure 6 *Photograph of Prototype Adapter with Post-Testing Modification*

Adding an additional ring to the design may also be a good idea. This ring could be placed just below the 'X' intersection of the vertical beams. The lower ring from the original design would also be lowered. This additional ring would be effective in reducing the maximum beam length and thus greatly delay buckling phenomena.

IV. Concluding Remarks

The largest lesson learned from this activity was the importance of the manufacturing process. Almost every problem that was manifested in the prototype was related to manufacturing:

- The so-called "clamping" force that complicated separation of mold and adapter.

- The use of pressure plates on the composite lattice elements would have forced a more rectangular shape, increasing the effective thickness of elements.

Significant time is spent in the classroom teaching the design process, but this was the first time for some of the team members to continue to a production level. It was also the first time that the team members had to consider the feasibility of manufacturing during the design process. An increase in the student’s ability for consideration of manufacturing concerns during the design process could have greatly reduced "return to the drawing board" modifications.

This competition should stand as an example for other national student design competitions. The framework and setup of the competition gave very surprising and robust motivation to the students. This team worked diligently for a three-month period, even staying awake overnight when necessary to meet deadlines

Since JPL required the manufacturing of a prototype, the students had to get a crash course in composite manufacturing. A lot of this was learned hands-on as the Georgia Tech Aerospace Machine Shop helped instruct the students in building the aluminum mold. However, as Georgia Tech did not have the facilities for curing composite structures of this size, the students also learned a great deal from Lockheed of Marietta, Georgia. This was a type of learning that only comes from hands-on experience and, in these days of concurrent engineering and design-for-manufacturing, will prove valuable to these Georgia Tech students throughout their careers.

V. Acknowledgments

We gratefully acknowledge the assistance given us by industry and by Georgia Tech. We are greatly indebted to Lockheed, Georgia Company and to Fiberite of Tempe, Arizona. Ms. Mary Gardea at Fiberite supplied us in excess with the composites used to manufacture the prototype. Mr. Tony Jackson and Mr. Dan Scolnik of Lockheed Aeronautical Systems Company in Marietta, Georgia graciously donated the use of their autoclave for curing our prototype. We also would like to thank Mel Allen of Lockheed for his invaluable advice in preparing the prototype for curing

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We thank Dr. Junjiro Onoda for sharing with us information on his work in this field. Finally, we cannot forget our fellow students, Karl Lentz and Caleb Branscome, who helped for many hours to lay-up the composite for the prototype.

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