

Independent Research: Composite Spar Manufacturing For use on the Human Powered Helicopter



Research Conducted at California State University

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Report written June 2011
Research performed throughout Spring Quarter 2011

Abstract

The purpose of this paper is to introduce the methodology of design and manufacturing extended length carbon fiber tubes to be used in structural applications. This project builds on independent research conducted by Mike Brickner, Andreas Ottinger, and Johannes Mendel at California Polytechnic State University throughout Winter Quarter 2011, whose research findings are presented in Appendix A.

Several goals were defined early on in Spring Quarter 2011 for the scope of this project. These included, but were not limited to: a) Testing of manufacturability methods for extended length carbon fiber tubing (≥ 3 ft); b) Establish design criteria with the help of computer modeling to assist in reliable tubing design.

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Introduction

Carbon fiber tubing is of particular interest to the Cal Poly Human Powered Helicopter team due to its very high stiffness-to-weight ratio. This project stemmed from the necessity of designing and building long, lightweight structural members for that application. Through thorough documentation and project development it is anticipated that the information and lessons learned during this special assignment will allow for an easy transition when the time comes for the Cal Poly HPH team to build their own tubing.

A solid foundation for manufacturing methods was laid by a special project under the same title started at Cal Poly during Winter Quarter 2011. This project, which can be found in its entirety in Appendix A, spent a great deal of time investigating suitable materials for use as mandrels. These mandrels are used to wrap strips of unidirectional T700 high tensile strength carbon fiber “prepreg” around them in order to form the inside diameter of the tubing. The T700, like other types of unidirectional carbon fiber, has different coefficients of thermal expansion relative to the fiber direction and transverse to the fiber direction. Unidirectional carbon fiber prepreg has a slightly negative coefficient of thermal expansion in the longitudinal (fiber) direction, but a large positive coefficient of thermal expansion (15 micro-inch/inch/°F) in the transverse (matrix) direction. What this means for the construction of carbon fiber tubing is that the tube will want to decrease in diameter upon cooling from its 250 °F cure temperature. This causes the selection of mandrel material to become important for the construction of unidirectional tubes. If the mandrel does not “shrink” away from the carbon fiber after curing at a high temperature, the tube will not be able to slide off the mandrel. For this reason polypropylene, with a coefficient of thermal expansion of 48 micro-inch/inch/°F, was selected as the mandrel material for curing unidirectional tubes. More information about possible mandrel materials will be explained in the manufacturing processes section of this report.

Required Materials

Mandrels

- Polypropylene
 - Length: 8 ft
 - Diameter: $\frac{3}{4}$ in
 - Color: White

- Softening Point: 300° to 350°F
- Finish: Smooth
- Tensile Strength: Poor
- Impact Strength: Good
- Hardness: Rockwell R79-R-115
- UL Rating: UL 94HB
- Purchased from McMaster-Carr
 - Item #: 8658K54
 - Price: \$1.88 per ft
 - Website: <http://www.mcmaster.com/#polypropylene/=c9ez5t>

Chemical Release Agent

- Silicone Mold Release
 - Brand: LPS, Dry Film, Silicone Lubricant
 - Non-staining
 - Non-corrosive
 - Heat Stable up to 500°F
 - Nonflammable
 - No class I or II ozone depleting chemicals
 - For use on rubber, plastic, and metal parts
- Purchased from Aircraft Spruce
 - Item Name: LPS MRX Silicone Mold Release
 - Item #: 09-00271
 - Price: \$10.65 per can
 - Website: <http://www.aircraftspruce.com/catalog/cspages/lpsSiliconeMold.php>

Carbon Material

- Carbon Fiber
 - Tensile Strength: 225 ksi
 - Thickness: 0.014 in
 - Width: 24 in
 - Unidirectional

Heat Shrinkable Tape

- Heat Shrinkable Polyester Tape
 - Brand: Dunstone, Hi-Shrink Tape
 - Width: 1.000 in (or ¾ in can be used)
 - Thickness: 0.0018 in \approx 0.002 in
 - Length: 100 yds.
 - Shrink Percentage: 20% \pm 2%
 - Release Coating: PTFE
 - Starts to Shrink: 150°F
 - Usage Temperatures: 175° to 350°F
 - Melting Point: 484°F
 - Shelf Life: Unlimited at Room Temperature
- Purchased from Dunstone Company Inc. or McMaster-Carr

- Item Name: Hi-Shrink Tape Release Coated, 220R
- Item #: 220R0100001001C
- Price: Request Sample
- Website: <http://www.shrinktape.com/products/hi-shrink-tape/release-coated.aspx>

Manufacturing Process

The following describes the steps necessary to manufacture carbon fiber tubes out of unidirectional prepreg.

1. The first step is to design a layup that will ensure an adequately strong/stiff is the result of the manufacturing process. To a large extent this will come with experience and testing of your tube specimens, but to assist in the initial design classical lamination theory (CLT) and beam equations can be used. Attached in the digital copy of this report is a modified version of Professor Joseph D. Mello's CLT MATLAB code. The code has been altered to allow for the design of circular tubes and to give stiffness/deflection calculations based on a cantilever loading condition. The code is programed in a standard .m format and the use of comment lines assist in understanding how the program works. Start with a layup that puts fiber in the direction of possible stresses and apply your loading conditions to determine if your design is adequate. Several iterations will likely be necessary to optimize the design and currently these must be done manually.
2. After designing the ply sequence for the tube being made remove the appropriate amount of carbon fiber prepreg from the freezer and allow it to thaw (start the layup when the carbon becomes workable, like a fabric). The polypropylene mandrels will need to be prepped in order for the tubes to come off after curing. This can be done by taping Teflon release cloth (shown in Figure 1) around the mandrels, however it is recommended to use a spray-on chemical release agent (shown in Figure 2) as this is easier to work with and leaves a cleaner finish on the inside of the tubes.



Figure 1: Polypropylene mandrel about to be wrapped by Teflon release cloth.



Figure 2: Spray-on chemical release agent used to prep mandrels.

3. The composite material needs to be cut to the correct width (shown in Figure 3) to wrap the prepped mandrels, equal to the circumference of the mandrel or previous layer. The diameter should always be measured after each ply is put on the mandrel as this gives the best results in terms of carbon fiber fit. It is recommended to use a T-square and a sharp box cutter over a large cutting mat to get the straightest cuts along the length of the fiber. After they have been cut to the correct width, the backing on the carbon need to be pulled off slowly and parallel to the direction of the material's fibers (shown in Figure 4). Note that the fibers will want to separate from one another easily once the backing is removed, therefore special care should be taken when wrapping the fiber on the mandrel.



Figure 3: Cutting prepreg composite sheet to the correct width.



Figure 4: Peeling the backing off cut prepreg composite sheet.

4. The sized and peeled composite material needs to be carefully wrapped around the prepped mandrels (shown in Figure 5). It should be wrapped evenly and meet perfectly together around the mandrel for best results. As the composite material warms from room temperature and handling, it will become tackier and should stick together as it is wrapped. A heat gun (shown in Figure 6) can also be used to speed up this process if the composite material is not staying in place. Pay special attention to placement during wrapping as the material will tend to become adhered to the ply below it very easily as the temperature of the material increases and it is very difficult to remove it without damaging the layup.



Figure 5: Laying-up prepreg composite sheet around prepped mandrel.



Figure 6: A heat gun set to 250 degrees F or lower can be used to slightly warm composite material.

5. Repeat steps 2 and 3 until the desired thickness for the tube is reached. Note that for tube layups requiring non-longitudinal fibers (off-axis plies) the width and length required for the wrap will be different. These can therefore be calculated by the following formulas:

$$\text{Cut Width} = \text{wrap circumference} * \text{Cos}(\text{ply angle})$$

$$\text{Cut Length} = \frac{\text{Tube Length}}{\text{Cos}(\text{ply angle})}$$

Important: When wrapping off axis plies it helps to cut the ends of the carbon strip to be wrapped at the correct angle using a protractor. This allows the end wrap to meet nicely and sets the wrap angle for the rest of the tube. Both ends should be cut the same direction, being careful to take into account which way the fibers will lay when wrapped onto the mandrel (+ angle or – angle). Lay the tube on the table and slowly work the fiber around the mandrel, being careful to match the seam of the carbon up on each wrap without overlapping it. **It greatly helps to leave the paper backing on the prepreg when wrapping off-axis plies, only removing it after the ply is completely finished.**

6. After the tube has reached the desired thickness, it needs to be wrapped with heat shrinkable tape (shown in Figure 7). This tape provides the necessary pressure to ensure a high quality finished tube with strength and stiffness characteristics to meet design specifications. Identify the side of the tape that is release agent coated from the factory (typically the outside of the tape). Start by taping this down to the mandrel off the end of the tube using Scotch tape. Begin wrapping the tape (it is necessary to have at least two helpers for this part, to rotate the mandrel) by holding it taught and allowing the two or more assistants to rotate the mandrel. Make several wraps on top of themselves as the beginning and ends of the tube, trying to achieve 50% tape overlap along the rest of the tube (shown in Figure 8). For more detailed wrapping directions, refer to supplier instructions in Appendix D.



Figure 7: Tube being wrapped with heat shrinkable tape.



Figure 8: Wrapping tube body with 50% overlap.

7. The tubes are now ready to be cured. The tubes should be placed in the oven in a way to make sure they are straight and can get evenly heated (shown in Figure 8). They should be cured per manufacturer recommendations for the particular fiber/matrix being used.

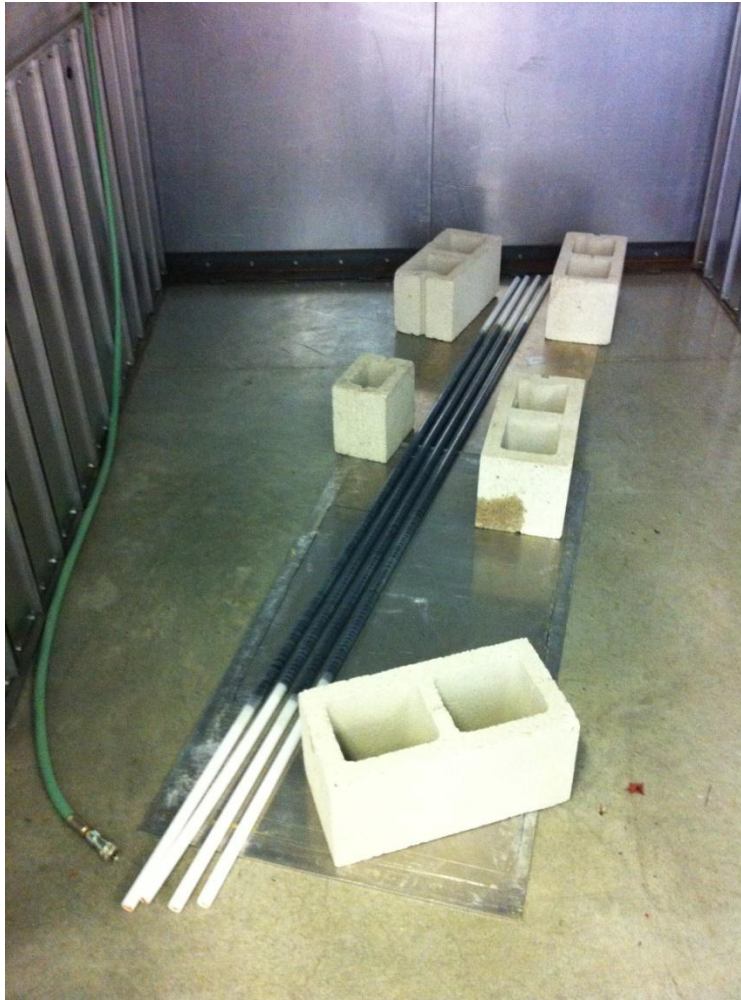


Figure 8: Finished tubes placed in the oven to be cured.

8. After the tubes have been cured, the heat shrinkable tape can be removed and the tubes can be slid off the mandrels. The ends of the tubes should be cut off using a diamond tile saw (available in the Mustang '60 machine shop) to create the best finish. A fine tooth band saw set to high speed works if a diamond saw is unavailable. The surface of the tubes can also be sanded down to create a mat finish and remove ridges left from the shrink tape. Wet sanding and/or use of a particulate mask is a necessary safety precaution for your health.



Figure 9: Finished tubes, un-sanded (left) and sanded (right).

Tubing Manufactured

April 11, 2011

Bake: 1 hour at 250°F

Length: 5ft-3in

Inside Diameter: 0.75in

Thickness of a layer: 0.006in

2 X [0_s]

2 X [0_s]

April 25, 2011

Bake: 1 hour at 250°F

Length: 5ft-3in

Inside Diameter: 0.75in

Thickness of a layer: 0.006in

1 X [$\pm 5^\circ/0^\circ$]

3 X [0_s]

Tube Testing

One of the uni-directional 5 ply carbon fiber tubes manufactured as part of this project, as well as two additional tubing layups, were tested by Human Powered Helicopter team member Sean Miller for comparison against theoretical CLT design figures obtained through the MATLAB code developed as part of this special research project. The tests were performed using the Instron machine located in the Composites and Structures laboratory on Cal Poly's campus. A special tubing fixture was modified for use on the project which can be seen in Figure 10 below. The results of the testing and more information on the tubing constructed can be found in his report, located in Appendix B of this document.

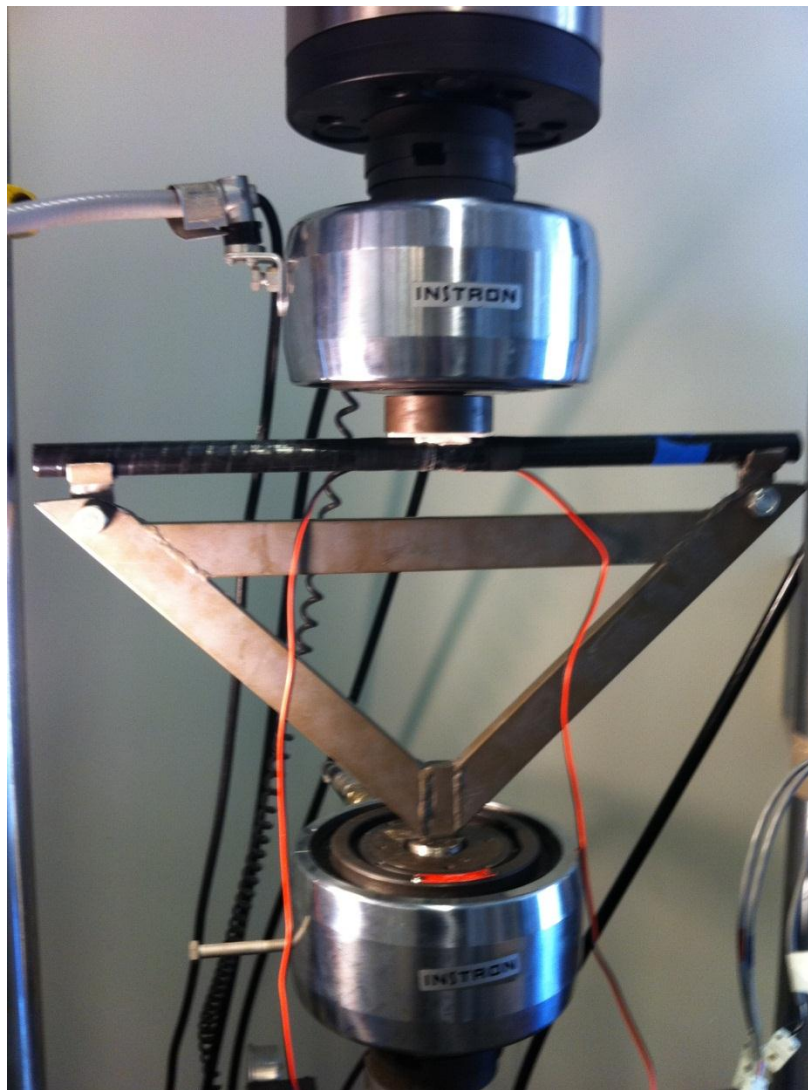


Figure 10: Three-point ultimate bending test of one of the carbon-fiber tubes created for this project.

Custom Curing Oven

A custom oven was designed and built in order to make 20-ft tubes for future HPH developments (shown in Figure 11). The oven was designed to allow curing of 250 °F and below carbon fiber tubing up to diameters of 5 inches. Its construction was based upon a design developed by Kirke Leonard, a Los Osos resident and carbon fiber enthusiast who has used a similar curing oven to create composite items for over 30 years.



Figure 11: Custom composite beam curing oven.

A complete list of oven building materials can be found below, but a basic description of its design is a 20ft long x 1.5ft wide x 1ft high wood frame lined with fiberglass insulation. Four passes of 1/16 diameter steel bailing wire line the top and bottom of the inside and are stapled in place. A variable output transformer (Variac) is used to adjust the voltage across the two ends of the wire which results in Joule's heating of the interior of the box. Initial testing of the oven shows that 85-90 volts across the wires allows for the inside of the oven to reach 225 °F in approximately 15 minutes. A lower ramp rate of about 5 °F/Min is desirable for the curing of typical carbon fiber products and therefore it may be necessary to adjust the voltage of the Variac throughout the curing cycle to achieve the proper ramp rates/ cure temperatures.

Oven Materials:

| Description | Quantity | Price (each) | Purchased at |
|----------------------------|-----------------|---------------------|----------------------|
| Silver Handles | 4 | \$3.67 | Home Depot |
| 3/32" Cable | 5 ft | \$0.30/ft | Home Depot |
| 3/32" Cable Ferrules | 2 sets | \$1.37 | Home Depot |
| 3-1/2 inch wood screws | 1 box | \$8.47 | Home Depot |
| Hinges | 4 | \$2.98 | Home Depot |
| Eyelets | 2 sets | \$1.18 | Home Depot |
| 9/16" Staples | 1 Box | \$2.97 | Home Depot |
| High Temp Tape | 1 Roll @ 50 Yds | \$9.99 | Miners Ace Hardware |
| 2x4-20ft | 2 | \$6.45 | Home Depot |
| 2x8-20ft | 2 | \$12.79 | Home Depot |
| 2x12-10ft | 4 | \$10.54 | Home Depot |
| Bailing Wire | 1 Roll | \$3.73 | Home Depot |
| R-19 Insulation w/ Backing | 48 Sq. ft Roll | \$19.78 | Home Depot |
| 130V-10amp Variac | 1 | \$155.00 | All Electronics Inc. |
| TOTAL | \$313.78 | | |

Oven Operation:

Note that when the oven is running someone should ALWAYS be present. Although the temperatures involved in curing the type of composites the oven was designed for are quite low (under 275 °F) there is always a risk of fire or electrical hazards.

The oven uses relatively high voltage (70-130 VAC) and therefore precautions should be taking to avoid the risk of shock. The wires contain high voltage and reach VERY high temperature quickly, DO NOT ATTEMPT TO TOUCH THEM WHILE THE OVEN IS RUNNING!

The operation of the oven begins by determining the size of the tube that is going to be cured. The oven will fit tubes up to approximately 5 inches in outside diameter. Once the tubing diameter is established, a way to support the tube must be determined. Currently, this team is working on developing supports that will allow for complete curing of the tubes while maintaining a large amount of adjustability for different sizes. For the time being, any support method consisting of elevated temperature supports (even wood works well) that are NON-

ELECTRICALLY CONDUCTING (bridging the wires in the oven will result in shorting of the oven wires and damage to the oven). A metallic support can be used, provided that it does not touch the heating wires in any place along the length of the oven.

Turn the Variac voltage knob to 0 volts before plugging it in. This is very important, as starting at elevated voltage will cause the fuse in the Variac to blow and replacements are NOT easily sourced locally. Make sure none of the heating wires inside or out of the oven are contacting/bridged by electrically conductive material.

Once all safety precautions have been taken, the Variac may be turned on. Slowly advance the knob on the top of the Variac to a medium starting voltage (35-50 volts). Allow the oven wires to warm for several minutes at this voltage before adjusting to higher voltages, verifying that the needle on the voltage display reads a voltage (if it does not then the 5 x 20 mm 10 amp fuse in the Variac needs to be replaced) . This ensures that the amperage of the oven stays below 10 amps due to the fact that as the bailing wire warms, its electrical resistance increases.

Monitor the oven throughout the cure and periodically check the temperature/voltage of the Variac to ensure that everything is still functioning properly.

Always keep a detailed log of the cure cycle that you used for each tube and include as much information as possible (times, temperatures, fixtures, tube diameters, etc.). This ensures that if a tube is produced with less than satisfactory strength/stiffness properties a design log exists to identify abnormalities in the cure cycle.

Conclusion

This project was a successful stepping stone to building full length carbon fiber tubing for Cal Poly's Human Powered Helicopter team and other Cal Poly projects. Continuing the ground work laid by last quarter's independent research team, this project has made advances in creating longer carbon fiber tubing, more quickly and more efficiently. Additionally, this project has developed tools that will aid in the design of carbon fiber lay-ups for carbon tubing and help to predict failure loads, strength and stiffness of the finished products. Finally, through the manufacturing of a 20ft long curing oven future Cal Poly students will have the opportunity to create extended length composite beams for various projects. This team hopes that through the creation of thorough manufacturing and design documents to record special projects such as this one, Cal Poly students will be able to continue our long tradition of learning by doing.