Independent Research: Composite Spar Manufacturing

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Overview

The goal of my research for Winter Quarter 2011 was developing a manufacturing process for composite spar manufacturing. The spars will be used in construction of rotor blades by the Cal Poly Human Powered Helicopter team. The research was performed with help from Eric Behne from the Cal Poly Human Powered Helicopter senior project team.

The composite spars have several requirements provided from the HPH team and their advisor, Kurt Colvin. The spars must have a 1 inch ID and eventually be manufacturable at lengths up to 25 feet. For this quarter's research, the goal was to manufacture a tube with a 1 inch ID and a length of at least 3 feet. After manufacturing a tube with these requirements we should be able to predict whether or not a 25 foot spar is possible, and provide direction for further research and testing. The thickness and strength/stiffness requirements have not yet been determined by the HPH team.

We successfully manufactured a 3 foot composite spar with a wall thickness of 0.060". For most of the composite tubes produced, the thickness varied from 0.035" to 0.090" depending on the carbon fiber ply layup and type of plies used.

I feel we have developed a manufacturing process that can be scaled to composite spars with lengths up to 25 feet. In the following pages I will detail the processes used including methods which were successful and methods which were unsuccessful.

Results

We found through testing using a mandrel and wrapping it in pre-impregnated material gave us the product we were looking for.

Manufacturing the carbon fiber spars with a mandrel is often used in industry for round tubes. This method uses a round material to form the carbon fiber's shape (acting as a sort of mold) which then the carbon fiber is cured on. The carbon fiber is typically cured at 250-350°F for 60-180 minutes (depending on the pre-preg being used) so the material must be able to withstand this temperature. The mandrel must then be removed from inside the carbon, leaving only the thin, lightweight carbon tube.

Within the different mandrels we tested, the teflon and polypropylene mandrels gave the best results. The material of the mandrel mainly affects how easy it is to remove the mandrel from inside the carbon fiber. They have a higher coefficient of thermal expansion than the steel mandrel (and the carbon fiber being cured) so the carbon fiber is easy to slide off the mandrel. With the steel mandrels I had to use a hydraulic press to remove the mandrel from inside the cured carbon fiber. This often resulted in damage in different ways (see figures at the end of report).

Manufacturing Options

When brainstorming we started simple at first, and looked at the idea of using a mandrel to form the carbon fiber around.

In industry the mandrels are often a centerless ground steel bar with a slight taper (a few thousandths per foot) to help release the carbon from the mandrel. We did order several 6 foot steel bars with a 1 inch OD, but did not yet have a chance to have them centerless ground and tapered.

Sometimes a silicone mandrel is used, and the entire assembly is placed inside a highly reinforced female mold. The silicone expands so much when heated it will exert several thousand psi against the carbon fiber pressing it out against the female mold, shaping it. This method requires a strong female mold, which is expensive for early prototypes so we decided to not use this method.

We decided to order mandrels with a 1 inch OD from several materials. These included steel, polypropylene, PVC and teflon. Teflon has the highest thermal coefficient of expansion, then polypropylene, PVC, and finally steel.

We found PVC does not have a high enough melting point for the carbon fiber curing process.

Manufacturing Process

The manufacturing process begins by preparing the mandrel. If there are any defects in the surface the carbon will form around or into them and make it harder to remove after the carbon is cured.

Then wrap the mandrel in teflon release cloth. (A wipe on release agent can also be used but the teflon release cloth was available to us in the composites lab)

The layout of the unidirectional carbon plies must be determined before beginning. I will detail the build for a 0,0,15,-15,0,0 layup. The carbon fiber needs to be cut in sheets that are as wide as the circumference of the mandrel. This will allow the sheet to wrap around and form a tight seam. So for the first layer (0° fiber direction) the fibers will run the length of the mandrel. The first sheet of pre-preg to cut will be a rectangle with a length equal to the length of the spar being produced and a width equal to the mandrel circumference.

The second layer will be the same as the first layer, but be sure to increase the diameter used by 2x the thickness of the pre-preg material.

The third layer is the first biased ply. This layer will be unidirectional fibers at a 15° offset. The end of the fibers will be cut at a 15° angle. The width of these fibers are circumference * cos(15°). The length is the length * cos(15°). Then line up the end on

the mandrel and wrap the fibers in a spiral around the mandrel. The seam will be a spiral down the length of the mandrel. After trying it once and visualizing it, it is much easier.

The fourth layer is the same as the third except the direction of the wrap is the opposite.

The fifth and sixth layers are the same as the first two layers, fibers are run along the length of the mandrel.

Apply shrink tape to the outside of the mandrel. Be sure to wrap it as tight as possible. Also, take note of the release coated side of the tape. If the tape is wrapped with the release coating out (and not against the pre-preg) it will be nearly impossible to remove.

A few notes we developed while making several prototypes:
- Using a heat gun on each layer of fibers as it is applied helps stick them together and hold all of the layers on the mandrel.
- When applying the next layer, be sure to offset the seam so they don't all stack up and create a weaker point in the spar.
- When wrapping the release cloth try to only tape the cloth in a few places to hold it on the mandrel because it will adhere to the carbon and make it harder to remove after the carbon is cured.
- The pre-preg material has a larger coefficient of thermal expansion in the matrix direction than steel (around the circumference of the mandrel). This means with any unidirectional material it will be tough to remove from a steel mandrel.
- The fiber direction of the material has a negative thermal coefficient of expansion so the 0-90 plies are easy to remove from the steel mandrel as it expands when cooled since fibers are running the circumference of the mandrel and are stronger than the matrix that is trying to shrink.

Next Steps

I think the next steps should be building longer carbon fiber spars. The spars also need to be constructed with less plies to reduce the weight. (We successfully built a three foot spar that weighed under 8 ounces, but it is not light enough for the HPH.)

There are several mandrels available for longer spars, including 6 foot steel bars and 6 foot polypropylene bars that were ordered from McMaster.

I think the steel bars should be centerless ground and tapered and tested with the unidirectional material.

Cantilever beam testing of the spars is also required to get an idea of their stiffness. Once the HPH team develops requirements, the layup required can be built and tested.

Figures for Reference:

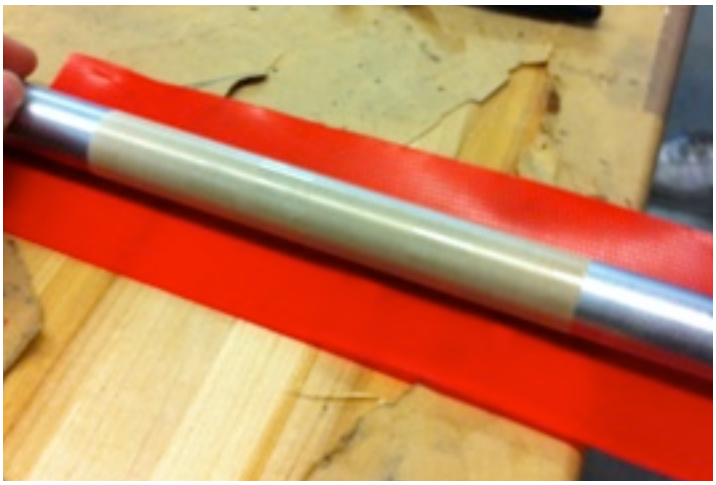

Figure 1: Wrapping the mandrel with teflon release cloth.

Figure 2: Cutting layers from the pre-preg roll.

Figure 3: A closeup showing 0-90 pre-preg sheet. The 0-90 was only used for prototype tests due to the availability of the material. Unidirectional material was later used.

Figure 4: A steel mandrel with 4 layers of 0-90 pre-preg. It is ready for the shrink tape to be applied.

Figure 5: A steel mandrel showing the unidirectional layers ready for the shrink tape to be applied.

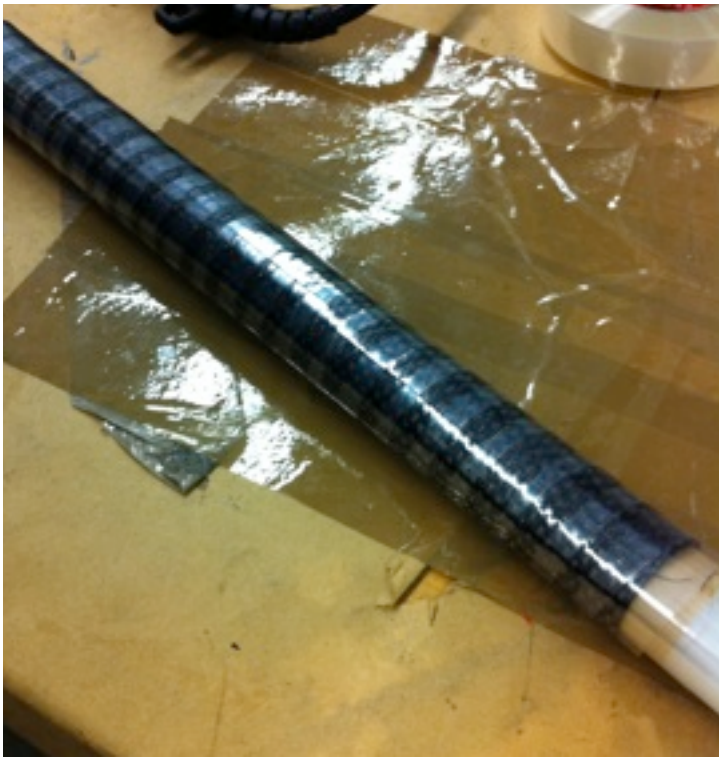

Figure 6: The 0-90 pre-preg with shrink tape applied.

Figure 7: Two steel mandrels, a PVC mandrel and Polypropylene mandrels ready to be cured. The Polypropylene mandrel was easiest to remove from the carbon. The PVC mandrel did not handle the required heat well.

Figure 8a: A three foot unidirectional spar with 0,0,15,-15,0,0 layup after being removed from the polypropylene mandrel. I was able to pull it off the mandrel by hand. It weighed less than 8 ounces.

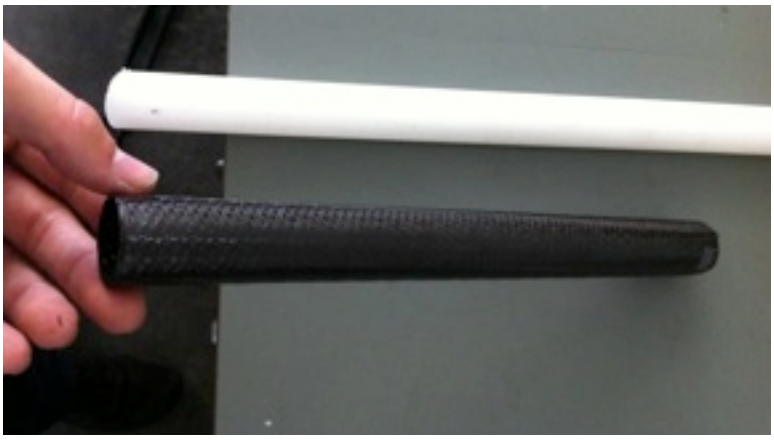

Figure 8b: A one foot 0-90 pre-preg spar after being removed from the mandrel.

Figure 9: A hydraulic press being used to remove the mandrel from a unidirectional pre-preg spar. I used a sleeve that was a net fit to the mandrel to shoulder against the carbon. The press is pushing the mandrel out the bottom.

Figure 10: On one spar the teflon release cloth was adhered to the carbon by tape used to hold the cloth initially. The release cloth bunched up rather than coming out with the mandrel. Once it started to grow in thickness it split the end of the carbon tube and ruined the spar.