Part 2 of The Jarvis Illustrated Guide to Carbon Fiber

Jim Jarvis adds a chapter to his method of building carbon fiber rockets.

Tech Tips Series by Jim Jarvis
WEDNESDAY, MAY 25, 2011

In December 2008, I documented the construction of a three-inch carbon fiber rocket in my *"TooCarbYen Tutorial"*. The documentation was converted into an article called *The Jarvis Illustrated Guide to Carbon Fiber Construction* and posted to Rocketry Planet in October 2009. In the time since the article was written, I have learned more about the strength of the rockets I've built.

Unfortunately, I've found (and exceeded) the limit of that strength on several occasions. The data suggest that for 3- and 4-inch rockets, the process summarized in the article will keep a rocket together up to about Mach 2.5. For more prolonged high-speed flight, such as the sustainer of a two-stage rocket, the limit might be a little lower. Since I want to fly faster than that, or at least to have more of a safety factor, I have experimented with several techniques that I hope will improve the strength and durability of my designs.

The project documented in The Jarvis Illustrated Guide to Carbon Fiber Construction, Part 2 is a 4-inch minimum-diameter two-stager that the author hopes to fly at BALLS 20.

I'm very happy with the outcome, so I've decided to do a companion article (let's call it Part 2), to document these procedures.

As before, Part 2 isn't about how you should build rockets, it's just about how I do it (now), with enough detail to fully document the process. If you're planning to challenge the "speed of carbon", feel free to incorporate these ideas into your own designs. Some of the techniques discussed in Part 2 are "advanced" in the sense that they require more building skill, equipment or time. In other cases, though, I've just come up with a better approach than what I included in Part 1.

The project documented in Part 2 is a 4-inch minimum-diameter two-stager that I hope to fly it at BALLS 20. The design is similar to my project at BALLS 19, except that in that flight, the sustainer came apart shortly after motor burnout. The rocket was at 30,000 feet and slowing through Mach 2.3 after over 20 seconds of flight. Nuts!

As usual at BALLS, Tony Alcocer brought back the pieces (from about 5 miles out this time). What I got back was a fin can with no fins and an upper airframe that was torn apart in at least three places. So, did the fins fail first or did the airframe? Or did the fins delaminate due to heating and then pull off the airframe? Unfortunately, I don't know. Consequently, I have taken the approach of trying to make incremental improvements in a number of areas. I haven't documented the entire build though. Instead, Part 2 includes just the things that I did differently or that I think are improvements over the techniques included in Part 1.

Here are the topics addressed in this article:

- Rolling stronger carbon fiber airframes;
- Laminating and attaching fins;
- Making an improved fin fillet;
- Vacuum bagging the tip-to-tip carbon; and

- Applying heat-resistant leading edges to fins.

Chapter 1 - Rolling Stronger Carbon Fiber Airframes

In Part 1, I presented a method for producing carbon fiber tubes. For 3- and 4-inch rockets, the procedure included five wraps of 5.7 ounce carbon fiber fabric with no compression applied during the lay-up. Unfortunately, when producing multiple-wrap tubes, it is difficult to apply compression because the cloth just tends to wrinkle. Peel-ply helps a little by minimizing the amount of epoxy on top of the carbon that is needed to provide a smooth surface for finishing, and I think it may also suck a little of the epoxy out of the lay-up. My experience is that five-wrap tubes containing between 50% to 55% epoxy can be produced by this method.

For the new build, I wanted to increase the number of carbon layers and to also incorporate some unidirectional carbon into the layup. Therefore, removing excess epoxy was even more important than normal to both reduce excess weight and to get the strength benefits of the extra carbon. Since compression in the form of vacuum bagging or heat-shrink tape could not be used, I decided to roll the tubes under tension. I did this by hanging a weight on the end of the carbon pieces as I rolled each tube.

I made two types of tubes for this build. First, I made carbon coupler tubes using a CTI 98mm motor case as the mandrel. These were six-wrap tubes made with 5.7 ounce 2x2 twill. I know from previous experience that these will fit inside my air frames without too much sanding. Second, I made nine-wrap airframe tubes produced from three wraps of 2x2 twill, three wraps of unidirectional material and then three more wraps of the 2x2 twill. Using tension, I was able to reduce the amount of epoxy to just under 50% (giving as much as a 10% reduction in the amount of epoxy in the tube). In addition, the tubes did not have the mushy feel that I have noted when rolling tubes without tension. I think the improvements were significant enough such that I will always do it this way in the future.

Before I get into the construction details on these tubes, I made one other change to my general building procedure. Specifically, I tried to do a better job of mixing my epoxy, particularly the large batches used for rolling the tubes. Instead of mixing by hand, I made a little stirring device and then used it with my drill press. I am sure that this resulted in better mixing of the epoxy compared to mixing by hand, particularly for batches above 100 grams.

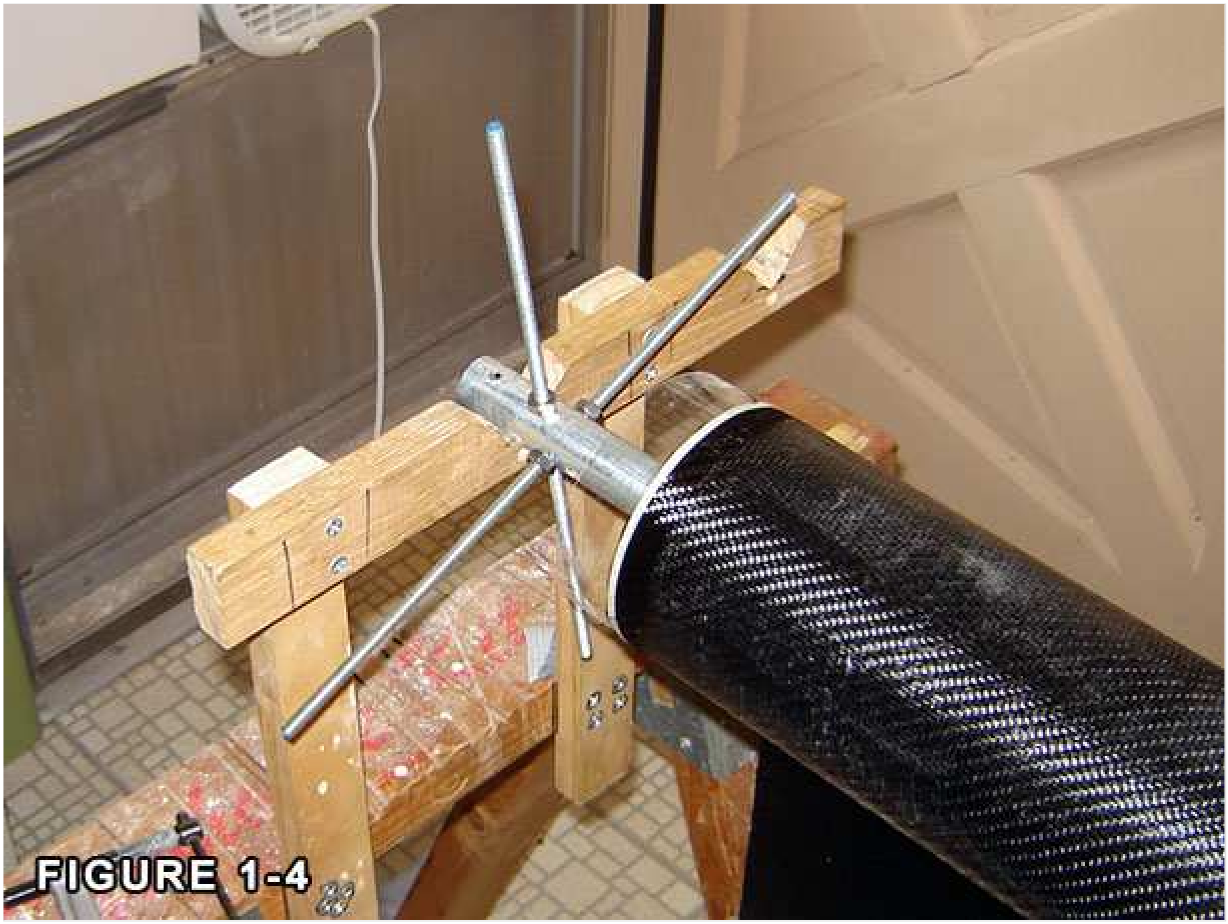
FIGURE 1-1

FIGURE 1-2

Figures 1-1 and 1-2 show the set-up I used for making the coupler tubing. For this six-wrap tube, I hung a 75-3500 motor case from the end of the carbon fabric to provide tension. I taped both sides of the cloth to the case and the result was actually pretty strong. Obviously, I had to devise a method for keeping the weight off the ground during the initial wraps. Once the weight got to within a few inches of the mandrel, I cut off the weight and then finished the layup.

FIGURE 1-3

For the airframe tubing, I used three separate pieces of cloth, and each piece was long enough to provide three wraps. As shown in Figure 1-3, I used a 98-17,500 motor case for the weight. As it turned out, the cloth pieces were just long enough to let me get started rolling the tube before the weight was pulled off the ground. I did not have any problems with the cloth slipping off the tubing once I got the wrap started.



A 98mm motor case is actually a fair amount of weight, and it was somewhat difficult to turn the mandrel while rolling the tube. As shown in Figure 1-4, I devised some handles to make turning the mandrel easier. I think I could have used even more weight and not had mechanical problems with the setup. However, the amount of weight I used seemed to provide a significant benefit. I don't think I would have been very happy with the outcome on these nine-wrap tubes without the modified procedure.

Before I leave the subject of tube making, let me pass along a better technique for getting the ends of the tubes square. In Part 1, I wrote about a method of rotating the tube on end and then measuring the "wobble" at the top of the tube. By lining up the edge of the tube with both an intermediate target and a mark on the wall, it is possible to quantify the amount of wobble with very good accuracy. The only problem with the method is that it is hard on the eyes and takes a lot of patience. The improved method uses a laser. It is more accurate and quantitative, and it is much easier to do.

FIGURE 1-5

Figure 1-5 shows a V-shaped support that the bottom of the tube fits into. The "V" keeps the tube in a fixed position as the tube is rotated (I check eight positions each time I measure a tube).

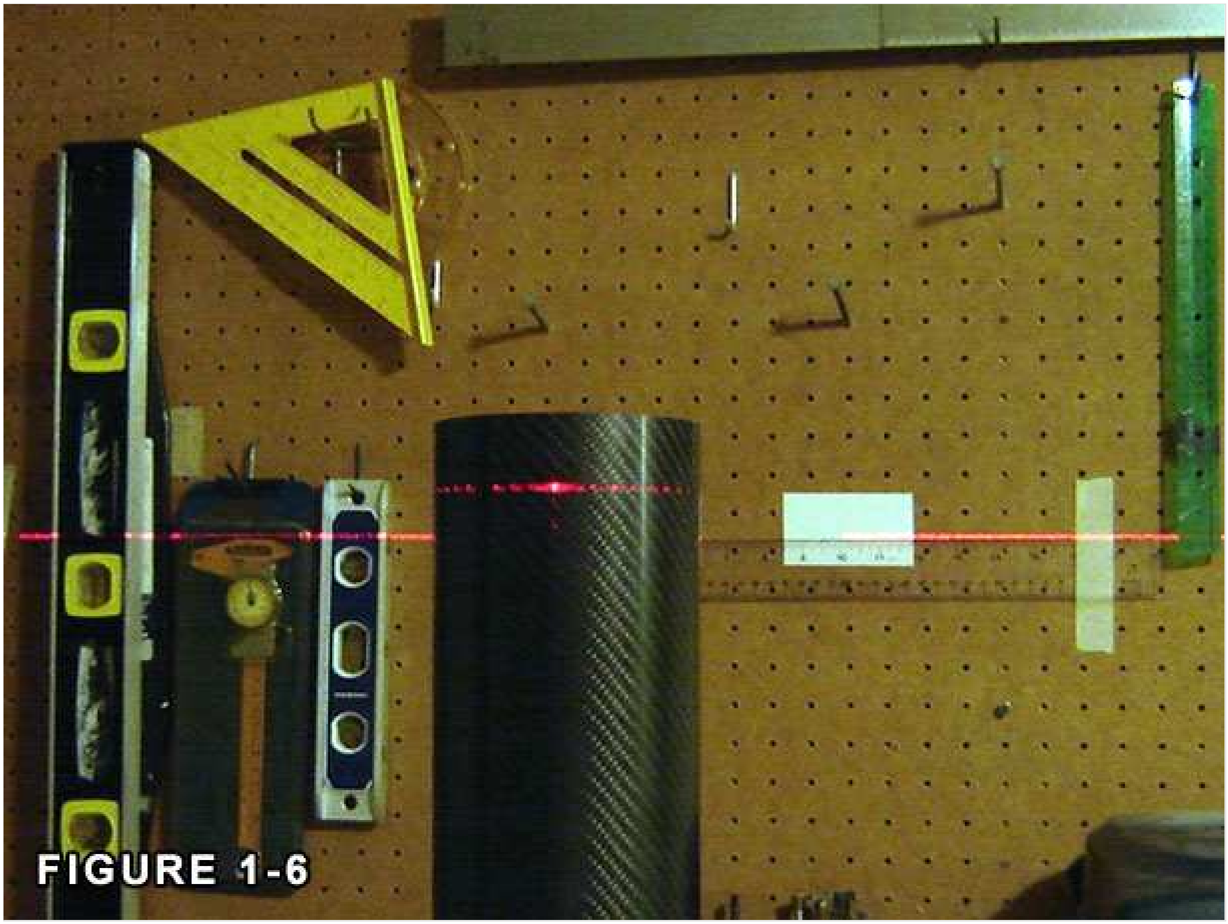


Figure 1-6 shows the use of the laser to quantify the amount of wobble in the top of the tube as the tube is rotated through each position. For the laser level I was using, the optimum distances were about five feet between the laser and the tube and about 10 feet between the tube and the scale on the wall.

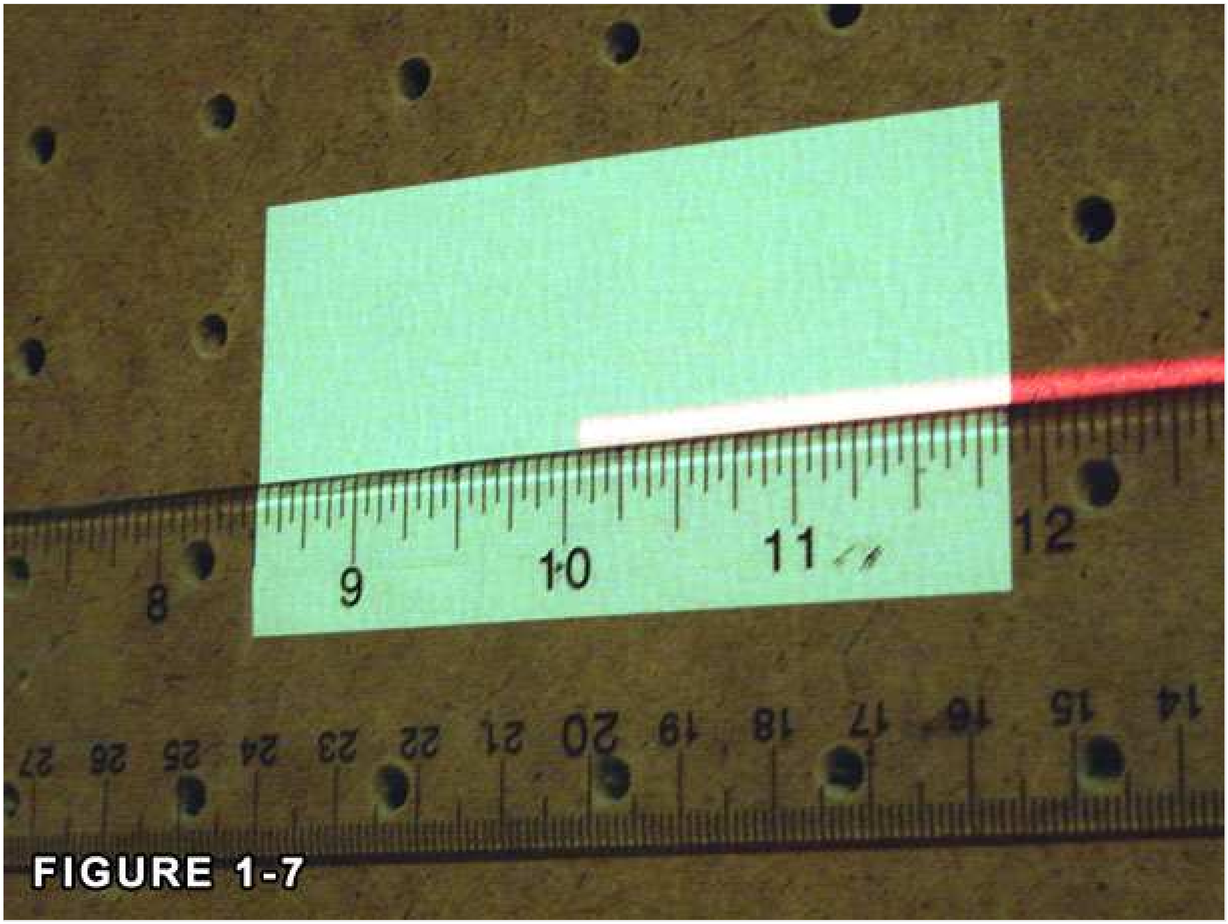


FIGURE 1-7

Figure 1-7 shows a close-up of the measuring scale. If the tube is not square, the laser line will move back and forth as you rotate the tube. Once the high side of the tube is located, you simply sand it down a little. This will make the tube a little more square; however, the bottom of the tube might not be flat. To fix this, the tube should be rotated on flat surface covered with sandpaper. The above process can be repeated several times until the laser indicator stops moving. I record the data for each pass to monitor my progress towards "square." It usually takes me three or four iterations if the tube isn't too bad to start with.

It's possible to get really accurate results with a little care. For example, it's not too hard to get all of the laser measurements to within a span of about 0.5 mm (0.02 inches). The 5/10 positioning provides a multiplier of two (the tube actually wobbles half as much as the laser indicator). On a 4" tube that is 48" long, you get an additional multiplier of 12 (the tube wobbles 12 times further than the error in the flatness of the tube). Therefore, for this example, the tube would be square to within 0.02 ÷ 2 ÷ 12 = 0.0008 inches (or better than a thousandth of an inch). I spent a couple evenings squaring up the tubes on every rocket I own.

Chapter 2 - Laminating and Attaching the Fins

My normal procedure for fins on 3- and 4-inch rockets is to start with 1/8" G10 and laminate it with typically five layers of carbon fiber fabric on each side. I remove excess epoxy by clamping the fins between a pair of hard surfaces such as ceramic tiles. However, it is very difficult to apply uniform pressure using C-clamps, and I have noted differences in the thickness of the fins from one point to another. As I said in Part 1, there is room to improve this procedure.

For the current project, I decided to try my hand at vacuum bagging. I didn't do anything out of the ordinary with respect to the bagging process, but since this was my first experience with it, I had a few things to learn. I laminated and then bagged two fins at a time, and each fin was covered on both sides with five layers of carbon. Overall, I made six fins for the new two-stager.

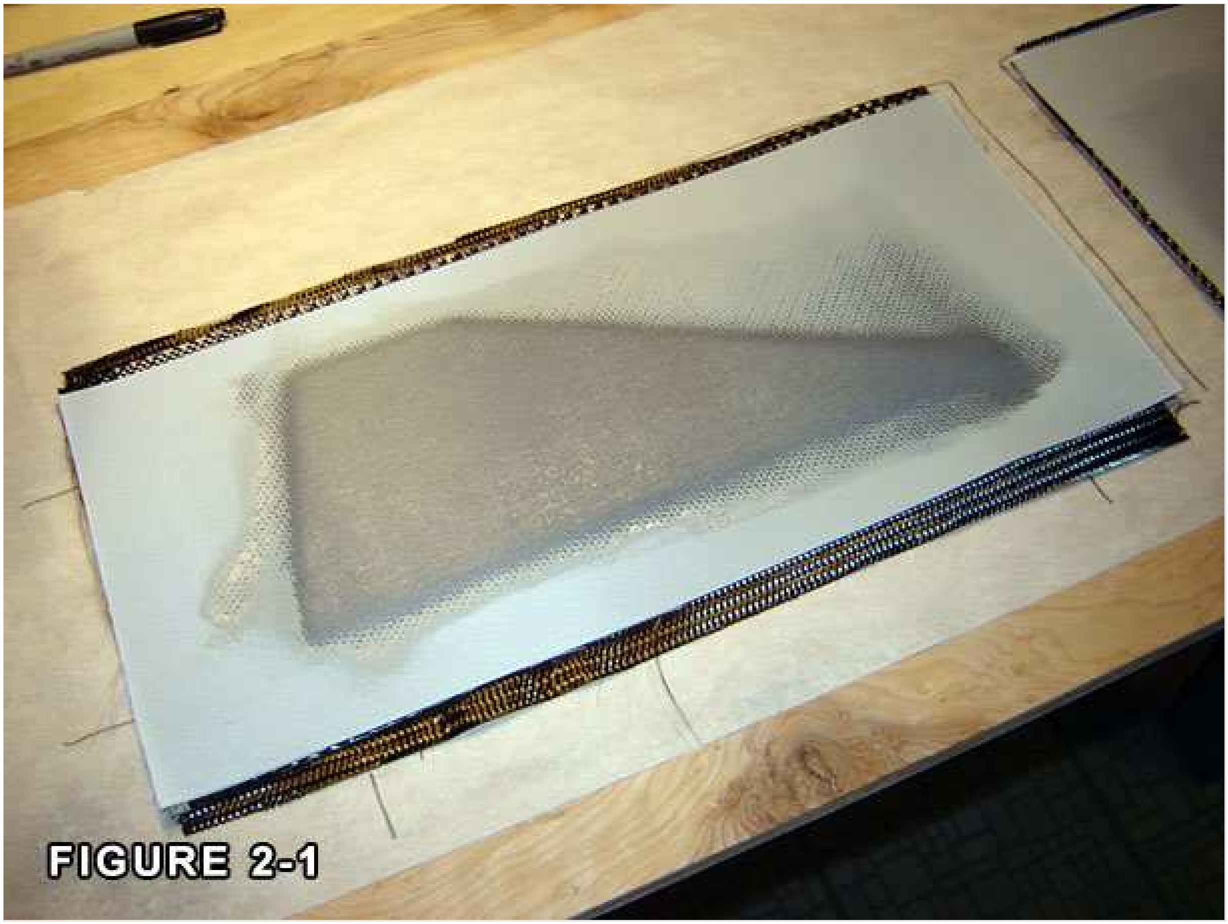


Figure 2-1 shows the start of the process. Here, I've covered one side of the fin with five layers of carbon fiber fabric and a layer of peel-ply (on these fins, the second and fourth layers of carbon were turned at a 45-degree angle relative to the other layers).

FIGURE 2-2

FIGURE 2-3

The peel-ply is covered with a perforated release layer (Figure 2-2) followed by three layers of breather material (Figure 2-3). I set up the fins on a piece of plywood so that I could flip them over to do the other side.

Figure 2-4 shows the bagging material taped to this board (with the other half of the bagging material tucked under the board).

FIGURE 2-5

FIGURE 2-6

Then, I just covered everything with a second board (Figure 2-5) and flipped everything over to expose the other side of the fins (Figure 2-6).

FIGURE 2-7

FIGURE 2-8

After completing the lay-up on the second side, I added a vacuum bag connector (Figure 2-7) and then applied sticky tape around three sides of the bag (Figure 2-8). I definitely prefer the softer sealing tape and also the high-elongation (stretchy) vacuum bag material.

I also found that putting lines on the bag material, as shown in Figure 2-9, made it easier to apply the sealant tape to the lower bag material and then seal the bag using the upper bag material (it's easy to get out-of-square when applying this tape, and once it's applied, it doesn't come off).

FIGURE 2-10

FIGURE 2-11

I sized the plywood boards that support the lay-up so that I could put the assembly in my oven to cure (Figure 2-10). After the vacuum is applied, the epoxy is pushed out of the lay-up and into the breather material (Figure 2-11). The final appearance of the laminated fin is shown in Figure 2-12.

I did all six of my fins using the method outlined above. There are a number of variations on the theme, and I'll give them a try over time. One modification that might make sense with thinner fin stock is to laminate only one side at a time and pull the lay-up down on a flat surface. This might help to ensure that no warp is introduced into the fins. Another modification might be to apply the breather directly over the peel-ply (i.e., omit the perforated release material). I didn't try this because I was worried about pulling too much epoxy out of the lay-up, and the perforated material seemed to do a pretty good job.

I got my vacuum pump at Harbor Freight. At least the price was right (about $150 with a 20%-off coupon). This is one product that definitely rates the extended warranty. I wasn't sure how much bagging I was actually going to do when I got it, but if you plan to do a lot of this, get a better pump.

With respect to attaching the fins, I would like to suggest an improvement to the method presented in Part 1. In Part 1, I used a piece of angle iron to scribe lines on the body tube (sort of borrowing the Estes "door jam" method).

FIGURE 2-13

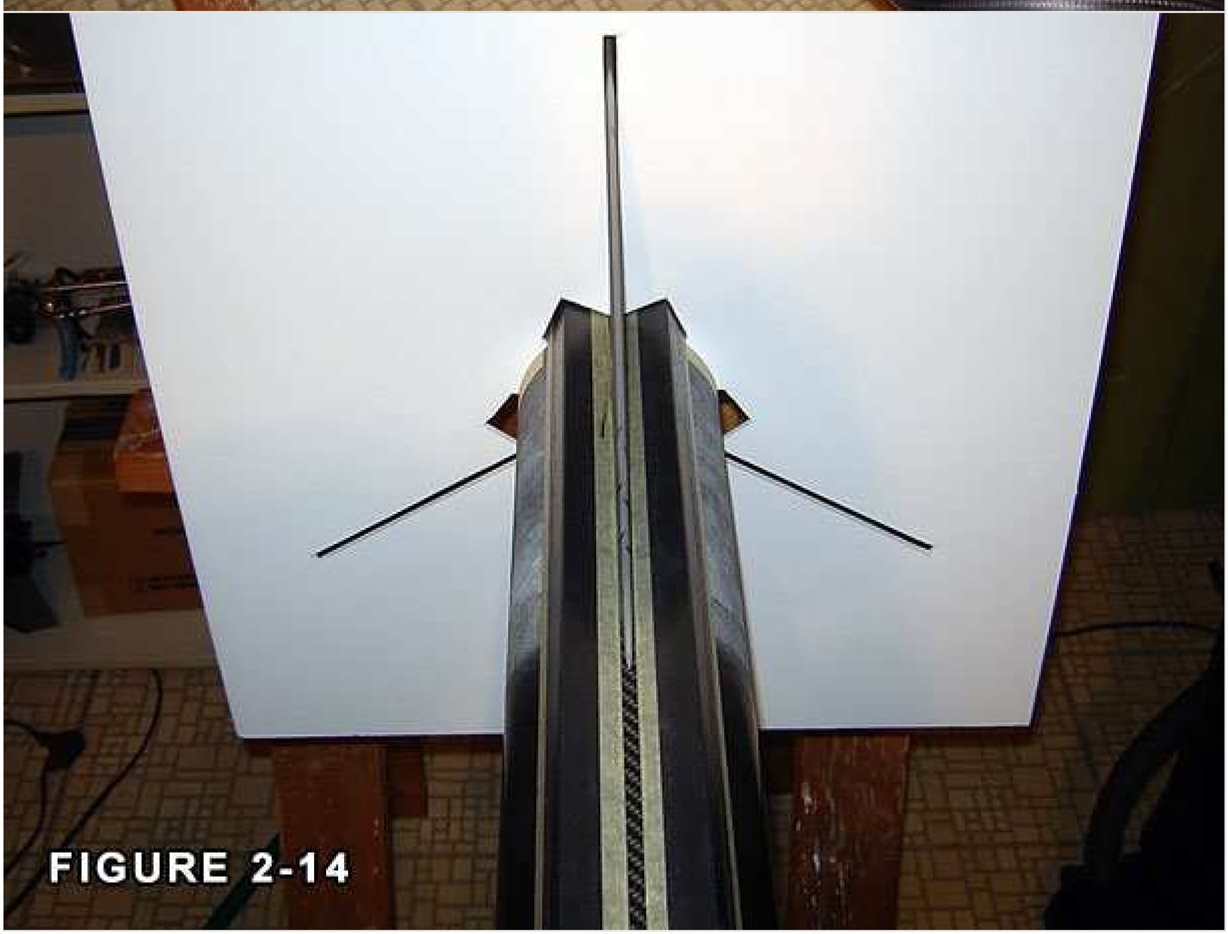


FIGURE 2-14

An even better approach is to use two pieces of angle iron as shown in Figures 2-13 and 2-14. Assuming the angle iron pieces are straight (check them!), it is almost impossible not to get the fins on straight. Note that in the Figures, I have made cutouts in my template to allow the angle iron pieces to pass through (so that the entire fin root can be clamped between the angle iron). I did that on all three fin slits. However, I think it would be better to make those cutouts on one fin slit only and then just move the template around for the second and third fins. The method shown in the Figures removes too much of the "circle" holding the template to the airframe.

Chapter 3 - Making an Improved Fin Fillet

In Part 1, I presented a method of making fin fillets using both Duralco 4525 (Cotronics) high-temperature epoxy and Aeropoxy Light epoxy filler. First, I made a moderate-size Cotronics fillet. Then, I applied the Aeropoxy Light filler over the top of the Cotronics to form a large-radius fillet. Finally, the tip-to-tip carbon was placed over the top of the Aeropoxy Light fillet.

The method presented in Part 1 has two drawbacks. First, the Aeropoxy Light material isn't as strong as a structural epoxy. Therefore, the bond of the fin to the body tube will not be as strong as it could be. Second, the strength of the joint will depend on a mechanical bond between the Aeropoxy Light and the Cotronics, and then between the Aeropoxy Light and the tip-to-tip carbon. As a result of these drawbacks, I have modified my procedure such that most of the fillet is composed of the Cotronics epoxy (I still use Aeropoxy Light at the front and back of the fin roots so that I can sand in an aerodynamic transition to the airframe). In addition, the surface of the Cotronics epoxy is produced using peel-ply to maximize the strength of the bond when the tip-to-tip carbon is applied.

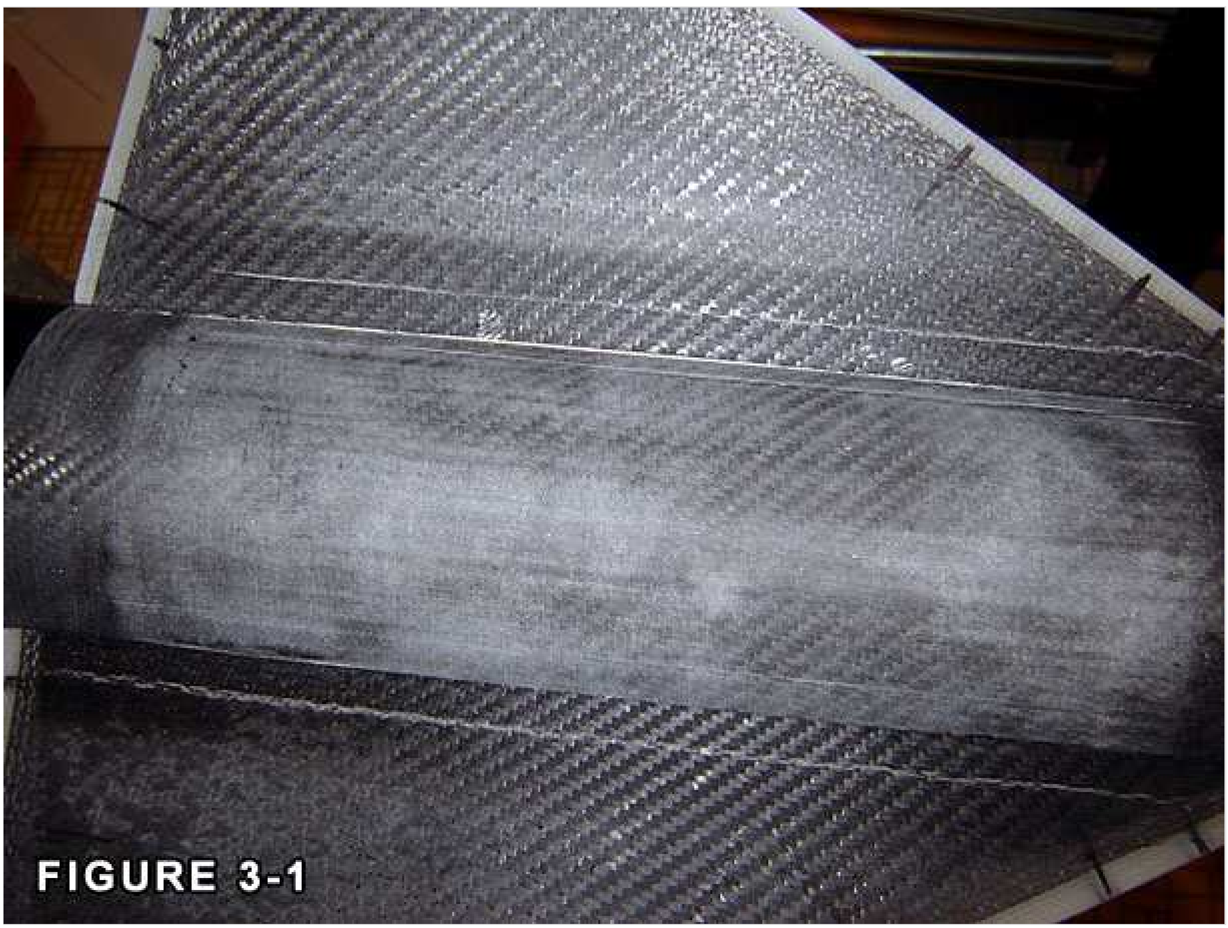


FIGURE 3-1

The fillets for this 4" rocket were formed using a 1-1/4" dowel. As in the method presented in Part 1, the first step is to use the dowel to score lines on the airframe (Figure 3-1). Then, tape is applied just outside of these lines to help remove excess epoxy.

Since I plan to use Aeropoxy Light at the front and back of the fillet, I have applied some tape at the locations where I want the Cotronics portion of the fillet to end (Figure 3-2).

FIGURE 3-3

FIGURE 3-4

The next step is to prepare the dowel that will be used to form the fillet. As shown in Figure 3-3, I have covered the 1-1/4" dowel with a layer of parchment paper followed by a layer of peel-ply. These layers need to cover at least half of the circumference of the dowel. Then, the peel-ply is wetted out with unmodified Cotronics epoxy (i.e., epoxy without any additives) as shown in Figure 3-4. I do this to ensure that the surface of the fillet will retain the full peel-ply texture. Just pressing the peel-ply into thickened epoxy will not give the desired finish.

After painting the dowels, I thicken the epoxy with both milled fiberglass (15% to 20% by weight) and then add enough fumed silica to the mixture so that the epoxy won't run (it doesn't take much silica to do this, but you want the fillet to retain its shape and not run out from underneath the dowel).


FIGURE 3-5

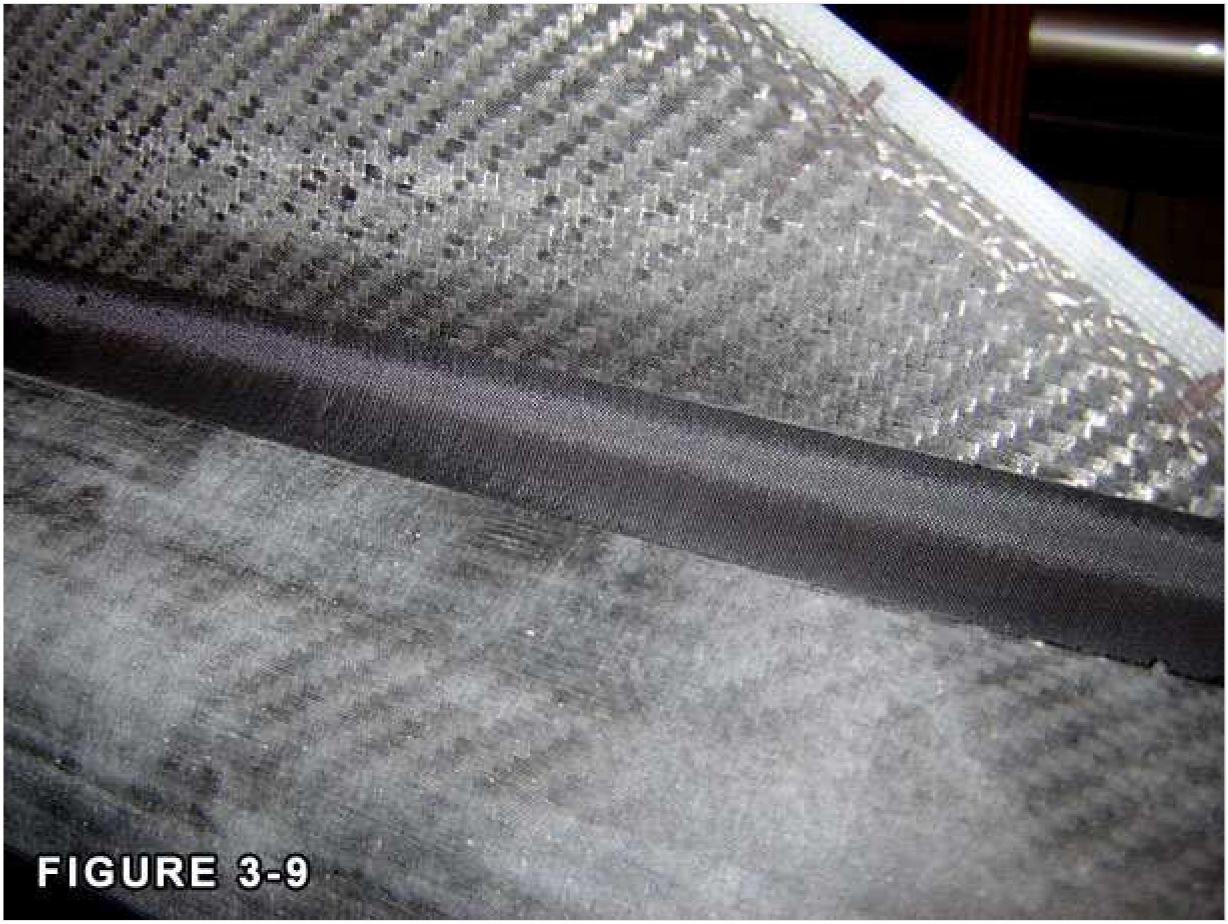
Once the epoxy is at the right consistency, it can be applied to the airframe (see Figure 3-5). I like to work the epoxy into the joint to make sure that the surfaces are fully wetted. Then, I use a dowel to both smooth out the epoxy a little and remove most of the excess. The idea is to leave a little excess epoxy, but not too much. Once these steps are complete, the tape at the front and back of the fillet can then be removed (these last few steps are illustrated in the upper fillet in Figure 3-5).

Finally, the fillet itself is formed by pressing the "painted" dowel into the epoxy at the joint (see Figure 3-6). It doesn't take much pressure to push out the excess epoxy, but you want the dowel to be in contact with both the body tube and then fin so that the fillet will be properly formed.

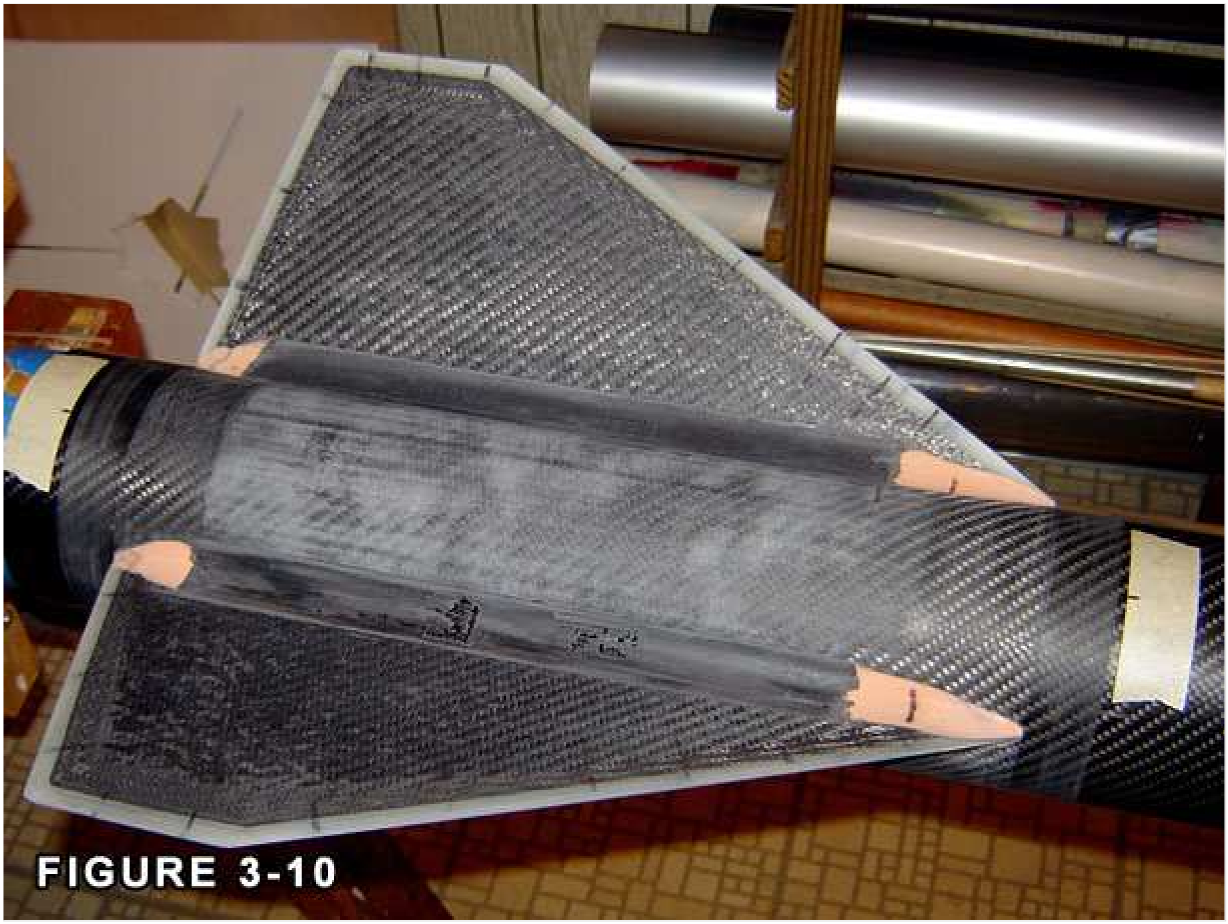

FIGURE 3-7


FIGURE 3-8

The Cotronics epoxy will set up at ambient temperature, or you can use an oven to speed things up. I use an oven, but however you do it, the part should be removed and disassembled as soon as the epoxy is no longer tacky (see Figures 3-7 and 3-8). The reason for this is that it is easier to remove the blue tape while the epoxy is still soft. In addition, some of the excess epoxy will creep into the areas at the front and back of the fillet. If the epoxy is soft, it can be cut out with a knife.



The final appearance of the Cotronics fillet is shown in Figure 3-9. That peel-ply texture is what I was looking to achieve.



To complete the fillets, I add small fillets of Cotronics up to the leading and trailing edges of the fin and then cover this with an aerodynamic fillet formed from Aeropoxy Light or Super Fil. This part of the process is essentially the same as discussed in Part 1. The final appearance of the fillets is shown in Figure 3-10.

Chapter 4 - Vacuum Bagging the Tip-to-Tip Carbon

The tip-to-tip carbon method presented in Part 1 used two layers of 5.7 ounce 2x2 twill carbon. As with the carbon tubes, I didn't use any form of compression. I've always felt that the results of the method were pretty strong; however, in the absence of compression, there is likely to be a fair amount of excess epoxy in the lay-up. The problem with this is not the extra weight. Rather, the excess epoxy means that the carbon layers are not tight against the airframe or against each other. The consensus of opinion is that this excess epoxy weakens the structure.

For the current build, I wanted to use three layers of tip-to-tip carbon. The first two layers would be unidirectional carbon coming into the airframe at slight angles relative to the horizontal. The top layer would be the 2x2 twill for cosmetic purposes. I knew that without compression, the amount of excess epoxy in such a lay-up would be substantial. Unfortunately, my experience with compression methods such as "bag-o-mortar" and other weight-based methods hasn't been very good, and I don't think they actually remove much epoxy. Therefore, I decided to develop a method for vacuum bagging the fin can.

The bagging method presented here is rather complicated. One reason for this is that I was trying to preserve the appearance of the top layer of the carbon. In addition, I wanted to tip-to-tip pieces to extend all of the way to the edges of the fins (to be compatible with my method of protecting the leading edges from heat damage. There are undoubtedly easier ways to do this if appearance is not an objective (i.e., if the rocket will be painted) or if it is acceptable for the tip-to-tip pieces to remain inside the perimeter of the fins. However, as I went through the process, I did attempt to quantify the amount of epoxy that was removed using the method. What I found was that fully half of the epoxy in the lay-up was removed through bagging. Therefore, I have no doubt that the end result was worth the effort, and I think bagging should be considered regardless of the method used.

I've broken down the entire process into the following steps:

- Making the support shelves;
- Preparing the airframe;
- Installing the shelf borders;
- Applying the carbon layers;
- Bagging the fin can; and
- Cleaning up.

Making the support shelves
The bagging method I developed is designed to do one fin section at a time. That is, the lay-up goes from the surface of one fin, over the body tube, and then across the surface of the adjacent fin. As I mentioned above, I wanted the carbon pieces to go all of the way to edge of the fin. However, I was concerned about what would happen when the carbon folded around the fins as the vacuum was applied. To avoid this, I made some support shelves that would support the carbon around the perimeter of the fins. These shelves would attach to the back side of the fins being laminated and would be designed to provide a smooth transition for the carbon beyond the edges of the fins.

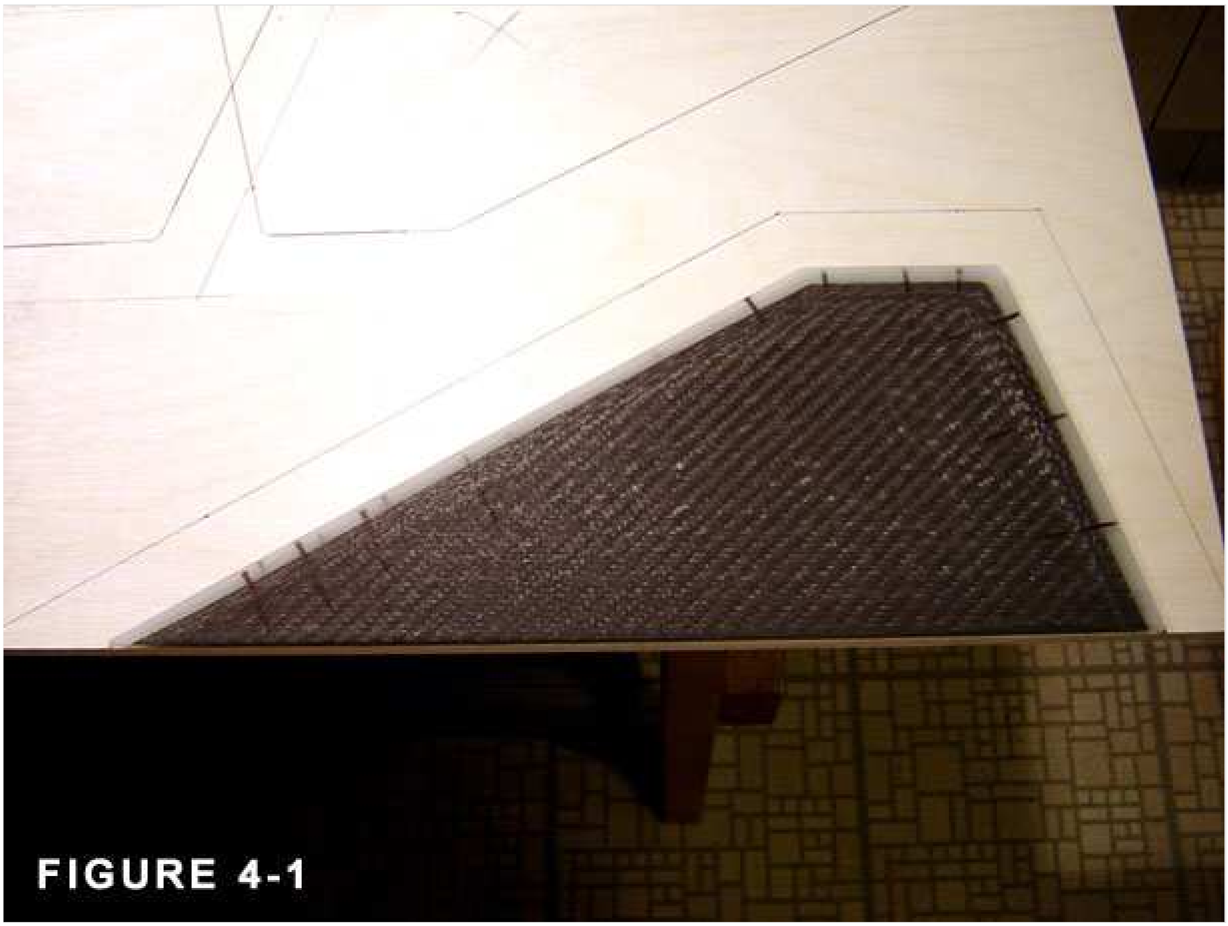


FIGURE 4-1

Figure 4-1 shows how I cut out the support shelves. Note that the shelves are about one inch larger on all sides (except the root edge) than the fins themselves. I wanted the shelves to go all of the way to the airframe. However, I had to cut out a bit of the material on the shelves so that they wouldn't run into the Cotronics fillet next to the tube.

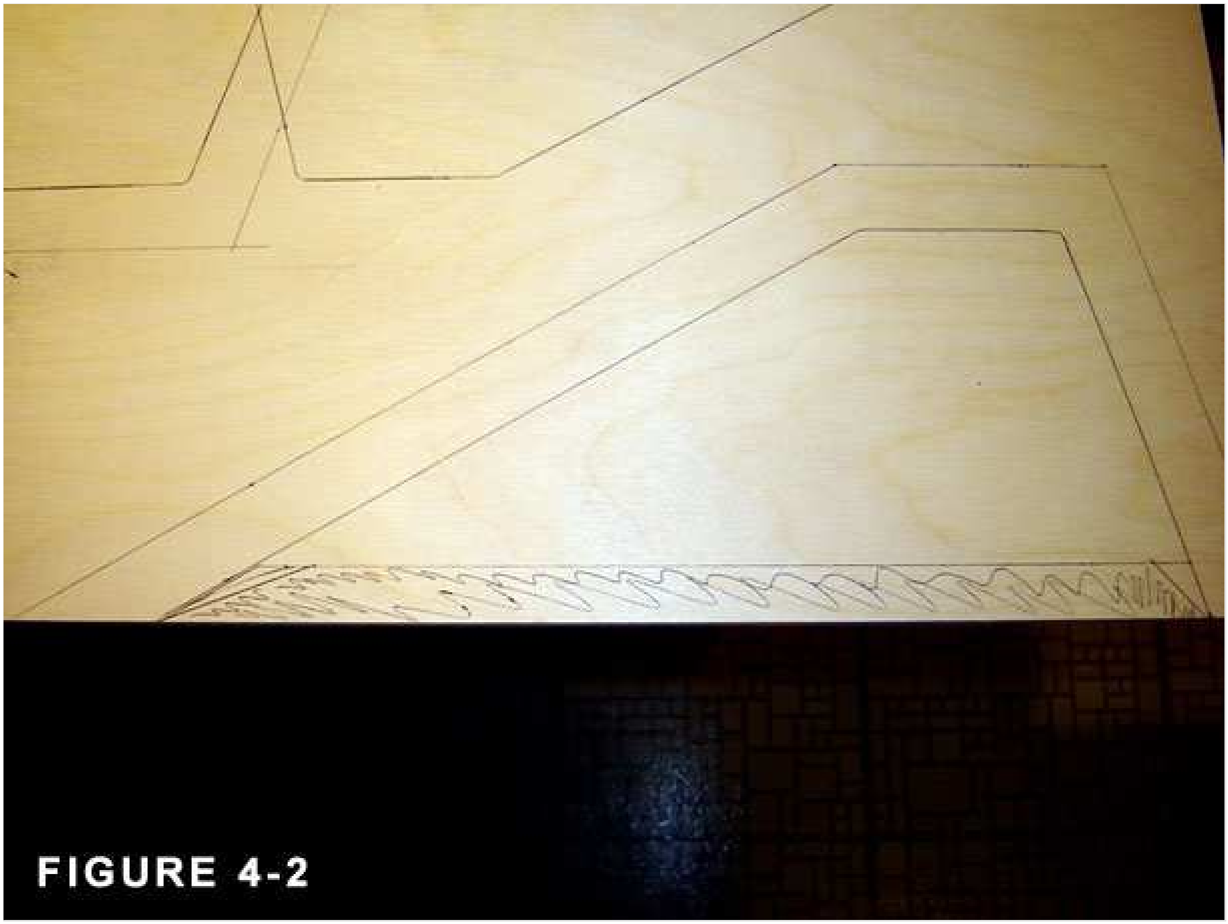


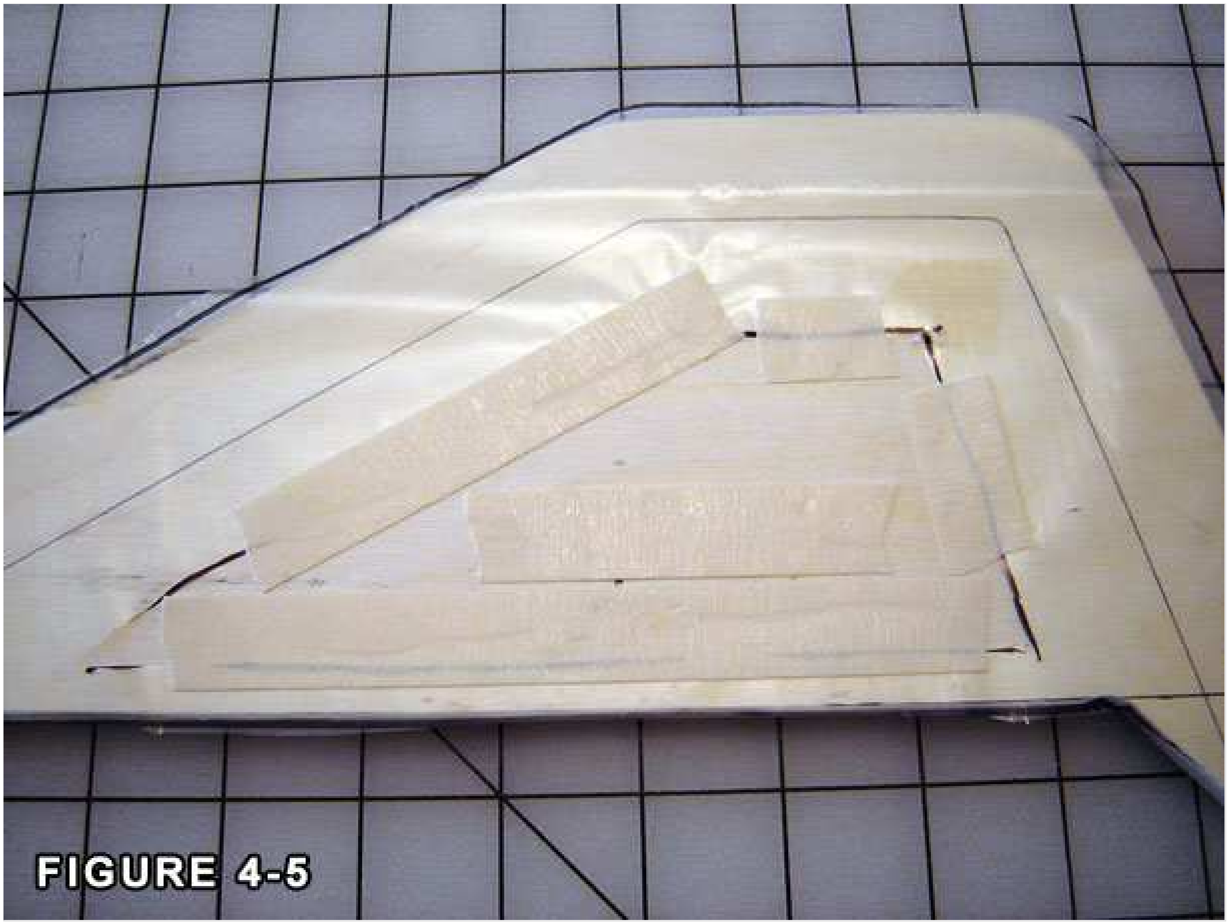
FIGURE 4-2

Figure 4-2 shows the material that I planned to remove. Once this material is removed, the shelf can fit flat against the back surface of the fins and the ends of the shelves will extend to the airframe. I made two shelves - one for the right side and another for the left side.

One problem that I wanted to avoid was inadvertently gluing the carbon pieces to the shelves. To avoid this, I planned to cover the shelf with a piece of release material (plastic film) having about the same size as the shelf itself. Unfortunately, if you cover the shelf with the release material, it becomes difficult to attach the shelf to the fin. To solve this problem, I cut a hole in the center of the release material, and then used double-sided tape to attach the release material to the shelf and the shelf to the fin. Pictures are worth a thousand words here.

Figure 4-3 shows the release material covering the entire shelf. Note that there is an extra inch of material (a tab) at both the front and back of the shelf. You can see the tab at the back of the shelf in the figure. This little feature is important later on.

Figure 4-4 shows the hole that I cut out in the center of the release material.

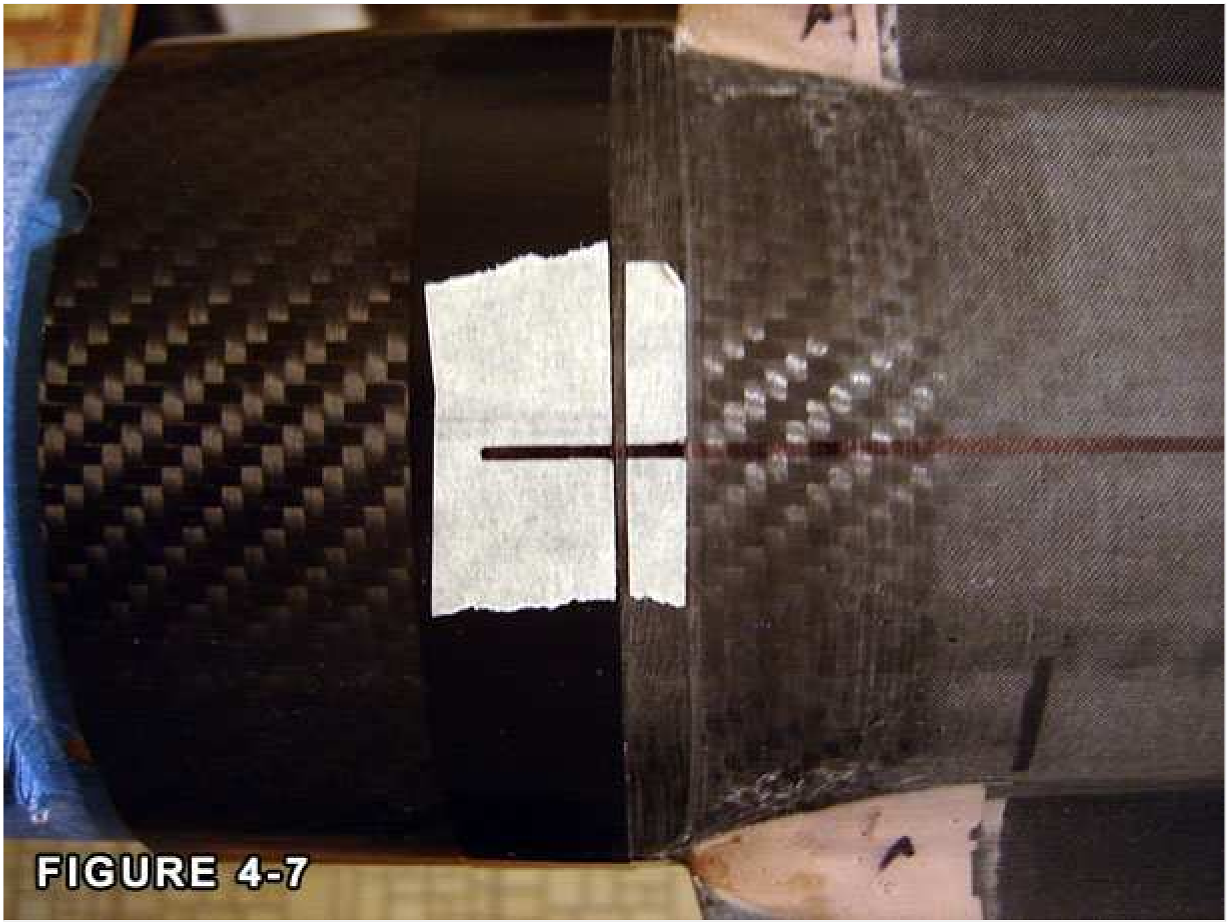


In Figure 4-5, I used double-sided tape to stick the release material to the shelf. This double-sided tape will be what holds the shelf to the underside of the fin.

Preparing the airframe
The next step in the process is to prepare the airframe. This includes marking out the areas where the carbon pieces will go and then attaching the shelves. Before I get in to this, I should explain how I planned to apply the carbon layers. As mentioned before, I planned to use three carbon layers. The first two layers would be unidirectional carbon and the top layer would be 2x2 twill. I planned to have the 2x2 twill layer extend from the front edge of the fin to the back edge of the fin. The unidirectional layers would be slightly shorter. Specifically, the first layer would be 3/8" shorter on each end and the second piece would be 3/16" shorter on each end. The purpose of this approach was to provide a transition in the thickness of the carbon layers (rather than an abrupt change in thickness at the start of the tip-to-tip layers). I also planned to apply a layer of peel-ply on top of the 2x2 twill layer. This layer would extend an extra 1/4" beyond the 2x2 twill layer.

Again, pictures help to explain the process. Figure 4-6 shows some masking tape applied to mark the positions of the pieces. The masking tape marks the center of the tube between the fins and provides a visual guide to be used when the carbon is applied. The area inside the masking tape pieces will be entirely covered with the 2x2 twill. The unidirectional carbon will be applied first. Since these pieces are shortly, they will fall inside of the masking tape pieces.

As I did in Part 1, I sanded groves in the airframe tube to allow the 2x2 twill layer to have a smooth transition to the airframe. The locations of these grooves are even with the leading and trailing edges of the fins (and the inside edges of the masking tape pieces). This can be seen more clearly in Figure 4-7.



The outside pieces of masking tape in Figure 4-6 will be used to guide the positioning of the peel-ply. Note that these tape pieces are positioned about 1/4" beyond the end of the 2x2 twill. The purpose of the peel-ply is to hold the 2x2 twill into the grooves in the tube and help to form a smooth transition to the airframe.

Finally, the close-up in Figure 4-7 shows a piece of electrical tape marking the boundary of the peel-ply layer. This will keep excess epoxy off of the airframe beyond the peel-ply. For a variety of reasons, electrical tape works well for this particular purpose.

With the airframe marked out, the next step is to attach the shelves. One thing I did before actually attaching the shelves was to apply some tape around the perimeter of the underside of the fins (see Figure 4-8). During the bagging process, excess epoxy will tend to leak around the edges of the fins. The tape on the backside of the fins makes this epoxy easier to remove.

Figure 4-9 shows this tape on the underside of the other fin. I used tape with a silicone adhesive this because it tended not to leave a residue and because the tape was very thin. Clear packing tape would likely work just as well.

FIGURE 4-10

FIGURE 4-11

With the backside of the fins masked, the shelves can be installed as shown in Figures 4-10 and 4-11. The shelves stick as a result of the double-sided tape shown in Figure 4-5.

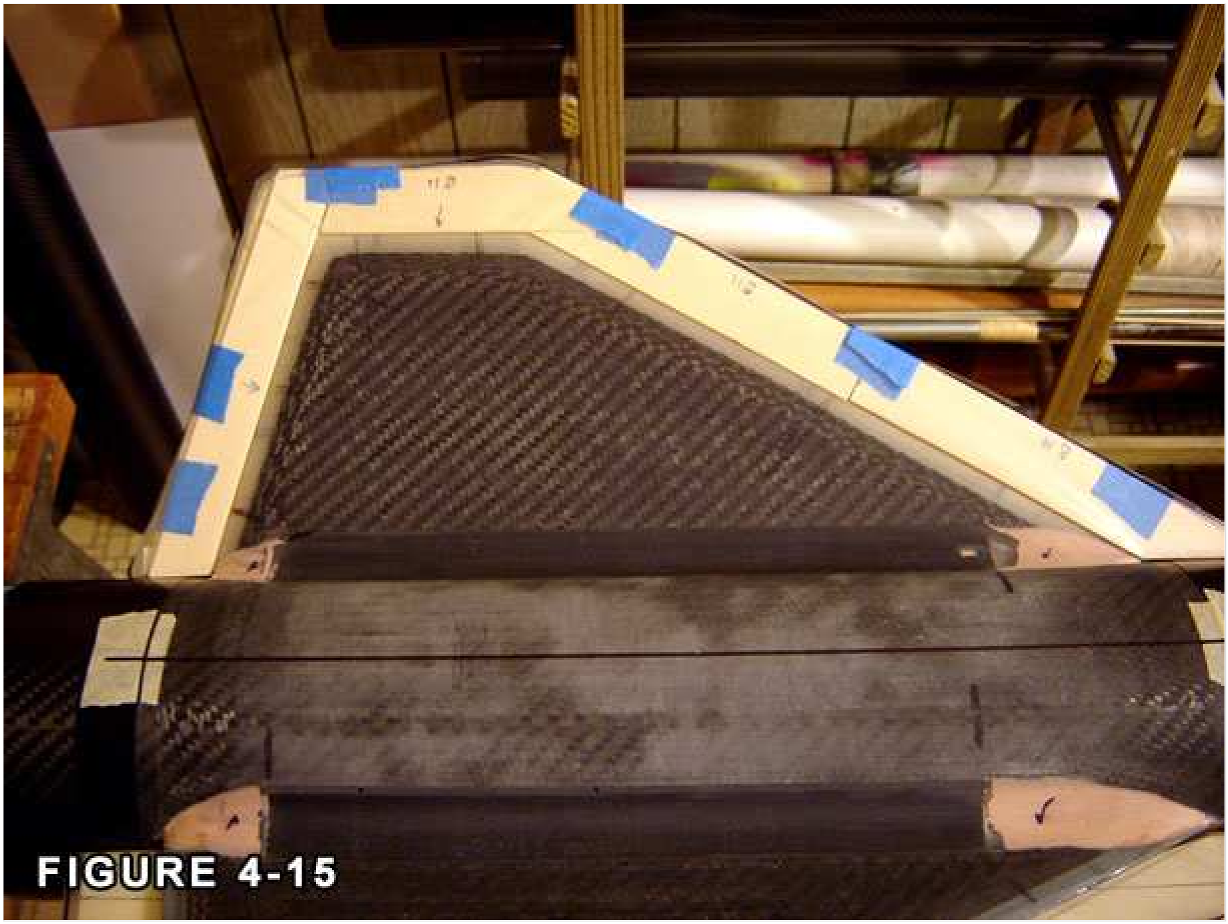
Installing the shelf borders

The core material for the fins was 1/8" G-10, and I applied a total of 10 layers of carbon. Thus, the thickness of the fins was approaching a quarter inch. Since the fins were beveled, there was about a 1/8" drop-off from the edge of the fin to the shelf.

I was concerned that the carbon and bagging material might get sucked into the beveled areas underneath the edges of the fins. Therefore, I made some transition pieces from 1/16" thick basswood, and these are shown in Figure 4-12.

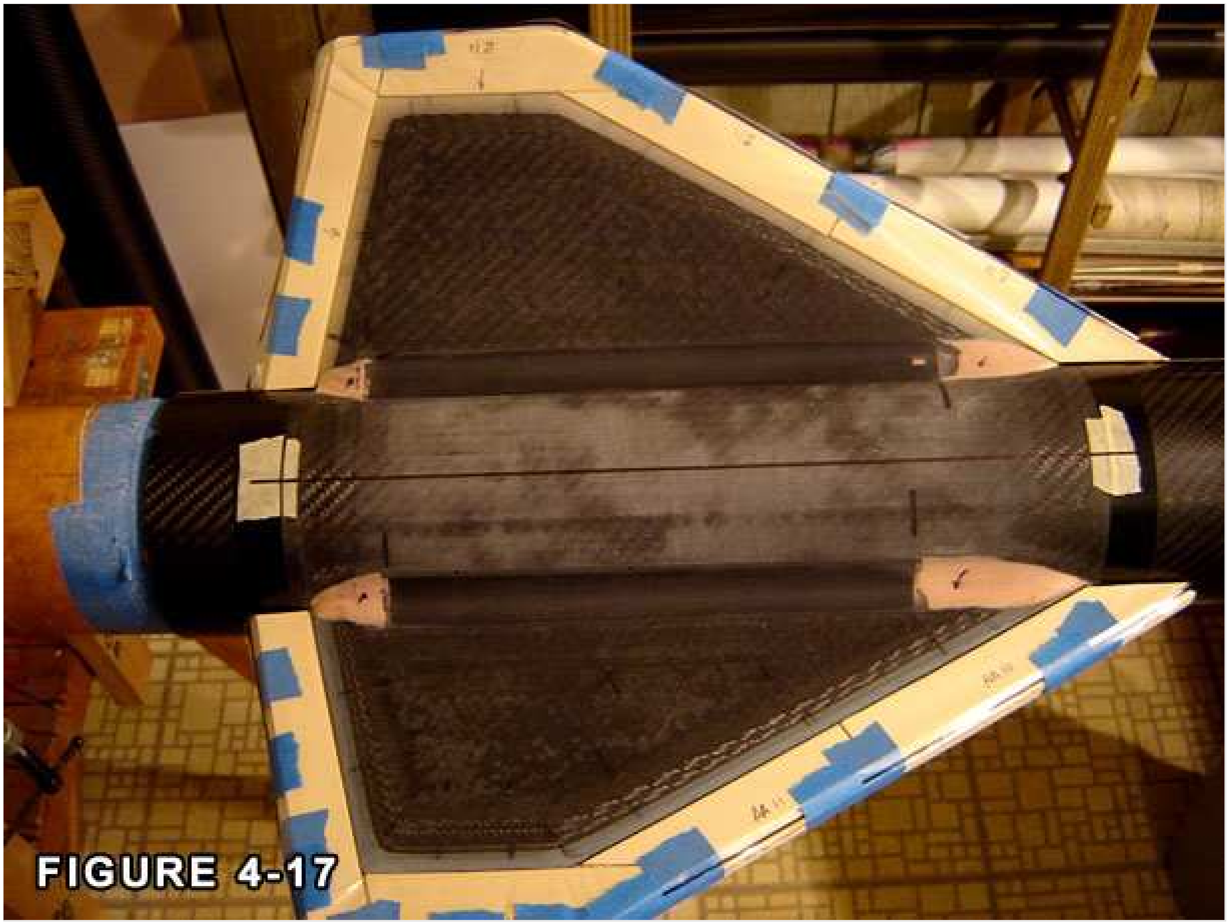
There are two sets of transitions for each fin. The first set slides underneath the edges of the fins (for my fins, the transitions slide underneath the fin edges by about 3/16"). Figure 4-13 shows the installation of the first set of transitions. Note that the transitions are installed underneath the release material so that they don't get exposed to epoxy. In this position, the transitions serve to block migrating epoxy from moving further towards the middle of the fin. That is, the migrating epoxy is held to the area that was masked in Figures 4-8 and 4-9, and the epoxy can only come in contact with either this tape or the release material. This makes cleanup much easier. In addition, the transitions help to support the edges of the fins against the force that will be applied by the vacuum. I was able to make one set of transitions, which I reused for all six tip-to-tip sessions.

Figure 4-14 shows the installation of the second set of transitions. These are placed even with the perimeter of the fin and they are also placed underneath the release material. Once the second set of transitions is in place, the release material can be smoothed down and taped to hold it in place (see Figure 4-15).



Note that the little tab on the release material shown previously in Figure 4-3 is very helpful for getting the release material to lay flat. It also helps to keep epoxy off of the transition pieces.

Figure 4-16 shows the back side of the shelf at this point, and you can see the release material tabs taped to the airframe. Figure 4-17 shows how everything is set up - we're ready to apply the tip-to-tip carbon.

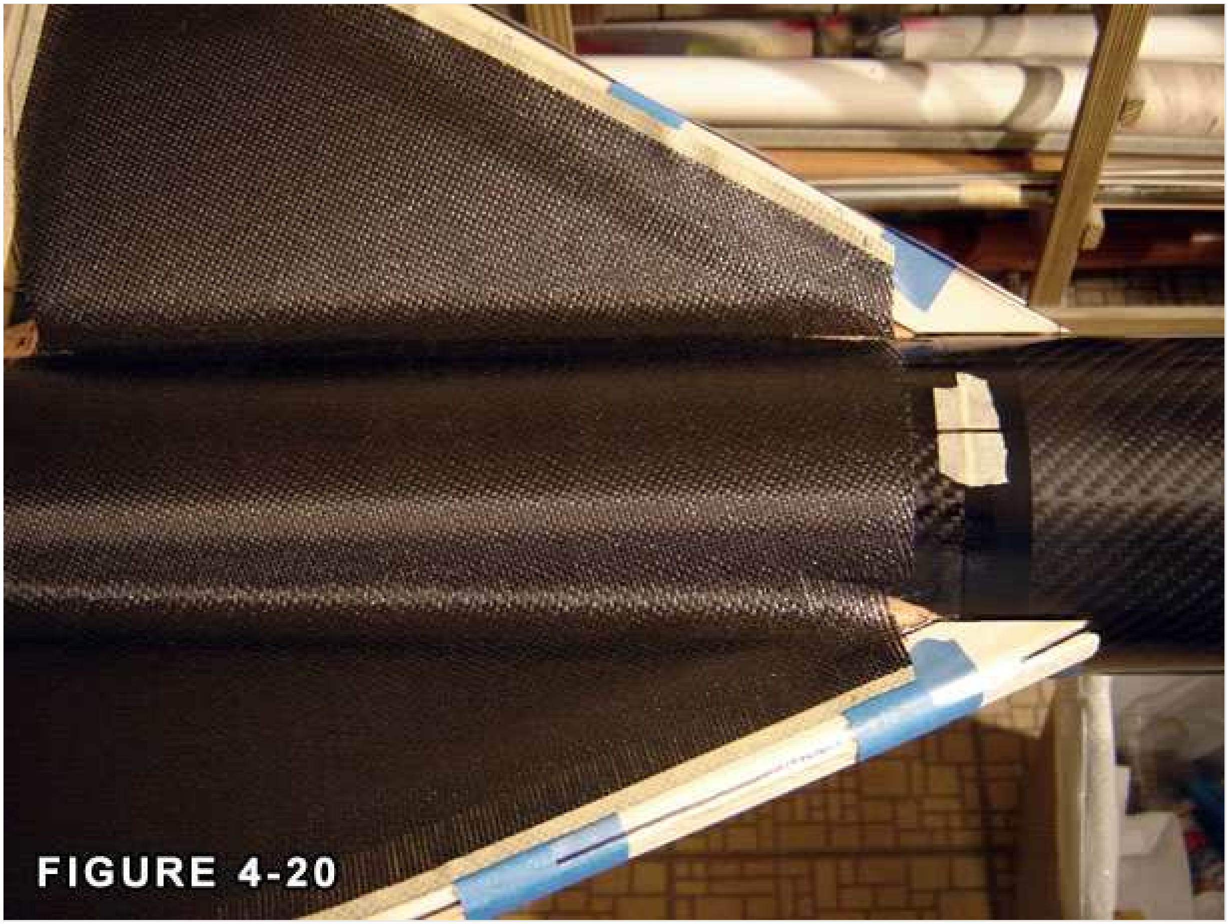


Applying the carbon layers

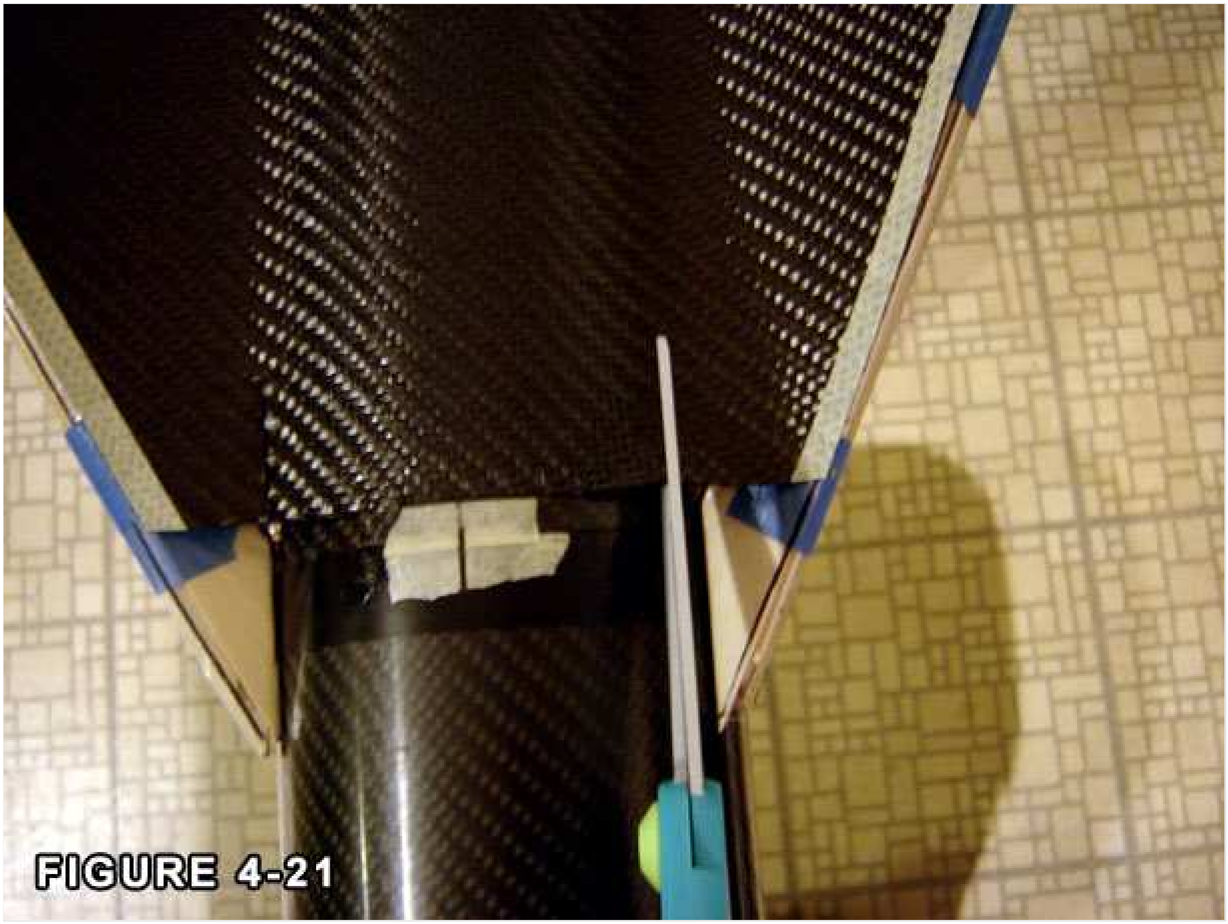
My plan for this rocket was to apply three tip-to-tip carbon layers. The first two layers would be unidirectional carbon applied at a slight angle relative to the root of the fin. Then, the third layer would be the 2x2 twill (to match the airframe appearance).

Figure 4-18 shows the layout of the unidirectional pieces. Note that the carbon piece in the lower right-hand part of the figure tilts slightly towards the right whereas the piece above it tilts slightly towards the left. This will make the tows, which run from left to right, come into the fin root at slight angles. The 2x2 twill will come straight into the fin root. I took this approach to maximize the amount of carbon going from left to right across the fins (I don't think vertically-oriented carbon tows provide much benefit).

The process for applying the carbon layers is essentially the same as I presented in Part 1. Figure 4-19 shows the application of the first unidirectional layer. Note how this layer falls between the masking tape guides as discussed previously. With the carbon in the position shown in Figure 4-19, I cut some small slits in the carbon corresponding to the Aeropoxy Light fillet transitions.



Even with vacuum bagging, the carbon over these compound curves won't sit flat. The slits are apparent in Figure 4-20, which also shows how the carbon layers extend about 3/4" beyond the perimeter of the fins, where they are supported by the shelf transitions.



In Figure 4-21, I'm cutting a slit in the third 2x2 twill layer. Note that this layer is applied even with the masking tape guides at the leading and trailing fin roots. I varied the location of the slits on the three carbon pieces so that they wouldn't overlap and leave a large gap.

Figure 4-22 shows the application of the peel-ply. The peel-ply layer goes up to the second tape mark and covers the "joint" between the 2x2 twill layer and the airframe. Note that there are also slits in the peel-ply layer. In Part 1, I emphasized the need to remove all of the air from underneath the peel-ply. If this is not done, the air under the peel-ply can leave holes in the epoxy surface that have to be filled. With vacuum bagging, I'm not sure this is quite as necessary (in theory, the vacuum should remove this air).

Bagging the fin can

The set-up presented above is the difficult part of the bagging process. Once this is done, the actual vacuum bagging is pretty simple. It does take two people though for these 4" fin cans, and my wife and I got pretty good at the process by the time we finished six fin sections.

Figure 4-23 shows the application of the perforated release material. Again, I have slits cut at the fillet transitions so that the release material will lay flat in this area. The perforated release material is then covered with three layers of thin bleeder/breather material (see Figure 4-24).

I think three is about the right number of layers given the amount of epoxy that was removed. Finally, I covered the breather material with another layer of release material in what turned out to be a futile attempt to reuse the vacuum bags.

With the lay-up covered, I extended the breather material up the airframe and installed the lower part of the vacuum attachment fitting (see Figure 4-25). Since the entire airframe will be bagged, it is necessary to cap off the ends of the airframe (otherwise, the bag would be sucked inside the airframe). On the aft end, I made an attachment to extend the airframe for a foot or so, so that the end of the bag would be further from the aft end of the fins (this part of the bag gets pretty distorted when the vacuum is applied).

FIGURE 4-26

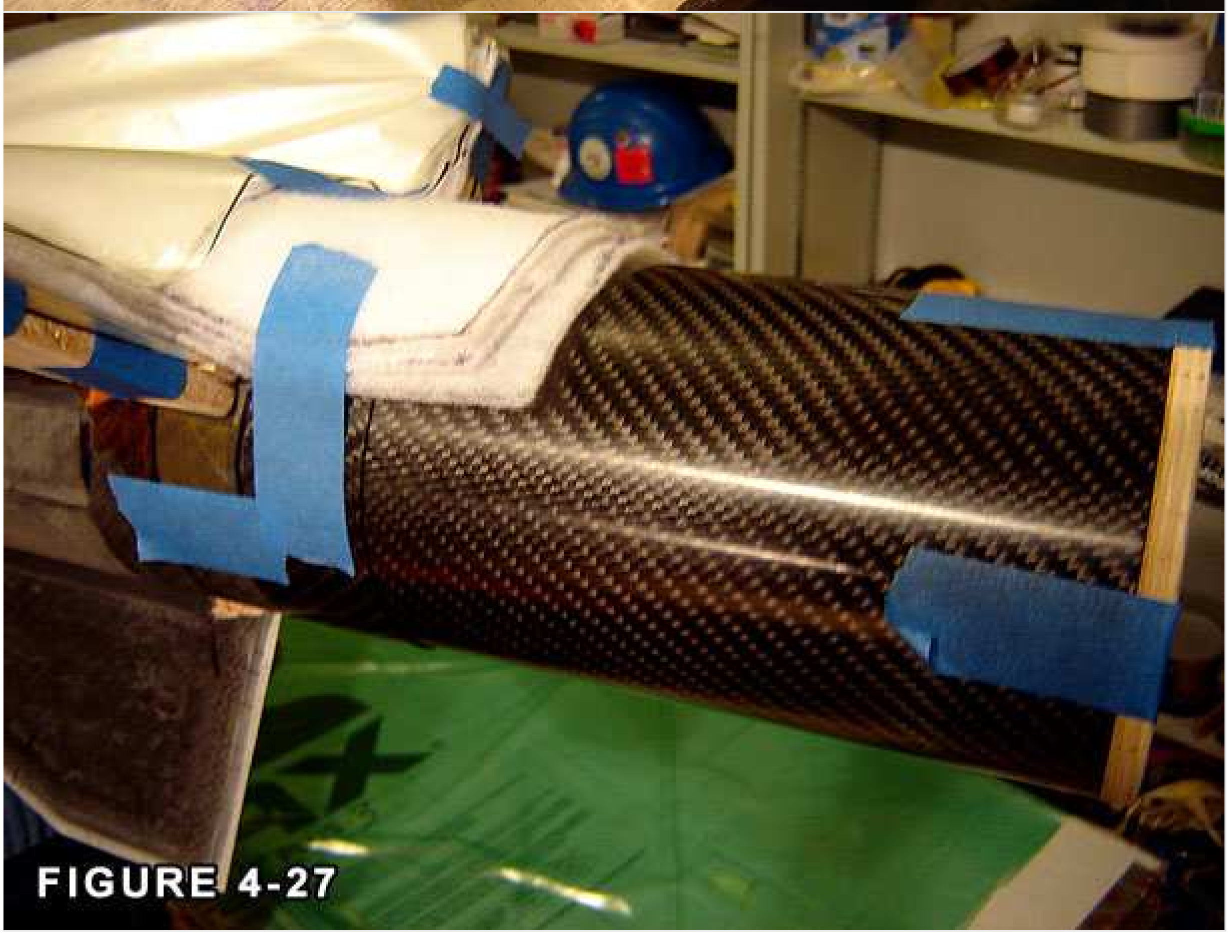


FIGURE 4-27

The attachment is shown both before and after installation in Figures 4-26 and 4-27, respectively. Similarly, I used a bulkhead to close off the top of the airframe. The whole assembly can now be inserted into the bag.

The bag I used was constructed of the stretchy bag material. I tried both the regular and stretchy materials, and I thought the stretchy material was far easier to use in terms of wrinkles, and it also seemed to do a better job of pushing down on the compound curve areas at the top and bottom of each fillet. The bag was made by simply folding in half a sheet of the bagging material (the bag really can't be too big by the way).

As shown in figure 4-28, the bag was sealed on the bottom and on the side, but open at the top.

In Figure 4-29, the rocket is inside the bag and the top of the bag is sealed with a bag clip (these clips are very handy, but the one I used had a temperature limitation of 125°F). Figure 4-29 also shows the installation of the upper part of the vacuum attachment, and Figure 4-30 shows the whole assembly placed in the oven.

FIGURE 4-30

Even with the stretchy bagging material, it's important to get the bag material pulled down without any wrinkles.

In Figure 4-31, I'm holding two "corners" of the bag material above the aft ends of the fins. My wife then held up the bag in a similar manner at the fore end of the fins to form a square. When the vacuum was applied, we just let the bag material get pulled down onto the fins.

Figure 4-32 shows how things look with the vacuum applied. Note that the bag material is smooth across the fins and the shelf transitions. This is the objective of using the shelves and fin transitions in the first place. What happens to the bag beyond that point doesn't matter.

My little vacuum pump has some limitations, but it does suck out pretty much all of the air (the vacuum gauge is pegged at -30 inches of mercury).

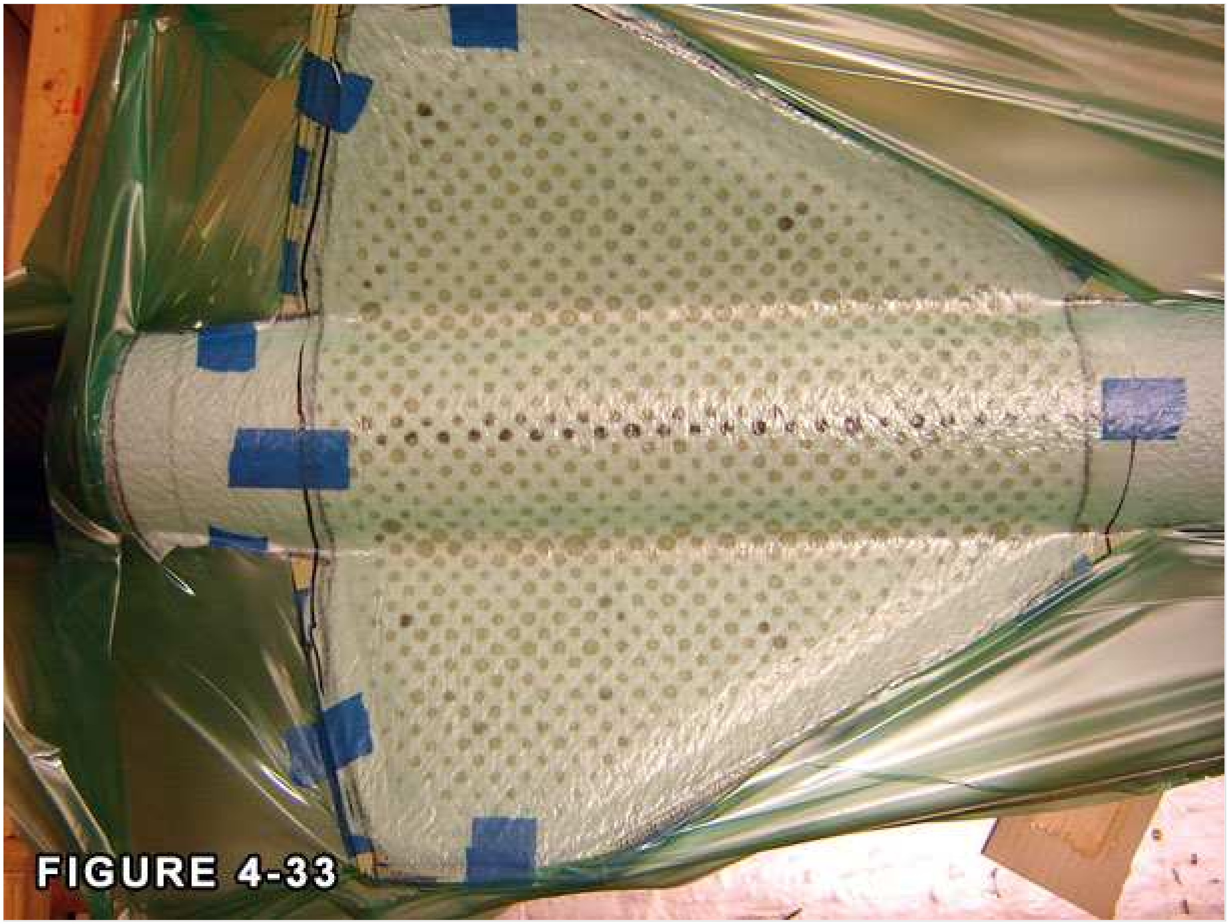


Figure 4-33 shows how things look after about an hour under vacuum. The amount of epoxy contained in the breather material represented about half of the epoxy applied to the lay-up. Mathematically, this is equivalent to reducing the percentage of epoxy in the lay-up from 57% to 40%.

Cleaning up

The lay-up should be removed from the oven as soon as the epoxy is no longer tacky. This makes it easier to trim away the excess carbon and to remove any stray epoxy. Since the epoxy can't be touched while it's in the bag, I placed a piece of paper in the oven that was painted with the original laminating epoxy. I removed the assembly from the oven as soon as this epoxy was no longer tacky.

Figure 4-34 shows how things look after removing all of the layers down to the peel-ply. The next step is to remove the shelves and the shelf transitions, and then the tape used to mask off the back side of the fins.

Figure 4-35 shows an example of how the epoxy has migrated underneath the fins (the epoxy tries very hard to do this in a process similar to vacuum infusion). The first shelf transition helps to minimize this, however, and if the epoxy migration can be limited to the tape, it just pulls off.

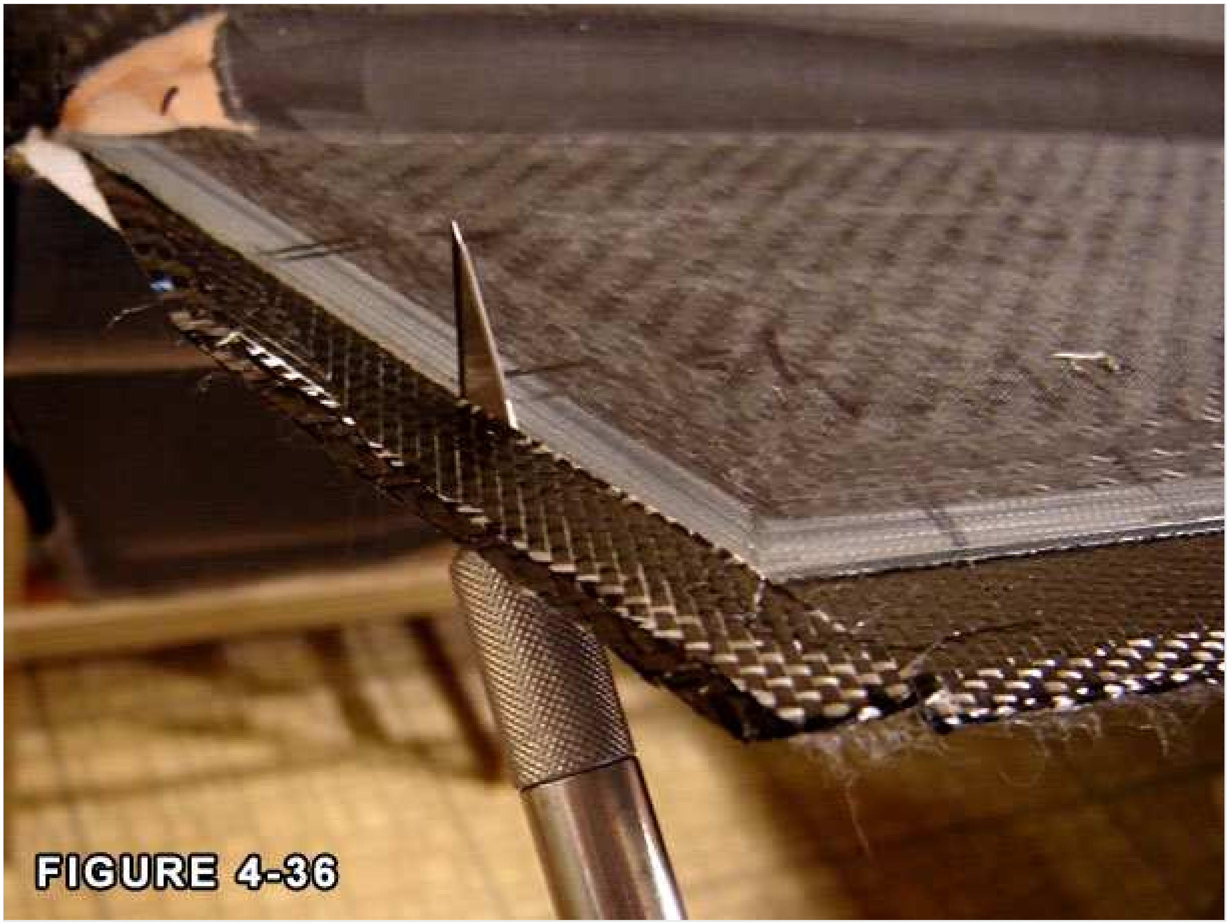


FIGURE 4-36

One reason I like to clean things up while the epoxy is still soft is that I can trim the carbon with a knife (see Figure 4-36). There is only a short window of time where this will work, so timing is important. Once the excess carbon is trimmed off, the peel-ply can be removed (see Figure 4-37).

Since the epoxy is still soft, now is the time to remove any stray peel-ply threads in the fillet transition area or across the airframe. These can be pulled out or shaved off with a knife. In the particular example shown in Figure 4-37, there was also a little excess epoxy just behind the aft fillets (the bag does not seal perfectly in this area). This also gets trimmed off.

I finished the fin can using the methods outlined in Part 1. Basically, I paint the area with six coats of epoxy and then sand everything down flat. In between coats, but not before the first coat, I lightly sand the area and then remove the dust with a vacuum and a tack cloth. Each coat of epoxy terminates a little higher up the airframe (ahead of the fins) or a little lower on the airframe (below the fins). When all six coats are applied, I sand everything down flat, trying to avoid sanding into the carbon itself.

Figure 4-38 shows how I mask off the area ahead of the fins (I do the same at the aft end). As shown in Figure 4-39, I use a foam roller to apply each coat of epoxy because I think a roller is the best way to put on a uniform, thin layer.

You might expect that I go through a lot of foam rollers (after all, there are six coats of epoxy on each of six fin sections). Actually, I remove excess epoxy from the roller with a paper towel and the put the roller in the fridge between coats. That way, I can reuse each roller at least three times. After each coat is applied, I smooth it out with a chip brush. This removes the small bubbles that remain as a result of using the roller.


FIGURE 4-40


FIGURE 4-41

Figures 4-40 and 4-41 show how things look after applying the first and sixth coats of epoxy. Piece of cake!

As I said at the start of this section, the method I use is rather complicated (actually, it is relatively straightforward, but it does take some time to do the preparation and then work through all of the steps). If having the tip-to-tip carbon extend to the edge of the fin is not an objective, and if the rocket will be painted, then there are probably much simpler ways to accomplish the benefits of bagging.

Although I have not tried this, I can envision an approach where the sticky tape would be placed around the perimeter of the fin, across the airframe and then around the perimeter of the other fin. Then, the lay-up would be done within the perimeter of this sticky tape, and only the area with the lay-up would be bagged (i.e., the "bag" would be a sheet of plastic covering the area within the perimeter of the tape rather than bagging the entire fin can). This approach would be relatively simple to do and would provide essentially the same strength and weight benefits as the method I used.

Chapter 5 - Applying Heat-resistant Fin Leading Edges

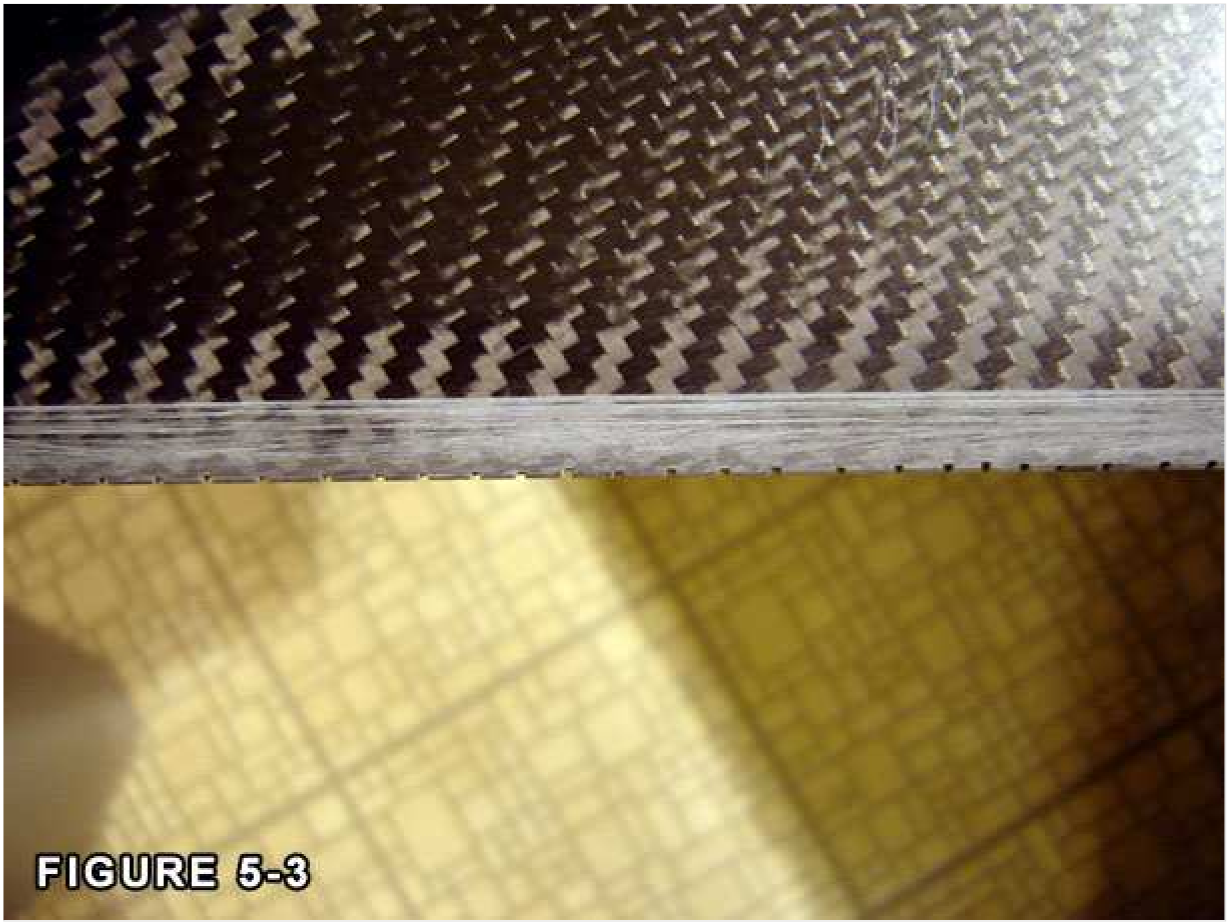
On most of my rockets, I have applied a coating of high-temperature Cotronics epoxy to protect the leading edges. In past efforts, I first sand down the fin to form a sharper leading edge (the edges after application of the tip-to-tip carbon are otherwise a little blunt). Then, I cover the edges with perhaps 4 or 5 coats of the epoxy. I try to have each layer be a little wider to avoid an abrupt edge where the Cotronics ends.

The above approach has always worked well, and I have never seen any obvious heat damage to my leading edges. However, the drawback of the process is that sanding the leading edge to produce a more aerodynamic shape exposes the edges of the tip-to-tip carbon layers. Although these are covered with the Cotronics, it is conceivable that if the coating failed, the edges of the carbon could be easily delaminated. This is more of an issue perhaps on two-stage flights, where the sustainer operates at higher speed for a longer period of time.

Since rocketry is a hobby, I decided to experiment with a built-up leading edge that would provide more protection and avoid the need to expose the edges of the tip-to-tip carbon layers. It turns out that it is only necessary to extend the leading edge by about 3/16" for my fins, but this can't be done by painting on multiple layers. The process I used is documented here, and I'm very please with the results.

The initial appearance of the fins is shown in Figure 5-1 (after vacuum bagging the tip-to-tip carbon and finishing the epoxy surface). The first step in the process was to roughen the area that would eventually be covered by the Cotronics (see Figure 5-2).

Then, after taking a deep breath, I used a hacksaw to cut some teeth into the leading and trailing edges to help my build-up adhere to the edge of the fins (see Figure 5-3).



The next part of the process was to make the forms to shape the epoxy. The forms I used for the trailing edges are shown in Figure 5-4. The "long" form is on the left (it will extend further in front of the leading edge) and the "short" form is on the right.

FIGURE 5-4

FIGURE 5-5

The idea is to form a "V" with these forms, as shown in Figure 5-5, and fill the volume between the forms and the leading edge of the fin with epoxy.

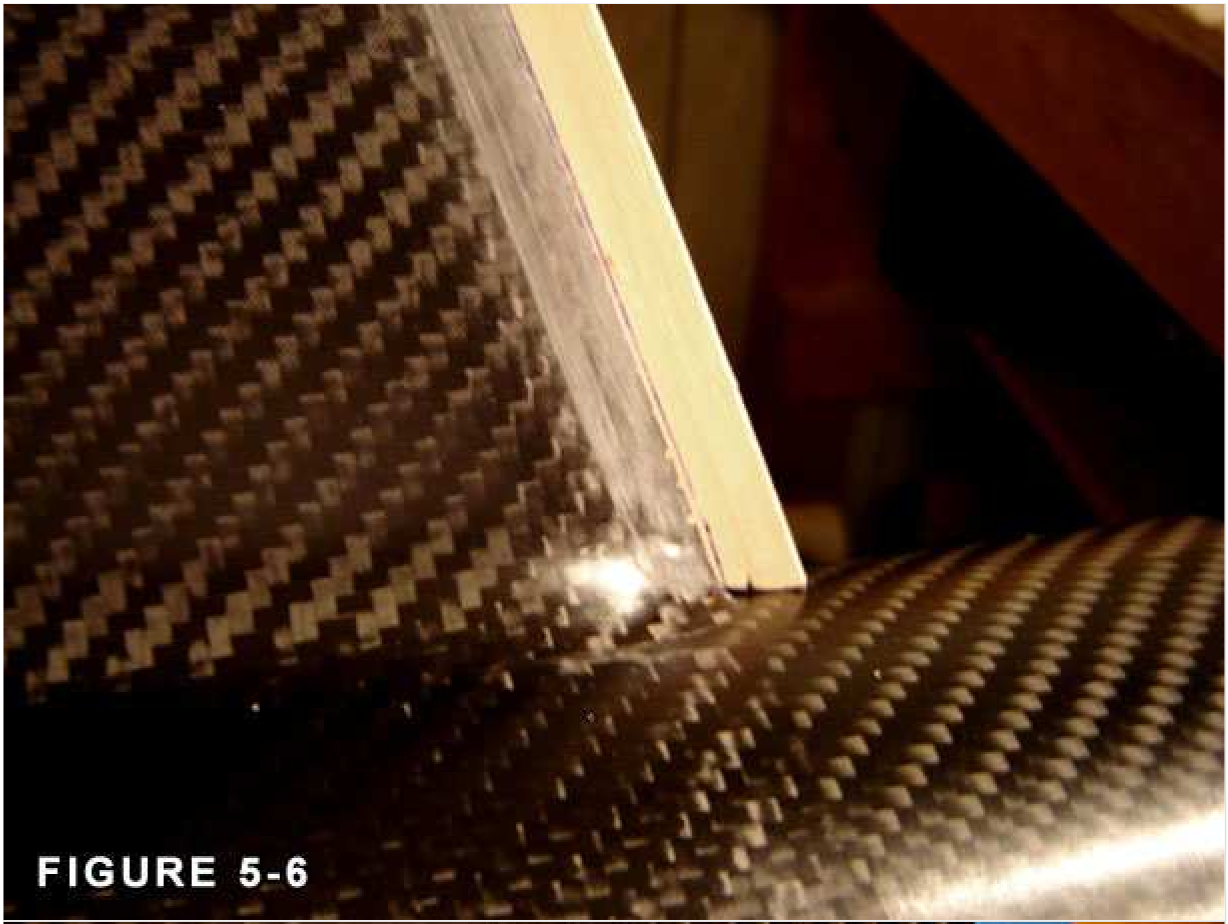


FIGURE 5-6


FIGURE 5-7

Figures 5-6 and 5-7 show the placement of the long and short forms, respectively. The shaved areas of these forms, as shown previously in Figure 5-4, are necessary so that the forms fit around the fin fillet. Figure 5-8 shows how the forms come together. Note that there is a small gap between them, which allows excess epoxy to escape when the forms are clamped together.


FIGURE 5-8

Figure 5-9 shows the forms for the leading edges. These are shaped differently because the fin fillet is harder to work around on the leading edge. However, they are otherwise constructed the same as the trailing edge forms. I should say here that the edge on the tip of the fin wasn't extended in the same manner as the leading and trailing edges. Instead, I just painted the blunt tip with the Cotronics.

Since the forms are going to contain the Cotronics epoxy, they need to be treated so that they can be removed after the epoxy is cured. I did this by covering any area that would be exposed to epoxy with clear packing tape (see Figure 5-10). Then, I used a paper towel to coat the packing tape with a thin layer of PTFE mold release. I used the same forms for all six fins, although I usually had to replace the packing tape.

FIGURE 5-10

When the leading edges are formed, I only want epoxy on the tip of the fin edges (i.e., forward of the point where I cut the teeth). Therefore, I want to mask off the areas of the fin where I don't want any extra epoxy.

Figure 5-11 shows how I taped off these areas. Similarly, I don't want excess epoxy on the airframe tube, so I masked that off as well (see Figure 5-12).

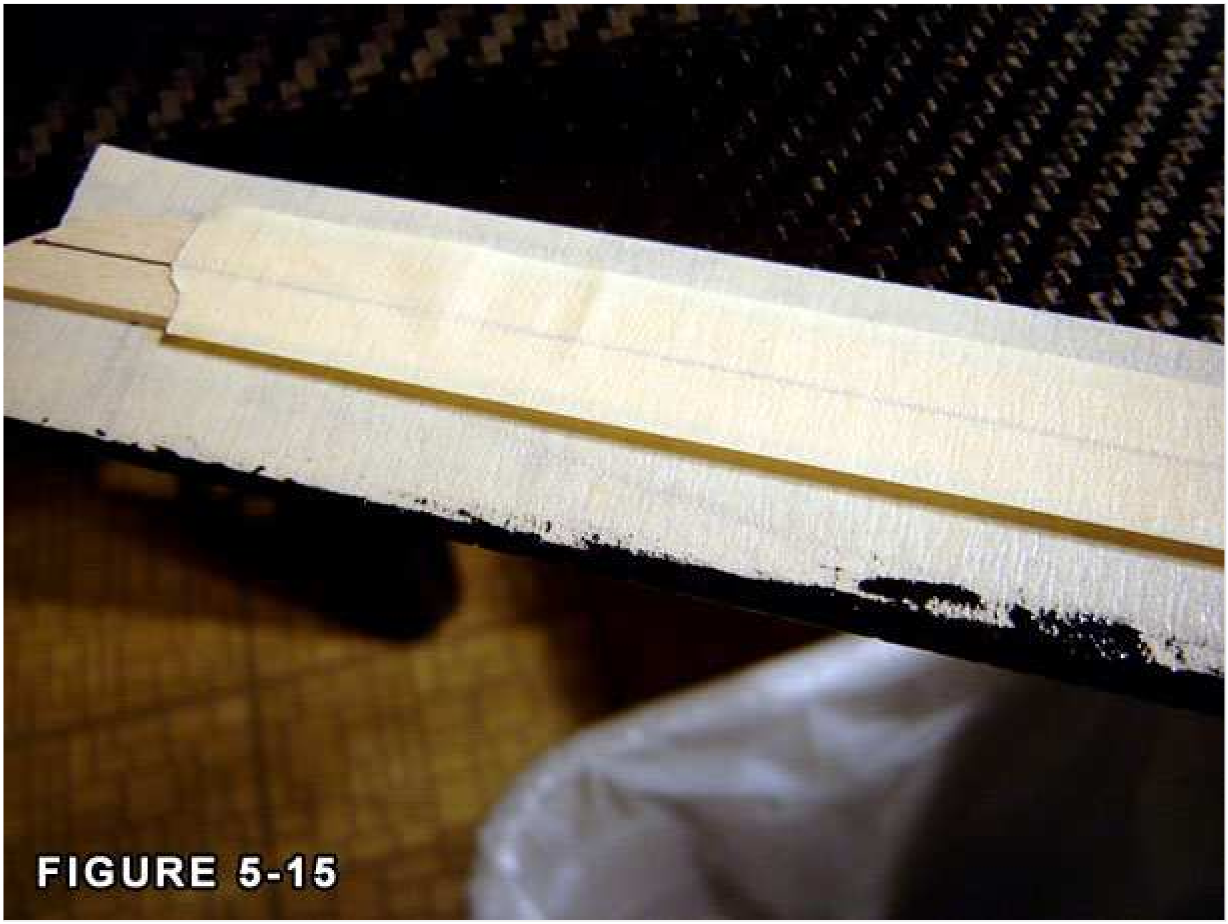
Conceptually, what I wanted to accomplish was to form a leading edge with an angle that matched the fin taper at the edge of the fin. Therefore, the forms needed to be in contact with the leading edge just at the point where the teeth were cut. Since the fins are tapered (i.e., rounded), there needs to be another support point to hold each form in place at the correct angle. I used a thin strip of wood about 5/8" back from the edge of the fin for this second support.

The first step here, as shown in Figure 5-13, is to apply a strip of double-sided tape and then mark a location 5/8" behind the edge of the fin. Then, the strip of wood is applied at this mark, and another layer of double-sided tape is placed over the top of the wood strip (see Figure 5-14).


FIGURE 5-14

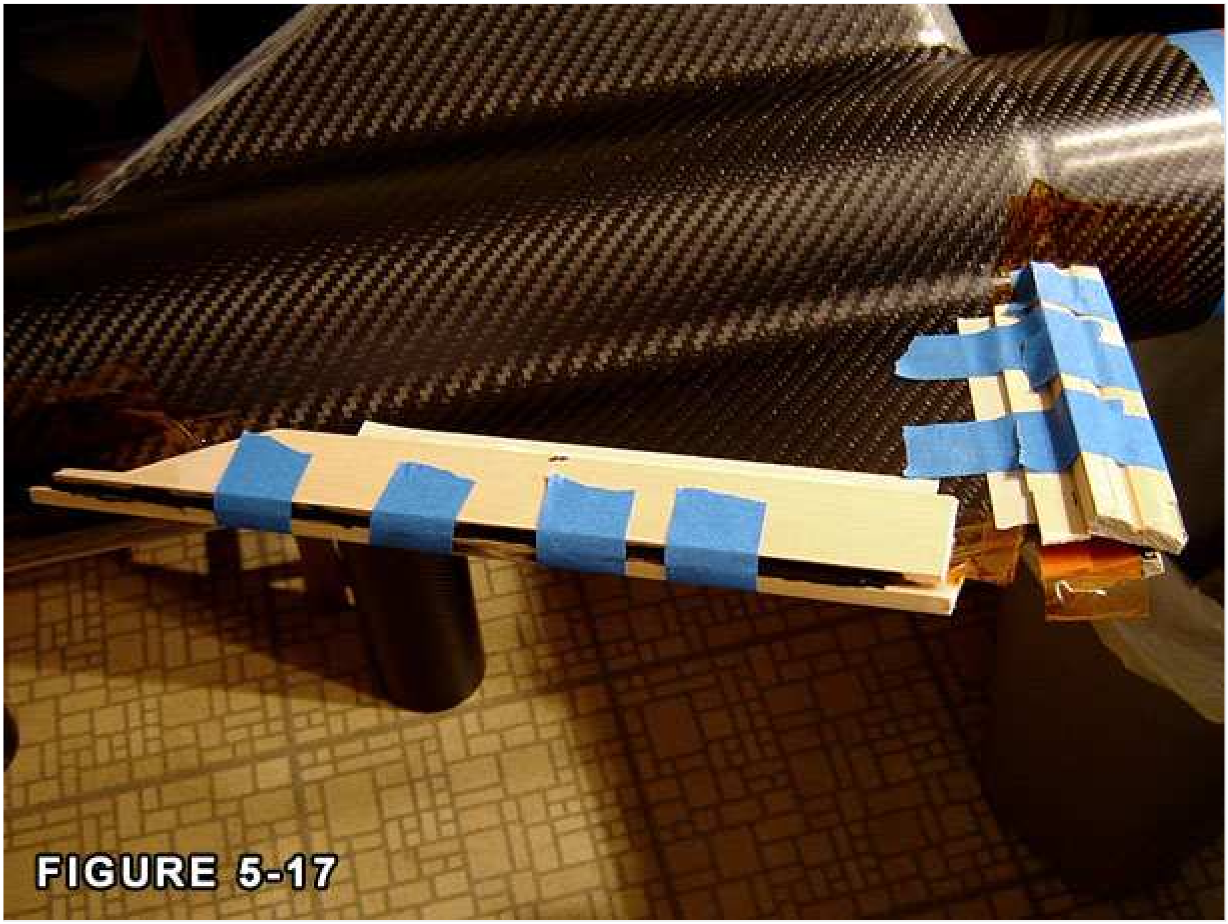
If everything is set up correctly, the forms on each side of the fin can will rest against the tape on this wood strip, and also against the leading edge at the "teeth", and extend the right distance to form the "V" to hold the epoxy. Obviously, setting up the geometry for all of this to happen is the difficult part of this process, and every rocket will be different.

With the supports in place, it is time to apply the epoxy. I start this process by painting the "teeth" with unfilled epoxy (see Figure 5-15).



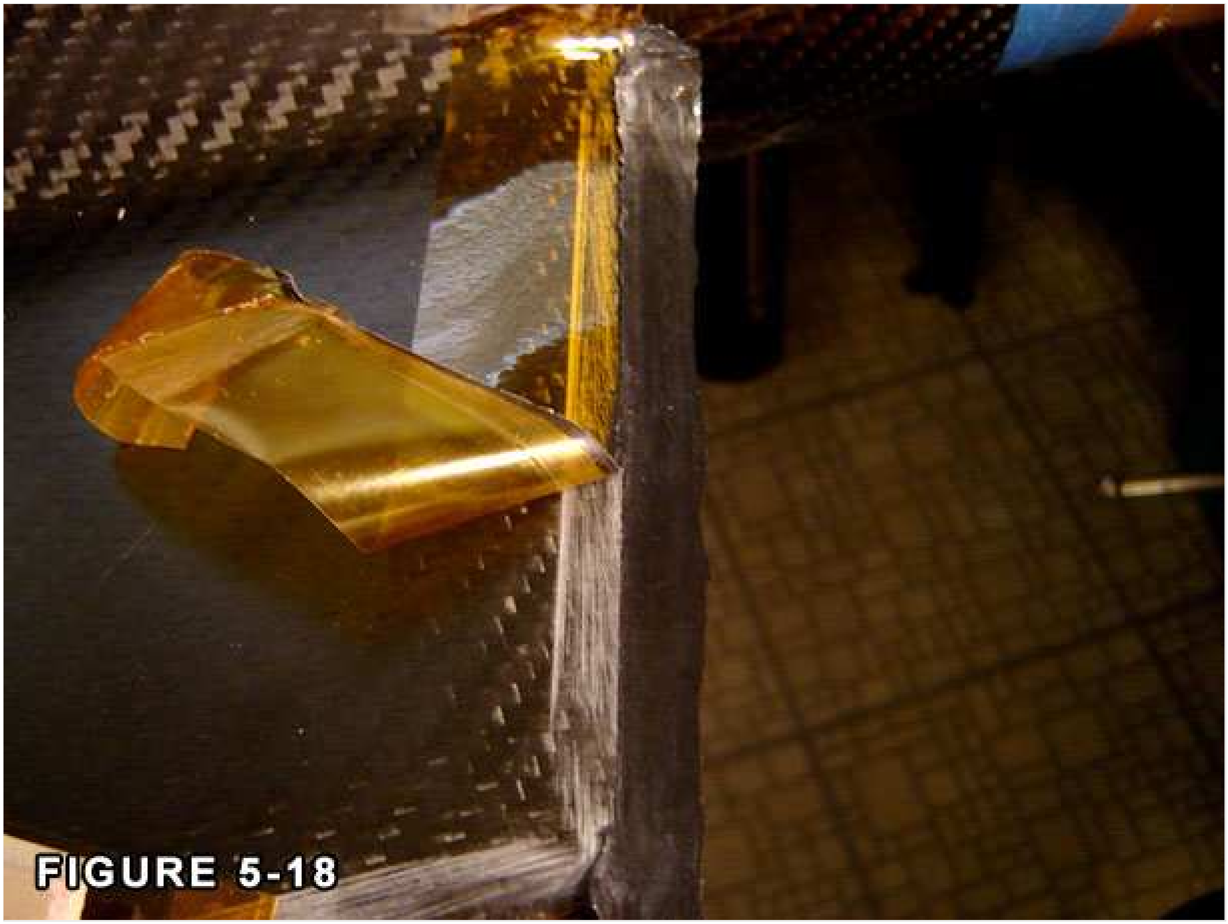
The objective here is to make sure all of the surfaces are wetted with epoxy and you want relatively thin epoxy to do that. Then, the "long" form can be set in place and the space in front of the leading edge can be filled with an epoxy/milled glass mixture (see Figure 5-16).

I made a mixture containing about 20% by weight of milled glass (this was as thick as I could make it without the mixture being "dry"). It is very important not to have any air bubbles in the epoxy as these would leave void areas. After this epoxy is applied, the "short" form can be set in place and the two forms can be squeezed together.



Some of the excess epoxy goes behind the leading edge into the masked-off area while the remainder oozes through the gap between the two forms (see Figure 5-17). Once the forms are together, they can be taped together to hold everything in place.

At this point, the assembly is placed in the oven to cure. Again, it is easier to perform subsequent steps (remove the forms, the tape, etc.) if the epoxy is still soft. I put a little epoxy on a piece of paper and place it in the oven along with the lay-up. I remove the assembly from the oven as soon as this epoxy is no longer tacky.



With the epoxy soft, the forms can be carefully removed and the mask tape can be pulled up (see Figure 5-18). The glue that oozed between the forms can usually just be torn off, and a knife can be used to trim away any other excess epoxy.

FIGURE 5-19

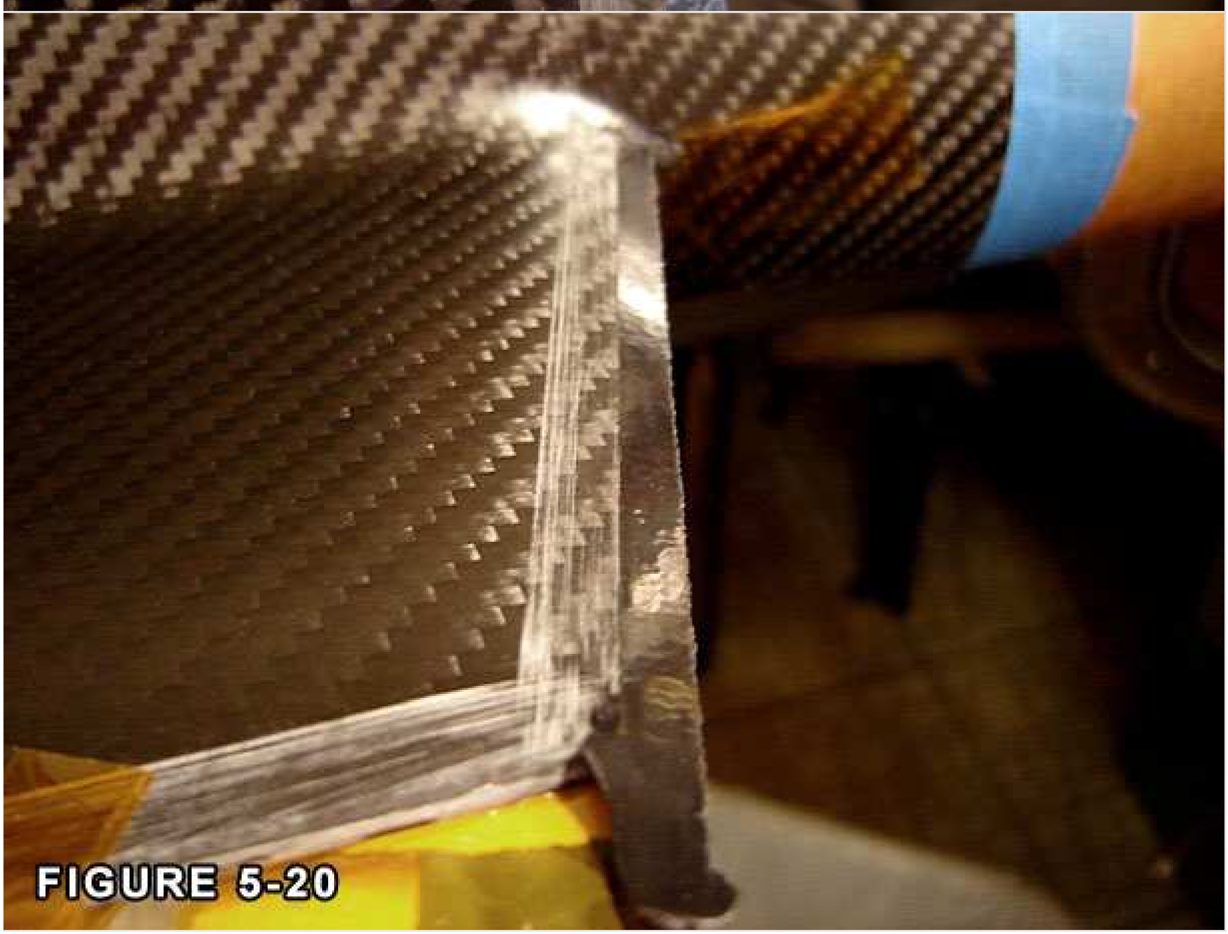
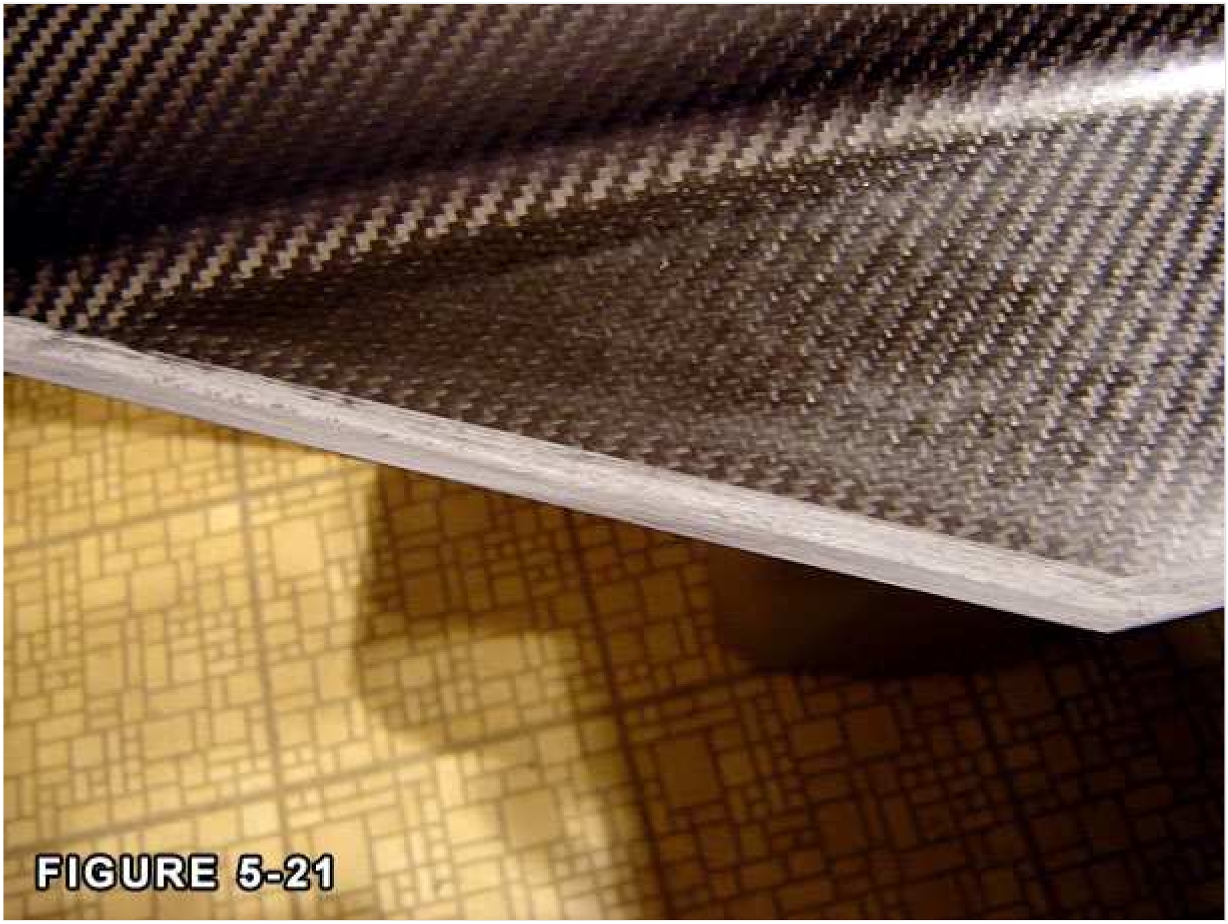


FIGURE 5-20

Examples of the result of the process are shown in Figures 5-19 and 5-20.



Once the epoxy has cured for a while, it can be sanded down flush with the surface of the fin (see Figure 5-21).

This process gives a very sharp leading edge. I dulled down the edge a little as shown in Figure 5-22.

With the leading and trailing edges complete, I then painted on five coats of Cotronics (thickened with a little milled glass and a little fumed silica). Each layer was a little wider and terminated a little closer to the edge of the sanded area that I made as the first step of this leading edge process. I sanded lightly between the coats, and the result after the fifth layer is shown in Figure 5-23.

I sanded smooth this final coat and then wiped on a thin coat of the Aeropoxy laminating resin to restore the shine.

The completed fin edges are shown in Figure 5-24. I really like the way this turned out!

Jim Jarvis is a high power rocketeer who resides in Austin, Texas, and flies with the Austin Area Rocketry Group. Jim holds a degree in Chemical Engineering from the University of Wisconsin and works as a project manager for a large engineering company, managing environmental control system projects on coal-fired power plants for the electric utility industry. For Jim's contribution of this article, he will receive a free Rocketry Planet T-shirt. This sponsorship is made possible by our friends at Graphix & Stuff, producers of high quality hobby apparel and vinyl signage. Want your own free gifts? Read the program details page *for complete information.*