LOW COST MANUFACTURE OF LAMINAR WINGS

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Abstract

The purpose of this construction method for wings and tails is to greatly reduce the labor costs and also to increase the wing's surface accuracy to the level required by laminar flow without profiling by hand. This method is suitable for any wing loading or planform, except that it requires that all curvature be simple and not compound. The accuracy is expected to come from the use of flat sheets and ribbons of precured prepreg of aramid/epoxy or carbon/epoxy, rather than having the prepreg's cure take place in the mold, as it is believed that the volume changes of the epoxy during cure is the major cause of warping and the consequent need for refinishing the wing's surface by hand. The adhesive used to form the wing surface sandwiches from precured prepreg sheets and foam is a liquid, which cures to a rubbery plastic, and whose elasticity prevents warping due to shrinkage during cure. All of the materials and processes used here are presently in commercial use for other purposes. The major piece of assembly equipment is a clamshell mold, of conventional design for the manufacture of sailplane wings, but with a modified method for applying a vacuum to the top and bottom wing surfaces to conform them to the mold.

Introduction

When the sailplane building industry changed from wood, cloth, and aluminum to fiber reinforced polymer (FRP) materials, there was widespread hope that the theoretical promise of laminar flow wings could be achieved in practice for the first time. This hope has long been realized. There was also another expectation at that time, in the 1960's; an expectation that the use of FRP materials would result in rapid, low labor, and extremely low cost mass production. This expectation was based on the plastic industry's reputation for rapid cycle time on automated machinery.

To date, this second hope has been disappointed for several reasons. First, there is no precedent for mass production in the aircraft industry. No matter how many of a particular model are built and no matter how many jigs are used, almost all assembly operations are by hand. Second, there is little familiarity in the aircraft industry with the extremely diverse vocabulary of processes accessible through FRP and polymeric materials. Third, the U.S. government and legal industry's certification procedures for aircraft made of novel materials are too expensive for the small ventures which have an economic incentive to innovate.

The result of these blocks to the assessment and application of FRP technology to the automated manufacture of aircraft has been that FRP is now used in aircraft in ways which usually result in cost increases rather than reductions. For example, the modern sailplane has more than its sleek lines in common with a thoroughbred racehorse. Where parts of aircraft or even whole helicopter fuselages are made from FRP in the war industry, production methods either use a great deal of hand labor or else use very expensive machines which mimic hand labor processes, such as filament winding. The reason this suboptimal use of FRP technology is so expensive is that the machines are using processes developed from hand labor with aluminum. Thus, designing an inexpensive production process and then designing materials to fit this process should result in much cheaper wings.

The example presented in this paper is sailplane wings, but economically more important applications for this technology are to commercial aircraft, where fuel consumption and production costs are the primary concerns. This example can be translated to commercial aircraft simply by changing dimensions and, for wet wings, specifying existing fuel proof materials throughout.

With the rapid rise in energy costs over the past decades, there has been a renewal of interest in maintaining laminar flow over the surfaces of aircraft. In this context, sailplanes can serve as a model, or at least a starting point, for the design of low cost, fuel efficient aircraft, regarding both structural efficiency and laminar flow. Unfortunately, both of these properties are coupled to the use of fiber reinforced polymers, which are presently extremely labor intensive. Thus the question is formulated: How it is possible to maintain the accuracy of surface contours necessary for laminar flow and the structural efficiency of FRP construction while eliminating the labor intensive hand layup and refinishing?

From the outset, three properties of any solution to this problem are evident: first, that the materials should be designed to conform to the manufacturing process, and not the reverse, as is usually the case. Second, due to the extreme accuracy requirements placed by laminar flow, any process which involves volume changes such as curing or heating large parts can be eliminated. Third, since automation always involves machinery and jigging which is more expensive than manual fabrication, the production runs should be long, and the cycle time of the process should be short.

The solution presented here is not, geometrically speaking, a general solution. Because the FRP is precured into flat sheets, this method can produce only those shapes with simple or "one dimensional" curvature; those surfaces which can be generated by bending a flat, inelastic sheet without wrinkling or stretching it. Thus, the wing's planform must be made up of segments with straight taper, and with separate pieces of flat FRP sheet cut to size for each segment. Nonetheless, a whole-wing mold can be used for making a wing composed of several segments with straight taper. This paper deals only with the manufacture of wings; however, the applications of this method are obvious to tail surfaces and to the portions of fuselages whose shapes can be made by bending a flat sheet, such as a variety of cylindrical and conical-type shapes.

Although sailplane wings are discussed here, this method is equally applicable to wings of any loading or size. The wing components used to illustrate this discussion are of ribbed, sandwich construction because that is more complex. Substituting single layer components or ribless construction does not change the manufacturing process except by eliminating some of the steps. Although sheets of cured fiber reinforced polymer (CFRP)— cured prepeg, that is—and plastic foam are the skin and core materials discussed here, other materials, such as aluminum sheet and honeycombs, are just as suitable to this method.

The materials and processes used here: manufacture of flat CFRP sheets, applying a thin layer of curing rubbery adhesive (CRA), and plastic film finishes, are all existing industrial processes. Thus it is assumed in this paper that the CFRP sheets and ribbons, the CRA in two part liquid form, and sheets of plastic film with a layer of pressure sensitive adhesive (PSA), which is used for protecting the wing's exterior surface from weather, will all be supplied to the airplane factory made to spec and ready for use. Due to the higher fiber loading, higher curing pressure and temperature, and more precise process control in making the CFRP, the manufacturing process presented here can result in better structural/weight properties when compared with conventional hand layup and prepreg methods.

Materials

Since the curing of prepreg produces volume changes in the mold, precured prepreg or aluminum is used for sandwich skins. CFRP sheets are produced in a heated press from prepreg. Almost any fiber, weave, and thermosetting or thermoplastic polymer matrix can be used. The most suitable present materials for aircraft are aramid or carbon fibers in an epoxy matrix.

For the outermost surface of sailplane wings, puncture and crack resistance are most important, so an aramid cloth is best. For spar caps, unidirectional orientation is best, so they can be made from CFRP ribbon, which may be made from carbon fibers for light weight. This ribbon may be cut from a sheet of CFRP with a cloth which has 98% of the fibers running in one direction. The taper in the spar cap can be made by using fewer and/or narrower plys of CFRP ribbon towards the wing tip. Alternately, a pultrusion may be used, but in this case the taper in thickness must be made by grinding. The spar web may use a carbon cloth CFRP for stiffness.

After being cut to shape, the sheets of CFRP are coated on one side with a layer of CRA. This two part liquid adhesive has the property of curing soon after it is mixed. The CRA may be applied without solvent with an airless paint spray gun, roller, or meyer rod. A spray booth with a conveyer belt would be used for mass production. After coating on the CRA, in a period of minutes to hours determined by the concentration of the curing agent, the adhesive turns from a tacky liquid which flows, adheres, and then cures at room temperature to a rubbery plastic which does not creep. Because the CRA, like the epoxy in prepregs, shrinks on curing, it must have a low enough modulus of elasticity to not warp the sandwich when it cures in the mold. Typical CRA materials are two component flexible epoxy or urethane.

The core material used in the sandwich wing surfaces, ribs, and webs can be plastic foam or a honeycomb, depending on the end use of the wing. However, the adhesive method used to fasten the core to its skins which is presented here is suitable for foam cores only, and another method of applying adhesive would be used for honeycomb cores. To avoid a heavy adhesive layer between the foam and its skins, the foam must be small celled. The same thin layer of CRA which was applied to one side of the CFRP sheets is also applied to both sides of the foam core material, so that the "wet", or uncured, CRA is always being placed against wet CRA during assembly.

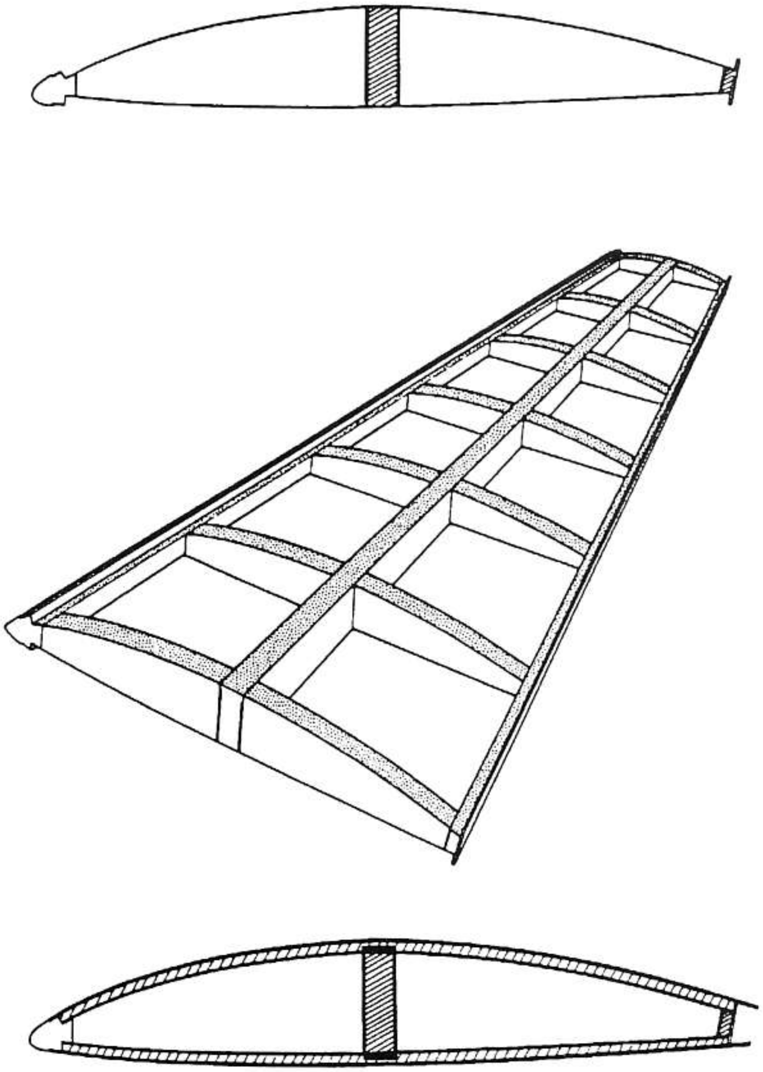


FIGURE 1.

In the example presented here, the wing frame consists of the leading edge, the ribs, the spar web and the trailing edge web, as is shown in Figure 1. These parts are assembled together using the same CRA, which is used in the sandwiches, although microspheres would be mixed in where it is necessary to fill voids. Alternately, a CRA which foams before it cures could be used to fill voids. The jig used to assemble the frame is merely a flat table with registration pins for aligning each part.

The leading edge is the region where the wing's profile must be maintained with the greatest accuracy. It must also be strong and hard enough to resist minor impacts. It can be made from a high density foam (say, 0.3 gm/cc or 20 lb/cu ft), which may be thought of as a synthetic hard wood which is not sensitive to moisture. Hand profiling the leading edge is suitable for very small production runs, while computer controlled milling is suitable for larger production runs.

If it is to be left outdoors, the wing may be finished by covering it with a thin white plastic film which is coated on one side with a non-curing pressure sensitive adhesive (PSA) and a release paper. This layer replaces the thicker conventional gel coat. White Tefzel or other fluropolymers would be good film materials because they are extremely weather resistant and easy to clean. Their very low surface energy, like that of the softer Teflon, prevents bugs and dust from sticking in the first place, thus promoting laminar flow. These materials, with a PSA coating and release paper, are commercially available as weather resistant coatings for sheet metal buildings from, for example, Dupont and Hochest.

Equipment

A sailplane wing mold is shown in Figure 2, and its operation is shown in Figure 3. It is used first to assemble the wing surfaces, and then to join the frame to the wing surfaces. This mold requires an accuracy of +.002 inches over its entire surface, with accuracy increasing toward the leading edge. The mold has registration pins to keep the upper and lower halves in alignment. A backing of thick sandwich panels give the

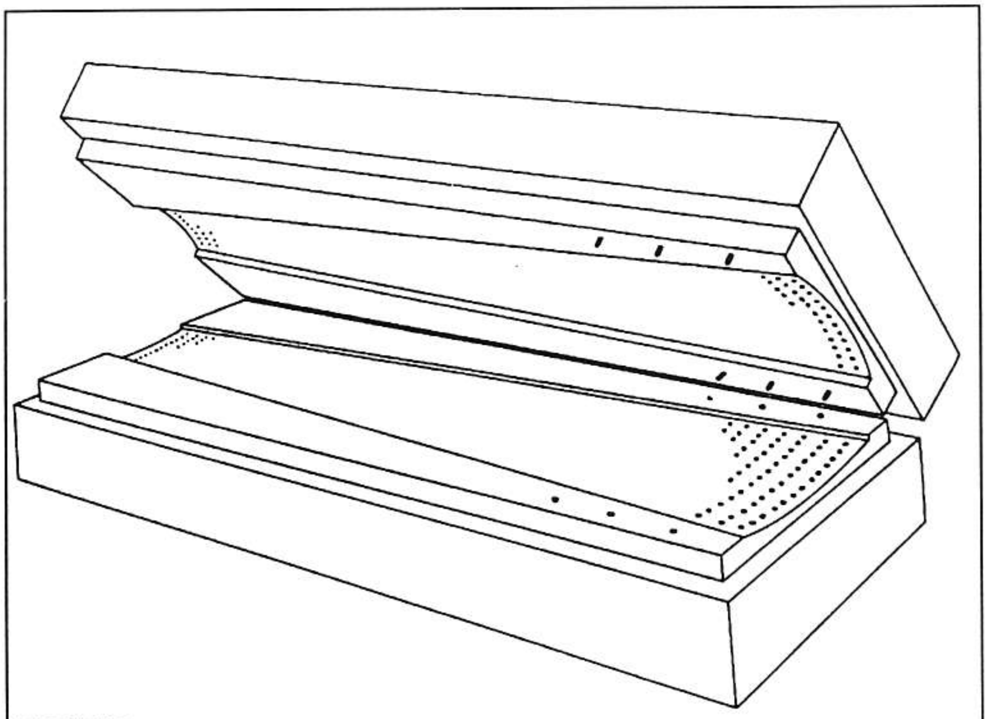


FIGURE 2.

mold extra rigidity. The mold halves for the upper and lower wing surfaces are hinged to assemble the complete wing, following the conventional clamshell procedure for assembling sailplane wings.

Unlike a conventional mold for sailplane wings, there is a grid of small holes in the mold surfaces, as shown in Figure 2. These holes are used with a vacuum bag to apply a vacuum to the wing surface sandwiches when they are being formed in the mold, thus making the wing surfaces conform accurately to the mold. After the sandwiches have cured in the mold, the vacuum is again used to hold the wing surfaces accurately in place for the clamshell assembly of the wing surfaces with the frame.

In order to allow the escape of any air pockets trapped between the surfaces of the mold and the wing, the mold surface must have a fine texture which does not reduce its accuracy. Alternately, a grid of fine channels may be milled into the mold surface, or a layer of, say, .005 inch thick polyester film may be placed between the mold surface and the wing surface. This film would have a "frosted" surface texture and a grid of small holes, both for the flow of air pockets to the vacuum holes in the mold.

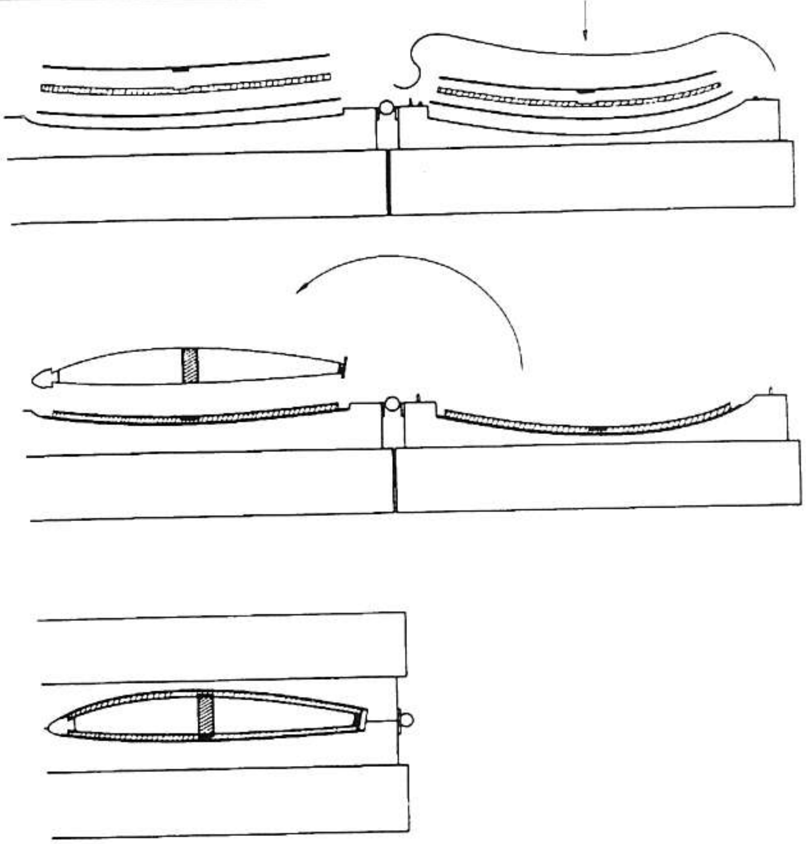


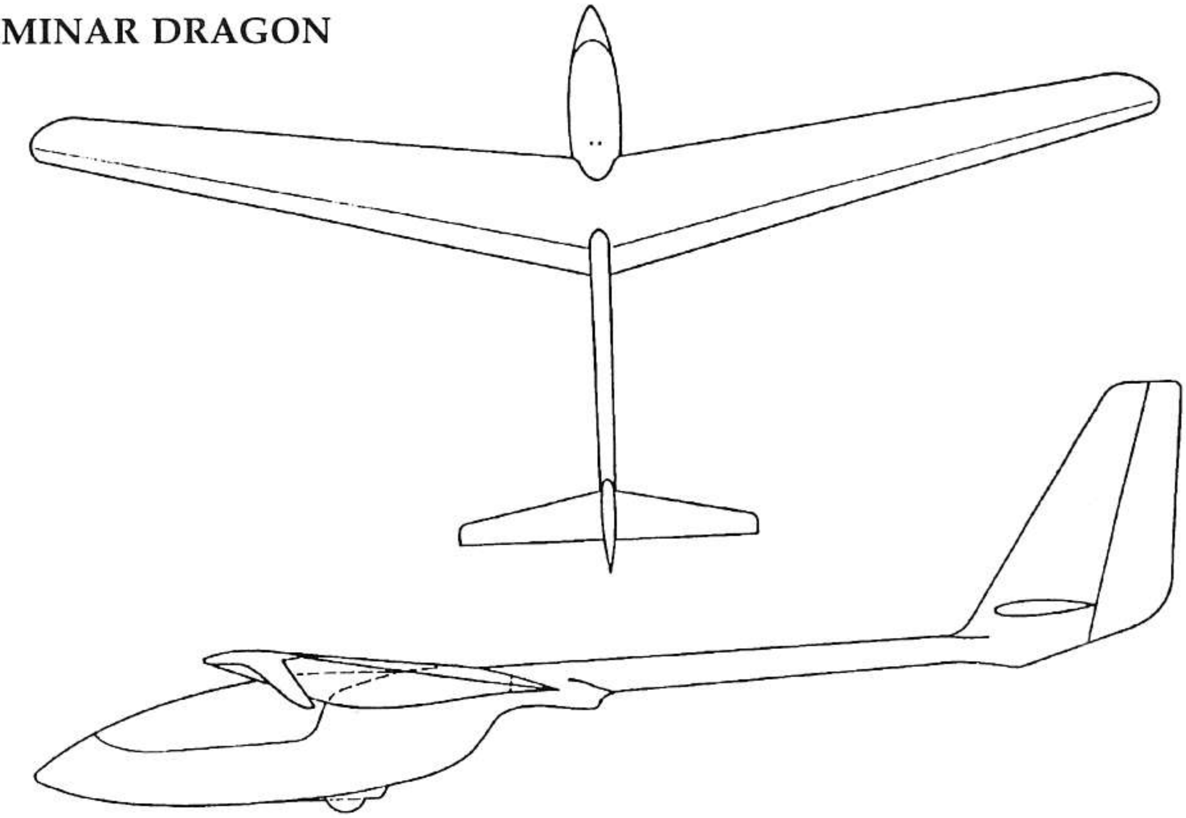
FIGURE 3.

Procedures

Where sandwich wing surfaces are used, the assembly procedure consists first of the parallel processes of fabricating the wing frame and the wing surfaces. Then the frame and wing surfaces are joined when the two halves of the mold are hinged together; see figure 3. To tailor the fiber material, orientation, and amount to the local flow of stresses, multiple layers of cut shapes of CFRP sheet and ribbon may be used in the following procedures.

The procedures which follow are for the frame and wing surfaces both made of CFRP/CRA/foam/CRA/CFRP sandwich material. If a single layer material is used instead of a sandwich for some of the parts, or if sparless and/or ribless construction is used, then the same procedures apply with the obvious sim-

LAMINAR DRAGON



Laminar Dragon

The Laminar Dragon is the Carbon Dragon adapted to high performance sailplane materials and laminar flow. To access the benefit of such a design, here are a set of assumptions and conclusions which have been extrapolated from the measured performance of the Carbon Dragon. To meet both the weight and laminar flow demands, new construction methods are desirable, if not essential.

Same as Carbon Dragon:

- configuration and proportions
- stall speed
- stress rating
- structural weight efficiency
- maximum lift coefficient
- root and tip cords and thickness

Changes:

- No foot launch
- closed cockpit
- 11° forward wing sweep
- span increased from 13.5M to 15M
- flapersons decreased from 30% to 20% of cord
- laminar run on wings and tail increases from 30% to 70%,
- parasite drag on fuselage decreases 50%, reducing wing and tail parasite drag by 50%

Specifications:

- span 49 ft
- wing area 165 ft 2
- aspect ratio 14.5
- empty weight 200 11
- pilot + parachute 11
- stress rating + 7.59

Calculated performance:

- sink 1.32 fps at 25 mph
- L/D 38 at 34 mph
- stall speed 20 mph
- maximum speed 75 mph

Comparison with Carbon Dragon:

- sink -25% at + 9% speed; 1/(1 - .25) X 1/(1 + .09) -1 = +22% Rise
- L/D = 46% at = 9% speed; (1 + .46) X (1 + .09) -1 = +59% Run

Conclusion:

Reducing parasite drag by 50% with laminar flow and streamlining results in a 20% increase in rise performance and a 60% increase in run performance.

plifications. Typical materials and dimensions for sailplanes are used throughout the following discussion.

The first step in fabricating the wing frame is to make the frame parts, which consists of:

The flat CFRP/CRA/foam/CRA/CPSA sandwiches used for making the ribs and webs are made by: laying a sheet of CFRP with a freshly applied CRA coating facing up on a flat table. Then an equal size and shape sheet of foam is coated on one side with CRA. The foam, CRA side down, is then placed on top of the CFRP. Then this CFRP/CRA/foam is coated with CRA, as is the second layer of CFRP, which then is placed CRA face down on top of the CFRP/CRA/foam/CRA, forming a CFRP/CRA/foam/CRA/CFRP sandwich. This flat assembly is then vacuum bagged on the table for the room temperature cure time of the CRA.

The above sandwich materials are then used to fabricate the spar web, the trailing edge web, and the front and rear ribs. The webs may be cut with a table saw and the ribs may be cut with a band saw. The ribs and webs may have reinforcing caps made of strips of CFRP and adhered with CRA to their edge surfaces. The ribs and webs are cut slightly undersize to allow room for the adhesive to the wing surfaces, which fills up any inaccuracies in fitting the frame to the wing surfaces. The wing surfaces are accurate because they are in the vacuum mold.

The leading edge is made from high density foam. It can be formed by computer controlled milling or hand profiled.

These frame parts are then assembled; see figure 1.

A table jig with registration pins is used. The frame can be removed from the jig as soon as the CRA has cured. A pressure sensitive type CRA, like "rubber cement," may simplify frame assembly.

We now take up the second track in building the wing. This track runs parallel to the frame fabrication above. This is the procedure for assembling the upper and lower sandwich wing surfaces in the mold halves:

The four or more CFRP sheets and two or more foam sheets for the sandwiches for the upper and lower wing surfaces are cut to size. For the spar caps and other places with stress concentrations, several layers of a ribbon or sheet of unidirectional CFRP freshly coated on both sides with CRA may be placed in the mold, with each layer cut to shape and oriented to match the flow of stress when the part is in use.

Joints between CFRP sheets or ribbons in the same layer are necessary because the CFRP sheets are not as large as a wing, and also where the wing's planform has several straight taper sections, which requires cutting separate sheets of CFRP for each section. These are butt joints for a smooth wing surface. The butt joint is strengthened by an overlapping strip of CFRP, which is adhered with CRA.

The above sandwiches are then covered with a plastic film vacuum bag and a vacuum is applied for the cure time of the CRA to consolidate the curvature of the sandwich while it is in the mold and for good adhesion between the CFRP and the foam.

The cured wing surfaces in the mold are now ready to receive the frame with its CRA adhesive:

The frame's bonding surfaces are coated with CRA with a paint roller or a brush.

The frame is placed on one of the wing surfaces in one of the halves of the mold, with the vacuum applied.

Then the other half of the mold, containing the other wing surface, is hinged closed over the frame and the mold is clamped shut for the cure time of the CRA.

The wing is removed from the mold, and is now ready for finishing, which involves:

Filling in any cracks in the leading edge seams with epoxy containing epoxy microspheres.

Optionally covering the wing with a fluropolymer finish film for weather protection, which is supplied with a PSA and release paper.

Summary of Manufacturing Methods and Materials for Laminar Sailplane Wings

Typical Materials

- Sandwich for wing surfaces, Ribs & Webs: aramid cloth or carbon and epoxy, .030" to .010n thick + small cell foam - Rohacell, specific gravity .03 g/cc or 2 lb/cu. ft. + flexible epoxy, .003"
- Spar Cap: carbon/epoxy unidirectional ribbon, + flexible epoxy, .003n
- Leading Edge: foam-Rohacell, specific gravity 0.3 g/cc or 20 lb/cu. ft.
- Frame Adhesive: flexible epoxy, .010n thick
- Exterior Finish Film: white Tefzel, .002n + acrylic PSA, .002n + release paper

Equipment

- Vacuum Clamshell Mold
- Spray booth with conveyer belt
- Computer controlled milling machine

Assembly Procedure

Make frame Parts:

- flat table & vacuum bag: assemble sandwiches for ribs & webs
- table saw: spar & trailing edge webs, accuracy .010"
- band saw: ribs, accuracy .010"
- mill leading edge, accuracy .001"

Assemble Frame:

- flexible epoxy + epoxy microspheres, .01"
- table jig, accuracy .010"

Assemble Spar Caps:

- unidirectional carbon fiber + flexible epoxy, .003"
- flexible epoxy, .003", cap to inner aramid cloth/epoxy

Assemble Sandwich Skins:

- Vacuum Mold
- aramid cloth/epoxy + flexible epoxy, .001"
- foam + flexible epoxy, .001"
- aramid cloth/epoxy + flexible epoxy, .001"
- vacuum bag

Assemble Wing:

- insert frame and hinge upper & lower skins together, accuracy .004"
- flexible epoxy + epoxy microspheres, .050"

Finish:

- fill leading edge seams, epoxy + epoxy microspheres
- cover wing with white Tefzel/PSA, .002"/.002"

Sources of Materials

Aramid and carbon CFRP are made by M.C. Gill Co., 4046 Easy Street, El Monte, California, 91731. This company makes both prepreg and CFRP. These CFRP's have up to 70-75% by volume fiber loading, and are available in thicknesses which are multiples of .010 inches.* Sheet size is up to 4 x 12 feet. The aramid cloth CFRP is made from a symmetrical weave of Kevlar 49 and epoxy, and its cost is from $5 to $20 per square foot, depending on thickness and quantity. Contact Cindy Walker or Martin Cohen at (818) 443-4022.

The unidirectional carbon cloth used to make, for example, the CFRP ribbon for spar caps, is made by Textile Products Inc., 2512 West Woodland Avenue, Anaheim, California, 92801. An example is product number 4475, which costs about $24 per square foot when made with intermediate modules carbon fiber. At $0.92oz/ft^2$, this cloth makes .010 inch thick CFRP. Contact George Kania at (714) 761-0401.

Carbon pulltrusions are made by Glass Forms Co., 271 Barnard Ave, San Jose, California, 95125. The minimum thickness is .O50 inches, and the fiber loading is 50-60% by volume. Set up costs are about $500. Contact Mike Guglielmo at (408) 297-9300.

A typical epoxy CRA is available from Lord Co., 2000 West Grand View Boulevard, P.O. Box 10038, Erie, Pennsylvania 16514-0038. It is product number 312. After mixing the two components, working life is 1-2 hours, and cured parts may be removed from the mold after about 24 hours at room temperature. Shrinkage during cure is less than 0.1%, young's modulus is 3,000 psi, elongation at break is 55%, glass transition temperature is 122°F, and viscosity is 2000 cps, which is thin enough to be sprayable. 312 costs $112 for one gallon and $27 per gallon for 55 gallons. Contact Brian Stull at (814) 868-3611.

These materials are only an illustrative starting point for a thorough search for, and testing of, the best off-the-shelf materials for any particular airplane. The author is not competent to specify materials, so any suggestions and corrections would be most helpful. Nonmilitary manufacturers and individuals interested in evaluating the methods and materials discussed in this paper are invited to contact the author at Suntek, 6817A Academy Parkway East, Albuquerque, NM 87109, USA; Fax (505) 345-9998.

- To build a laminar version of the Carbon Dragon sailplane, .010 inches is just about the right thickness for the wing sandwich skins.