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One-shot Manufacturing Techniques Developed for Carbon Fiber Prepreg Components

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One-shot Manufacturing Techniques Developed for Carbon Fiber Prepreg Components

by

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If you told me six years ago when I finished my undergrad degree that I would be finishing a PhD, I probably would have laughed and called you crazy. But here I am, and I don’t regret it. I have learned quite a lot (including that there is a lot that I don’t know) over my years here and cannot show my appreciating enough to the large number of people that helped me get here.

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Abstract

The need for faster and more accurate manufacturing methods for composite parts continues to grow. Co-curing composite structures can decrease manufacturing time by eliminating secondary operations such as grinding, jigging, bonding, and fastening while creating lighter and more accurate parts. As a demonstrator for co-curing techniques, a six-meter carbon fiber wing for a high-altitude and high-speed dynamically soaring unmanned aerial vehicle (UAV) was designed and manufactured in one cure cycle. Two wing-skin molds were created using low density tooling board, with the mold geometry directly machined into the material, reducing tool manufacturing time and cost. An aluminum insert was used to create a trailing edge cavity while maintaining a simple parting line of the wing tool. Three removable forms made of polystyrene foam inside of the wing cavity were used to position six internal webs and, after curing and removal of the forms, resulted in a hollow wing with internal webs. The resulting wings showed some defects in the wing skins but overall produced structurally sound parts.

Expanding on the previous co-curing techniques, a 1.1-meter carbon fiber horizontal stabilizer with internal structure and an elevator connected by a composite flexure was designed and manufactured in one cure cycle. The stabilizer is used in a high-altitude and high-speed dynamically soaring unmanned aerial vehicle (UAV). The top skin is used as the flexure, creating a seamless top surface between the stabilizer and elevator. Three removable forms made of polystyrene foam were used inside the stabilizer to position a spar web and center rib, which after curing and removal of the

forms resulted in a hollow stabilizer with an internal web and rib. The resulting stabilizers showed minor defects in the wing skins but overall produced structurally sound parts.

The demonstrators showed the great potential for creating complex composite parts and assemblies using only a single cure cycle while needing little finishing work and no secondary bonding, resulting in high precision at relatively low cost.

Utilizing the components produced, the JetStreamer was able to be assembled and flown in Weldon, The JetStreamer is believed to be the largest unmanned aircraft to demonstrate dynamic soaring.

1. Introduction

1.1 Overview

Advanced composites have typically been reserved for high performance structures such as military aircraft, Formula 1 cars, America's Cup boats, etc. However, as increased emphasis is being placed on energy efficiency, increased effort is being put towards reducing component weights in order to achieve this goal. Vehicle manufactures, in particular, are looking to increase fuel efficiency by reducing vehicle weights. Composite materials are an attractive option to reduce structural component weights while maintaining the same level of structural integrity. Some early commercial adoptions of this approach are seen with companies such as BMW and Boeing. Carbon fiber reinforced plastics (CFRP) account for the largest share of structural weight for the BMW i3's body[1], and is being used to prove structural composites use in a commercial high-production environment. Additionally, the Boeing 787 Dreamliner is 50% composite by weight [2] and is a contributor to the 20% increase in fuel efficiency compared to its predecessor. Boeing saw an average weight saving of 20% when compared to conventional aluminum component designs [2]. While these are just a couple high profile examples, the use of composites to reduce structure weight can be seen throughout many industries. Growth rates of 6 to 9 % for the automotive composites market alone are expected over the next few years and supports the notion that structural composites will be used more and more [3].

However, the move towards composites structures is not without compromise. Raw material costs are typically the largest contributor to component cost (independent of processing method) followed by labor and plant costs [4], therefore any reductions material requirements or labor can have significant impacts on part costs. Decreasing weight, manufacturing time, and overall cost while retaining or improving accuracy will become even crucial for the industry to grow as composites continue to be used in a variety of structural components.

1.2 Current Trends

Co-curing complex components, which would traditionally be made of serval parts, can offer significant reductions in cost and manufacturing time by eliminating time intensive (and possibly weight adding) secondary operations. However, co-curing components puts special demands on the design of the parts as well as the tooling. It typically requires more careful consideration of the manufacturing process during the part design.

Pushes towards one-shot (or single cure) manufacturing are being made across the composites industry, independent of the resin technology used. Hexion partnered with DD-Compound and Wilson Custom Composites to produce single-shot infusions for marine application such as Formula One race boats [5]. Examples using one-shot Resin Transfer Molding (RTM) include an Airbus 320 spoiler made by British Aerospace Airbus Limited under the SimRTM [6] project. The spoiler was made of CNC machined foam cores and a number of carbon fiber preforms, placed in a heated aluminum mold and infused in one shot. Romano [7] designed and manufactured an RTM composite aileron for an Avanti P180 and was able to reduce the component weight by over 20%, costs by 30%, and part count from 21 to 2. Zilberman [8] achieved a 50% reduction on manufacturing time and a 35% reduction in cost by creating an aileron for the Heron TP UAV in a one-shot RTM process. Hopmann [9] was able to produce an entire CFRP engine hood in one-shot with fast cycle times. These works reinforce that one-shot processing can have significant improvements for manufacturing time and cost.

One-shot components using prepreg appear to be less common than RTM processes and the like. However there are commercial examples such as Axxon Composites [10], among others, who produces full carbon prepreg masts with an internal web in a single cure. Marstrom Composites makes a number of one-shot carbon fiber items using prepreg, including boat hulls, dagger boards, and masts [11]. For one-shot components using pre-impregnated reinforcements (prepreg), Smart Tooling [12] offers reusable inflatable bladders that are rigid at room temperature but malleable at elevated temperatures. Prepreg is laid up on the rigid bladders, then transferred into molds and cured, with the bladders being extracted afterward in a malleable state. The bladders simplify the manufacturing of complicated parts with internal structure in a single-shot.

There are studies on some of the processing techniques utilized for one-shot prepreg components include work such as Huang's [13] investigation of corner radii sizing and manufacturing techniques for co-curing of blade-stiffened panels. The work showed that with proper manufacturing techniques and correct corner radii, bond strengths similar to traditional fastening methods could be achieved between the stiffener and panel. Li [14] performed simulation work to determine warpage and internal stresses of blade stiffeners during cure; not unexpectedly their work indicated that co-curing of the blade stiffener could result in greater deformations of the final part after cure than with secondary bonding. Work has been done to develop manufacturing techniques for co-cured hat-stiffened panels. Kim [15] evaluated various molding techniques for co-cured hat-stiffened panels, with inflatable internal molds showing excellent bond performance verses other bonding techniques. Huang [16] investigated stiffened composite panels as well and concluded that co-cured stiffeners exhibited better properties than secondary bonded stiffeners. GKN Aerospace [17], under the OOA Composite Processing Phase II program, has been developing out-of-autoclave (OOA) technologies and created a lightweight, blended aircraft wing box featuring integrally stiffened skins, complex contours and four different stringer shapes. The parts used vacuum bag technology and low-cost tooling which becomes practical when curing outside the autoclave environment. Additionally, under the Structures Technology Maturity (STeM) project, GKN produced a winglet with a one-piece, co-cured upper skin and waffle stiffener while the lower skin was mechanically fastened [18]. This shows that one shot composites are desired in the industry and research supports the potential gains of the one-shot processing.

However, there appears to be far less work that bridges the gap between novel prepreg manufacturing concepts and the production of the complex structures seen in industry. Mei [19] created a tetrahedral truss core in a single shot process but is still for a flat panel. [20-23] investigate complex core structures, however their usage is on constant thickness parts and are produced through multiple steps.

These works have shown that one-shot manufacturing has significant interest to industry since it can decrease processing time, and costs over more traditional methods. Work has shown novel internal structures are possible with one shot manufacturing across all resin technologies. However, there is an apparent lack of published work that implements these concepts to more complex geometries using prepreg.

1.3 Objective

This work's goal is to provide real-world techniques for creating complex one-shot prepreg components, thus bridging the gap between research and industry implementation. This work includes utilizing novel techniques for creating internal structures and the use of flexures to create single parts that would traditionally be manufactured in multiple pieces and joined. Utilizing the techniques presented, reductions in part count and manufacturing time are achievable and as a result can decrease overall part costs.

The JetStreamer, a high-altitude high-speed UAV glider designed for dynamic soaring in jet streams, was utilized as a test platform for the development of complex one-shot prepreg components. Dynamic soaring is a technique to extract energy to propel a glider using only horizontal winds. Dynamic soaring is often done by RC model flyers at low altitudes, but numerical simulations indicate that dynamic soaring could be performed also in high-altitude jet streams, e.g. [24-26]. An early concept rendering of the JetStreamer is shown in Figure 1. The wing was a good candidate for single-shot manufacturing since precision, manufacturing time and cost were of importance for the project.

Figure 1. JetStreamer Concept Rendering

This work will detail the two significant prepreg component's (wing and horizontal stabilizer) design and manufacturing along with overviews of other component manufactured for the JetStreamer

Section 2 is on the design and manufacture of the JetStreamer's six-meter wing. The wing has a truss-like internal structure that runs the entire length of the wing and was produced in a single shot.

Section 3 is on the design and manufacture of the horizontal stabilizer and elevator for the JetStreamer. The horizontal stabilizer and elevator were able to be produced together and in a single by joining the two using a composite flexure.

Sections 4 and 5 are overviews of other components manufactured to complete JetStreamer.

Section 6 is on the test flights of the JetStreamer in Weldon, California.

2. Single-shot Wing for a Dynamically Soaring UAV

The design of the JetStreamer is beyond the scope of this paper and the aircraft design will be treated as givens. The pertinent parameters for the structural design of the wing are shown in Table 1.

Table 1. Wing Design Parameters

Wingspan	6 m
Root chord	375 mm
Tip chord	204 mm
Airfoil thickness	13%
Ultimate design load factor	20 G
Never exceed speed (sea level), V_{NE}	135 m/s
Maximum takeoff mass	50 kg

The main aircraft requirements that affected the structure were the following: the high aspect ratio wing required for a high lift-to-drag ratio, high g-load capabilities to achieve high turn rates at high speeds, and a high terminal speed in a dive. Carbon fiber prepreg was chosen for the aircraft due to its high strength, stiffness, and ease of creating complex components. This paper covers the basic structural design and manufacturing techniques developed for the wing for the JetStreamer.

2.1 Structural Design of the Wing

2.1.1 Materials and Internal Structure

The prepreg Gurit SE84LV with Toray T700 unidirectional carbon fibers was chosen for the wing construction for its high strength, decent toughness and stiffness, and low cure temperature. Some stiffness properties of the Gurit system were not available, thus for the design the well documented material properties of AS4 fibers with Hercules 3501-6 resin was substituted when necessary. The AS4 fibers have a 231 GPa tensile modulus [27] versus the T700 fibers' 230 GPa [28]. The 3501-6 resin has a tensile modulus of 4.24 GPa (0.615 Msi) [29] versus 3.9 GPa for SE84LV [30]. The relatively small difference in stiffnesses of the two fibers and two resins suggest that some properties of the AS4/3501-6 system can be used with sufficient accuracy for the T700/SE84LV system. A summary of the pertinent material properties used for the present design is given in Table 2, with T700/SE84LV properties taken from [30] and AS4/3501-6 properties from MIL-HDBK-17-3F [31].

Table 2. Presently Used Unidirectional Carbon Fiber Ply Properties

Carbon Fiber Ply Weight [30]	150 g/m²
Ply Thickness [30]	0.15 mm
0° Tensile Strength [30]	2658 MPa
0° Tensile Modulus (E_1) [30]	222 GPa
0° Compressive Strength [30]	1166 MPa
90° Tensile Modulus (E_2) [30]	9 GPa
Shear Modulus (G_{12}) [31]	6 GPa
Poisson’s Ratio (ν_{12}) [31]	0.334
Minimum cure temperature [30]	80 C
Minimum cure time at minimum cure temperature [30]	12 hours

The Gurit system can be cured under vacuum and heat without the use of an autoclave. A truss-like internal structure as depicted in Figure 2 was chosen to provide shear strength, support for the wing skins, sufficient strength and stiffness of the cross section, and simple connection to the fuselage. This geometry allows the wing to be manufactured in a single cure with no secondary bonding.

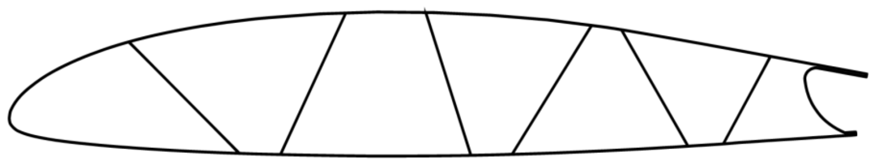

Figure 2. Cross Section Geometry of JetStreamer Wing

2.1.2 Spar Cap Design

With the JetStreamer's design mass of 50 kg and ultimate load factor of +/-20 g, the wing had to be designed to withstand a 9810 N load. For design, it was assumed that the load on the wing was evenly distributed along the span with the fuselage attached mid-span; this is a conservative estimate for symmetric flight conditions (where loads tend to be more elliptically distributed) but not necessarily a conservative estimate for a wing with ailerons and/or flaps deployed.

The bending moment on the wing was assumed to be carried by spar caps composed of span-wise unidirectional fibers,oriented built into the top and bottom wing skins. An 800 MPa ultimate compression strength was used for the spar-cap plies; this is lower than the value in the data sheet to account for various manufacturing defects, as well as crippling in the flanges (for example Figure 5.7.2(f) in [31] shows about a 20% decrease in compressive strength due to crippling for a plate with a width to thickness ratio of 10:1). The upper and lower spar caps were assumed as identical thin laminates and the sole contributor to the bending strength of the wing. The stress in the spar caps, σ, is approximately

$$\sigma = \frac{M}{A_f d} \tag{1}$$

where A_f *is* the cross-sectional area of one spar cap, M is the bending moment, and d is the thickness of the airfoil; these parameters vary along the wingspan. For the design case above, neglecting the mass of the wing and assuming the total aircraft mass in the fuselage, the distributed load on the wing is $\omega = Nmg/b = 1635\ \mathrm{N/m}$ and the bending moment is

$$M = \frac{1}{2}\omega y^2 - \frac{1}{2}\omega b y + \frac{1}{8}\omega b^2 \tag{2}$$

where b is the wingspan and y is the distance from the wing centerline (butt line). The initial ply width, w_{init}, for the spar cap was chosen to be 90mm with each subsequent ply decreasing in width by 2 mm in order to create a spar cap with a slightly trapezoidal cross section. This allowed for a reasonably smooth inner surface for the wing skin plies laid over the spar caps. From Eq. 1, using the geometry of the wing, spar cap shape, and load case from Eq. 2, the stress in the flange is approximated as:

$$\sigma = \frac{\frac{1}{2}\omega y^2 - \frac{1}{2}\omega b y + \frac{1}{8}\omega b^2}{nt\left(w_{init} - \frac{n w_{dec}}{2}\right)\left(d_{max} - y\frac{\left(d_{root} - d_{tip}\right)}{2}\right)} \tag{3}$$

where n is the required number of plies, t is the ply thickness, and w_{dec} is the decrease in width per ply (2mm in this case). The maximum airfoil thickness was used as the wing spar height, varying from d_{root} =48mm at the root and linearly decreasing to d_{tip}=26mm at the wing tip. Figure 3 shows the number of plies required for the stress in the flange to be less than 800MPa as a function of distance from the wing's centerline.

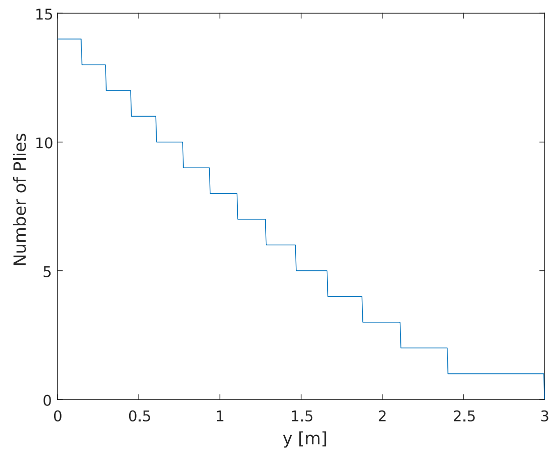

Figure 3. Required Number of Spar Cap Plies vs. Distance from Centerline

2.1.3 Spar Web Design

To carry the shear load in the wing and provide support to the wing skins, a multiple-webbed internal structure as shown previously in Figure 2 was chosen. The internal structure was designed to be co-cured with the wing skins and spar caps, which allowed a complete wing to be produced in a single cure cycle.

The webs were designed using a symmetric and balanced $[+45,-45]_s$ layup of unidirectional fibers. From laminated plate theory, material properties given in Table 1, and an 800 MPa ultimate ply compression strength, the maximum shear strength, τ_{cr}, for the laminate is 400 MPa. Assuming the fuselage was mounted mid-span, the minimum required web thickness at the root, t_{root}, if only a single web were used, would be:

$$t_{root} = \frac{n_{max} m g}{2\tau_{cr} d_{root}} \tag{4}$$

where n_{max} is the ultimate load factor, m is the mass of the aircraft, d_{root} is the height of the web at the root of the wing, and g is acceleration due to gravity. The required laminate thickness for the web is ~0.3 mm at the root and decreases towards zero at the wing tips. The minimum 4-ply laminate has a thickness of 0.6 mm, thus a single web could carry the wing's shear load. This, however, neglects shear buckling of the webs.

A rough, yet for the present purpose sufficiently accurate, estimate of shear buckling stress of a web can be obtained by approximating it as a simply supported infinitely long strip with orthotropic properties. The height of the strip is modeled as the web height at the wing root (48 mm). An approximation for shear buckling stress, τ_{buckle}, is [27]:

$$\tau_{buckle} = \frac{k_3 \sqrt{C_2} D_{22}}{t_{web} d_{root}^2} \tag{5}$$

where

$$C_2 = \frac{D_{12} + 2D_{66}}{D_{22}} \tag{6}$$

and D_{ij} are plate bending stiffnesses determined using the properties in

Table 1. In the present case $k_3 \approx 48$ (k_3 varies with C_1 and C_2 from Table 2.5 in [32]). Thus, the theoretical shear buckling stress was approximately 35 MPa per web. While the total load cannot be supported by a single web without buckling, the six webs give a total shear load capacity of ~6000N, which yields a ~1.2 factor above the ultimate design load. The buckling load of the webs is expected to be higher since the edges are elastically connected to the wing skins and not simply supported. Further, the webs near the center of the wing were reinforced with an additional set of $[+45\ -45]_s$ unidirectional plies to handle localized loads from the fuselage, further increasing the shear buckling strength.

2.1.4 Torsional Divergence

Torsional divergence occurs at a critical dynamic pressure, q_{div}, beyond which a small disturbance will lead to large deformation of the wing. From [33] the governing equation for wing divergence is:

$$\frac{d}{dy}\left[GJ\frac{d\theta}{dy}\right] = -q_{div}aec^2\theta \tag{7}$$

where GJ is the cross-section torsional stiffness, θ is the angle of twist along the wing, e is the ratio of the distance between the quarter-chord of the airfoil and center of twist to the chord length, a is the finite-wing lift slope, and c is the chord length; θ, GJ, e, c are in general functions of y. Estimating the center to twist gave a location at 36% chord, i.e.

e=0.11. For the JetStreamer the finite wing lift slope, a, was ~5.72 rad^{-1}. The other parameters were assumed to vary along the length of the wing.

To approximate the cross-sectional torsional stiffness, it was assumed the wing skins were of constant thickness. Since the airfoil is the same for the whole wing the torsional stiffness scaled to the third power of chord length. The chord and torsional stiffness of the JetsStreamer wing were modeled as:

$$c(y) = C_{root}\left(1 - \left(1 - r_{tip}\right)\frac{2y}{b}\right) \tag{8}$$

$$GJ(y) = GJ_{root}\left(1 - \left(1 - r_{tip}\right)\frac{2y}{b}\right)^3 \tag{9}$$

where C_{root} is the root chord, r_{tip} is the ratio of the tip chord to the root chord, b is the wing span and GJ_{root} is the torsional stiffness of the root profile. Using the properties from Table 1 and laminated plate theory, the shear modulus, G, for a $[+45,-45]_s$ layup was approximately 34 GPa. Using the JetStreamer's airfoil geometry and laminate thickness of 0.6 mm, $GJ_{root} \approx 15300$ Nm^2.

q_{div} is an eigenvalue for Eq.7, with the first non-zero value being of interest. The boundary conditions are zero angle of twist at the root, $\theta(0) = 0$, and zero rate of twist at the wing tip, $d\theta/dy(b/2) = 0$. Solving numerically using MATLAB's boundary value solver with an unknown parameter gives a divergence speed of 321 m/s at sea level. While this approximation is no longer accurate since it is well into the compressible flow region, it indicates that the wing has sufficient torsional stiffness to avoid torsional divergence within its flight envelope. Divergence is highly dependent on e, and as e

changes with the addition of the webs calculations were also performed for *e*=0.05, 0.10, 0.15, 0.20, 0.25, resulting in divergence speeds of 475 m/s, 336 m/s, 274 m/s, 237 m/s, 212 m/s, respectively. All these are well above the V_{NE} (135 m/s).

2.1.5 Control Reversal

Control reversal occurs when the twisting moment created by a control surface deflection causes enough twist of the wing that the resulting increment in lift is opposite of that desired. Expanding Eq. 7 to include terms for the additional twisting moment generated from a control surface deflection and allowing the dynamic pressure to vary results in:

$$\frac{d}{dy}\left[GJ\frac{d\theta}{dy}\right] = -qaec^2\theta - qc^2\left(e\,\frac{\partial C_l}{\partial \delta} + \frac{\partial C_m}{\partial \delta}\right)\delta \tag{10}$$

where δ is the control surface deflection, $\partial C_l/\partial\delta$ is the lift coefficient per control deflection, and $\partial C_m/\partial\delta$ is pitching moment coefficient per control deflection. The JetStreamer uses a 22% chord control surfaces along the entire wing and therefore $\partial C_l/\partial\delta$ and $\partial C_m/\partial\delta$ are 2.81 and -0.65, respectively [34], independent of *y*. Assuming δ is a small deflection and constant along the span and using Eqs. (8-9), the twist of the wing due to control surface deflection can be determined. This allows the roll moment from one wing to be calculated as:

$$M = \int_0^{\frac{b}{2}} qc\left(a\theta + \frac{\partial C_l}{\partial \delta}\delta\right) y\,dy \tag{11}$$

Reversal occurs when this moment equals zero. Solving this problem numerically using MATLAB's boundary value problem solver gives a reversal speed of approximately 218 m/s. Suffice to say that the reversal speed is beyond the V_{NE} of 135 m/s. Variation of *e* had minimal effect on reversal speed (only few m/s).

2.2 Tooling for Manufacturing the Single-shot Wing

For manufacturing the JetStreamer's six-meter wing in a single shot, four main components were required: a top wing-skin mold, a bottom wing-skin mold, trailing edge mold inserts, and forms to create the internal web.

2.2.1 Mold Materials

For the wing-skin molds, General Plastics FR-4718 tooling board was chosen due to its high glass transition temperature. FR-4718 however did not possess the requisite strength and durability for the smaller trailing-edge inserts; rather, 6061 aluminum was used. The internal web forms needed to be stiff enough to hold their shape during layup and debulking, while also being sufficiently compliant that small variations from the desired form geometry would not prevent the wing-skin molds from closing completely. They needed to be removed after curing the wing. Low density polystyrene was chosen as it fulfilled these requirements.

2.2.2 Wing-Skin Mold Design and Manufacturing

The top and bottom wing skin molds were manufactured using the FR-4718 tooling boards with high-temperature fiberglass laid up on the backside and mounted to a strong and stiff steel truss as sketched in Figure 4. For a large-scale part such as the wing, the difference in coefficients of thermal expansion between the tooling board and the steel can result in large differences in expansion. Over the seven-meter length of the mold, at the cure temperature of 85 C the tooling board will increase in length by approximately 21 mm from room temperature (20 C), while the steel structure will only grow by about 5 mm. This difference does not allow for rigid connections between the tooling board and the supporting structure. A support was designed using 24 flexible 1 mm thick 4130 chromoly steel plates bent into Z configurations. These connected the steel truss to the mold as sketched in Figure 4.

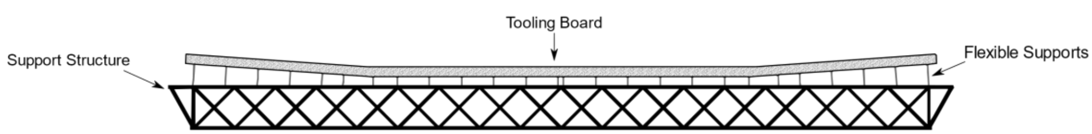

Figure 4. Lower Wing Mold

The Z-plates (shown in Figure 5) allowed for high strength and stiffness in the vertical and chord-wise directions of the mold while providing flexibility for expansion in the span-wise direction. Allowing the molds to expand prevented thermal stresses from developing and causing undesired deformations. The supports were made such that the deflections were within the elastic range of the material. The tooling board was rigidly mounted to the steel structure at mid-span to give a relative expansion of approximately 8 mm at either wing tip.

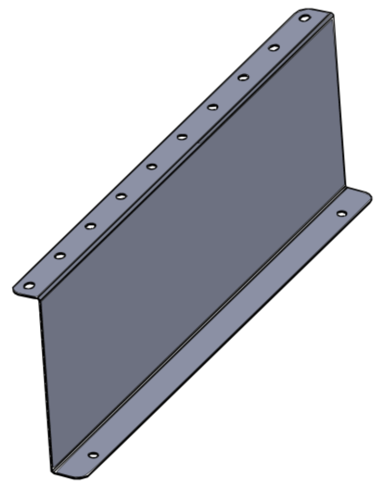

Figure 5. Flexible Mold Support made of chromoly steel

2.2.3 Control Surface Considerations and Trailing Edge Insert

In order to minimize the gap between the main wing and the control surfaces for aerodynamic reasons, a recess in the trailing edge of the wing was used, Figure 2. The recess precluded the use of a two-piece mold with a simple parting line at the trailing edge. A mold insert was designed to allow a simple parting line of the wing-skin molds while creating the desired recess. The insert would be removed from the wing once it had been cured and demolded. A cross section of the mold geometry with the insert is shown in Figure 6.

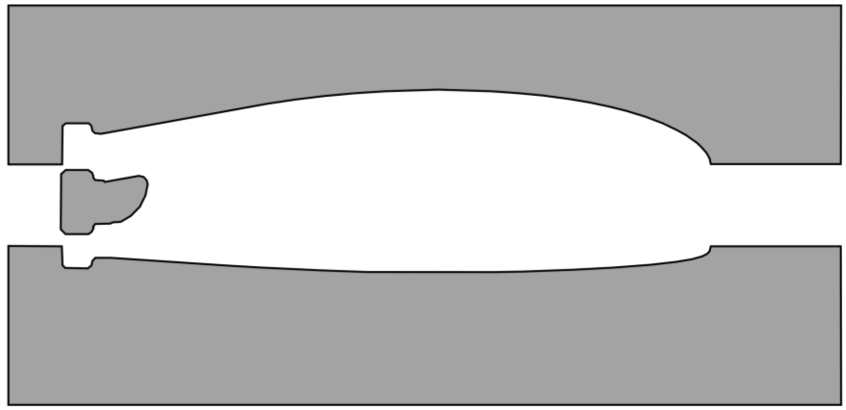

Figure 6. Mold Cross Section with Upper Mold, Lower Mold, and Trailing Edge Insert

Aluminum inserts were machined, in spite of a mismatch in thermal expansion to the molds (CTE is $47 * 10^{-6}K^{-1}$for General Plastics FR-4718 and $24 * 10^{-6}K^{-1}$for 6061 aluminum). To reduce the impact of the mismatch, the trailing edge inserts were made in 150 mm sections that could move span-wise as the molds expanded. Since the tooling board expands at a rate greater than the aluminum, small gaps of ~0.2 mm were expected to develop between each of the trailing edge inserts at the cure temperature. These small gaps were expected to fill with excess epoxy, but easily removed and sanded flat after demolding, and believed to have no significant effects on the laminate.

2.2.4 Machining the Wing Molds

Once the tooling boards were mounted to the steel trusses, the mold geometry was CNC machined directly into the boards, Figure 7. High accuracy of the finished molds was obtained.

Figure 7. Machining of Tooling Board Mold

After machining, the molds were sealed with Pro-Set M1012/M2010 epoxy to fill the pores and provide a harder surface. The mold surfaces were then sanded, starting with 400-grit sandpaper and working up to 1000-grit in increments of 200. Sanding was done to remove any surface irregularities and provide a high-quality mold surface finish. The molds were then release coated with Chemlease's release system MPP-2180, 15 Sealer EZ, and 41-90 EZ, in accordance with the recommended procedure.

This process replaces the traditional method of machining a male plug and pulling a female mold from the plug, lowering the cost of materials and reducing manufacturing time.

2.2.5 Internal Web Forms

Each polystyrene foam form was encased in a lay-flat tubing vacuum bag and placed under vacuum to pull the bag tightly against the forms. The lay-flat tubing performed two functions, it was used to apply atmospheric pressure inside of the mold during the cure cycle to compact the prepreg, and it allowed for the removal of the form after curing. To allow access to the ends of the tubing, the wing tips were left open. Figure 8 shows the layup schematic for creating the wing with internal structure in a single-shot process.

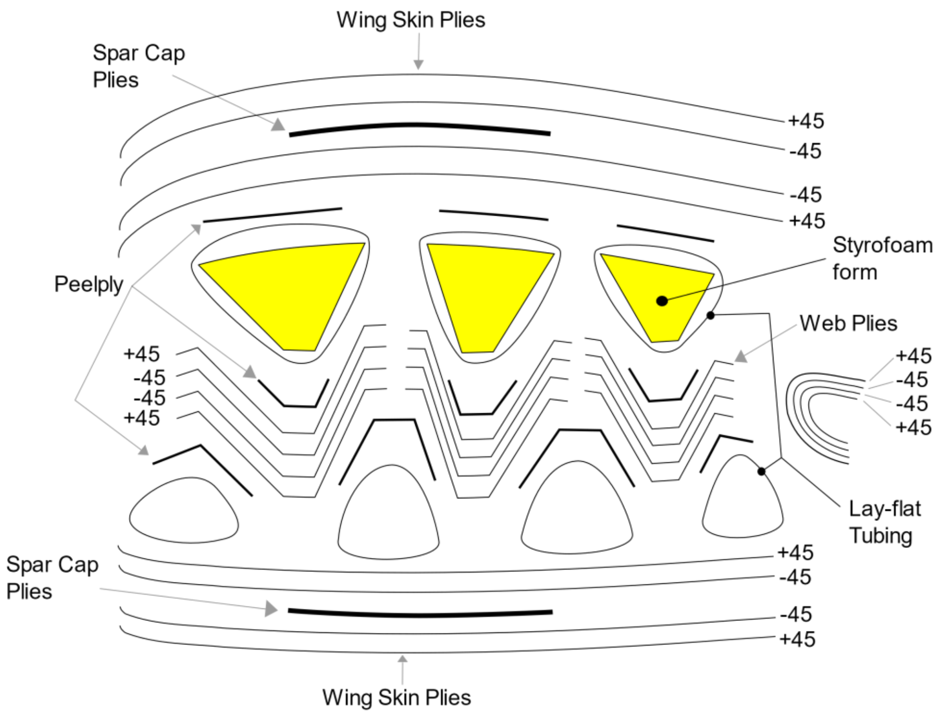

Figure 8. Wing Layup

The use of the lay-flat tubes, however, raised the concern that the internal tubes would inflate at different rates and cause the web plies to move due to pressure differentials between the tubes. The worst-case would be tubing moving between the wing skin plies and the webs, preventing the two from being bonded together. To reduce this risk, the molds were brought under vacuum slowly to allow the internal tubing to expand evenly and exert similar pressures on either side of the web plies. This procedure was very successful.

2.3 Manufacturing Procedure

2.3.1 Wing Skin and Spar Cap Layup

The whole tool for the wing consisted of two wing molds, a trailing edge insert, and three polystyrene foam forms. The first +45 wing skin ply was laid into the top and bottom molds and vacuum debulked. The first -45 wing skin ply was then laid down and vacuum debulked. Next, the first spar cap ply was laid down from wing tip to wing tip and debulked. The additional spar cap plies were laid down and vacuum debulked in sets of three. Finally, the set of -45 and +45 wing skin plies were laid over the spar caps and debulked to complete the wing skins.

The top and bottom skins were laid up in the same manner, except for the leading edge (LE) at the split line. For the bottom wing-skin mold, only the two first plies extended to the mold line at the LE, while the subsequent plies were 5 mm shorter. For the top wing-skin mold, all plies extended past the split line at the LE, the first two plies by 5 mm and subsequent plies by 10 mm. This created a strong yet lightweight joint between the top and bottom wing skins.

2.3.2 Internal Web Layup

The three full-span polystyrene forms for the six internal webs were placed into lay-flat tubing vacuum bags and evacuated to bring the tubing tight against the forms. Peel ply strips were used to aide in air extraction from the prepreg and were placed span-wise along the top and bottom of each vacuum-bagged form. A small amount of 3M 77 spay adhesive was used to hold the peel plies in place. Care was taken to ensure the peel plies would not interfere with the bond between the wing skins and webs. The vacuum-bagged forms were then positioned onto the top wing-skin mold (the wing was built upside). The first +45 web ply was laid over the forms and vacuum debulked. The remaining -45, -45, +45 plies were then laid down and vacuum debulked to complete the webs. The trailing edge plies were laid onto the trailing edge inserts and placed into the mold. Peel ply strips and lay-flat vacuum bags were placed into the open valleys between the polystyrene forms, completing the layup for the wing as shown in Figure 8.

2.3.3 Curing Procedure

After the bottom wing-skin mold was lowered onto the top wing-skin mold, the two were sealed together. The outside of the seven internal lay-flat vacuum tubes were sealed to the ends of the mold where they exited, while venting the inside of the tubes to atmospheric pressure. As the molds were slowly evacuated, the lay-flat tubing inside of the wing expanded to fill the wing cavity. Once under full vacuum, the mold assembly was cured at 85 C for a minimum of 12 hours and, after cooling, a completed wing was ready for removal from the molds.

2.3.4 Trailing Edge Insert and Vacuum Bag Removal

The cured wing was removed from the molds with the inserts remaining in the trailing edge. The inserts were then removed from the wing, resulting in a complete trailing edge recess but with small epoxy ridges formed at the gaps between the inserts. The excess epoxy ridges were easily removed and sanded smooth.

Next, the polystyrene forms and lay-flat tubing were removed using solvents, such as acetone, to soften or dissolve the foam. Once the foam was softened, the internal bags were twisted to release them from the walls and pulled out of the wing tip. This resulted in a hollow carbon fiber structure that only needed minor flash removal and sanding.

2.4 Tests Sections and Final Wing

2.4.1 Small-scale Tests

Small-scale test sections were initially made to prove the method and determine any major problems with the process before manufacturing the full-scale wing. The small-scale tests showed sufficient compaction and bonding of the web and skin plies. The webs showed excellent straightness despite the lack of control of inflation rates of the internal bags and no guarantee of contact with the polystyrene forms once the mold was closed. A typical test section is shown in Figure. 9.

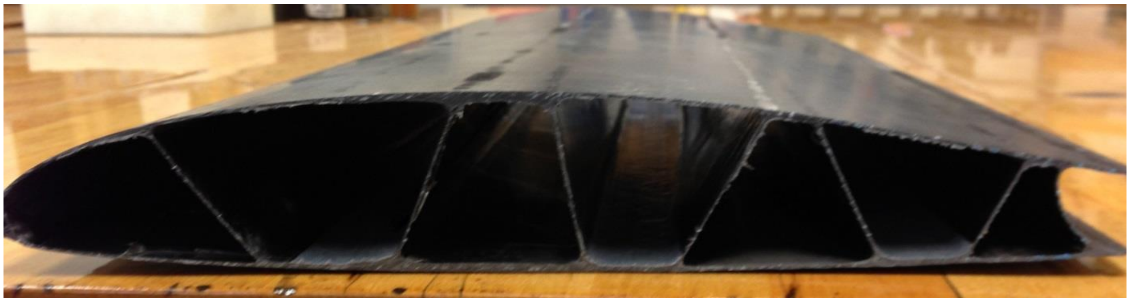

Figure. 9. Wing Test Section

Small defects on the wing skin surface were present but appeared to be mostly cosmetic in nature and did not appear to have a significant impact on the mechanical performance of the structure, as outlined later. The defects were typically on the wing skin surface coinciding with the locations of the internal webs. Figure 10 shows defects commonly seen in the small-scale test sections. The reason for the defects is most likely the relatively low force in the corners between the webs and the skins during cure and thus poor compaction. Pressure intensifiers could possibly be used to reduce the defects.

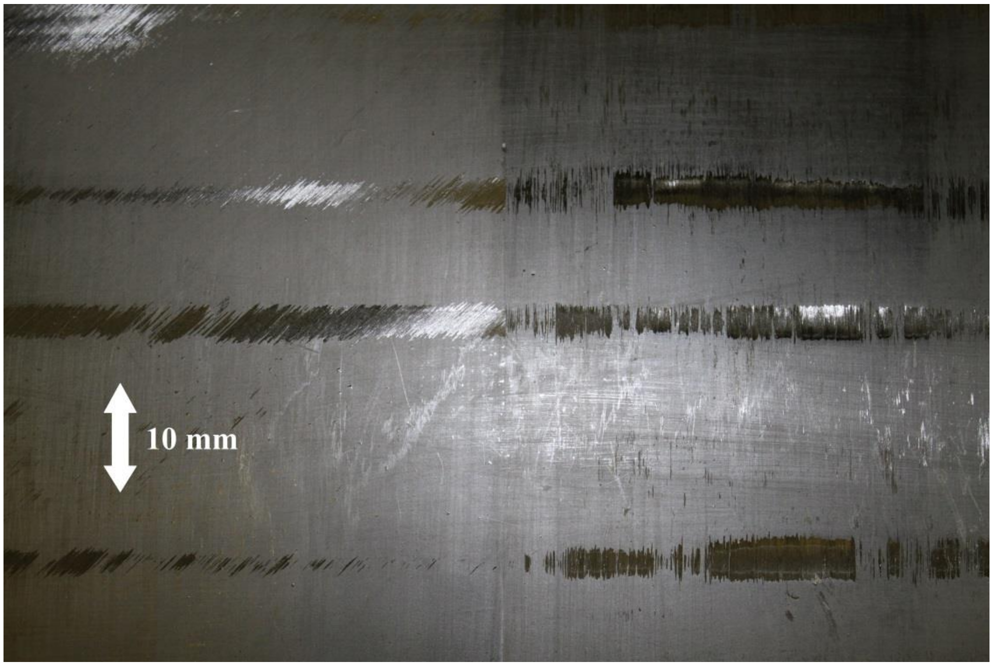

Figure 10. Typical wing skin defects

2.4.2 Full Scale 6-meter Single-shot Wing

In the full UAV wing, some areas of delamination in the wing skins were present that were not seen during the small-scale tests. These defects could be from a variety of sources including the CTE mismatch between the large tooling board and the wing laminate, insufficient temperature ramp rates of the laminate, and temperature, etc. The wing was cured at 85 C, just over the lowest allowable temperature (80 C) in an attempt to minimize the effects of the CTE mismatch.

Similar to the small-scale test, cosmetic defects were present on the wing skin coinciding with the locations of the joints between the webs and wing skins. The internal webs performed well and appeared straight and compact. The final weight for the six-meter wing was a 7.5kg. The demolded part is shown in Figure 11.

Figure 11. Finished Full-scale wing

2.4.3 Proof Load

The finished wing was proof-loaded with a 3.5 kN distributed load to verify basic wing integrity. Revising the previous assumption for mass distribution with a wing mass of 10 kg including actuators, wiring, etc, the loading corresponds to approximately a 9 G loading. This is well below the ultimate load of 20 G; however, it was considered sufficient for continued construction and initial flight tests of the JetStreamer.

2.4.4 Fuselage Attachment Testing

After the wing was cured and trimmed, mounting hardware for the wing/fuselage joint was bonded to the webs inside the wing. These attachments consisted of stainless steel plates bonded onto two of the internal webs as sketched it Figure 12. A test section using this attachment method was placed in an Instron testing machine and loaded to failure. A load of approximately 17kN (~40G load factor) was achieved before bond failure between the load plates and web occurred. The test is shown in Figure 13. This verified that there was sufficient strength of the wing/fuselage connection as well as sufficient shear strength of the wing.

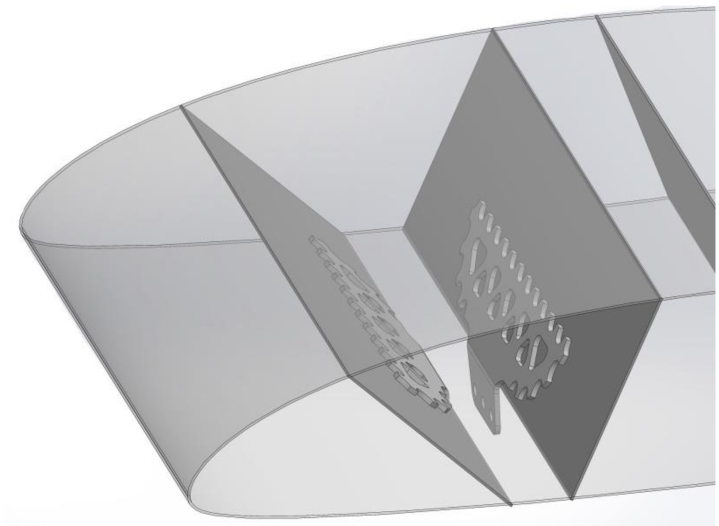

Figure 12. Fuselage Attachment Plates

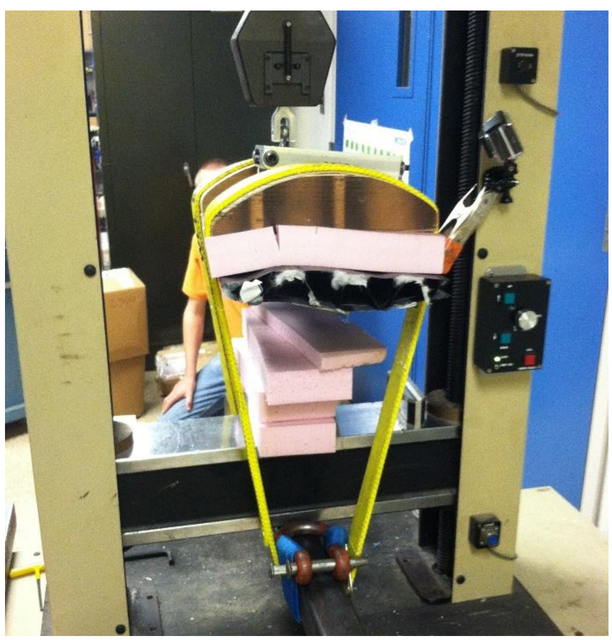

Figure 13. Fuselage Attachment Testing

2.5 Results

The technique was in general very successful since a six-meter wing was able to be successfully produced in a single shot. The techniques used have the potential for considerable savings in part weight, manufacturing time, and cost through the elimination of secondary operations on a fairly large and complex composite structure. While imperfections were present, they can likely be reduced with further development, equipment, and design considerations.

3. Horizontal Stabilizer for the JetStreamer UAV

A one-shot horizontal stabilizer with an integrated elevator could reduce both manufacturing time and part weight compared to traditional methods. A horizontal stabilizer with internal structure, consisting of integrated spar caps, a spar web, and a center rib could be produced in one shot using the techniques developed for the JetStreamer's wing. The present work explores the design and manufacturing of a horizontal stabilizer and elevator joined by a flexure in a single-shot process. A reduction in component weight is achieved though the elimination of a hinge and secondary operations, such as drilling and bolting or bonding. An additional benefit of utilizing a flexure is that debris tolerance is significantly higher due to the lack of any moving components. Some of the pertinent parameters of the JetStreamer's horizontal stabilizer are shown in Table 3.

Table 3. Jetstreamer Horizontal Stabilizer Parameters

Horizontal Stabilizer Span	1.1 m
Horizontal Stabilizer Root Chord	330 mm
Horizontal Stabilizer Tip Chord	220 mm

3.1 Horizontal Stabilizer and Elevator Design

3.1.1 Flexure design

The gains from moving to a flexure, however, are not without sacrifices elsewhere. The flexure has a spring rate that traditional hinges do not have. This places an additional load on control surface actuators that must be accounted for. Additionally, flexures can have deformations out of the plane of the flexure (a flexure is not a perfect single degree of freedom joint). Thus the load case can have significant impacts on the practicality of using a flexure.

A plain elevator is used in this design with the flexure being part of the top skin and a gap between the elevator and horizontal stabilizer. A sketch of the layout is shown in Figure 14.

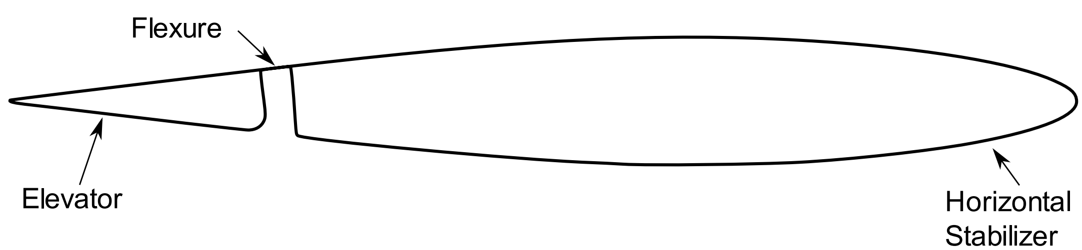

Figure 14. Horizontal Stabilizer and Elevator Layout

The length of the flexure was chosen to s=10 mm. This required a 10mm gap between the horizontal stabilizer and elevator to accommodate the desire +/-30 degree elevator deflection, θ. The radius of curvature for the flexure can be assumed to be fairly constant, as would the case be if it were subjected to a pure moment. The curvature is determined from the control surface deflection requirement. With a known curvature the maximum strain of the flexure is a function of its thickness and when an upper bound is placed upon the strain, an upper limit to the flexure thickness is obtained.

For the horizontal stabilizer, Gurit SE84LV with RC200T 2x2 carbon twill weave was chosen for the skin plies. Using the top skin of the horizontal stabilizer and elevator for flexure allows for a continuous top surface which simplifies the mold and layup of the part. The flexure was designed for the Gurit system with properties given in Table 2. From the properties in Table 2, the lowest estimated strain to failure along the fiber direction is ~1.65%.

Table 4. Gurit SE84LV RC200T Ply Properties

Cured Ply Thickness [30]	0.23 mm
0º Flexural Strength [30]	847 MPa
0º Flexural Modulus [30]	51.2 GPa
90º Flexural Strength [30]	857 MPa
90º Flexural Modulus [30]	51.5 GPa

The skin plies will be oriented along the +/-45 direction to maximize torsional stiffness of the stabilizer. The chord-wise strain limit for the flexure is then ~2ε_{fiber} which is ~3.3%. The maximum flexure thickness is then:

$$t_{max} = \frac{4\epsilon_{\text{fiber}} s}{\theta} \tag{12}$$

where t_{max} is the maximum allowable flexure thickness, s is the flexure length, and θ is the deflection angle of the elevator. The maximum ply thickness was calculated as ~1.26 mm. Thus up to 5 plies could be used without strain failure.

3.1.2 Flexure Stiffness

Knowing the moment required to achieve the desired deflection is needed for ensuring actuators are properly sized for the application. The flexual modulus in the chord-wise direction of the wing skin plies, using laminated plate theory with plies oriented in the +/-45 degree direction gives approximately a 26 GPa flexural modulus. Again, assuming a flexure of length s is under a pure moment with a flexural modulus E, the spring rate K (Nm/rad) of the flexure is

$$K = \frac{EI}{s} \tag{13}$$

where

$$I = \frac{b_s t^3}{12} \quad (14)$$

where b_s is the span-wise width of the flexure (and equal to the span of the horizontal stabilizer) and t is the flexure thickness. The estimated spring rate was 2.9 and 23.1 Nm/rad for the one and two ply thick flexures, respectively. Thus 1.5 and 12.1 Nm are required for the respective flexure thicknesses at full deflection, θ=30 deg. Hitec HSB-9370TH servos were chosen for the JetStreamer and these have a maximum torque of ~2.4 Nm with a 60 degree swing. Use of a two ply flexure would require 5 servos to overcome the flexure stiffness alone and was deemed ineffective for this application along with any other higher ply counts. However, about 60% of the torque of a single servo would be sufficient to overcome the single ply flexure's stiffness at full deflection. The spring rate of the single ply flexure was deemed acceptable for this application, though further understanding of the implications of the flexure design were investigated.

Flat specimens were created to verify the design using both one and two ply layups, with a total thickness of 0.26 mm and 0.46 mm, respectively when cured under vacuum using peelply, Dahlar Release bag 125, and breather. Both ply thicknesses could be repeatedly bent +/-30 degree without failure or audible cracking.

3.1.3 Aerodynamic Hinge Moment and Actuator Requirements

The aerodynamic hinge moment is needed for actuator sizing. The Simplified Design Load Criteria of FAR 23 [35] was used to estimate aerodynamic loads on the horizontal stabilizer. While the JetStreamer's design falls outside of the allowable design parameters for the design code due to its high aspect ratio wing, it was assumed to give a reasonable approximation for tail loads and was presently deemed acceptable. From A23.11 [30], the chordwise distribution of pressure was assumed to be of the shape

$$P(x) = 3\overline{w}\frac{(c-x)^2}{c_f^2} \tag{15}$$

where $\overline{w}$ is the average surface loading from FAR23's Figure A5 [35], c is the chord length, c_f is the elevator chord, and x is the chordwise position from the leading edge. The hinge moment is

$$M_h = b_s \int_{c-c_f}^{c} P(x)(x-(c-c_f))\,dx = \frac{\overline{w}c_f^2}{4} \tag{16}$$

Using the average stabilizer chord c = 275mm with a 22% chord control surface, the average surface loading for the JetStreamer was estimated at $\overline{w}$=3256 N/m^2 from FAR23 Figure A5 [35] and thus a hinge moment of ~3.3 Nm was computed. Thus the two Hitec servos were deemed to have sufficient torque to meet the requirements for overcoming both the aerodynamic forces and required flexure torque.

3.1.4 Out of Plane Deflection of the Flexure

Since a flexure has an additional degree of freedom compared to a traditional hinge (a displacement perpendicular to the flexure plane as sketched in Figure 15, the magnitude of this deflection should be estimated.

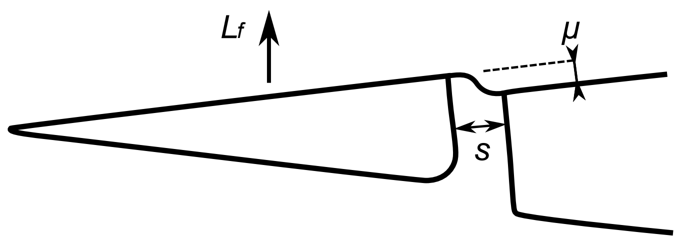

Figure 15. Out of Plane Deflection of Elevator

A simple estimate is obtained if it is assumed that any displacement of the elevator in the vertical direction will be a pure translation with no rotation (due to the restraints from the servo). The lift force on the elevator, L_f, was calculated to be 217 N and obtained by integrating Eq. 4 over the elevator's area.

The flexure was modeled as a cantilever beam with a vertical displacement, μ, at the tip and constrained to have zero rotation. The force at the flexure tip was assumed to be the flap lifting force, L_f. The vertical displacement was estimated as:

$$\mu = \frac{L_f s^3}{12EI} \qquad (17)$$

Evaluating gives approximately a 0.62 mm deflection. This displacement was considered acceptable and expected have little effects on the aerodynamics.

3.1.5 Spar caps and internal structures

The internal structure was designed and manufactured in a similar fashion to that of the JetStreamer's wing. Therefore, the design will not be covered in detail in this paper. For determination of the ply requirements for the spar caps, web and mounting hardware, a 985 N distributed load, determined by integrating the surface loading, $\bar{w}$, over the area of the horizontal stabilizer and elevator was assumed on the stabilizer. The starting spar cap width of was chosen to be 50mm decreasing by 2mm for each additional ply. Two spar cap plies were required at the wing root and decreased to zero at the wing tips. For web sizing, a 493 N shear load at root that decreased to zero at the wing tip was used with a root web height of 38.5 mm. Two web plies were deemed sufficient for the load case.

3.2 Manufacturing of One-Shot Stabilizer and Elevator

3.2.1 Mold Design

Aluminum was used as the mold material since it was cost effective for the mold size, easy to manufacture, and high tolerances required for the flexure could easily be achieved. Bosses were designed into the mold to create cavities to house two control servos. A profile of the mold geometry is shown in Figure 16 and the finished molds are shown in Figure 18.

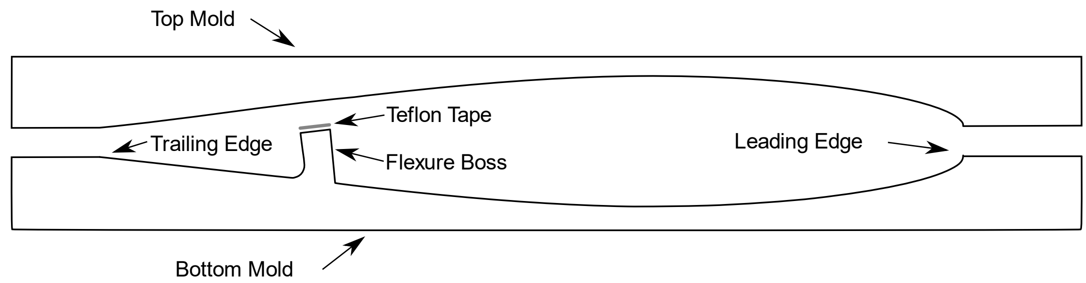

Figure 16. Mold Geometry

Control of the gap between the flexure boss and the top mold was critical to ensure proper compression on the flexure ply. A strip of Teflon was utilized along the top of the flexure boss to apply pressure to the flexure ply while allowing for some variation in the gap size.

3.2.2 Foam Insert Design

Polystyrene forms and internal vacuum bags were used to create the internal web and rib for the stabilizer using a method similar to what was used for the JetStreamer wing; see Figure 8. A polystyrene form in the front on the stabilizer was used to position the span-wise web. The forms were placed ahead of the web to avoid interference with the bosses for the servos. The front form was split in half to accommodate the center rib while a small polystyrene form was used in the rear half to stay clear of the servo bosses. The layout divided the inside of the stabilizer into four sections, all of which were filled with lay-flat vacuum tubes, while only three sections contained forms. Semicircles cut into the profiles of each of the forms allowed for excess lay-flat material to be gathered in those areas and creating a smooth surface elsewhere on the form. The span-wise web was chosen to be a continuous member for structural integrity while the rib was divided in two by the web. An exploded view of the internal structure and forms is shown in Figure 17 (flanges on the rib laminates that attach to the web and flexure boss are omitted for clarity).

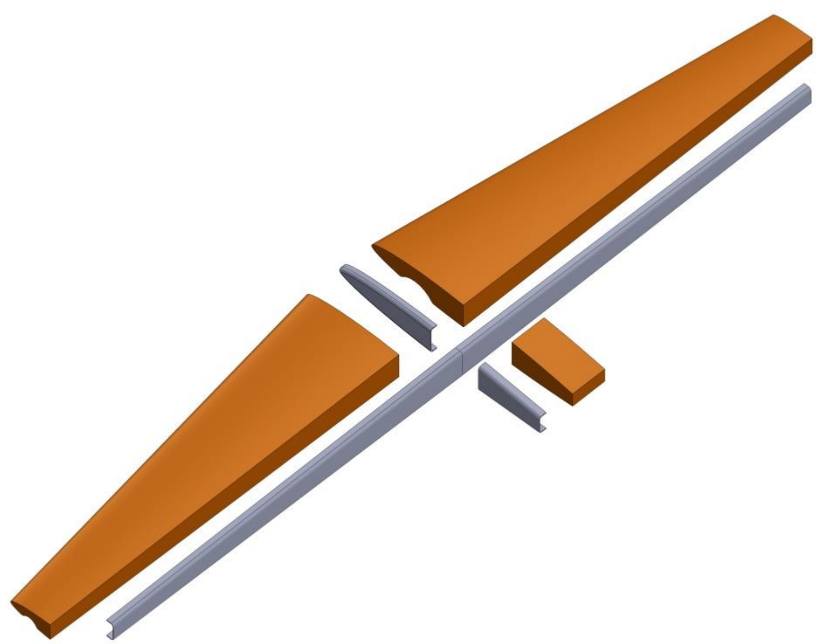

Figure 17. Insert and Internal Structure Layout. The flanges of the ribs where they mate to the spar web were removed for clarity.

3.2.3 Mold Manufacturing

The top and bottom skin molds were machined to the desired geometry utilizing a CNC milling machine. Once machined, the molds were sanded using 220 grit sandpaper, working up to 1000 grit in increments of 200 to create a smooth finished surface as shown in Figure 18. A 1mm thick strip of Teflon tape was adhered to the top of the flexure boss, as shown in Figure 14. Chemlease 41-90 EZ mold release was applied to the molds according to the manufacturer's instructions. This finished the mold preparation.

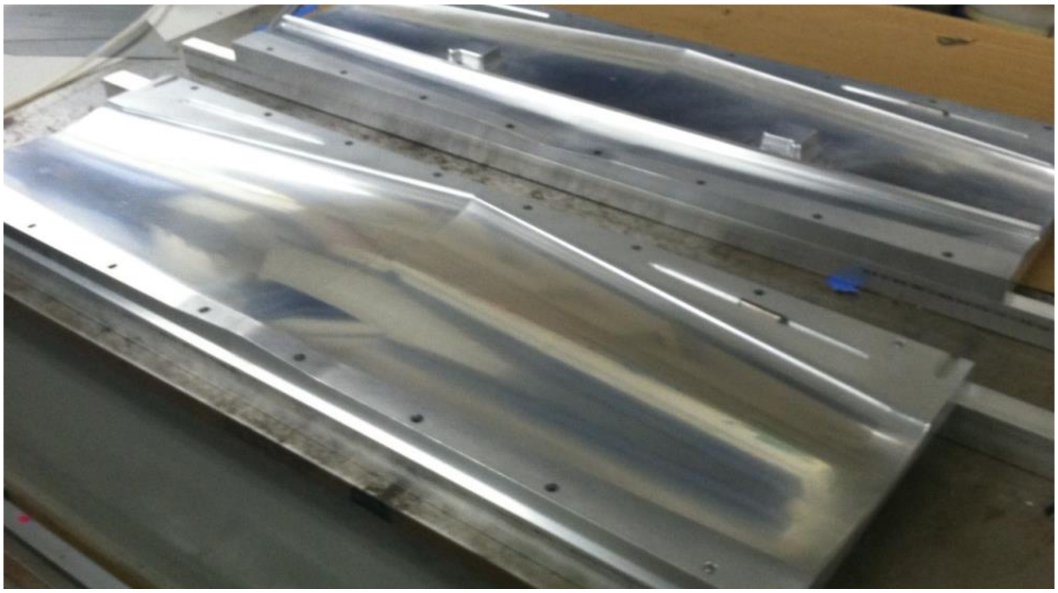

Figure 18. Finished Skin Molds

3.3 Stabilizer and Elevator Layup Procedure

A schematic of the layup is shown in Figure 19.

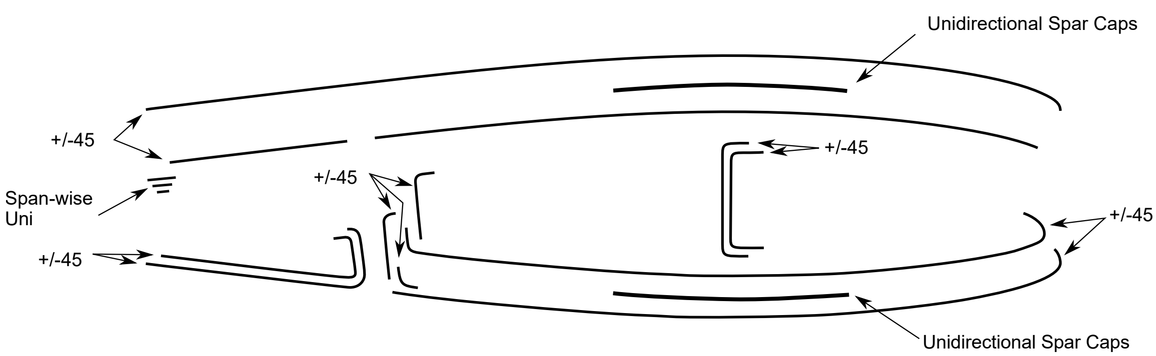

Figure 19. Horizontal Stabilizer and Elevator Layup

3.3.1 Top Skin Layup

A +/-45 skin ply was first laid down over the entire top skin mold. At the leading edge the ply was flush to the front mold parting line and ended at the trailing edge of the elevator. The ply was debulked using a cracked ice pattern vacuum bag to aide in air extraction. The two spar cap plies were laid down and debulked. The next +/-45 ply consisted of two pieces that were separated by the flexure. The stabilizer portion of the ply began 5mm recessed from the mold's leading-edge parting line and ended at the flexure. The elevator portion of the ply was laid down beginning at the rear edge of the flexure and ended 2mm short of the trailing edge. Finally, three strips of unidirectional fiber, of widths 6mm, 4mm, and 2mm, were laid span-wise along the trailing edge. The unidirectional fibers were used to assist in bonding of the trailing edge.

3.3.2 Bottom Skin Layup

The first +/-45 ply was laid down with the ply extending 5mm beyond the leading edge parting line, and ended at the corner of the flexure boss. Additional prepreg was applied to the servo bosses for complete mold coverage. Next a +/-45 ply was laid from the corner of the flexure boss and extended past the top of the boss by 10mm. Finally, a +/-45 ply was laid from the trailing edge of the elevator to 10mm past the top of the flexure boss. A 20mm wide +/-45 ply was laid along the bottom corner of the flexure boss to reinforce the joint. This completed the first skin ply for the lower skin mold. The mold was then debulked using a cracked ice pattern lay-flat tube while supporting any plies extending beyond the mold. The two spar cap plies were then laid down and debulked. The second set +/-45 plies were laid down with the first ply front extending 10mm past the leading edge parting line and ending 5mm up the flexure boss. The next ply was laid down beginning at the corner of the flexure boss extended 15mm past the top. The second +/-45 ply for the elevator was laid down with the rear 2mm short of the trailing edge and the front extended 15mm beyond the top of the flexure boss. A lay-flat tube was then places along the length of the elevator section of the mold. Four more lay-flat vacuum tubes were used in the stabilizer as described in a previous section.

3.3.3 Rib and Web Layup

The polystyrene forms were encased in lay-flat tubing and placed under vacuum for the layup. The two plies for the front half of the rib were laid over the edge of one leading edge forms with 10mm flanges extending on the top, bottom and rear for joining to the skins and the spar web. The second leading edge form was then pressed up against the rib plies, resulting in a vacuum bag on either side of the rib laminate which allowed for compaction. Next, the web plies were laid along the rear of the leading edge forms with the plies extending 10mm onto the top and bottom surfaces. The forms were placed into the mold and created a continuous span-wise web. The rear rib plies were then laid over the rear form with a 10 mm flange on all sides and placed into the mold, completing the center rib. A lay-flat tube was placed in the remaining section that did not have a polystyrene mold.

3.3.4 Closing the mold and curing

All vacuum bag ends were brought to the tips of the horizontal stabilizer and elevator. The molds were closed while ensuring the overhanging ply ends were properly oriented to avoid incomplete bonding or stray plies from being included in the flexure. The entire mold assembly was then envelope bagged, with the outsides of the internal lay-flat tubing sealed to the envelope bag, and slowly brought under vacuum while allowing the internal bags to expand. The mold was cured in an oven at 100 C for 4 hours and then allowed to slowly cool to room temperature.

3.4 Finished Stabilizers

A total of five stabilizers were manufactured, one of which is shown in Figure 20.

Figure 20. Finished Stabilizer and Elevator. This one has 5 mm wide strips of unidirectional carbon fiber placed on both sides of both skins; these increase cross sectional stiffness and buckling strength and in a sense work as lightweight ribs.

The surface finish for the stabilizers was excellent with only a few minor areas of resin pooling. One area of concern was that in some of the stabilizers, extra material had migrated into the flexure (a portion of the overlap would fold the wrong way) and greatly increase the stiffness of the flexure. Figure 21 shows a flexure which had good compaction and corner geometry. Additionally, in one of the stabilizers a vacuum bag had moved between the spar web and the skins. While not completely separated, it was significant and is a condition that should be avoided. Apart from these issues the five stabilizers were very good.

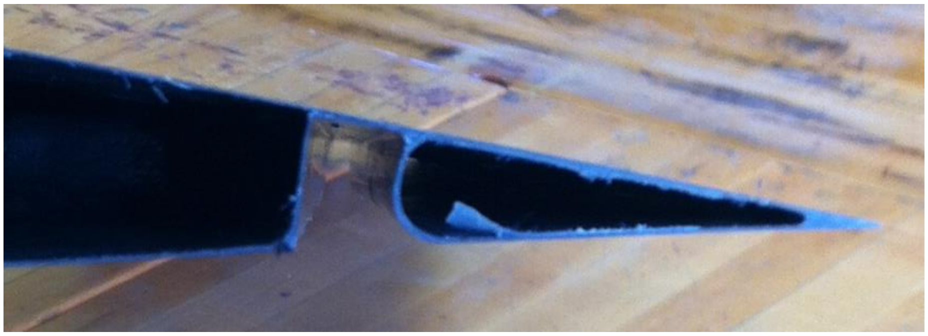

Figure 21. Flexure Detail

3.5 Load Testing

A simple load test of the first stabilizer was done by loading the top surface with lead shot bags. Figure 22 shows the test. The stabilizer was able to withstand a 333N load but upon increasing the load in the next increment of 111N, bucking would occur in the lower skin near the root. The buckling was elastic and reversible and did not lead to any damage. The four stabilizers produced later had single ply 5 mm wide unidirectional strips placed chord-wise spaced 50 mm apart on the outer and inner surface of the wing skins to increase the skin stiffness, functioning similar to a rib. These can be seen in Figure 20. With the addition of the unidirectional strips, the stabilizer would withstand the 444 N proof load without skin buckling. This was considered sufficient for use on the JetStreamer UAV.

Figure 22. Horizontal Stabilizer Load Test

3.6 Results

Complete horizontal stabilizers with internal structure and integrated elevators were produced successfully in one shot. There were some defects in the stabilizers, but they are not considered insurmountable with continued development of the technique and layup procedure. The area for largest improvement would be in avoiding movement of stray plies to ensure the flexure only contains the desired number of plies. The technique presented shows potential for creating one-shot assemblies using flexures that would have traditionally been produced as separate components.

4. Fuselage and Vertical Stabilizer

The fuselage and vertical stabilizer were combined into a single structure to once again minimize molding operations and secondary operations. The fuselage and vertical stabilizer for the JetStreamer were produced using more traditional mold materials and methods, therefore it will not be covered in great detail.

4.1 Fuselage Design

The fuselage skin and vertical stabilizer skins were 2 plies of the RC200T prepreg with SE84LV oriented +/-45 (0 being the aircraft centerline) for torsional stiffness. Spar caps were integrated into the tail section of the fuselage and vertical stabilizer using the same design methods as in the previous sections. Additionally, the vertical stabilizer had an internal web similar to that of the horizontal stabilizer

4.2 Fuselage Mold

The molds for the JetStreamer fuselage and vertical stabilizer were chosen to be all carbon fiber in order to match the CTE of the part to be made. First male plugs were machined using General Plastics FR-4512 for the two halves. Figure 23 shows one being machined.

Figure 23. Fuselage and Vertical Stabilizer Plug Mold Machining

After machining the mold surfaces were sealed with resin and sanded to a fine finish similar to the previous molds. Mold release was then applied to finish the tool.

Dry carbon fabric was then laid over the plugs and prepped for an infusion. Once prepared, the fabric was infused with Airtech ToolFusion 3. The carbo molds were cured on the plugs at 50 C for 12 hours. The molds were removed from the plugs and a free-standing post cure was performed up to 120 C to raise the working temperature of the molds. A finished mold is shown in Figure 24.

Figure 24. Finished Fuselage and Vertical Stabilizer Mold

4.3 Manufacturing

The layup and techniques utilized for manufacturing were similar to those previously presented for the horizontal stabilizer. Once the shell was completed, composite bulkheads were installed for the wing attachments as well as a bulkhead to close out the tail section. A composite floor was also laid in to strengthen the nose and give a mounting surface for the necessary electronics and batteries. Attachments for the horizontal stabilizer bonded and riveted into the tip of the vertical stabilizer.

4.4 Horizontal Stabilizer Mount

Since transportation of the JetStreamer was necessary, the horizontal stabilizer was chosen to be removeable as well as replaceable if any damage occurred. This meant a mounting solution was necessary that could bear the necessary loads and accurately locate the horizontal stabilizer on the vertical tail while being easily removeable in the field. Figure 25 show the mounting assembly and Figure 26 show the cross-section of the mount.

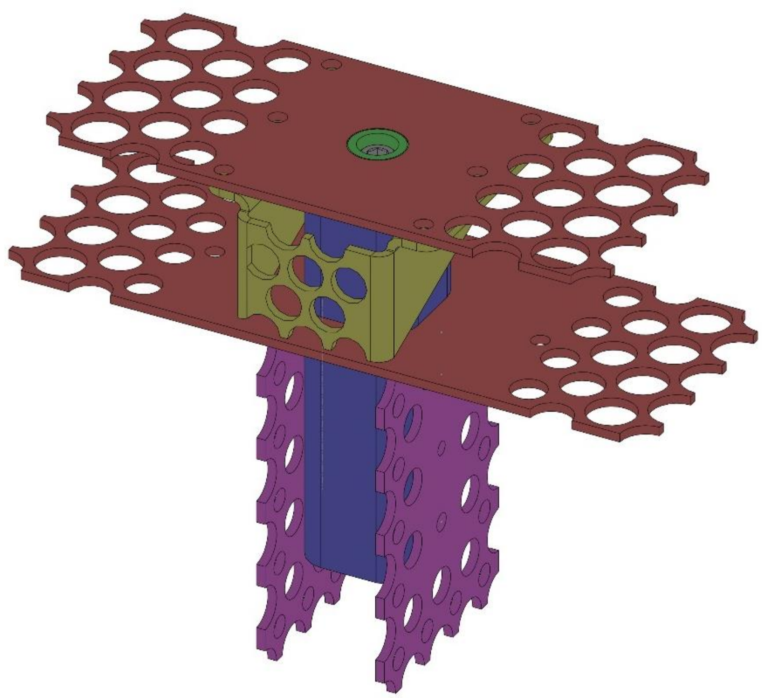

Figure 25. Horizontal Stabilizer Mount

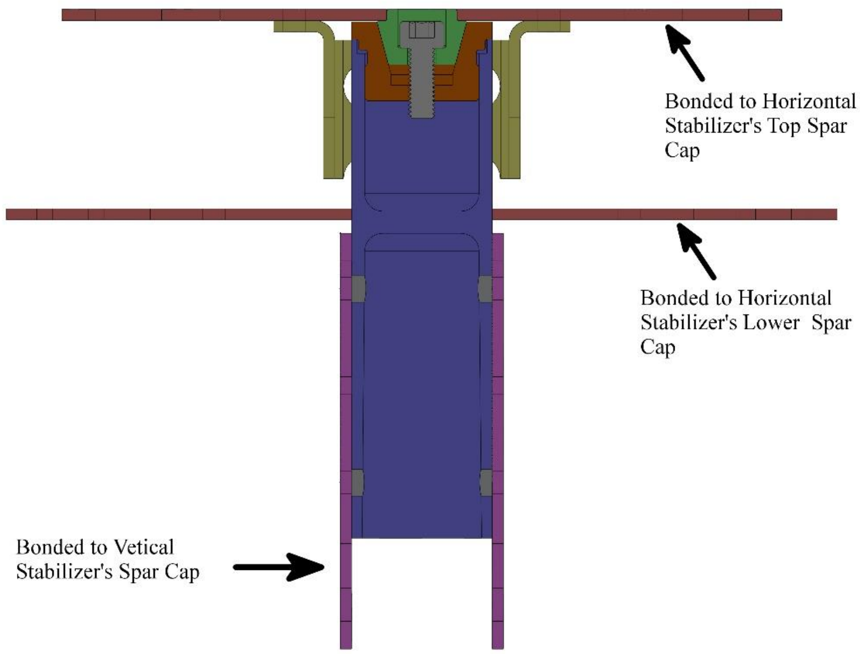

Figure 26. Horionztal Stabilizer Mount Cutaway

A square aluminum post (shown in blue) was riveted to a set of bond plates (shown in magenta), the assembly was then bonded to the spar caps of the vertical stabilizer. The post was used to locate the horizontal stabilizer as well as transfer a majority of its loads into the vertical stabilizer. A nut plate was also positioned in the nose of the vertical stabilizer to securely fasten the nose of the horizontal stabilizer. Atop of the square post, a threaded insert (shown in orange) with a tapered hole was used as a receiver for the horizontal stabilizer and ensured the horizontal stabilizer was properly positioned. These set of parts were designed to be permanent parts of the vertical stabilizer.

The mating pin (shown in green) was welded to the top bond plate (shown in red). The two were then bonded to the top spar cap of the horizontal stabilizer utilizing a fixture to ensure consistent placement across multiple parts. An additional bond plate (also shown in red), with the profile of the square tube cut into it, was bonded to the lower spar cap of the horizontal stabilizer. A final bond plate (show in yellow) was riveted to the top bond plate and bonded to the web of the horizontal stabilizer to carry any of the lifting loads. Thus with the removal of the bolt holding the mating pin in place, the horizontal stabilizer and bond plates could be lifted off of the post with ease.

Under a symmetric load on the stabilizer, the bond plates attached to the spar caps would behave the same as the spar alone in terms of load transfer. The holes shown at the ends of the bond plate are used to provide adequate plug shear strength for the interface between carbon and steel. However, in the case of asymmetric loads on the horizontal stabilizer, any moment would then be transferred through the post and into the spar caps for the vertical stabilizer.

The design allowed for easy removal and replacement of the tail (only having to remove two bolts), while being rigid and strong enough to support the horizontal stabilizer and any of the associated load. Figure 27 shows the two the two assemblies separated.

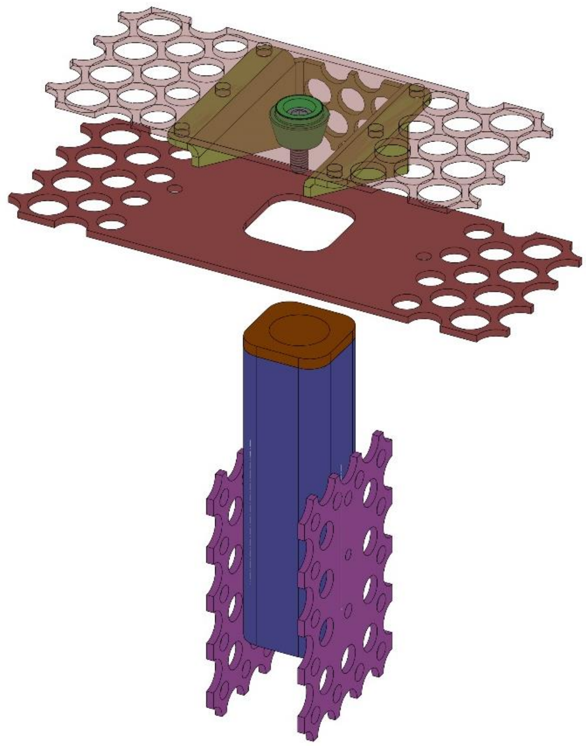

Figure 27. Separated Tail Mount

4.5 Results

A single fuselage was produced for the JetStreamer. Overall, quality of the part was very good with excellent surface finish and minimal imperfections. The rib in the vertical stabilizer showed no vacuum bag movement or any other concerns. The hardware for mounted of the tail was easily installed and load tested. A picture of the fuselage and attached tail is shown in Figure 28.

Figure 28. Fuselage with Horizontal Stabilizer

5. Ailerons and Flaps

5.1 Design

Plain flaps and ailerons were utilized the entire length of the wing. The control surfaces for the Jetstreamer were hollow and once again produced in a single shot utilizing internal vacuum bags. However, no internal structure was present on these components. Utilizing a [+45/-45/+45] layup of SE84LV with T700 for the skin, the same material as was used for the main wing, a light yet torsional stiff control surface could be manufactured quickly and easily. Skin thickness for durability was the main consideration for the ply count since ample torsional stiffness could be achieved using few plies.

5.2 Molds

The molds for the control surfaces were simple two-piece aluminum molds mounted on larger aluminum tubes for stiffness. The molds were CNC machine, then sanded and polished to a fine finish. The molds were release coated with Chemlease 41-90EZ and, after curing, ready to use. Figure 29 shows one of the four pairs of molds for the control surfaces.

Figure 29. Control Surface Molds

5.3 Manufacturing and Results

The control surfaces single skin parts with no internal structure. The layup for the control surfaces was a [+45/-45/+45] of the SE84LV with T700 fibers. A lay-flat tube was placed in the center to inflate when brought under vacuum. Three complete sets of control surfaces were produced for the JetStreamer with minimal defects. Figure 30 shows one of the completed control surfaces.

Figure 30. Completed Control Surface

6. Completed Aircraft

With the necessary components completed, the final assembly and wiring of the Jetstreamer could be done. Figure 31 show the completed JetStreamer after paint.

Figure 31. Completed JetStreamer

6.1 Flight Testing

The JetStreamer was disassembled and shipped to Weldon, California for initial flight test and evaluation of large scale dynamic soaring. Figure 32 shows a launch from one of the test flights.

Figure 32. Launch of the JetStreamer

Figure 33 shows the JetStreamer during a dynamic soaring loop.

Figure 33. JetStreamer during Dynamic Soaring

Successful test flights of the JetStreamer were flown and it is believed to be the largest unmanned aircraft to have successfully demonstrated dynamic soaring.

7. Conclusions

A novel approach was developed for the manufacturing of a high aspect ratio wing with a co-cured internal structure. A six-meter UAV wing was designed and manufactured using carbon fiber prepreg with co-cured spar webs and integrated spar caps. The wing used disposable polystyrene foam forms enclosed by vacuum bags to produce an internal structure in one cure cycle with no secondary bonding. The technique was in general very successful and has a potential for considerable savings in part weight, manufacturing time, and cost through the elimination of secondary operations on a fairly large and complex composite structures. While imperfections were present, they can likely be reduced with further development, equipment, and design considerations.

Additionally, complete horizontal stabilizers with internal structure and integrated elevators were produced successfully in one shot. There were some defects in the stabilizers, but they are not considered insurmountable with continued development of the technique and layup procedure. The area for largest improvement would be in avoiding movement of stray plies to ensure the flexure only contains the desired number of plies. The technique presented shows potential for creating one-shot assemblies using flexures that would have traditionally been produced as separate components.

The completed JetStreamer was successfully flown in Weldon, California and is believed to be the largest unmanned vehicle to demonstrate dynamic soaring.

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10.Vita

Jacob Bruce Patterson was born in Austin, Texas on May 4th, 1989, to Bruce and Laura Patterson. After graduating from McCallum High School in Austin, Tx, he attended Lehigh University in Bethlehem, Pennsylvania. In January of 2012 he completed a Bachelors of Science in Mechanical Engineering with honors. He then received his Masters of Science in Mechanical Engineering in January 2014. After graduating with his PhD he plans to work in industry with focus on prototype development projects.