POST-PROCESS DEFORMATION OF THERMOPLASTIC MATRIX COMPOSITES APPLIED TO VERTICAL AXIS WIND TURBINE BLADES

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ABSTRACT

Thermoplastic matrix composites have become an important subcategory of structural composites, particularly due to the enhanced potential for recycling. While recyclability is clearly a key attribute, the ability to reshape and reform thermoplastic matrix composites also offers potential advantages from perspectives of design and manufacture.

With the advent of thermoplastic matrix materials that are processed through in-situ polymerization, composite manufacturing processes that rely on low resin viscosities become possible. The resin infusion of the Elium thermoplastic resins has been described in numerous articles and is the basis for this research effort. However, the focus of this current article is on design and manufacturability possibilities offered by the resulting thermoplastic matrix composite, which allows complex designs to be realized from relatively simple molded geometries, through post-process deformation.

As an example of the possibilities, thin straight, hollow carbon fiber reinforced Elium airfoils were infused. Following processing these airfoils were reheated to deform the ends and simultaneously fusion join to end attachment plates, followed by a second reheating step to bend the airfoils to form ‘C’-shaped blades for a small, Vertical Axis Wind Turbine technology demonstrator.

End attachment plate joint test results are described, as are details of the post-process deformations carried out. The results of this manufacturing technology demonstration show that acceptable joint strengths are readily attained. Further, a technique was developed which enables bending of the airfoils with limited fiber buckling and at relatively low forces, resulting in good repeatability. Future efforts on post-process deformation would require more in-depth evaluation of the fiber path and fiber path lengths to remove fiber buckling in regions such as the inside of the bend.

Keywords: Resin Infusion, Thermoplastic, Joining, Post-Process Bending
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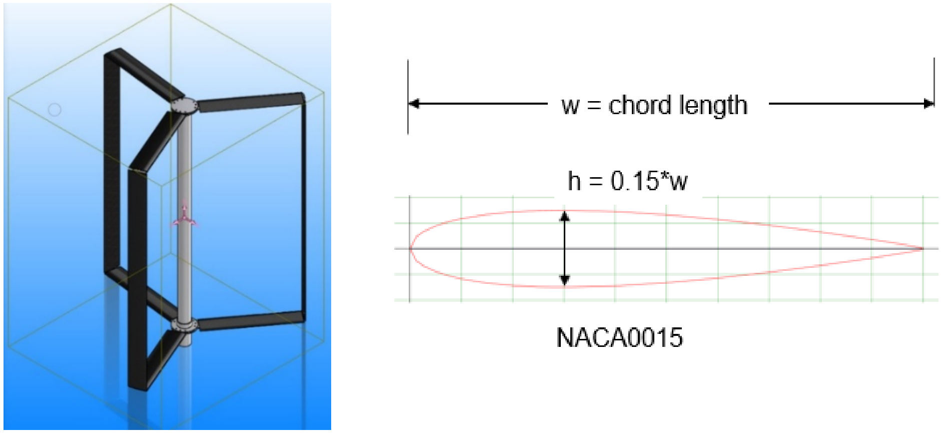
1. INTRODUCTION

In the design and manufacture of composite components it is common to attempt to minimize the number of sub-components and mold a single article. However, in many cases, what might seem a relatively simple geometry can result in very complex, if not impractical tooling/molds. The component under consideration in this discussion is a Vertical Axis Wind Turbine (VAWT) blade for a lift-based design where each blade has a ‘C’-shape configuration, nominally 2m (79”) in vertical length, as shown in figure 1a. A NACA0015 symmetric airfoil profile, as shown in figure 1b, was chosen and thus, this cross-section becomes the base geometry. This airfoil cross-section was to be implemented as a hollow composite with a constant chord length of nominally 152mm (6”), which results in a maximum thickness of only 23mm (0.9”). Molding a straight section of this airfoil cross-section from a fiber reinforced composite is relatively straight forward; however, creating a mold set capable of producing the complete hollow ‘C’-shaped blade of this hollow cross-section becomes a challenge. Added to the geometric challenge is the need to attach each end of the blade to the hub assemblies on the tower, which is an added complication.



(a) (b)

Figure 1. VAWT blade configuration

To alleviate the complexities that would be introduced by attempting to mold the ‘C’-shaped blade as a single composite component, the initial VAWT conceptual design, based on conventional composites manufacturing experience, included more traditional brackets that were to join straight blade sections to each other as well as to the hub on the rotor mast. (Figure 2)

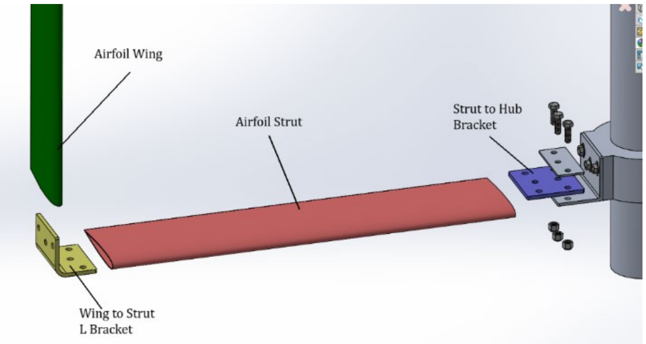


Figure 2. Assembly concept with straight composite airfoil segments and bonded connections

However, this project was developed to evaluate the application of a fiber reinforced thermoplastic matrix composite, specifically based on the Elium® 150 in-situ polymerizing thermoplastic resin provided by Arkema, to such a VAWT. While much of the emphasis of this larger effort was to characterize the recyclable thermoplastic material and composite structural design, in order to take full advantage of the material properties of such composites, a significant part of the activity was to examine the potential advantages of thermoplastic matrix composites related to manufacturability. To that end, an investigation was undertaken into the application of post-process deformation in the manufacture of 'C'-shaped blades, starting from straight, hollow, resin infused airfoils. In addition, this work investigates the deformation of the airfoil at the transition to the hub plate attachment and the joining of the airfoil to the hub plate bracket. Ultimately, the findings were intended to provide the groundwork to inform decisions for larger scale manufacturing techniques applicable to a commercialization strategy.

2. EXPERIMENTATION

To investigate post-process reshaping a technique was first developed to produce the hollow airfoils, via resin infusion of Elium® 150, which is a resin, that when mixed with between 1-3% Luperox AFR40 initiator, results in a low viscosity (100 cps) pre-polymer. At room temperature the Elium® 150/Luperox mixture, reacts within 30 – 60 minutes to form a thermoplastic polymer of the methacrylate family with a glass transition temperature (T_g) >110°C [1]. This low viscosity enables practical room temperature infusion-based processes to be used to produce thermoplastic matrix composites.

Much of the experimental evaluation of post-process deformation and end fitting fusion joining was performed using glass fiber reinforced Elium® 150 to better manage the cost compared to utilizing the carbon fiber reinforcement desired for the final product. The studies described for the evaluation of post-process bending of the airfoils is primarily qualitative in nature, while the study of the end fitting joint strength includes quantitative information.

2.1 Blade Infusion

Since a key aspect of the hollow blade was the outer aerodynamic surface, the planned molding method revolved around closed external molds that would result in a high quality, molded exterior aerodynamic surface. While pultrusion could, at least in concept, be utilized to manufacture this hollow airfoil geometry, it was not an option for this project, which focused on resin infusion. A hollow blade was desirable from a cost, weight and manufacturability perspective. Thus, the infusion process that was developed remains a traditional contact mold process, resulting only in one high quality surface, except that it is done inside a pair of clamshell composite mold halves.

Clamshell molds were produced from glass fiber reinforced epoxy, starting with a preliminary set which were nominally 0.8m (32") in length and building to a set 1.6m (64") long. These shorter molds were used for infusion studies as well as for post-deformation sample preparation. Ultimately, a set of molds which were 3.5m (138") long were manufactured, from carbon fiber reinforced epoxy, to create the 3.3m (129") hollow carbon fiber reinforced Elium® 150 airfoil sections which would be used to form the final 'C'-shaped demonstration blades.

The hollow airfoil manufacturing approach involved a tubular vacuum bag inside the dry reinforcement preform, with appropriate infusion media between the inner vacuum bag and the preform, as shown schematically in figure 3. (The specific amount, style and position of the expendables was adjusted as the process was developed and as the required airfoil length increased.) The molds were closed on this preform assembly and then placed into a larger lay flat tube bag which was then sealed to the inner bagging film creating an envelope-style vacuum bag.

The relatively small dimensions of the hollow airfoil cross section proved to be a challenge for reinforcement positioning in preparation for resin infusion molding, as well as for removal of the infusion media, from inside the airfoil, after processing. Many different expendable materials and process techniques were attempted before a final process was defined that resulted in good repeatability and successful part infusion.

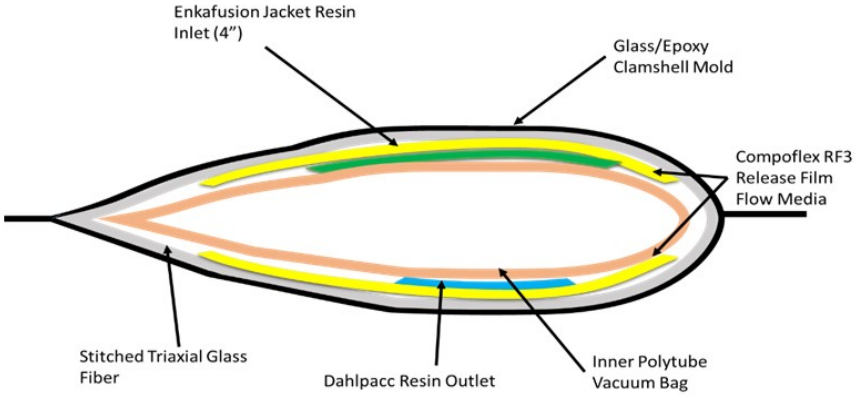


Figure 3. Schematic of materials stack-up in the assembled mold halves.

All preliminary infusion trials used 3 plies of an 885 g/m^2 stitched triaxial glass fiber fabric (VectorPly E-TLX 2400) as the reinforcement preform. The infused and processed thickness of the hollow airfoil wall, with this triax glass preform, was nominally 2.1mm (0.083"). The geometry of the hollow airfoil is shown in the lower left of figure 4.

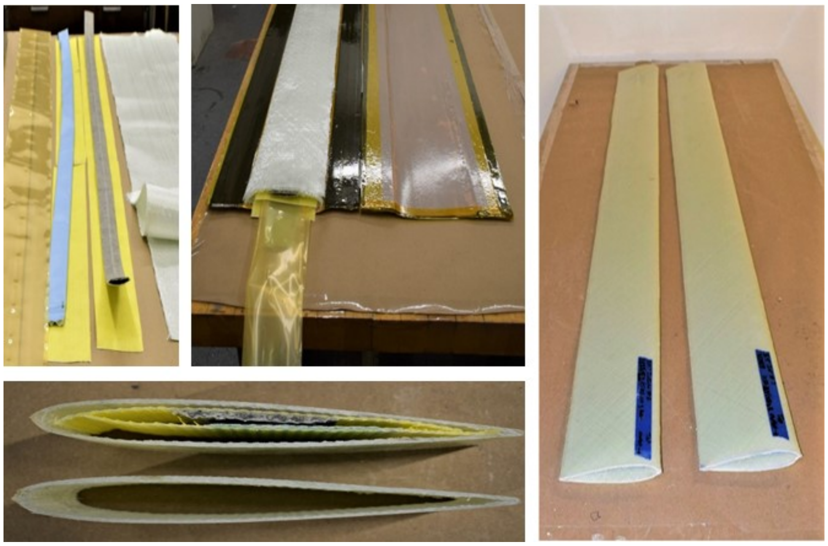


Figure 4. Consumables (top left), preform in the mold (top middle), airfoil cross section with and without the consumables (bottom left), and 1.6m (64") hollow fiberglass airfoils (right).

Iterations on this manufacturing process focused on reducing the consumables required through the implementation of infusion-specific materials. Compoflex® RF3, shown as yellow strips in the top left of figure 4 and also obvious in the infused section view on the lower left of the same figure, is a combination of distribution media and peel ply that greatly simplified the manufacturing process as it reduced the consumables required.

Additionally, the Compoflex® RF3 had a much lower release force than the previous peel ply, facilitating eased removal of the consumables. Dahlpac MC79, shown as the blue strip in figure 4, was chosen for the vacuum outlet as it has a low profile and prevents resin from flowing out of the system while maintaining vacuum throughout the infusion. Jacketed Enka fusion, shown as the grey strip in the top left image in figure 4, was determined as the preferred resin inlet material due to its low profile which increased the available space inside the airfoil and reduced the effort required to remove the consumables.

Minimal changes to the manufacturing process were required to transition from the glass fiber reinforced airfoils to the carbon fiber reinforced airfoils manufactured using braided and stitched uni-directional (UD) carbon fiber reinforcement. The 610 g/m^2 (18oz/yd^2), 101mm (4") braided carbon fiber (Z56L400R), supplied by A&P and equivalent braid supplied by Highland Composites simplified the manufacturing process as it could be placed over a flat mandrel and rolled back over itself capturing the three plies of VectorPly C-LA 0912 stitched 312 g/m^2 (9.2 oz/yd^2) UD carbon fabric with a 41 g/m^2 (1.2 oz/yd^2) chopped glass mat to serve as an integral flow media. This resulted in the final desired stacking sequence $[\pm 45/0_3/\pm 45]$ along the top and bottom of the airfoil, and [±45/±45] at the leading edge and trailing edge, which was consistent with the planned reinforcement for the final demonstration blade set. Figure 5 shows the sequence of steps in preparing the carbon fiber preform for infusion and a resulting 1.6m (64") carbon fiber reinforced Elium® 150 hollow airfoil.

Figure 5. Adaptation of 1.6m manufacturing process to braided carbon fiber. From left to right shows the consumables, preform set-up, placement of the final ply, preform in mold, and the 1.6m carbon fiber airfoil.

Hollow glass fiber reinforced airfoils, produced in the 1.6m (64") mold set, formed the basis for end fitting joining trials as well as for post process deformation experiments. The 1.6m (64") molded carbon fiber reinforced airfoils were used for final infusion evaluation and proof of concept for both joining and bending prior to producing the actual VAWT blade set.

2.2 End Fitting Fusion Joining

Fusion bonding, or welding, was investigated for the blade-to-tower attachment. Fusion bonding is one of three distinct categories of joining methods for polymeric materials that also includes mechanical fastening and adhesive bonding. The process itself can be subdivided based on the heat generation mechanism at the bondline [2]. All methods of fusion bonding thermoplastics utilize the principal of heating a polymer to above the glass transition temperature at the interface to create a viscous state, then by applying pressure and bringing the bonding surfaces together polymer chains can entangle, and upon cooling form a bonded area of entwined polymer chains in a process called autohesion [3]. Experiments were carried out to evaluate the effectiveness of fusion bonding via heat welding fully processed Elium® 150 composite plates to the VAWT blade in order to determine the required bond area for the loading conditions. These experiments investigated both joining process parameters and surface texture of the laminates to be bonded. ASTM D3528 was followed to determine the Double Lap Shear Strength (DLSS) of bonded specimens [4].

2.2.1 Double Lap Shear Specimen Preparation

A method was developed to generate double lap shear strength specimens from sections of the infused hollow airfoils and infused flat laminates that were consistent with ASTM D3528 dimensions, as shown in figure 6. To meet the ASTM specimen requirements, the infused flat laminates were produced from the same reinforcement material, but twice the thickness of the hollow airfoil laminate. Surface texture variations were attained from the imprint of the different consumable materials on both surfaces of the flat laminates, during the resin infusion process.

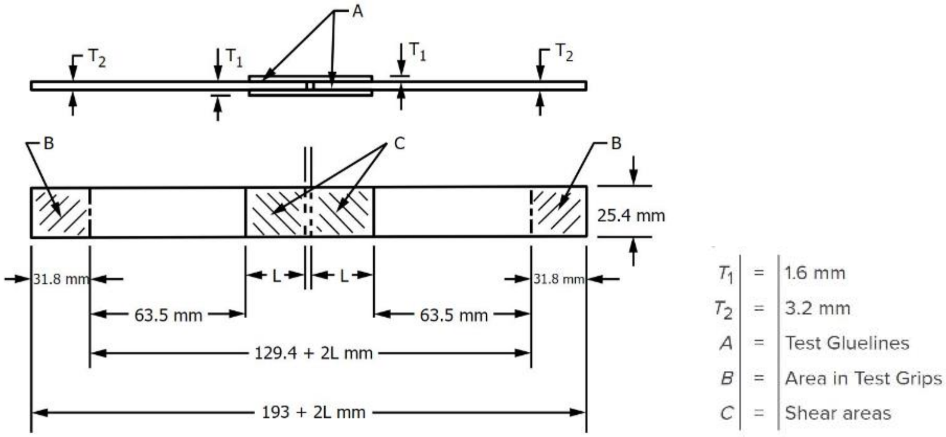


Figure 6. Double lap shear sample configuration and definitions according to ASTM D3528 [4]

For each test sample plate, which would ultimately be cut into 4 double lap shear coupons, a short, 28mm (1.1”), length was first cut from an infused hollow airfoil. Two panels, each 108mm (4.25”) long by 127mm (5”) wide, were then cut from a larger resin infused flat laminate which was approximately twice the thickness of the airfoil wall. As indicated in Section 2.1, the triaxial glass reinforced airfoil laminate was made from 3 plies with a processed thickness of 2.1mm (0.083”). The flat laminates were made up of 6 plies of the same glass fiber reinforcement, resulting in a nominal thickness double that of the airfoil. The short airfoil section and these two flat laminate panels then needed to be assembled, by sliding the two flat laminate panels inside the hollow airfoil section and crushing the airfoil, at temperature, resulting in a fusion bonded test sample plate with a cross section consistent with the ASTM specimen of figure 6.

To manufacture consistently sized composite double lap shear test plates fixturing was required to hold the two flat laminate panels in alignment, with the correct separation and to accurately position the airfoil section to generate a consistent bond overlap. The fixturing that resulted was a set of identical matched dies. These dies were made from 19mm (¾”) thick aluminum with areal dimensions of approximately 200mm x 200mm (8”x8”) to just fit into the heated press. A 28mm (1.1”) wide by 2.5mm (0.1”) deep trough, approximately 190mm (7.5”) long was milled in the middle of each die half to position the airfoil section while a 127mm (5”) wide x 1.8mm (0.07”) deep machined area and four dowel pins correctly oriented the matching upper die half and position the flat laminate plates being bonded to maintain a 2.5mm (0.1”) wide spacing between the two 108mm (4.25”) long adherends, in accordance to ASTM 3528. The die set and the positioning of the test sample plates can be seen in figure 7. Test sample plates were prepared by aligning the airfoil section and the two adherend flat laminate panels in one half of the die set and then placing the second die half on top and putting this assembly in the hot press. The platens of the hot press were then closed, applying the specified temperature and pressure for a predetermined period of time, which flattened the airfoil section onto the two plates creating the joint. (figure 7)

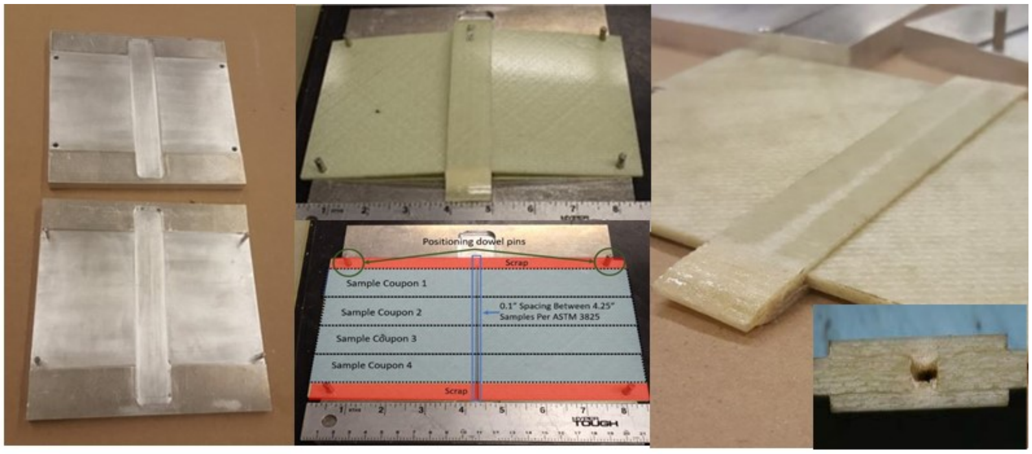


Figure 7. ASTM specimen assembly dies (left), fusion bonding specimen fabrication on the die (center), after bonding (right) and coupon cross section (inset)

The resulting sample plate was then cut into four double lap shear coupons as shown, schematically, in figure 7. Thus, the final test specimens are comprised of two 108mm x 25mm (4.25” x 1”) laminates separated by 2.5mm (0.1”) and bonded on the top and bottom faces with a second adherend (the flattened airfoil section) providing an overlap contact length of 12.7mm (0.5”) on each flat laminate for a total shear area of approximately 645mm^2 (1 in^2). The top and bottom adherends that simulate the airfoil blade are half the thickness of the 108mm (4.25”) laminates to create an equal cross section throughout the joint.

2.2.2 Experimental Approach – Test Variables Evaluated

The study performed was constructed more in the form of a filter rather than a complete full matrix analysis. Preliminary testing utilized glass fiber reinforced Elium® 150 components and investigated the process variables, (i) applied pressure, (ii) cooling method, and (iii) time at temperature. The temperature evaluated was fixed at 200°C, based on the Elium® 150 properties.

The pressures were 185 psi and 370 psi and the times at temperature evaluated were 5 minutes and 10 minutes. In addition to the process variables, four different surface textures of the resin infused flat laminates were investigated. Surface texture was predicted to have an effect based on both contact area during the heated compression and the resulting effective bondline thickness [5,6]. As indicated in Section 2.2.1, the surface texture was varied through the use of different expendables in contact with the two surfaces of the flat infused laminates. The inside surface finish of all of the airfoil sections was held constant as that introduced by the Compoflex® RF3 which was used in all the airfoil sections of interest.

The four surface textures to be investigated were manufactured by having a single laminate, approximately 710mm x 710mm (28"x28"), divided into, originally, three separate sections each containing a different surface release ply that provided varying degrees of roughness, as seen in figure 8. The first material used was a 300 g/m^2 flow media with release film called Compoflex® RF3. Compoflex® RF3 is a combination of peel ply, release film and flow mesh, used to control flow rate, distribute resin and release consumables from a composite laminate, and is seen on the left in figure 8. The section in the middle of figure 8 utilized a standard green flow media on top of Release Ply Super A from Airtech, which is a 139 g/m^2 heavy weight nylon peel ply. The nylon peel ply was selected for its large weave. The final surface texture was created using G-FLOW™, a structural flow media made with 100% glass fibers, specifically for infusion processes. This is a 500 g/m^2 heavy weave and open mesh which increases resin flow rates during infusion without adding an external or internal flow media.

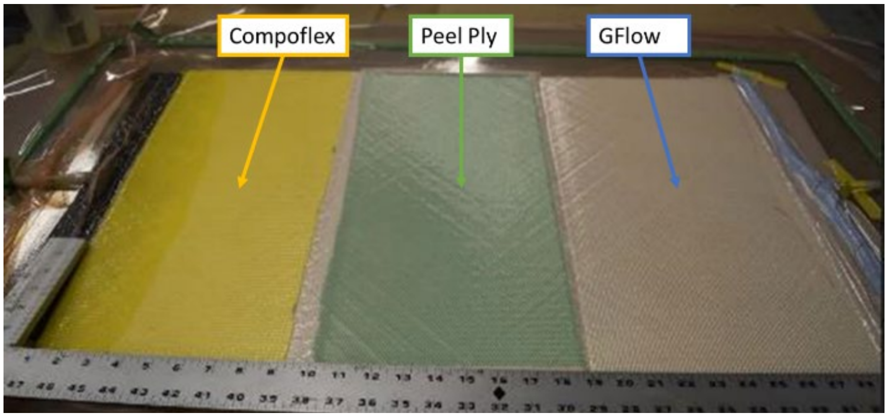


Figure 8. Preparation of the flat plate surfaces using Compoflex, Peel Ply and G-Flow

The surface created by the G-FLOW™ had the largest vertical profile; however, exhibited a smooth, glossy finish as the vacuum bag was placed directly over the G-FLOW™. Unfortunately, difficulties arose in preparation of this surface and ultimately, the G-FLOW™ surfaced panel was not included in the texture comparison. The surface texture resulting from the Compoflex® had the second roughest surface followed by the Peel Ply. This large flat laminate was subsequently used as the feedstock to produce the 108mm x 127mm (4.5"x5") flat adherends for the double lap shear specimens. Compoflex® and Peel Ply were left on the laminate and removed just prior to compression molding the double lap shear specimens to provide a fresh surface for bonding and reduce the possibility of the surface becoming contaminated. Test groups of each of these two surface textures were also lightly sanded with 220 grit sandpaper resulting in both an as-removed surface finish and a sanded surface finish, and thus, 4 different surface textures.

Table 1: Specimen Conditions Evaluated

#	Surface Texture		Consolidation pressure applied		Cooled under pressure	Hold time at 200°C
	Expendable Material used at Surface	Sanded with 220 Grit	(MPa)	(psi)		(minutes)
1	Compoflex®RF3	No	1.28	185	Yes	5
2	Compoflex®RF3	No	2.56	370	No	10
3	Compoflex®RF3	Yes	2.56	370	Yes	10
4	Peel Ply	No	1.28	185	No	5
5	Peel Ply	No	2.56	370	Yes	5
6	Peel Ply	Yes	1.28	185	Yes	5
7	Peel Ply	Yes	2.56	370	Yes	5

Specimens were loaded in tension in an ATS Series 900 load frame using wedge-lock grips to transfer the load into the double lap shear joint at a rate of 0.127 mm/min (0.005 in/min). After each specimen had failed, the maximum load and images of the fracture were recorded.

2.3 Blade Bending

Post-process reforming of the thermoplastic composite material is a desirable approach that could allow opportunities to shape somewhat complex geometries from more simple, molded, composites. By reforming the composite, a simple and consistent cross section may, for instance, be molded at long lengths, cut to appropriate length, and then, in the case of a wind turbine blade, curved (Darrieus) and/or bent (Giromill) into the final blade geometry. Some of the challenges entail maintaining sufficient integrity of the composite and the overall aesthetics of the finished blade during the time the thermoplastic matrix composite is in a low stiffness form.

The first, simplest trial was to heat the hollow airfoils section and free bend it around a tube of approximately 4” diameter. However, in these very preliminary trials, a clear problem was buckling of the inner radius of the 90 degree bend due to in-plane compressive forces as the stiffness drops at temperature, as seen in figure 9. In addition, the difference in arc length of the inner and outer surface of the bent airfoil means that the buckling of the inner surface will occur.

Figure 9. Buckling in preliminary trial 90 degree free bend of airfoil geometry

To minimize this buckling, and improve the overall quality in the bent region follow-up trials made use of matched molds. A nominally 200mm (8”) length of the hollow blade was heated to 200°C in a hot press and crushed, resulting in a flattened section thickness of approximately 6.3mm (0.25”). This was then placed between a matched die set, before losing significant heat, and reshaped. This approach helped reduce the inner surface buckling; however, because there was no measurable in-plane shear, the fiber length around the outside of the bend was still notably greater than that around the inside of the bend, and bulging of the inner surface, at the edges of the die, occurred as seen in figure 10.

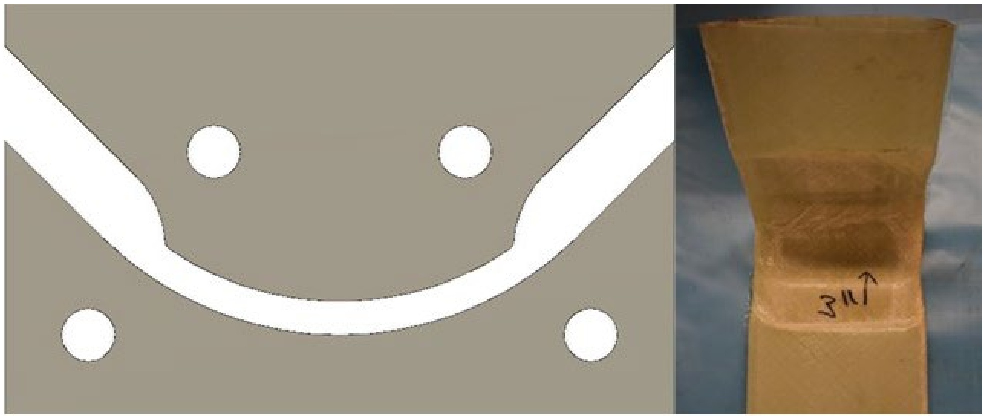


Figure 10. Trial 90 degree matched die set and resulting bend

A second die set was designed and fabricated that included a reverse bend in an attempt to maintain equal inside and outside fiber lengths, as shown in figure 11. While the bend quality did improve slightly, there were still corner quality issues. In addition, in use of both die sets it was difficult to consistently position the mid-point of the bend at the planned location along the length of the airfoil segment. The airfoil test segments shifted relatively easily, and this lack of ability to position the bend along the length of the blade reduced the confidence in being able to produce multiple demonstrator blades of consistent dimensions and accurate spacing between the required pair of bends. Thus, between difficulties related to accurate location of the bend and that the geometry was becoming far more complex that a simple 90 degree arc an alternative bending approach was developed for the final VAWT demonstrator unit.

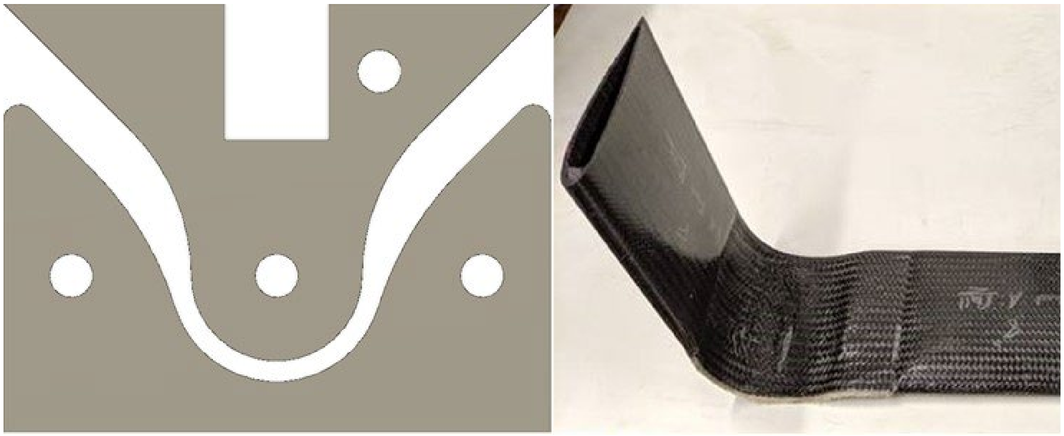


Figure 11. Matched bend die design with equal inner and outer surface lengths.

The final bending fixture design was based on a wiping die, or tube bender. The key components, two cylinders, are shown schematically on the left of figure 12. The central cylinder is 100mm (4”) in diameter and the smaller “wiping” cylinder is 50mm (2”) in diameter.

Figure12. Wiping die set and resulting double bend test article

With this approach the smaller outside roller rotates while it is swung around the inner (fixed) cylinder and is set to maintain a consistent, controlled radial gap as shown in the middle image of figure 12. The radial gap is set, based on the thickness of the heated and flattened 200mm (8”) length of airfoil, at nominally 6.3mm (0.25”). This wiping, or ironing, action around the outer surface of the airfoil, and the relatively stationary nature of the inner surface, resulted in acceptable and reproducible bends as seen on the right of figure 12. In addition, a key factor of this design is related to fixturing the end of the airfoil, using the pre-drilled mounting holes, at a specific distance from the bend. While this is necessary to stop the blade from sliding through the wiping die set, it is also critical to the accurate and repeatable positioning of the two bends in the final demonstration blades. Those bends had to result in a specified “bend-to-bend” distance as well as the specified upper and lower tower to bend distance.

3. RESULTS

3.1 Double Lap Shear Test Results of Glass fiber Reinforced Elium® 150 Fusion Joints

Four specimens of each configuration, listed in Table 1, section 2.2.2, were tested. The mean and standard deviation of each group is presented in Table 2. For both surface finishes the maximum joint performance was statistically the same, with the highest double lap shear strength value with the Compoflex®RF3 surface finish at 15.8 ± 0.4 MPa versus 15.5 ± 0.4 MPa for the Peel Ply surface finish. To put this in perspective, the failure load for these specimens was over 2,040 kg (4,500 lbs). Comparing the 7 cases of Table 2, it can be seen that cooling under pressure seems to yield preferred properties for both the Compoflex®RF3 and the Peel Ply textures. It also seems that the higher consolidation pressure yielded slightly improved performance and that a 5 minute hold at 200°C was sufficient; however, the data is inconclusive in terms of the need for sanding of the surfaces. Thus, for the planned VAWT blade set it was determined that, based on the conditions evaluated, the fusion joining process was insensitive to surface condition and hold time at 200°C, but that cooling the press under pressure was important as was the higher 2.56 MPa (370 psi) pressure.

Table 2: Double Lap Shear Testing Results

#	Surface Texture		Consolidation pressure		Cooled under pressure	Hold time at 200°C	Lap Shear Strength	Lap Shear Strength
	Expendable Material used	Sanded	(MPa)	(psi)		(min)	(MPa)	(psi)
1	Compoflex	No	1.28	185	Yes	5	14.0 ± 0.5	2023.7 ± 69.6
2	Compoflex	No	2.56	370	No	10	7.4 ± 0.5	1067.1 ± 69.4
3	Compoflex	Yes	2.56	370	Yes	10	15.8 ± 0.4	2286.8 ± 50.9
4	Peel Ply	No	1.28	185	No	5	11.6 ± 2.0	1679.3 ± 286
5	Peel Ply	No	2.56	370	Yes	5	15.5 ± 0.4	2251.9 ± 64.5
6	Peel Ply	Yes	1.28	185	Yes	5	14.8 ±0.6	2145.2 ±87.4
7	Peel Ply	Yes	2.56	370	Yes	5	15.4 ±0.2	2239.6 ±26.5

For specimens with the higher failure strengths there was damage to the underlying composite plate adherend. As shown in figure 13, one of the airfoil-sourced adherends of the double lap shear coupon generally was fully debonded from the coupon, while the second airfoil-sourced adherend remained attached to one of the flat plate adherends. Figure 13 also shows the damage in the original flat plate adherend for the Compoflex®RF3, specimen #1, indicating that the joint was strong enough that failure was transferred into the composite laminate. Note that the Compoflex®RF3, specimen #1 joint parameters resulted in the highest measured performance. Thus, the indication is that the highest double lap shear values observed are limited by the laminate and not the joint itself, suggesting that there is little to gain by further joining process parameter optimization.

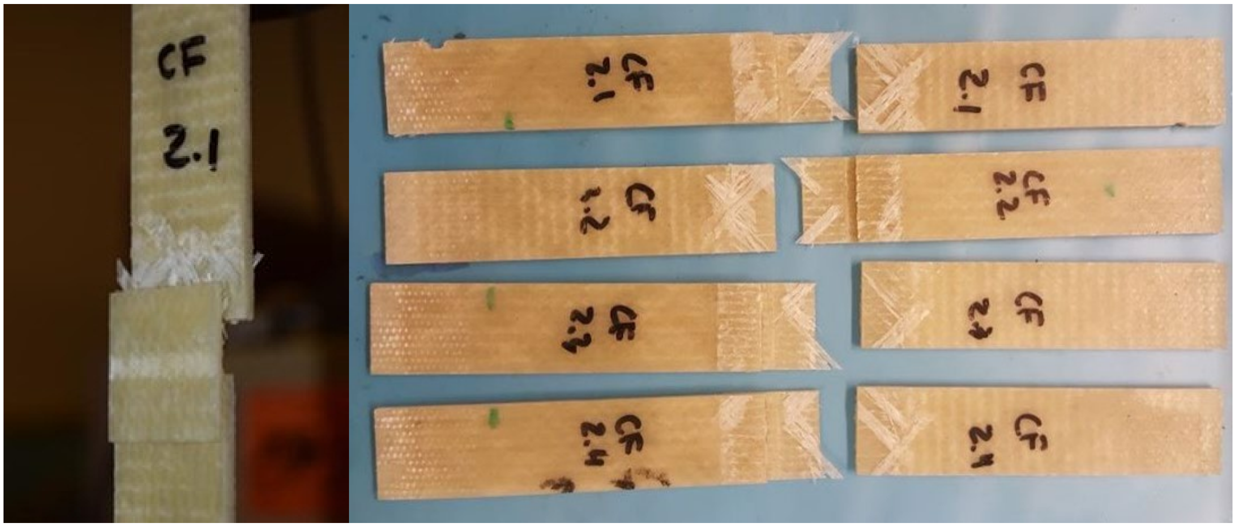


Figure 13. Failure surface morphology - Compoflex®RF3, Specimen #1 (Table 2)

3.2 Joining and Post-Process Deformation as Applied to VAWT Blades

Using the 3.5m (138”) mold set developed within the VAWT project a number of 3.5m (138”) hollow carbon fiber/Elium® 150 airfoils were resin infused. With confidence in processes developed for end-fitting fusion joining and post-process bending, as described in previous sections, all the pieces were ready to complete the blade set for the VAWT prototype.

To facilitate the final joining operation a set of matched aluminum tool plates, shown in figure 14, were CNC machined. Based on the hollow airfoil size and the results of the joining study, a generous bond area of 100mm x 100mm (4” x 4”) was designed into the tool plates. This set of tooling plates included locating points for the 3 mounting holes which were pre-drilled in the carbon fiber/Elium® 150 mounting plates. There was also a positive stop machined into the die set to accurately locate the hollow blade section. From the original CAD model, the overall length of the bent blade, from attachment holes on the top tower mounting tab to the attachment holes on the bottom tower mounting tab, was determined to be 3.35m (132”). This measurement was used to ensure that the relative position of the fusion bonded end-fitting plates was correct and consistent between the 3 blades of the blade set. The resulting hollow airfoil length required was 3.28m (129”). This whole assembly was placed in a hot press, heated to 200°C and compressed to fusion bond the end fitting with the blade-end contour, as shown in figure 14. Joining parameters used, 200°C, Peel Ply texture, 2.56MPa, held for 5 minutes and cooled under pressure, were based on the results of section 3.1.

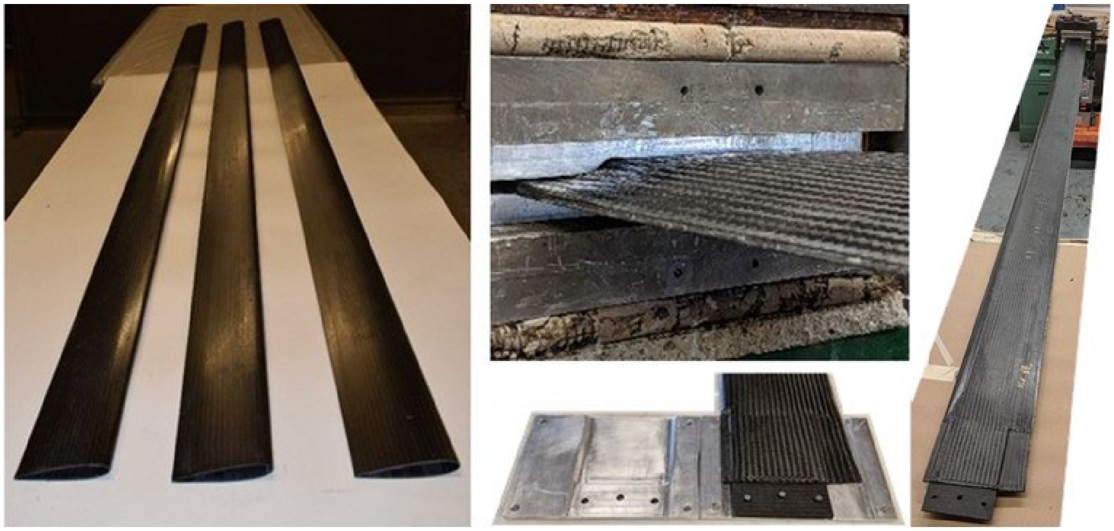


Figure14: Trimmed 129” blades (left), Thermoforming of the mounting tab (middle), straight blades with integrated mounting tabs (right)

With end-fittings joined to both ends of each of the three blades, the mounting tabs could be used as reference features to locate the regions of the airfoil that were to be heated and bent to a 90° angle. These regions were placed in the heated platen press fitted with flat platens and pressed, once the thermoplastic matrix composite reached 200°C. The airfoil was quickly transferred to the wiping die bending jig and the heated section was bent around the fixed 4” diameter mandrel by the sweeping motion of the steel roller, as described earlier. This sequence of steps was critical to ensure that the bent regions were correctly positioned and the same for each of the three blades in the set. Once the bend was complete it was allowed to cool, once again becoming rigid, prior to removal from the fixture.

Figure 15 shows a blade after completion of each of the steps of the bending process. It is important to note that the composite is very flexible in the region heated to 200°C in advance of the bending operation and must be well supported and held in alignment during cooling to reduce the likelihood of sagging or twisting and a resultant misalignment.

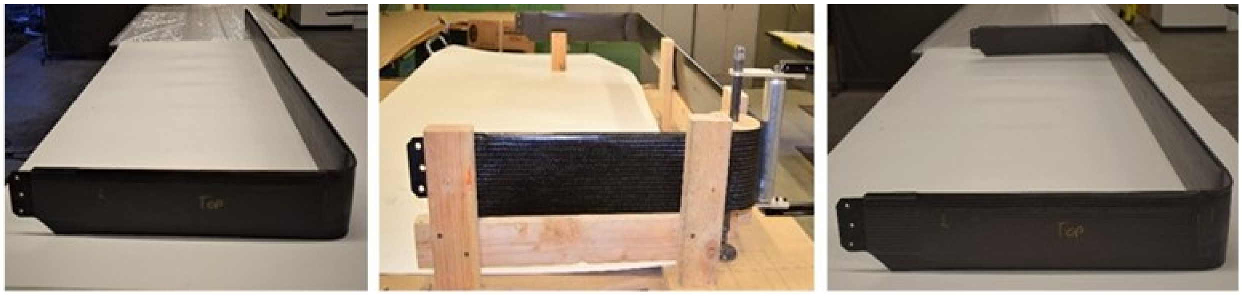


Figure 15. Post-process bending procedure of the 3.28m (129”) airfoils

The resulting blade set, figure 16 (left), was used to generate a non-functioning proof of concept for the VAWT rotor assembly, shown in figure 16 (right). Further, the rotor assembly demonstrated the added manufacturing functionality available through the use of a thermoplastic matrix composite.

Figure 1: Full-scale VAWT rotor assembly

4. CONCLUSIONS

Fusion bonding process parameters were varied to investigate the effects of time at temperature, surface texture, applied pressure and rate of cooldown. From the testing it was determined that, for the glass fiber reinforced Elium® 150 composites, double lap shear strengths in excess of 15MPa (2,200 psi) could be realized. Further, it was realized through post failure evaluation that the highest failure strengths were related to failures within the composite adherend, indicating that the fusion bond was no longer the limiting factor. The joint tests indicated that the fusion joining process was more sensitive to applied pressure and rate of cooling than to time at temperature and surface texture. The higher pressures tested and slower cooling rates were preferred. Post-process bending was evaluated in a more qualitative way, but several approaches were tested before settling on a wiping action to generate the 50mm (2") radius, 90° bends. Due to the differences in the inner and outer arc lengths the bends were prone to fiber buckling on the inner surface. However the wiping die approach minimized fiber buckling without having to create complex reverse bend profiles to equalize the inner and outer arc lengths.

The combination of post-process deformation and fusion joining, available through the use of the thermoplastic matrix composite, helped demonstrate post-process bending to remove the need for discrete connections between the horizontal and vertical sections of a 'C'-shaped Vertical Axis Wind Turbine blade. A complex, molded geometry resulted without complicated molds or multiple blade segments that would have been required if a thermoset matrix composite were used. This effort demonstrated that, in addition to the desirable aspect of recyclability, thermoplastic matrix composites can also enable alternative designs and manufacturing approaches.

5. ACKNOWLEDGMENT

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