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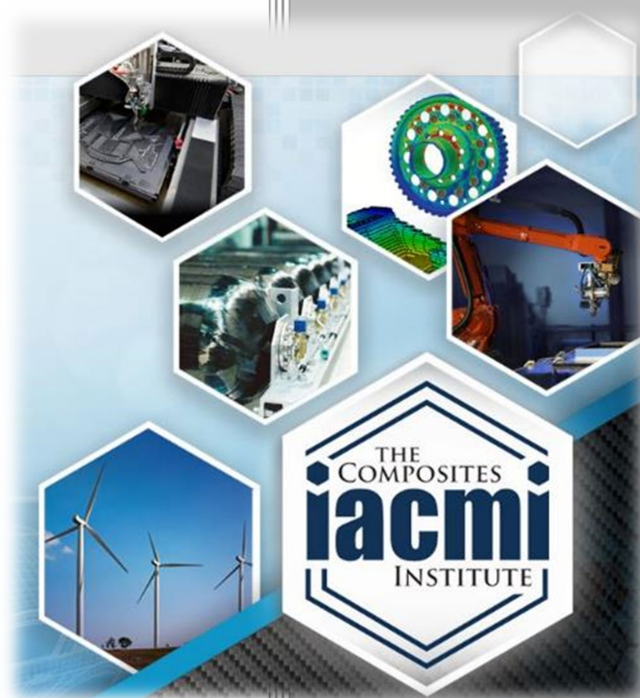
Vertical Axis Wind Turbine (VAWT) with Thermoplastic Composite Blades



Participating organizations:
SHC, CSU, NREL, Arkema
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U.S. DEPARTMENT OF ENERGY

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Vertical Axis Wind Turbine (VAWT) with Thermoplastic Composite Blades

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1. LIST OF ACRONYMS

AEP – Annualized Energy Production
ASTM – American Society for Testing and Materials (formerly)
CAD – Computer Aided Design
CFD – Computational Fluid Dynamics
CFRP – Carbon Fiber Reinforced Polymer
CSU – Colorado State University
DLSS – Double Lap Shear Strength
DMA – Dynamic Mechanical Analysis
DSC – Differential Scanning Calorimetry
FEA – Finite Element Analysis
GFRP – Glass Fiber Reinforced Polymer
HAWT – Horizontal Axis Wind Turbine
IACMI – Institute for Advanced Composites Manufacturing Innovation
ILSS – Interlaminar Shear Strength
LCOE – Levelized Cost of Energy
MDF – Medium Density Fiberboard
NREL – National Renewable Energy Laboratory
SHC – Steelhead Composites
TE – Techno-Economic
TGA – Thermogravimetric Analysis
NACA – National Advisory Committee for Aeronautics
UD – Uni-Directional
VARTM – Vacuum Assisted Resin Transfer Molding
VAWT – Vertical Axis Wind Turbine

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2. EXECUTIVE SUMMARY

Rising concerns about global climate change, planet pollution and increasing use of energy have accelerated wider utilization of renewable energy sources. A recent trend in energy system development is decentralization of power generation systems. The opportunity for individuals or organizations to generate electricity locally decreases losses and part of the electricity price caused by the long-distance power transmission. Vertical axis wind turbines (VAWTs) cannot compete with traditional horizontal axis wind turbines (HAWTs) on the basis of aerodynamic performance or maximum power output generated for a given footprint. However, their ability to perform at a wide range of wind speeds, indifference to wind direction, simplicity of fabrication, transportability and maintainability make them ideal candidates for decentralized installations in urban and residential areas.

The project team including Steelhead Composites (SHC), Colorado State University (CSU), National Renewable Energy Laboratory (NREL) and Arkema Inc. designed and fabricated a VAWT rotor assembly with thermoplastic composite blades using novel infusion and fabrication techniques. This full-scale VAWT rotor assembly was designed for a rated power output of 0.5-1 kW, as estimated through analytical computational fluid dynamics (CFD) methods. Those CFD simulations were combined with structural finite element analysis (FEA) to optimize the shape and composite layup of the wind blades.

Much of the emphasis of this program was to characterize the recyclable thermoplastic material and composite structural design, in order to take full advantage of the material properties of such composites. Additionally, this project examined the potential of thermoplastic resin systems to transform the way VAWT rotor assemblies are joined both in the factory in in the field, by utilizing thermally welded joints to minimize field failure. The infused composite blades manufactured during this program are an excellent example of these benefits made possible by the Arkema thermoplastic resin system. This prototype blade manufacturing also provided the groundwork to inform decisions for larger scale manufacturing techniques applicable to a commercialization strategy.

There is specific commercial interest for small scale VAWT’s that are competitively priced, perform to expectations, and have environmentally conscious end-of-life characteristics. Economic analysis was also conducted to compare designs and material usage, providing an estimated levelized cost of energy (LCOE) for the VAWT. The next steps for commercialization would include testing of the rotor assembly to verify predicted performance, specification of the balance of plant components (generator, inverter, etc.), and identification of a manufacturing partner with capability to scale-up production. This program has showed the potential for a commercially viable product through detailed analysis, material characterization and prototype fabrication.

3. INTRODUCTION

Distributed wind power generation is relevant for mobile and rural locations, where small wind turbines are able to offset the relatively small energy demand. Wind turbines for use in distributed systems are generally rated at a maximum capacity no larger than 10 kW. That size turbine can be sufficient for small residential and off-grid commercial or industrial use. In some applications, a capacity of no larger than 1 kW is desired to reduce both the cost and scale of the turbine structure and components. For instance, many marine applications install wind turbines rated between 200 and 500 W to contribute power to the craft. Those same size turbines can be employed at cell phone towers, remote oil and gas installations, remote industrial monitoring sites, or even for mobile recreational use.

The primary goal of this Technical Collaboration project was to demonstrate the design and economic feasibility of a VAWT rated between 0.5 and 1 kW using fiber reinforced thermoplastic composites. Emphasis was placed on the techno-economic analysis of these small wind turbines, structural design optimization using composite properties, computational simulations to determine potential power harvesting capability and process optimization of composites using thermoplastic resins.

Composite materials, in general, are beneficial for their high strength-to-weight ratio which is a critical advantage to lightweighting structures. Many common composite materials include thermoset resins as the matrix material to bind together the reinforcing fibers. Those thermosets cure to a permanent finished state that provides excellent strength, but limited ability to post-process or recover the materials at end of life. Due to the prevalence of thermosets, many industrial processes have been developed around the thermoset resin processing characteristics.

Thermoplastics are another category of resins that offer advantages in their finished state, including durability, impact toughness, ability to reform, and recyclability. In general, thermoplastics require processing that is distinct from traditional thermoset processing. However, Arkema Inc has developed a liquid thermoplastic resin – the Elium® product line – that behaves much like a traditional thermoset, allowing standard manufacturing techniques to result in products that harness the advantages of thermoplastics, including the potential to reclaim materials at end of life. Arkema's Elium® is a 2-part system that forms a thermoplastic polymer of the acrylate family. The design concepts for this project were all based on the usage of thermoplastic composites in the blades themselves. Future design concepts could incorporate more thermoplastic composites into the rotor assembly, but those efforts would likely require a larger investment in manufacturing capability demonstration.

During this program, Steelhead Composites collaborated with NREL to identify the key factors of VAWT design that affect their techno-economic assessment (TEA) in specific mobile or distributed applications. Subsequently, Steelhead and CSU considered three or four design variations of VAWTs, examining lift-based (Darrius, gyromill, etc.), Savonius and drag-based designs that can take advantage of composite materials. Computational Fluid Dynamics (CFD) and finite element (FE) simulations were used to benchmark the power harvesting capabilities and structural performance of each design.

During the subsequent phase of the program CSU and Arkema worked closely together to investigate different composite processing, including but not limited to pultrusion, infusion, filament winding and additive fiber placement. Design for manufacturability was considered as well to ensure that these turbines are economically viable for mobile and distributed applications. The project culminated in harmonizing all of the above aspects in a prototype design fabricated for demonstration in July 2019.

Steelhead Composites is partnered with Daedalus Composites, a company that produces high-end, zero-emissions yachts. These yachts harness multiple sources of renewable energy, including wind power through the installation on each yacht of 2 or 3 turbines, each rated at approximately 200-500 Watts. Since wind power is not the primary source of energy, the primary requirement for any wind turbine installed on the vessel is not necessarily maximum power generation, but rather modest power generation, with emphasis on aesthetics, small form factor, low noise, negligible vibrations, and providing power at low wind speeds. This specific company is an indicator of interest within the marine sector.

Beyond the marine sector, there are commercial opportunities that have been identified with very similar technical requirements as the list above, that would also benefit from a deployable structure, making the inherently small form factor even better suited for packing and transport. Specifically, disaster response efforts could benefit from a low-cost solution such as this that could be distributed to far reaching areas where the return of power will be delayed. A small VAWT could provide an additional power source that would allow for basic electrical requirements (e.g., lighting, cell phone charging) to be met. Other potential market opportunities lie within recreational campers including tent, recreational vehicles, and off grid enthusiasts, as well as exploratory science and military uses. Applications for these turbines, or scaled versions, could also be to supplement power to cell phone towers (especially in developing regions), at oil and gas wells, and in sustainable building complexes in both rural and urban environments.

According to the 2016 Distributed Wind Market Report (August 2017 per DOE contract DE-AC05-76RL01830 PNNL-26540, available at https://www.energy.gov/sites/prod/files/2017/08/f35/2016-Distributed-Wind-Market-Report.pdf), Primus Wind Power, a US-based small wind turbine manufacturer, experienced record sales of their 160-400 Watt turbines during the year 2016. The main customers for these small turbines were within the oil and gas and telecom industries, as well as domestic and international remote military installations. Per that same report, it is estimated that 95% of sub 10 kW turbine installations during 2016 went into remote, off-grid locations. That general trend supports the increased sales volumes of small turbines (200-500 Watts), indicating a market interest.

The goal of this project was to develop a preliminary design of a VAWT that can now be used to better explore market potential. The proposed technology is intended to stand apart from the currently available products through its unique combination of materials allowing for recyclability at end of life. This VAWT offering will provide more consumer options when aesthetics and ease of deployment are required.

While this project strictly focused on the conceptual design of a VAWT, the long-term goal is to develop a product to be certified to national standards, which is a direct goal of the DOE Competitiveness Improvement Project (CIP).

4. BACKGROUND

Vertical axis wind turbines (VAWTs) have been in use in various forms for millennia, dating back to early Persian and Chinese civilizations. Early embodiments were drag-based and primarily used for agricultural needs. Drag based devices, often referred to as “Savonius” designs for a more modern design by a Finnish engineer of the early 20th century, are generally not considered very efficient, and to this day still mostly serve agricultural needs and are rarely used for electrical power generation. An alternate approach to VAWT designs is to use aerodynamic forces to increase efficiency. These lift-based VAWT designs are often referred to as a “Darrieus” style turbine due to the patents filed by a French inventor of that name in the early 20th century.

General advantages of all VAWTs include their ability to operate in winds from any direction, their reduced structural requirements for any central mast, the ability to locate the balance of plant below the rotor on the ground, and an overall simplicity compared to the control requirements of horizontal axis wind turbines.

Sandia National Laboratory conducted exhaustive research on VAWTs from the late 1970’s through the 1990’s, focusing on the Darrieus configuration due to inherent efficiencies. The research included a 17 m research turbine and a 34 m Test Bed turbine rated at 500 kW (in a 12.5 m/s wind). Many major insights were gained during those research efforts that demonstrated some of the advantages, as well as limitations, of VAWT designs. Although that research was focused on much larger systems than the current program, similarities exist between all VAWT designs no matter the scale.

Limitations of the blades themselves were found during the Sandia studies, when the blades were made of extruded 6063 aluminum. Fatigue failure was common. An approach with a true Darrieus configuration is that the blade loading can be primarily in tension, which is well-suited for reinforcements within composite materials. And those same composite materials tend to handle fatigue very well. Development of a Darrieus VAWT using thermoplastic composite blades can directly address some of the primary limitations identified during the Sandia research.

The project team for this effort was brought together due to their complementary expertise. Steelhead Composites was the industry lead, providing perspective on product commercialization strategy as well as composite structural design and computational fluid dynamic analysis to assess turbine performance. Colorado State University, through its Composite Materials, Manufacture, and Structures Laboratory, assessed the processing capabilities for the liquid thermoplastic resin, as well as characterized the physical and mechanical properties of representative composite materials. The National Renewable Energy Laboratory oversaw the project tasks and provided a technoeconomic model to assess the overall economic viability of the VAWT. Arkema Inc contributed materials as well as processing expertise to help steer the coupon and prototype manufacturing efforts.

Initial efforts focused on the design and economic analysis of the VAWT to reduce the production costs of the carbon fiber reinforced composite blades, as well as to reduce the embodied energy contained therein. Initially in the program, Steelhead, using inputs from CSU and NREL, conducted computational fluid dynamics (CFD) studies to simulate the wind flow behavior through the VAWTs and to help predict important design parameters like torque and power generated by the turbine due to the wind flow. The goal of the CFD analysis was to determine the mechanical loads such as pressure on the blades and torque on the turbine assembly and to estimate the torque and power coefficients of the turbine resulting from the steady wind flow under fixed rotational speed.

Subsequent to CFD analysis, structural finite element (FE) analysis was used to gain insight into the strength and rigidity demanded of this turbine in service. The internal stresses within the composite blade and turbine structure were determined. By their very nature, composite materials are directional materials, and can be fabricated according to designs that most efficiently use their load-carrying capabilities. Therefore, the expected blade deformation under both extreme wind loading and centrifugal loading from rotation was used to optimize the composite material.

Based on the VAWT conceptual designs, a techno-economic (TE) model was developed using NREL's experience modeling the economics of different wind turbine system technologies. The purpose of the TE model was to provide a cost basis to evaluate different technologies. An output from the fully developed TE model was the levelized cost of energy (LCOE), which considers capital expenditures, fixed charge rates, annual energy production, and operational expenditures. Inputs to the model were derived from the Arkema Elium® system and processing parameters specific to different manufacturing methods. The TE model aided in decisions – and will aid in future decisions towards commercialization – to reduce the LCOE for the wind turbine system developed through this project. The model will continue to be a valuable tool to compare VAWT designs across a thorough set of parameters, including the energy required for manufacturing.

5. RESULTS AND DISCUSSION

Subtask 4.5.2

Techno-Economic Analysis of a Vertical Axis Wind Turbine for Mobile Applications

In this subtask, a techno-economic (TE) model was developed using NREL's experience modeling the economics of different technologies used with wind turbine systems. The purpose of the TE model is to provide a cost basis to evaluate different technologies. An output from a fully developed TE model is the levelized cost of energy (LCOE), which considers capital expenditures, fixed charge rates, annual energy production, and operational expenditures. The TE model will aid in future decisions to reduce the LCOE for the wind turbine system developed through this project.

The TE model used inputs from composite material databases, including the Arkema Elium® system evaluated in IACMI project 4.2, as well as the material characterization data provided under the scope of this IACMI project. Processing parameters from different manufacturing methods were evaluated in the TE model. The TE model will be a valuable tool to compare future design revisions and improvements across a more complete set of parameters, to include the energy required for manufacturing using assumed, relevant manufacturing techniques for each candidate revision.

Additional inputs were provided based on the 2D CFD analysis conducted under Subtask 4.5.3, which showed an estimated upper bound of annual energy production (AEP) of 1000 kWh/yr. The development of that estimate is further described in the relevant subsection of this report. Using 1000 kWh/yr as an upper bound, additional knockdown factors were then applied to account for soiling losses (1%), controls losses (1%), collection losses (3%), and H-rotor aerodynamic losses attributed to the struts and corners. For reference, the H-rotor configuration mentioned here is a style of VAWT that is comprised of completely vertical airfoils that are mounted to the central axis via horizontal members, forming the shape of an "H".

A literature review suggests that the aerodynamic losses associated with the H-rotor design will reduce performance from the theoretical by anywhere from 20 – 60%. 3D CFD, or actual field testing, would have greatly reduced this uncertainty, but was outside the scope of this program. As such the techno-economic analysis considered an upper bound of 60% and a lower bound of 20%. It is expected that the final optimized rotor will leverage thermo-forming and thermo-welding capabilities of the thermoplastic matrix blade materials to minimize aerodynamic losses due to the struts and corners to 20% or better. The projected AEP's for 20% and 60% H-rotor losses are 750 kWh/yr, and 350 kWh/yr, respectively.

The levelized cost of energy (LCOE) was then calculated using the expected AEP as an input, as well as estimates for additional required capital expenses and operational expenses. Those expenses were either applied at a reasonable rate charge based on the size of the VAWT or using a representative piece of equipment to capture a reasonable cost outlay for all turbine components and installation requirements.

Additionally, multiple manufacturing methods (i.e. GFRP VARTM, injection molding, and aluminum extrusion) were considered for the blade manufacture in order to provide some comparison of the relative costs associated with common and relevant manufacturing techniques. Reasonable assumptions were made to approximate tooling costs and tooling life based on an expected annual production of 1000 turbines. The details of the assumed manufacturing costs can be seen in Appendix A.

As expected, the costs to manufacture the CFRP blades using a VARTM process, as performed under this study, would be much higher than the costs to either injection mold or extrude the blade profiles out of aluminum. VARTM processing of a carbon fiber reinforced blade set for a single rotor assembly was estimated at a retail cost of $940, approximately 6% more expensive than an equivalent blade set out of glass fiber reinforced composite, but with much greater stiffness. For comparison, a set of plastic injection molded blades is estimated at a retail cost of $614 while an aluminum extrusion leads to a retail cost of around only $291 for a blade set. It is important to consider the plastic or aluminum materials available for those cheaper manufacturing methods would not provide the required mechanical properties as determined through finite element analysis of the rotor assembly structure, and in the case of aluminum would not stand up to the fatigue requirements of a VAWT.

Assuming a VARTM process is employed for manufacture of the carbon fiber reinforced blades, then the resulting LCOE depends greatly on the actual AEP of the turbine. Simply using the estimates as a means to define a range of expectations, an LCOE of $0.48/kWh was calculated using a 20% H-rotor reduction factor (AEP of 750 kWh/yr), and an LCOE of $1.04/kWh was calculated using a 60% H-rotor reduction factor (AEP of 350 kWh/yr).

These LCOE estimates fall in an appropriate range when compared to the small wind LCOE data presented in the DOE 2016 Distributed Wind Market Report (https://www.energy.gov/sites/prod/files/2017/08/f35/2016-Distributed-Wind-Market-Report.pdf), with the LCOE plot from that report shown here for reference (Figure 1). That benchmark suggests the importance of driving the LCOE down through two main avenues: (1) verify and optimize rotor performance to maximize AEP, and (2) reduce manufacturing costs of the carbon fiber reinforced composite blades. Discussion of future steps for both of those are found in the following subsections of this report.

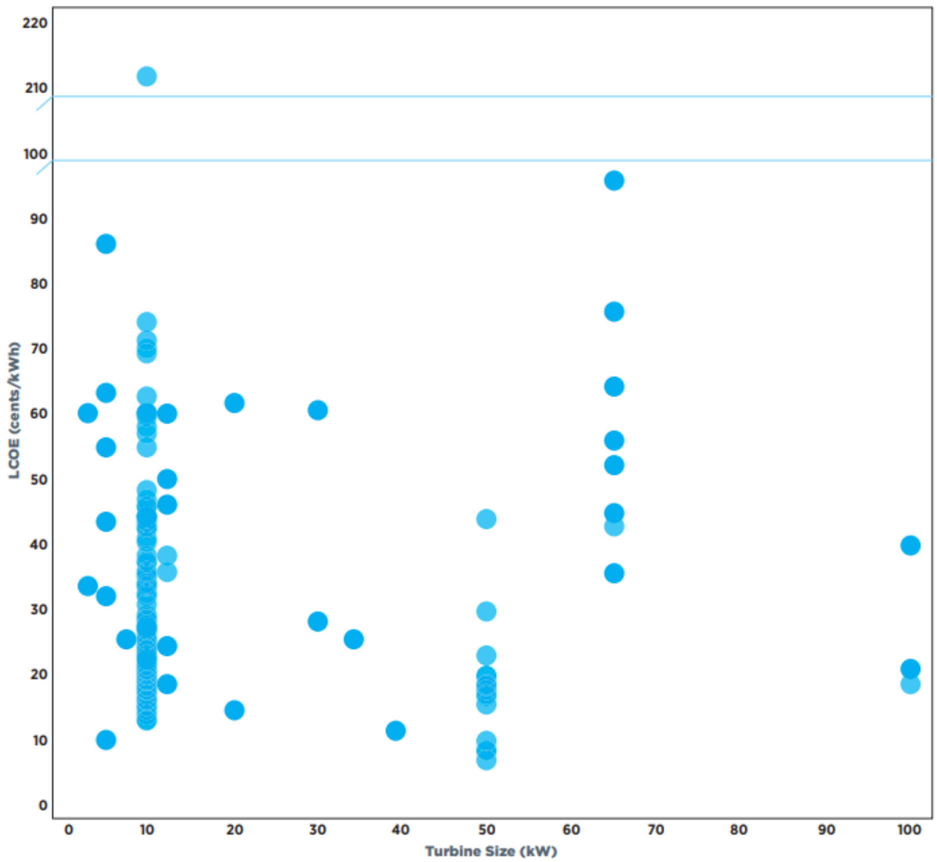


Figure 1: LCOE data from DOE 2016 Distributed Wind Market Report

Subtask 4.5.3

Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) of VAWT Concepts

Conceptual efforts were focused on lift-based Darrieus and giromill (H-rotor) designs. Assessments of blade shapes were conducted to establish the overall dimensions of the blades and strength requirements. Representative, symmetric airfoil profiles were selected based on their previous employment in VAWT designs. The NACA 0012 and 0015 airfoil profiles were selected for further investigation (Figure 2).

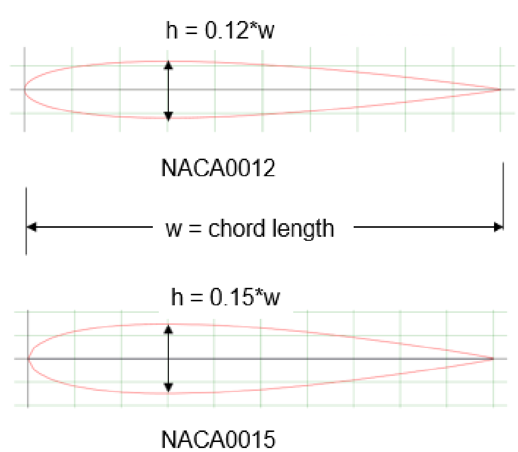


Figure 2: Example NACA airfoil profiles

A comparison study was run by assessing their performance using a 2D CFD analysis at a fixed windspeed of 10 m/s across a range of operational tip speed ratios (TSR), or λ. TSR is a common method to describe the rotational speed of the turbine relative to the windspeed, calculated as shown, where ω is rotational speed and r is the radius of the VAWT:

$$\lambda = \frac{\omega r}{v_{wind}}$$

The CFD was performed with OpenFOAM CFD software using incompressible steady state Reynold's averaged Navier-Stokes (RANS) simulations with a k-ω SST turbulence model. Figure 3 shows a discretized mesh used for the 2D CFD analysis consisting of the 3 aerofoil blades, the central post and the flow field. Figure 4 shows an example output from postprocessed results of a single CFD simulation. During the computational run, the wind pressure acting on the blades is calculated over multiple cycles until the torque and power outputs have stabilized. The resultant load and moment represent that steady state scenario. From those resultant forces and moments, the torque coefficient, c_T, and power coefficient, c_p, can be calculated as follows:

$$c_T = \frac{T}{\frac{1}{2}\rho {v_{wind}}^2 r^2 h}$$

$$c_p = \frac{P}{\frac{1}{2}\rho {v_{wind}}^3 r h} = c_T \lambda$$

The parameters c_T and c_p were computed for several different rotational velocities of the wind turbine at a fixed wind speed (for a given λ). Figure 5 shows a compilation of results from multiple CFD simulations.

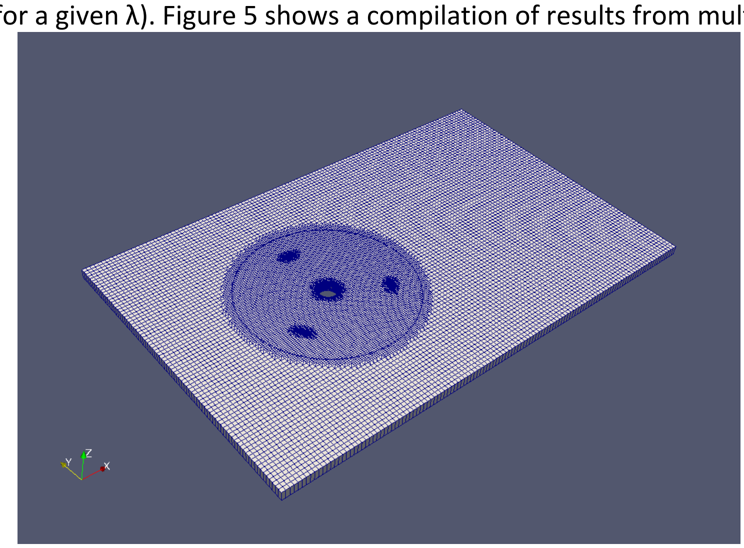


Figure 3: Overview of OpenFOAM mesh for CFD analysis

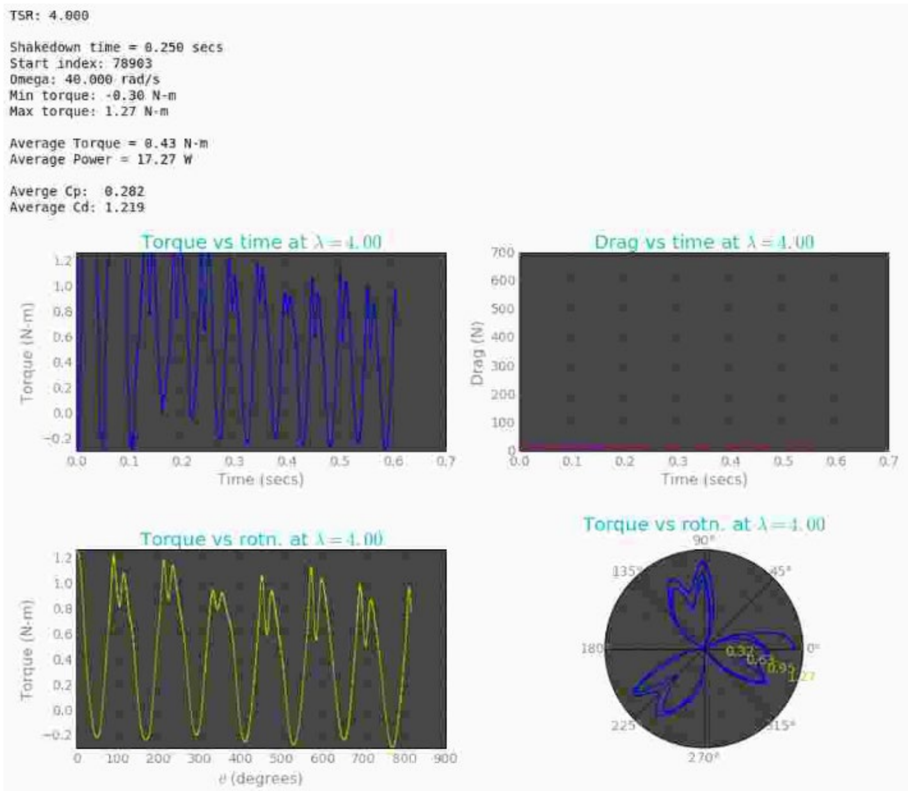


Figure 4: Example post-processing of OpenFOAM CFD analysis

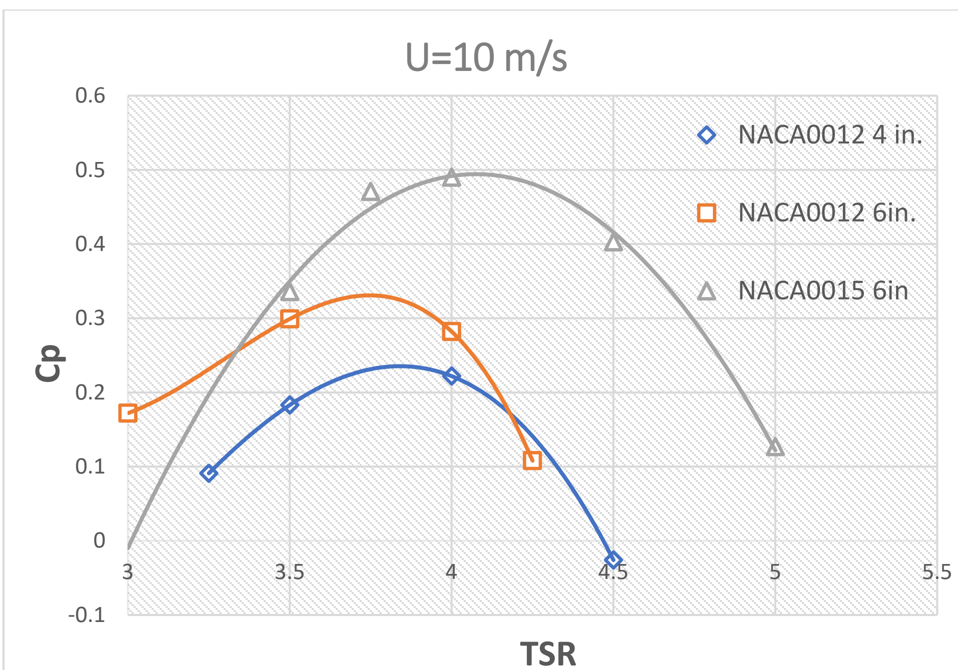


Figure 5: 2D CFD predicted power curves for various airfoil geometries and sizes

The 2D CFD assumes that the vertical airfoil blades are at a fixed distance from the rotor mast. Generating meaningful results from 3D CFD of predicted performance turned out to be beyond the scope of this project due to the excessive computing time required (Figure 6). In the future, 3D CFD could be a useful tool to predict performance differences between the Darrieus (egg beater) and giromill (H-rotor) configurations. Most importantly, the 2D CFD simulations are to be considered an upper bound of performance of this VAWT rotor assembly.

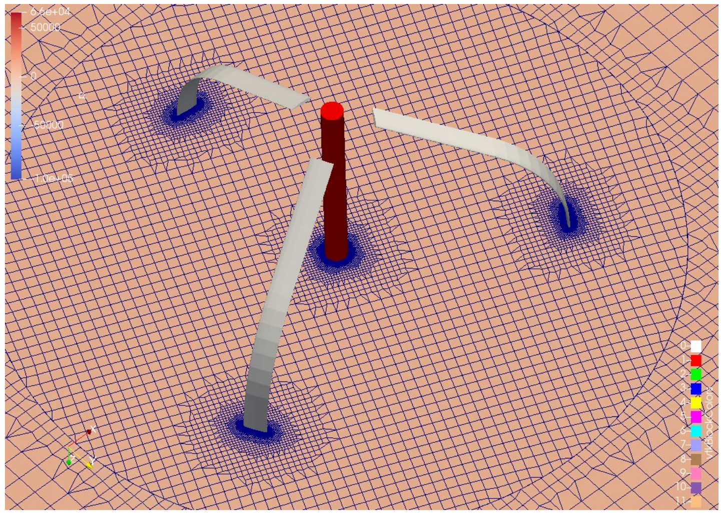


Figure 6: Overview of 3D CFD mesh in OpenFOAM

A decision was made to fabricate a prototype giromill (H-rotor) configuration for ease of manufacture, despite the fact that aerodynamic effects of the corners tend to reduce performance. The giromill configuration does have the comparative advantage of having all of the acting airfoil shapes at the maximum radius, as opposed to the swept airfoils of the Darrieus configuration that reduces the radius across the majority of the blade length for a given maximum radius. Even so, the literature suggests that the aerodynamic losses of the giromill or H-rotor configuration are substantial.

Given the outputs from the 2D CFD simulations, it is possible to calculate an estimated AEP by assuming efficiencies and losses to represent the as-of-yet unspecified balance of plant (Figure 7). An overall driveline efficiency of 98% was assumed to account for coupling losses. A generator was assumed to be sized with maximum power rating of 1500 Watts based on the scale of the VAWT considered for this program and the anticipated rated power (at 11 m/s windspeed) of 500-700 Watts. To capture the effects of inefficient generator operation at lower rotational speeds, a representative generator efficiency curve was applied to the data.

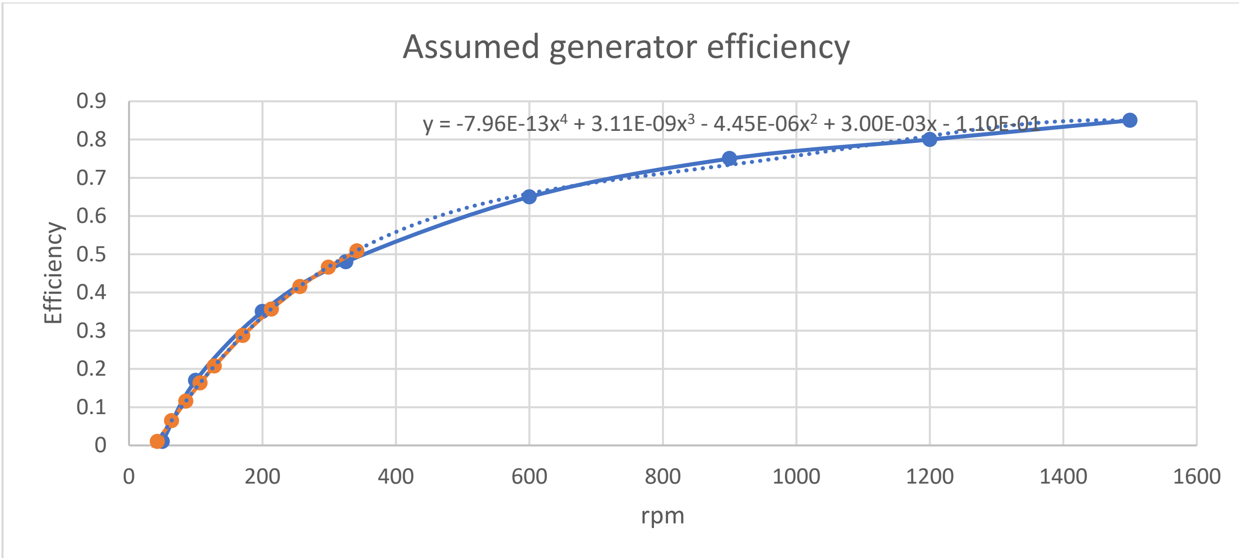


Figure 7: Representative generator efficiency curve

A large assumption was made as to the naturally-driven TSR of this VAWT rotor assembly. Until further testing and validation is conducted, all of these estimates should only be considered as ballpark estimates and are in no way intended to represent actual performance of a VAWT with this design. For the sake of estimating energy production, the VAWT was assumed to operate at a TSR of 3.75. By applying the efficiency curve and losses, the expected power output from the generator is shown in the figure below, with the maximum theoretical power output from the 2D CFD analysis shown as the dashed line (Figure 8).

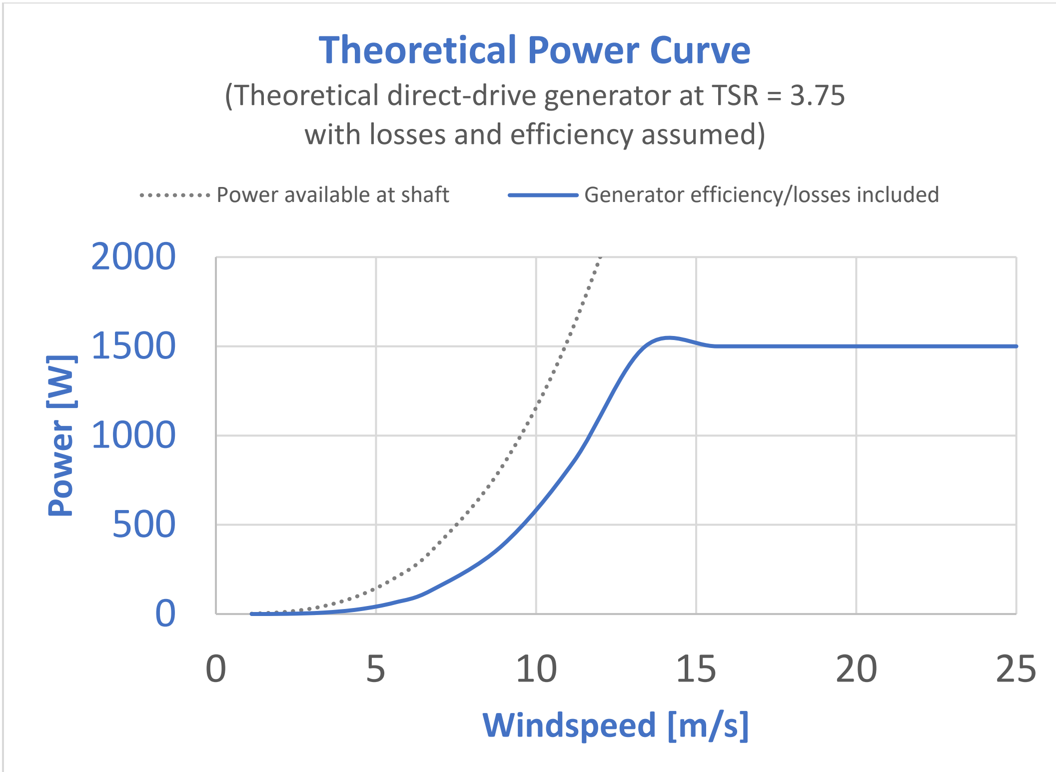


Figure 8: Theoretical maximum and potential power generation based on 2D CFD analysis with assumed losses

It is common to estimate the annual energy production (AEP) using a Weibull distribution for the windspeed. In this case the Weibull parameters were set with a shape parameter of 1.49 and a scale parameter of 4.86, providing a mean windspeed at 5.4 m/s that is very representative of a Colorado site (Figure 9). Applying the theoretical power curve to this Weibull windspeed distribution suggests a theoretical power output by the generator of almost 1000 kWh/yr. An actual turbine is unlikely to produce that much power, though, due to losses that are unaccounted for (aerodynamic end effects, ground shear, electrical losses after the generator, etc) and the fact that the 2D CFD input should be considered an upper bound.

Until further testing and validation is performed, a true AEP value cannot be assigned. Based on literature reviews and relative performance, actual AEP will be significantly lower than the theoretical power output calculated. These preliminary estimates are only a first step in providing a ballpark that would be useful for further design (specifying the balance of plant components) and commercialization efforts.

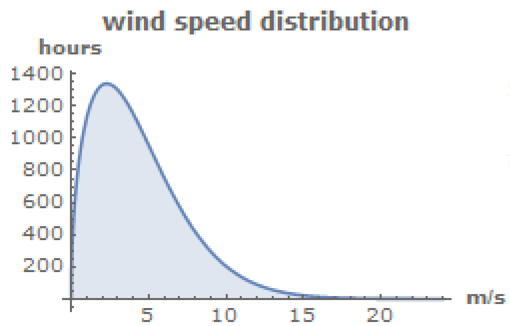


Figure 9: Weibull windspeed distribution plot using scale and shape parameters representative of CO conditions

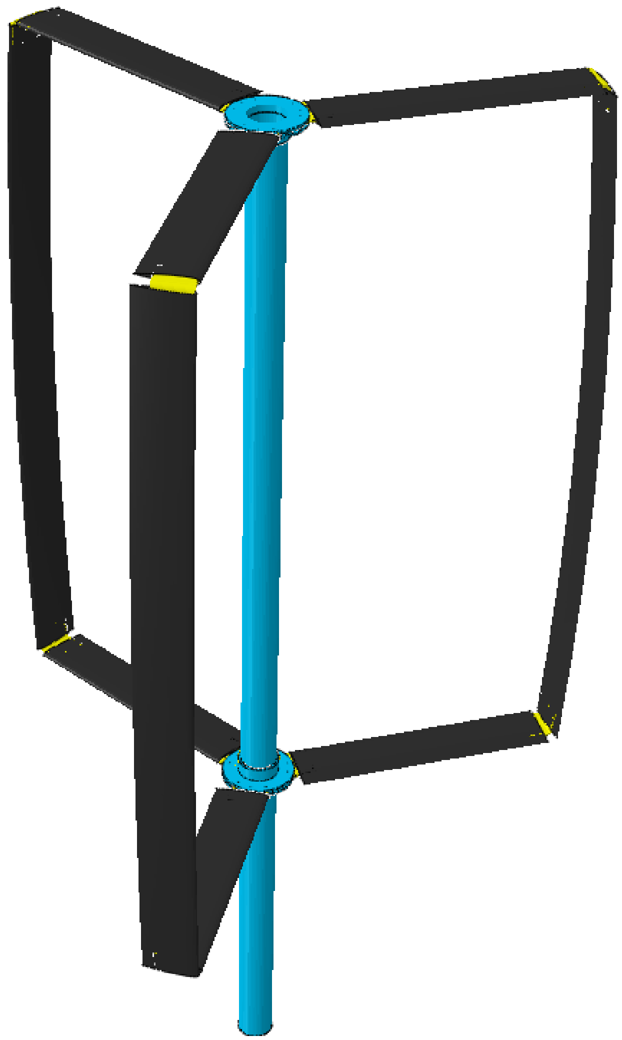


Figure 10: Initial conceptual rotor assembly showing metal brackets (yellow) and curved vertical blades used in FEA structural comparison

The initial conceptual design included more traditional brackets that were to join the blade sections to each other (horizontal to vertical) as well as to the rotor mast. Later in the program as the characteristics of the Elium® thermoplastic were better understood, those brackets were eliminated for reduced part count and mass.

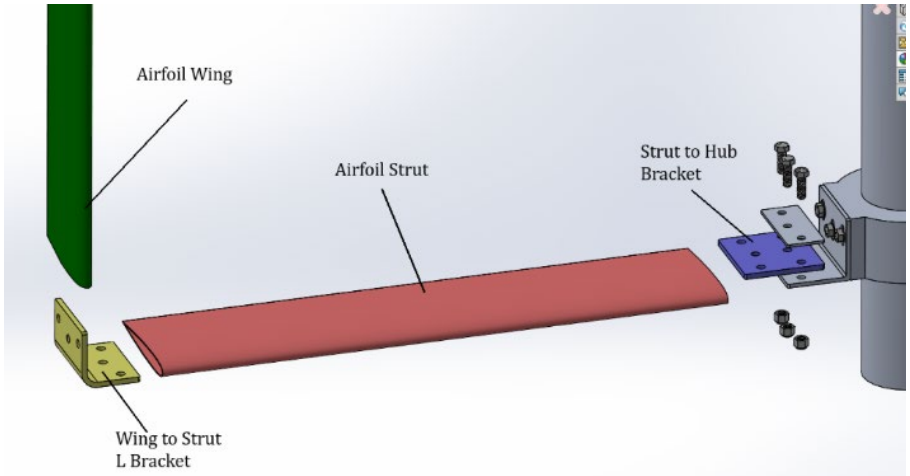


Figure 11: Detail view of components for initial conceptual assembly with metal brackets

With the loading scenario better defined by the preliminary CFD analysis, the next step was to define the blade assembly in CAD (Figure 10, Figure 11) followed by structural analysis using FEA. As shown in Figure 12, the finite element model in ABAQUS commercial FEA software incorporated orthotropic composite properties that were outputs from Subtask 4.5.5 of this program ($E_1 = E_2 = 7.74$ Msi, $G_{12} = 0.56$ Msi, $\nu_{12} = 0.072$). The rotor assembly was subjected to static pressure from 27 m/s (60 mph) winds. Three different configuration types of an H-rotor VAWT assembly were modeled and analyzed:

1. Straight blade with 4 plies of biaxial reinforcement
2. Straight blade with 8 plies of biaxial reinforcement
3. Curved blade with 8 plies of biaxial reinforcement

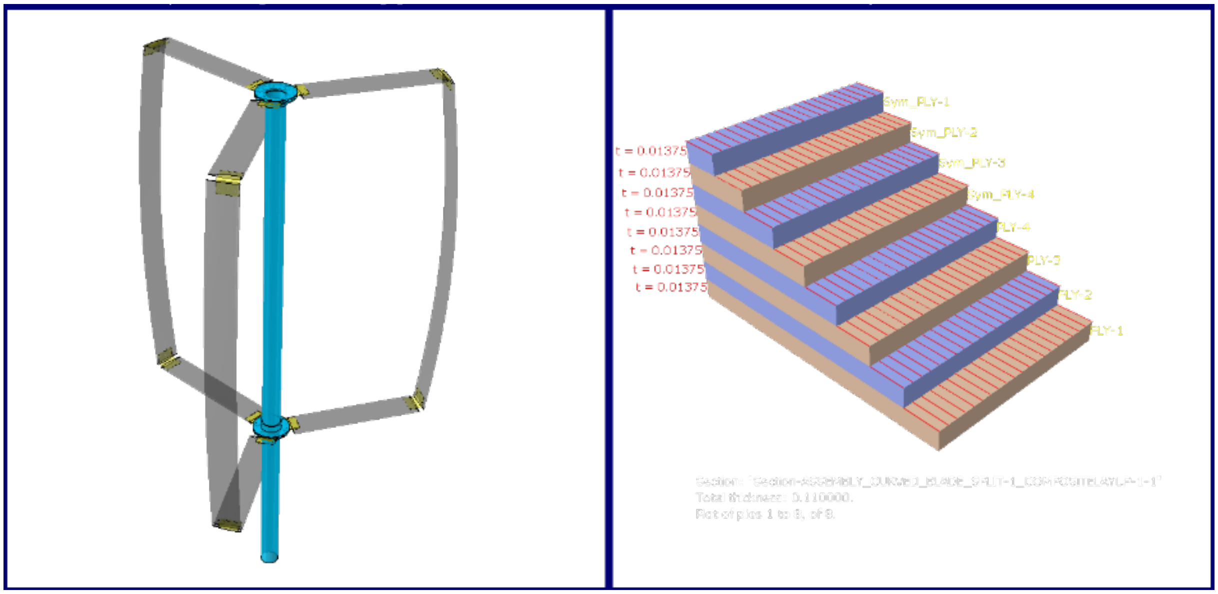


Figure 12: Rotor assembly (left) and composite sequence (right) inputs for the FEA

The objective of this analysis was to compare the structural performance and stiffness of the blades subjected to a static wind pressure of 60 mph. Figure 13 shows the contour plot of the maximum deflection in a 8-ply blade as predicted by FEA. Figure 14 compares the deflections of the blades with three different composite layups, with the straight blade using an 8-ply configuration showing the highest stiffness. Based on these results, the rotor configuration and composite structure for the prototype were specified as the straight blade configuration with 8 plies of reinforcement.

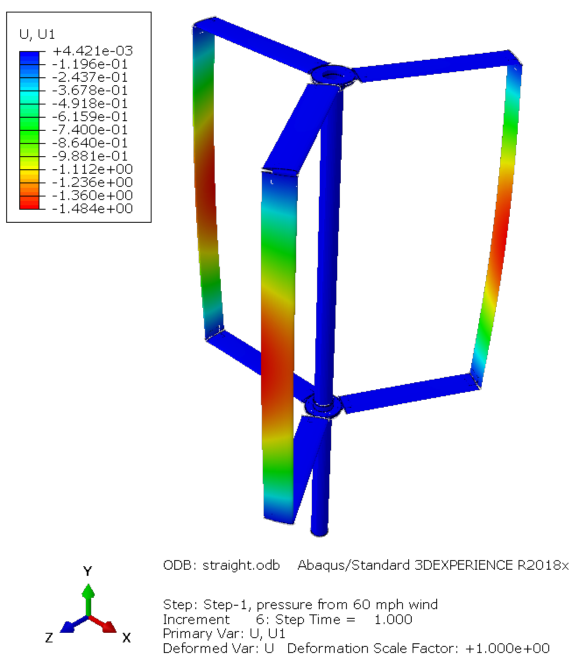


Figure 13: Plot of rotor deflections under 60 mph steady state wind, static application (8 ply composite)

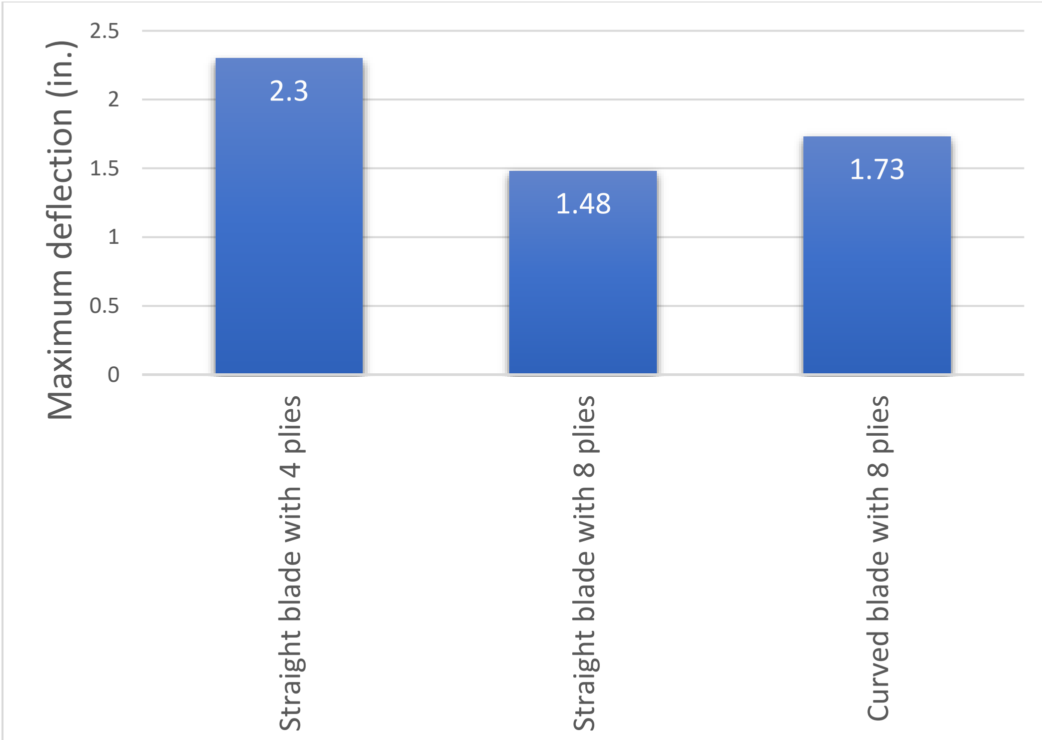


Figure 14: Comparison of magnitude of maximum deflections for various composite structures and geometries

An additional finite element simulation was performed to determine the natural frequencies of the rotor assembly and to ensure that the natural frequencies are sufficiently high to not cause excessive vibration during the startup operation of the blades. Figure 15 shows the different mode shapes of the blade structure as envisioned for the prototype construction. Through this analysis, it was determined that the stiffness of the central post was the driving factor for the first few mode shapes.

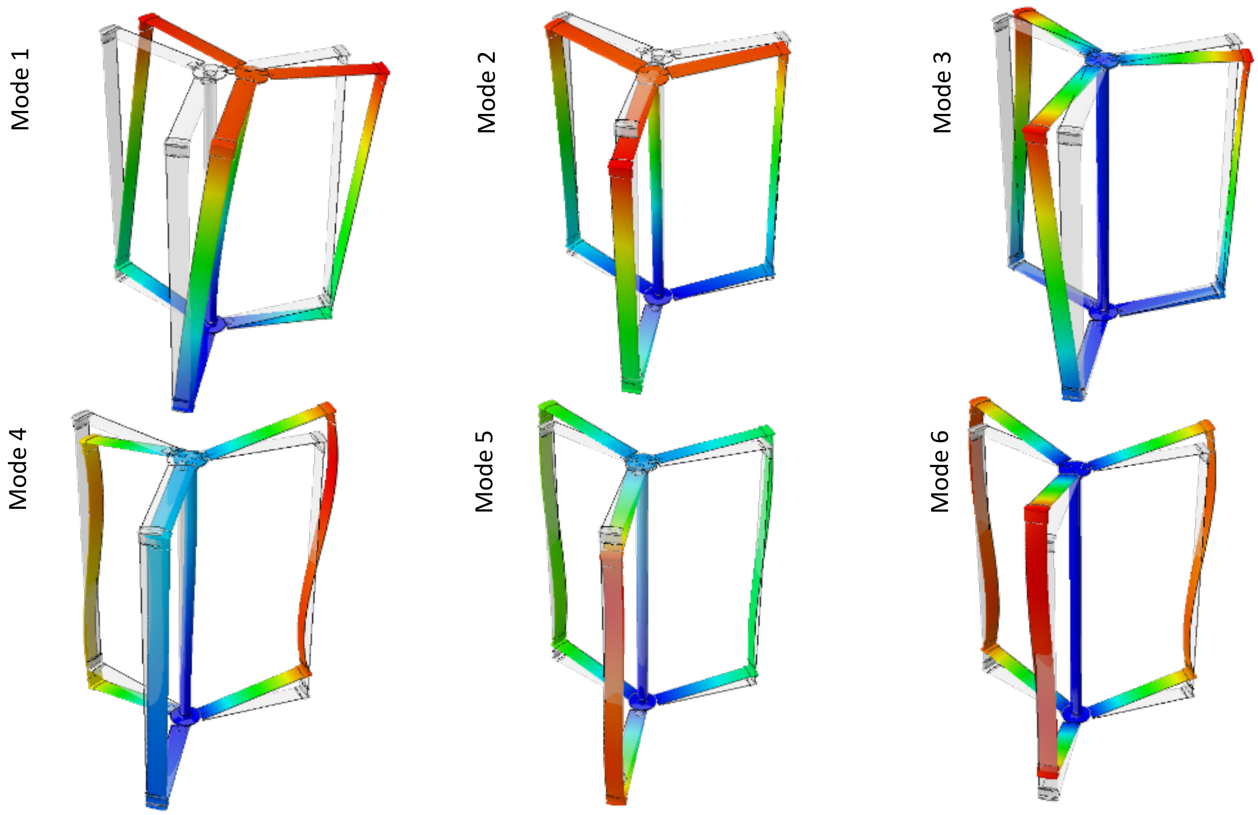


Figure 15: Natural frequency analysis of VAWT rotor assembly

Subtask 4.5.4

Novel Processing of VAWT Blades Using Carbon Fiber Reinforced Thermoplastics

From a composites processing perspective, this project was conceived to demonstrate the ability to use resin infusion molding to create high aspect ratio, hollow, carbon fiber reinforced Elium® thermoplastic airfoils to be used in the VAWT application. Further, manufacturing and assembly concepts, only practical with thermoplastic matrix composites, were to be demonstrated, including fusion joining and post molding deformation.

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 might be a future manufacturing approach for 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 is still a traditional contact mold-based process, resulting only in one high quality surface, except that it is done inside a pair of mold halves. While the resin infusion process is commonly used in industry to produce hollow composite structures such as large horizontal axis wind turbine blades, these structures typically have relatively large inside dimensions and require multiple parts, manufactured separately, to be joined using adhesives.

Preliminary Infusion Trials – 32" mold set

In order to perform preliminary hollow airfoil manufacturing trials, a 32" long master was machined from medium density fiberboard (MDF), as shown in Figure 16. The surface was sealed to enable the production of molds. Two fiberglass reinforced epoxy mold halves were produced from this master, which, because the airfoil is symmetric, results in a complete mold set. (Figure 17) Sealant material was applied to the flanges of the mold halves to contain the infused resin.

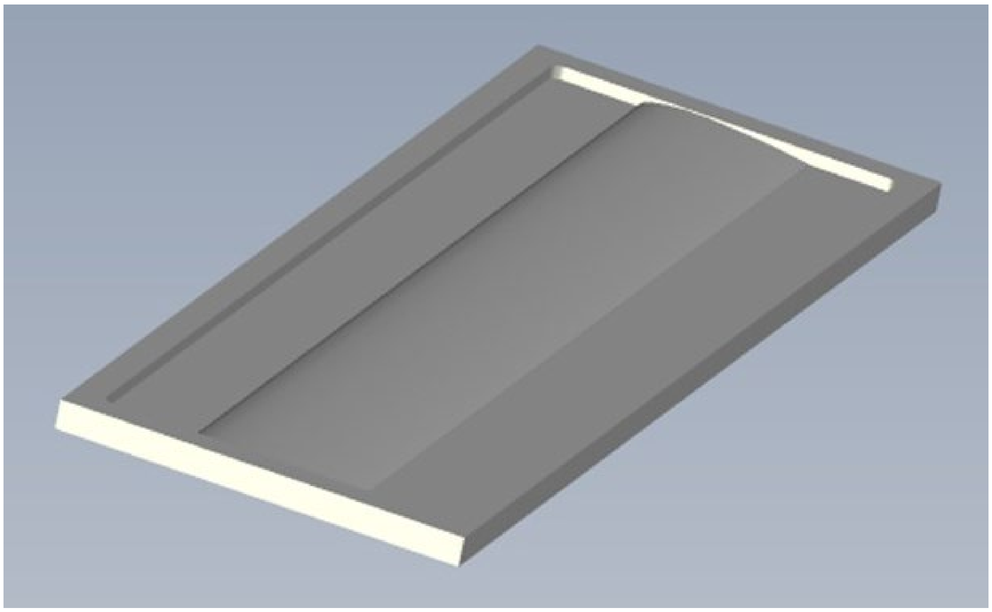


Figure 16: CAD image of MDF master for 32'' mold manufacture

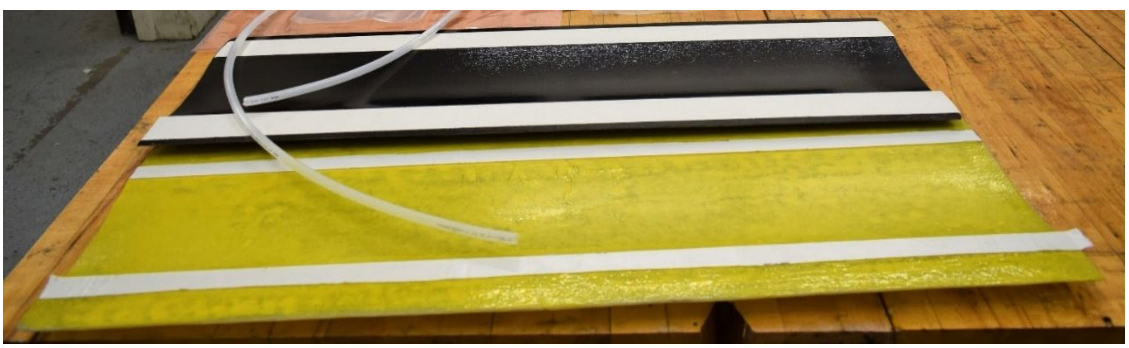


Figure 17: 32'' molds manufactured from MDF master

Using this 32" mold set, initial experiments were performed to determine areas of principal difficulty and, in general, the overall practicality of the proposed manufacturing approach. In this approach flow media, resin inlets, and a vacuum outlet are positioned on a tubular plastic vacuum bag that is placed over a simple flat plastic mandrel. The reinforcement is wrapped around the flow media, bagging and mandrel and placed in the mold. A larger tubular plastic vacuum bag is pulled over the mold and sealed to the inner bag, resulting in an envelope bag that consolidates the fibers to the inside mold surface and holds the mold halves together. The material sequence is shown schematically in Figure 18.

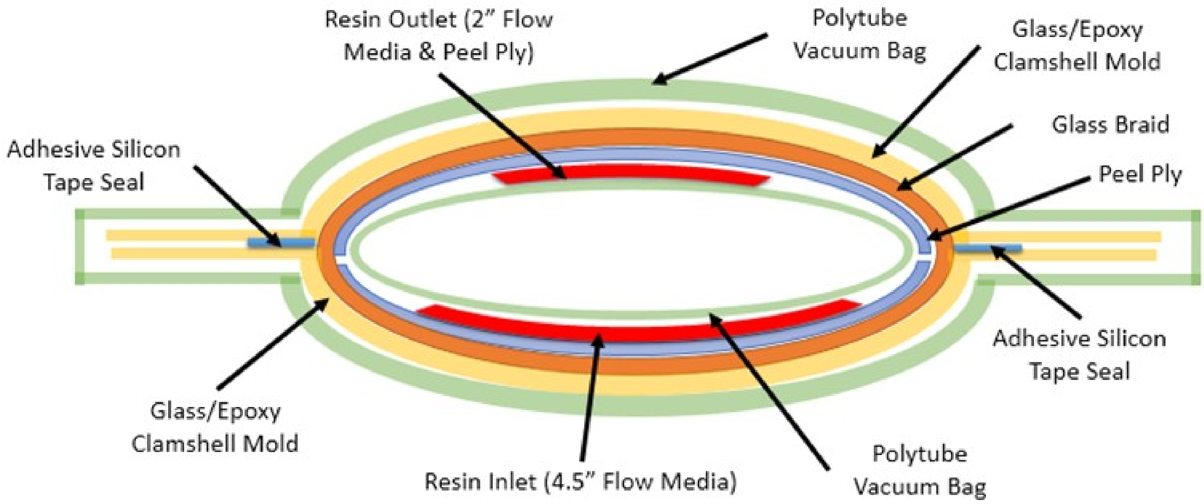


Figure 18: Schematic of preliminary materials stack-up in the assembled mold halves

The initial manufacturing approach, shown in Figure 19, successfully produced a glass fiber reinforced Elium® composite with a hollow airfoil cross section; however, this process was inconsistent and large dry spots along the leading and trailing edges were commonly observed. The limited repeatability of this process was attributed to poor control of the position of consumables and unintended pleating of the inner vacuum bag and peel ply. The removal of consumables was often a challenge in this manufacturing process due to the relatively high release force of the peel ply as well as consumables becoming physically trapped along the trailing edge.

Figure 19: Initial manufacturing process to infuse a 32''-long hollow airfoil cross section. From left to right shows the Resin inlet and outlet, Consumables on the mandrel, preform in mold, fully bagged mold, airfoils after demolding.

The limited success shown in these initial trials led to the manufacture of two additional mold halves from the MDF master, which were originally used to enable parallel manufacturing trials resulting in more information in a limited time. However, as better results were achieved through numerous modifications, including different flow media, it was determined that the 32" lengths were too short to give a good idea of the scalability of the process to the almost 12' long airfoils that would be required for the demonstration articles. Thus, the two sets of 32" molds were joined together to produce an airfoil mold set 64" in length.

Advanced Infusion Trials – 64" mold set

The relatively small dimensions of the hollow airfoil cross section (6" chord and 0.9" thickness) proved to be a challenge for reinforcement positioning in preparation for resin infusion molding, as well as for removal of the infusion media 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, without using excessive quantities of the Elium® resin.

Iterations of the 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 20, is a combination of distribution media and peel ply that greatly simplified the manufacturing process as it reduced the consumables required. Additionally, the Compoflex had a much lower release force than the previous peel ply, facilitating the removal of the consumables. Dahlpac MC79, shown as the blue strip in Figure 20, 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 20, 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.

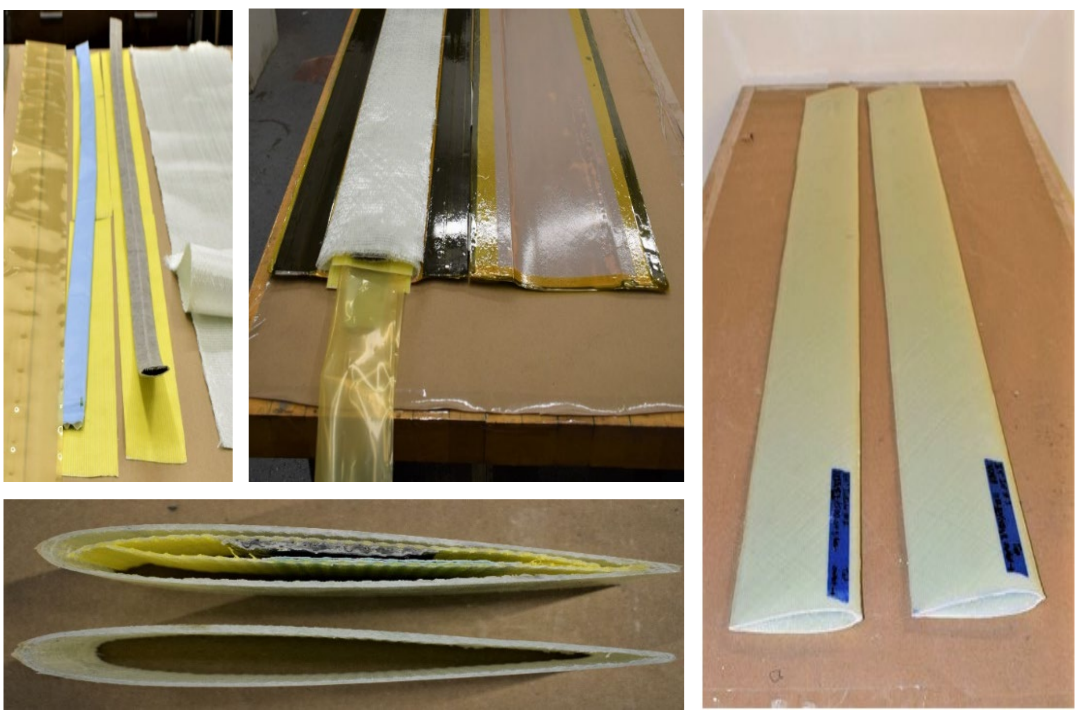


Figure 20: Improved manufacturing process for glass fiber blades up to 1.6m. Consumables (top left), preform in the mold (top middle), airfoil cross section with and without the consumables (bottom left), 1.6m glass airfoils (right),

Figure 21 schematically shows the updated materials stack-up in the 64" molds. These resin infusion specific materials made possible the infusion in the 64" molds. The resulting quality and uniformity of wetout was good, and the Compoflex RF3 enabled separation, and removal, of the expendables from the inside of the airfoil.

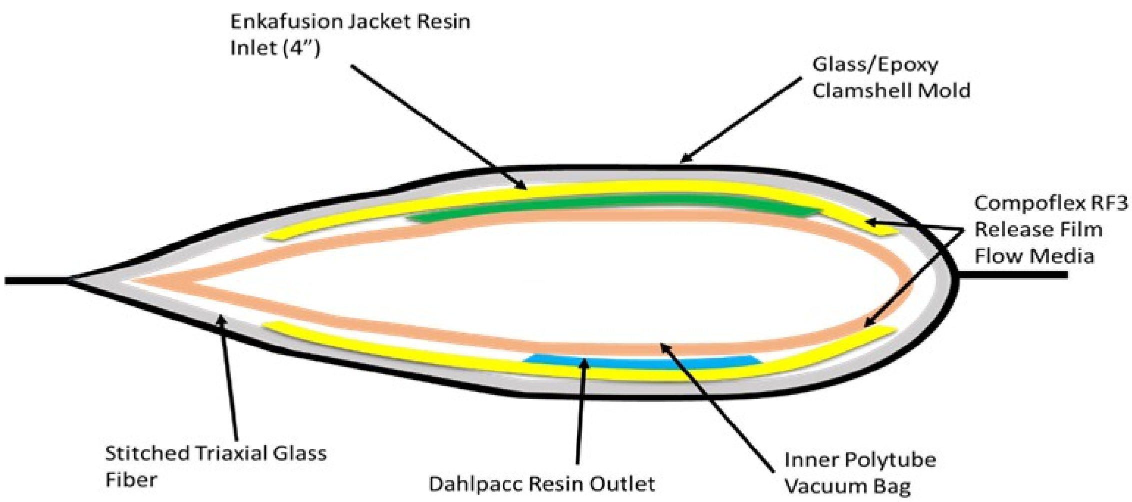


Figure 21: Schematic of materials stack-up in the assembled mold halves based on 64" mold trials

Thermocouples placed along the top, bottom, leading edge, and trailing edge, as well as FLIR imaging, recorded temperatures in excess of 100°C during the polymerization process. The resin inlet located along the top of the airfoil contained relatively large volumes of resin and resulted in an exothermic reaction strong enough to compromise the inner polyethylene tube bag, and higher temperature tube bag was procured for the majority of the 64" airfoils manufacturing trials. Additionally, the temperature at these locations was high enough to cause the resin to boil and generate localized regions of defects and an associated high void content as indicated in Figure 22. To overcome this effect of the exotherm, the temperature was controlled in subsequent infusions by placing bags of ice along the top of the outside of the mold once a temperature of 50°C was reached inside the mold.

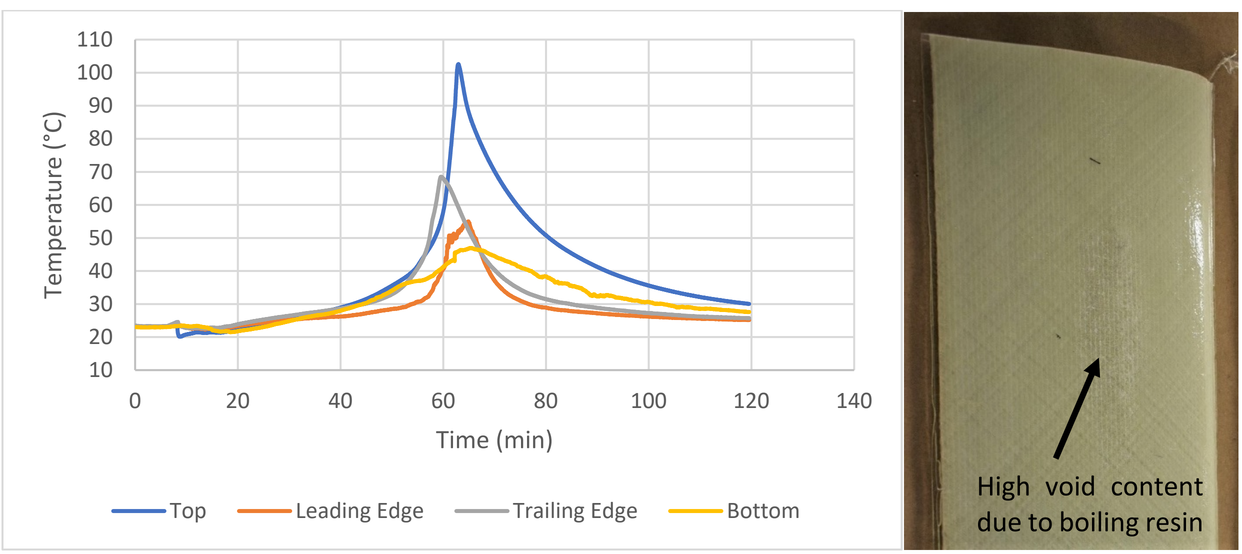


Figure 22: Temperature profile of a 1.6m glass fiber airfoil (left) defects caused by high temperature resin

Based on the process modifications discussed, the repeatability and quality of the resulting hollow airfoils was very promising. However, while the infusion of the 64" airfoils seemed to proceed rapidly. More effort was necessary to quantify the infusion rates if sufficient confidence in the process was to be gained to continue to scale the length up to the proposed 12'. It is important to recognize that the manufacturing plan for the hollow airfoil that would lead to scalability was based on an idea of moving the resin rapidly down the length of the blade through the inlet media. In this way, the actual wetout path, from inlet to vacuum outlet, was to be around the wetted perimeter of the airfoil rather than down the length. However, this meant that rapid filling of the jacketed EnkaFusion was necessary. Thus, additional characterization of the process parameters was performed through measurements of the mass flow rate of the resin.

The measurements in the resin flow rate throughout the infusion improved the understanding of the flow path and how changes in the position and size of consumables effected the location of defects such as dry spots or resin rich regions. Modifying the diameter of the resin inlet and changing the size and location of break zones was found to eliminate the majority of the defects and improve the repeatability of the manufacturing process. The average mass flow rate at the start of the infusion was approximately 8 g/second, slowing significantly after 2 minutes and continuing to drop to 0.5 g/second by the 10 minute mark, as seen in Figure 23. The cross-section schematic of the infusion set up, Figure 21, shows the resin inlet and flow media at the top of the mold. This jacketed EnkaFusion section fills up rapidly with resin in the first 2 minutes. The resin flow decreases significantly as it flows radially around the leading edge and trailing edge as this region does not have flow media and therefore functions as break zones, slowing the flow and improving the uniformity of wetout through the reinforcement preform. The resin fills the bottom half of the mold slowly over the next 7 minutes. The increased repeatability gained through the improved consumables and characterization of process parameters was determined enough to proceed to testing with carbon fiber reinforcement and to initiate the final 12' long tooling plans.

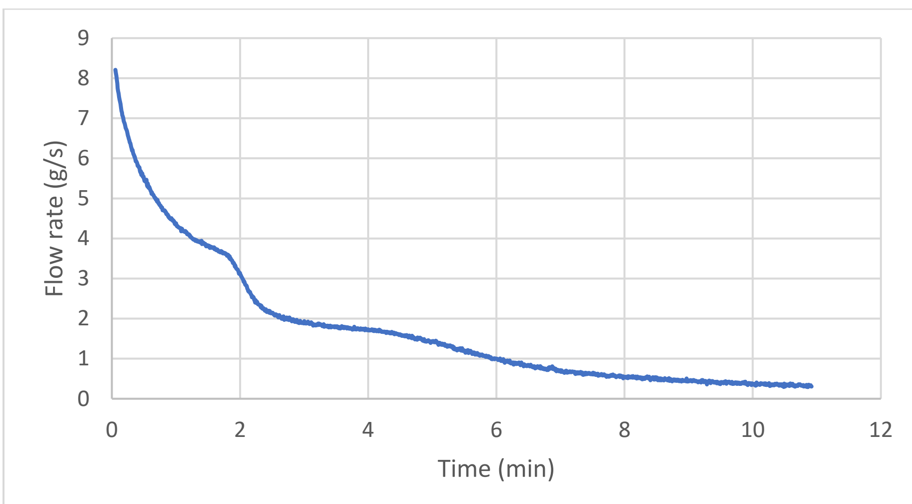


Figure 23: Resin flow rate of a 1.6-meter glass fiber airfoil

Minimal changes to the manufacturing process were required to transition from glass fiber airfoils to carbon fiber airfoils manufactured using braided and stitched uni-directional (UD) carbon fiber reinforcement. The 18oz braided carbon fiber, supplied by Highlands Composites and A&P, simplified the manufacturing process as it could be placed over the mandrel and rolled back over itself capturing the three plies of VectorPly C-LA 0912 stitched 9oz UD carbon fabric with integral 1.2oz chopped glass mat to serve as an integral flow media. This resulted in the final desired stacking sequence [±45,0_3±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 24 shows the sequence of steps in preparing the carbon fiber preform for infusion and a resulting 64” carbon fiber reinforced Elium® 150 hollow airfoil.

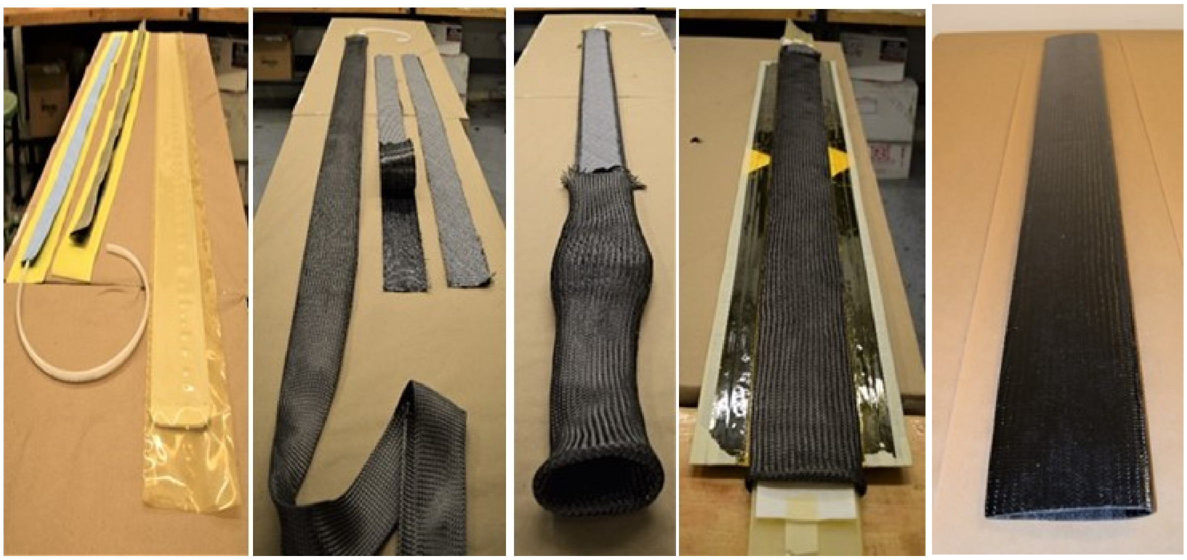


Figure 24: Adaption of 64’’ manufacturing process to braided carbon fiber. From left to right shows the consumables, preform set-up, placement of the final ply, preform in mold, and the 64’’ carbon fiber airfoil.

Additional hollow glass fiber and carbon fiber reinforced airfoils, produced in the 64” mold set, formed the basis for end fitting joining trials as well as for post process deformation experiments. Through the infusion of a number of these 64” blade sections further confidence was gained related to the processing and resulting quality.

Fusion Joining Study – Blade-to-Tower end-fittings

Fusion bonding, or welding, was investigated for the blade-to-tower attachment. Experiments were carried out to evaluate the effectiveness of fusion bonding via heat welding Elium® composite plates to the VAWT blade in order to determine the required bond area for loading conditions. These experiments investigated both processing parameters as well as surface texture of the laminates to be bonded which was generated by the imprint of the manufacturing consumables used during the resin infusion process. ASTM D3528 was followed to determine the Double Lap Shear Strength (DLSS) of bonded specimens. The variables were first tested using glass fiber/Elium® laminates, as the amount of carbon fiber reinforced Elium® 150 was in short supply early in the project. When acceptable values for lap shear strength were obtained for the glass fiber test samples the change to carbon fiber/Elium® sample testing took place using the surface texture and processing parameters that displayed the most consistent and highest values for lap shear strength.

Specimens were prepared using a hot press and custom machined tooling in which a narrow section (1”) of the hollow airfoil blade section was flattened, at temperature, onto a pair of composite panels arranged end-to-end, but not touching, resulting in a panel which was then cut into a number of double lap shear coupons. The geometry of the sample coupons to be tested are shown in Figure 25. Test specimens are comprised of two 4.25” x 1” laminates separated by 0.1” and bonded on the top and bottom faces with a second adherend providing an overlap of 0.5” for a total shear area of 1”. The top and bottom adherents that simulate the airfoil blade are half the thickness of the 4” coupons to create an equal cross section throughout the joint. Mechanical testing was required to validate the use of fusion bonded mounting tabs used to connect the blades to the central hub. Double lap shear coupons, Figure 26, were manufactured to determine the interlaminar shear strength (ILSS). Joining process variables that were investigated included temperature, surface texture, consolidation pressure, and cooling rate.

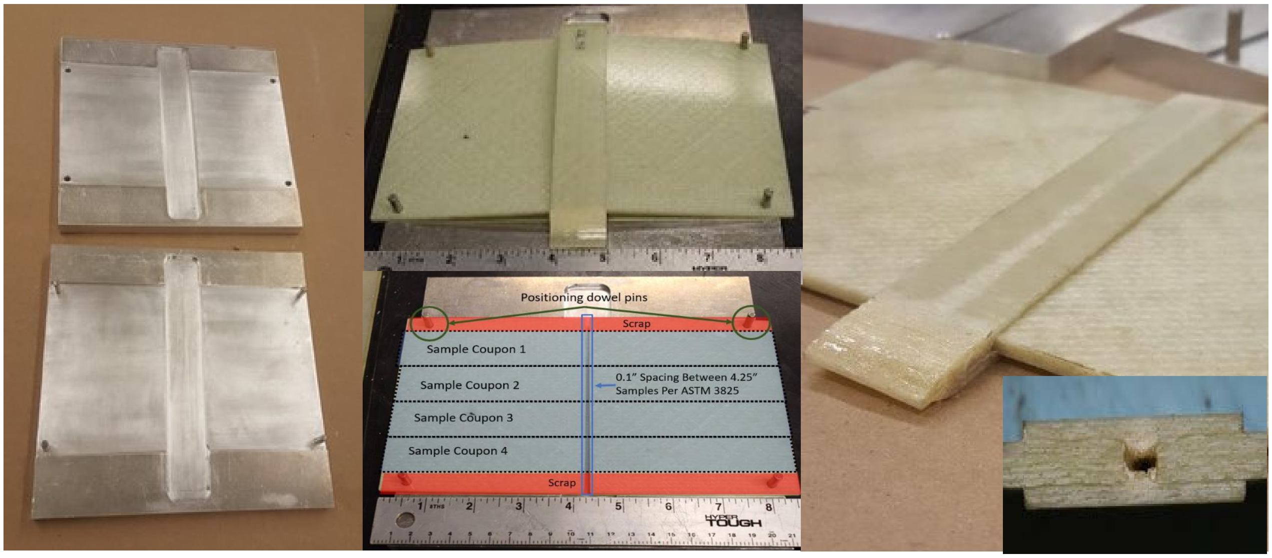


Figure 25: Fusion bonding specimen fabrication in mold (left), after bonding (right) and coupon cross section (inset)

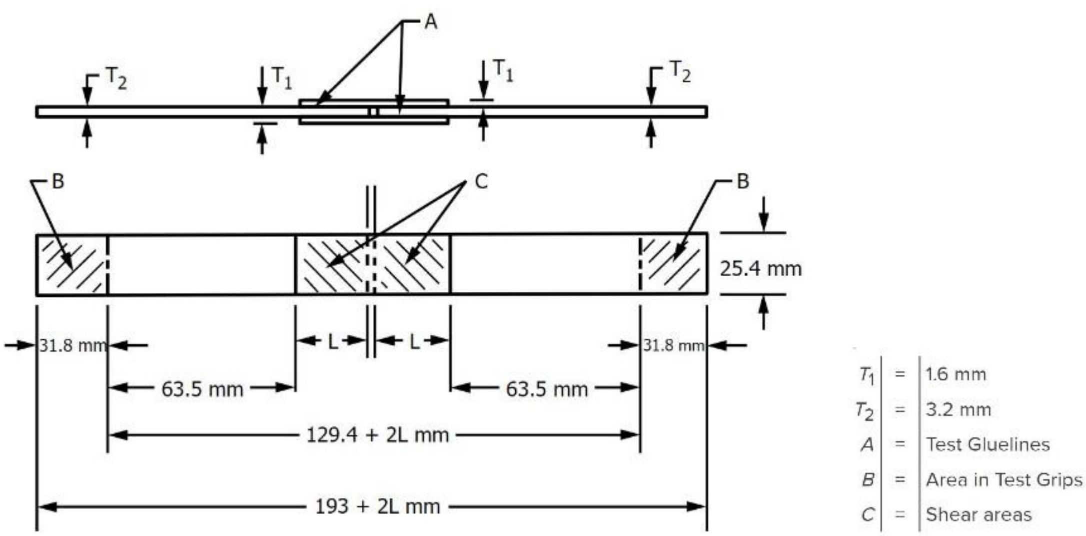


Figure 26: Double lap shear sample configuration and definitions according to ASTM D3528

After being cut to the proper dimensions the test specimen is loaded in tension at a rate of 0.005 in./min and loaded until failure.[1] After the specimen had failed the maximum load, type of failure, and images of the fracture area were recorded.

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® components and investigated (i) applied pressure, (ii) duration at temperature, (iii) cooling method. The surface textures were created during molding of the composites, prior to fusion bonding, using a variety of materials, including PeelPly, GFlow

[1] The detailed procedure can be found at https://compass.astm.org/EDIT/html_annot.cgi?D3528+96(2016)

and Compoflex, as seen in Figure 27. The temperatures evaluated were 180°C and 200°C. The pressures were 185 psi and 370 psi and the time at temperatures evaluated were 5 minutes and 10 minutes. The higher temperature (200°C) consistently gave higher bond strengths for any set of other variables. The higher pressure resulted in fiber wash and thus, follow-on trials were all performed at 185 psi. The longer hold time consistently resulted in higher shear strength values. It was also true that cooling in the aluminum compression dies was preferred over more rapid, air cooling.

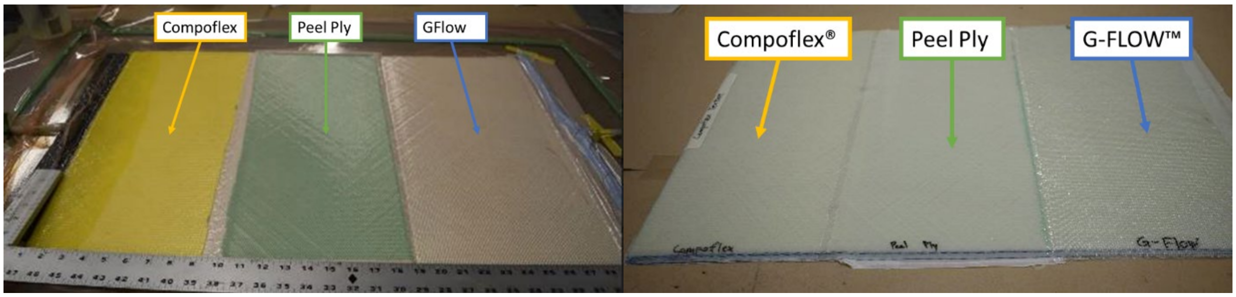


Figure 27: Preparation of the flat plate surfaces using Compoflex (yellow), Gflow (green) and Peelply (white)

Using the best parameters determined in the filtering study, 200°C, 185 psi, 10 minute hold at temperature and pressure and cooling in the hot press for a slow cooling rate, trials were performed using the three different surface textures on the flat plates. The inside surface of all airfoils was generated through molding with Compoflex against the inner/vacuum bag surface. Thus, only texture variations on the flat plate surfaces were considered.

Test results for the various textures are shown in Figure 28. The average values were 1086 psi for Gflow, 1793 psi for Compoflex and 2057 psi for the peelply texture. However, as is clear from the figure, statistically the Peelply and Compoflex may actually be hard to differentiate. Each of the values presented are based on double lap shear testing of 10 repetitions. The results of the double lap shear tests show that with the right combination of surface texture and processing temperature and pressure, inter-laminar shear strengths of over 2300 psi (16 MPa) were achieved with glass fiber reinforcements, which approaches the interlaminar shear strength of the laminate.

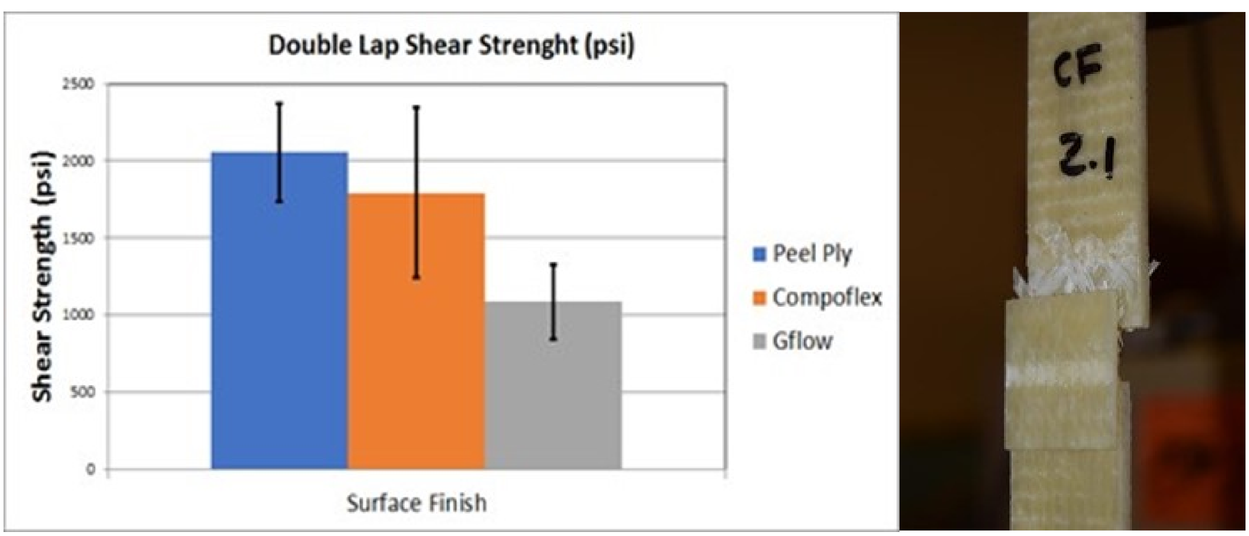


Figure 28: Effect of texture on fusion joint strength

Based on these results for the glass fiber reinforced Elium® 150 results, 10 carbon fiber reinforced Elium® 150 specimens were created using the parameters judged best. The carbon fiber reinforced double lap shear specimens were produced at 200°C, 150psi, held for 10 minutes at temperature and pressure and cooled in the hot press. The surface texture on the flat plates was molded in using peelply and the inside surface of the airfoil was that of the Compoflex. Carbon fiber reinforced Elium® 150 fusion bonded panels and specimens are shown in Figure 29.

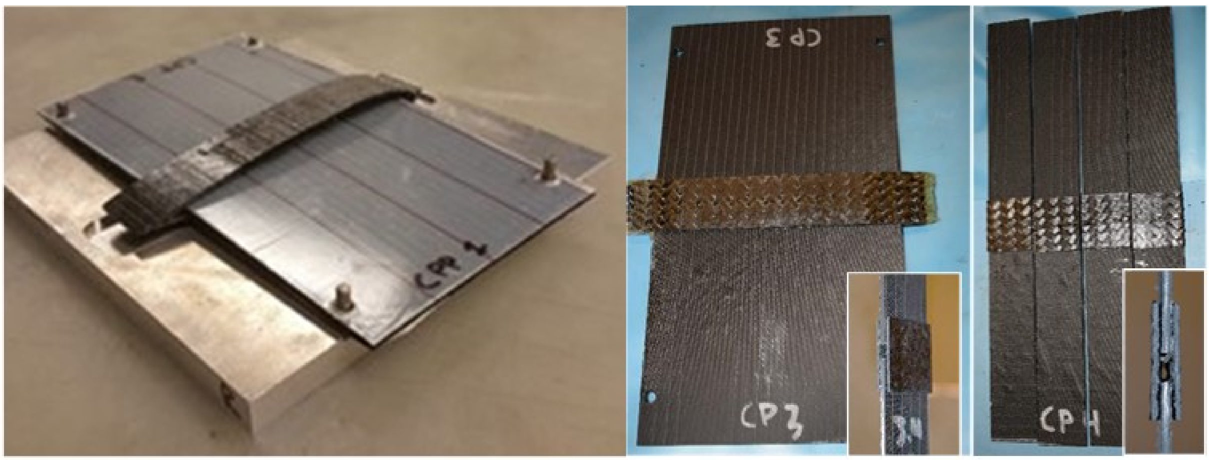


Figure 29: Carbon fiber reinforced Elium® 150 specimens for fusion joint strength study

The average of the results for the double lap shear of these carbon fiber reinforced panels was just under 1,100 psi, which was comparable to the lowest performing group of the glass fiber reinforced specimens. Additional efforts on optimized parameters for these carbon fiber reinforced panels and airfoils was not undertaken, as even this value of shear performance was considered satisfactory for the current application.

To facilitate the final joining operation a set of matched aluminum tool plates were CNC machined. Solid models are shown in Figure 30. Based on the hollow airfoil size and the results of the joining study, a bond area of 4” x 4” was designed into the tool plates. This set of tooling plates includes 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 to accurately and repeatedly locate the hollow blade section. This whole assembly was placed in a hot press, heated and compressed to form the fusion bonded end fitting with the blade-end contour.

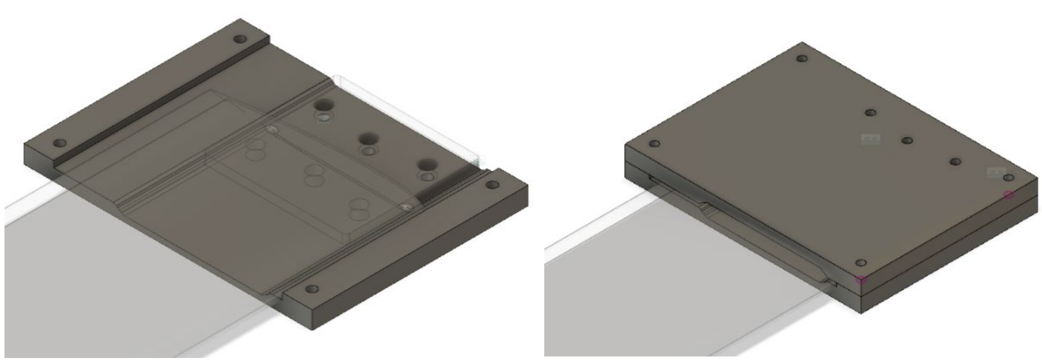


Figure 30: Aluminum matched die design for end fitting installation/joining

Figure 31 shows the initial trial blade end insert fused in place. With a 4"x4" joined area and a conservative 1,000 psi joint strength, this configuration, with a 16,000 lb pullout force, was deemed sufficient. No fatigue trials were part of this phase of the project.

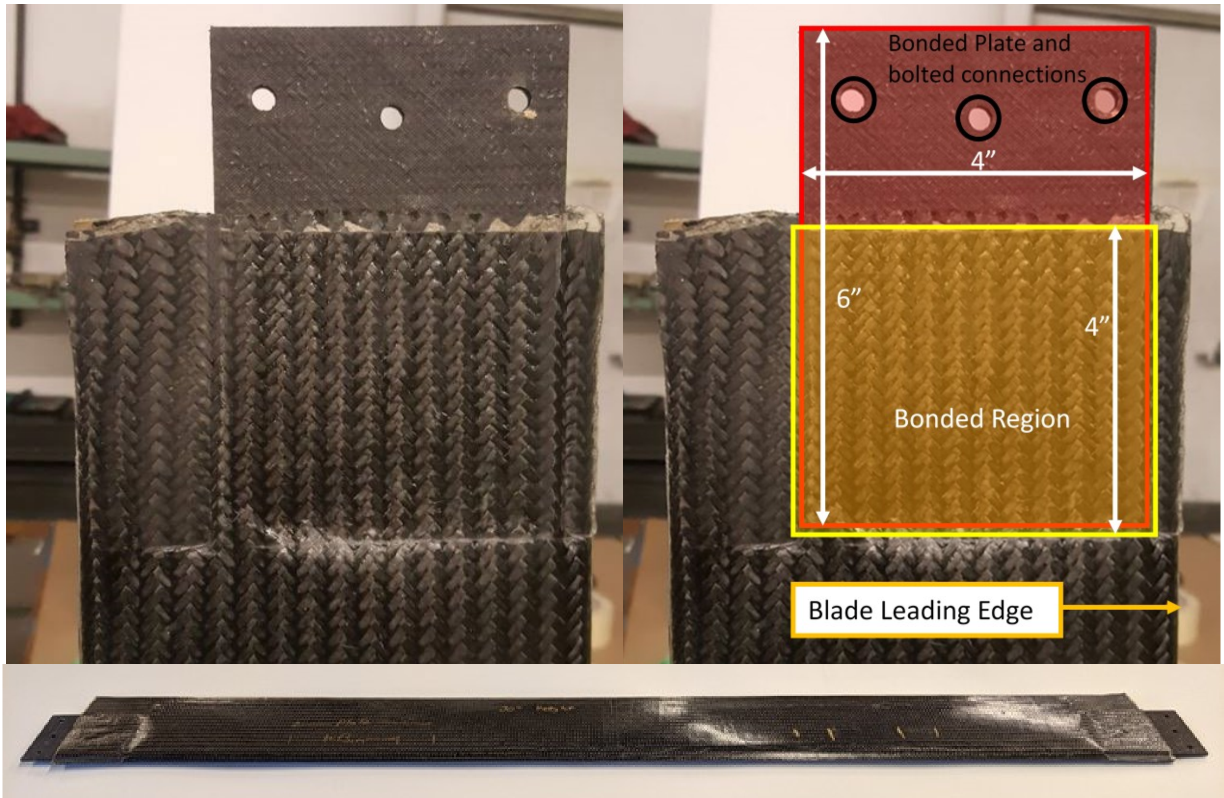


Figure 31: Trial end-fitting fused into airfoil section demonstrating the chosen 16in^2 bond area and a trial section of blade

Post-Process Deformation Development

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. Initial trials with glass fiber reinforced sections showed potential that, with further refinement of the processing parameters (mold temperature, mold time, cooling fixture, cooling rate, etc.), were then applied to the carbon fiber reinforced blades incorporated into the full-scale prototype.

The first, simplest trial was to heat the hollow airfoils section and free bend it around a tube of approximately 4" diameter. In these very preliminary trials, a nominally 0.25" thick fiberglass/Elium® 150 plate was inserted inside the airfoil profile in the bend area to add structure. However, a clear problem is the 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 32. Also, based on these trials, it was determined that further efforts would not include the additional internal plate and that for purposes of demonstration the remaining work would utilize only the molded airfoil material in the bent corners.

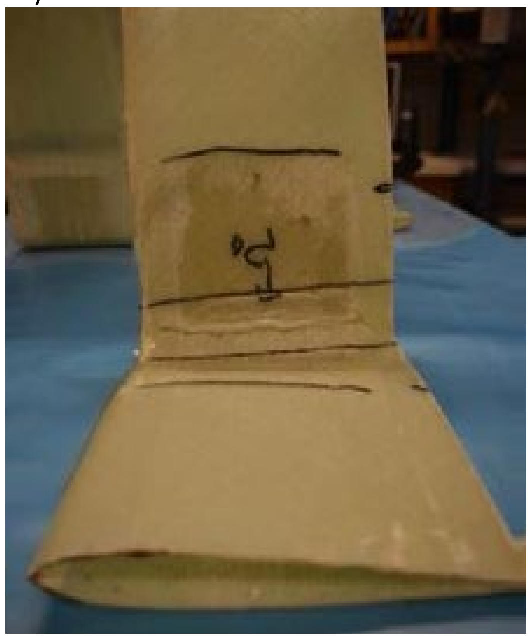


Figure 32: Preliminary trial 90 degree free bend of airfoil geometry with internal plate.

To minimize this buckling and improve the overall quality in the bent region the following trials made use of matched molds. A short section of the hollow blade (~8" length) was heated to 200°C in a hot press and crushed, resulting in a section thickness of approximately 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. (Figure 33)

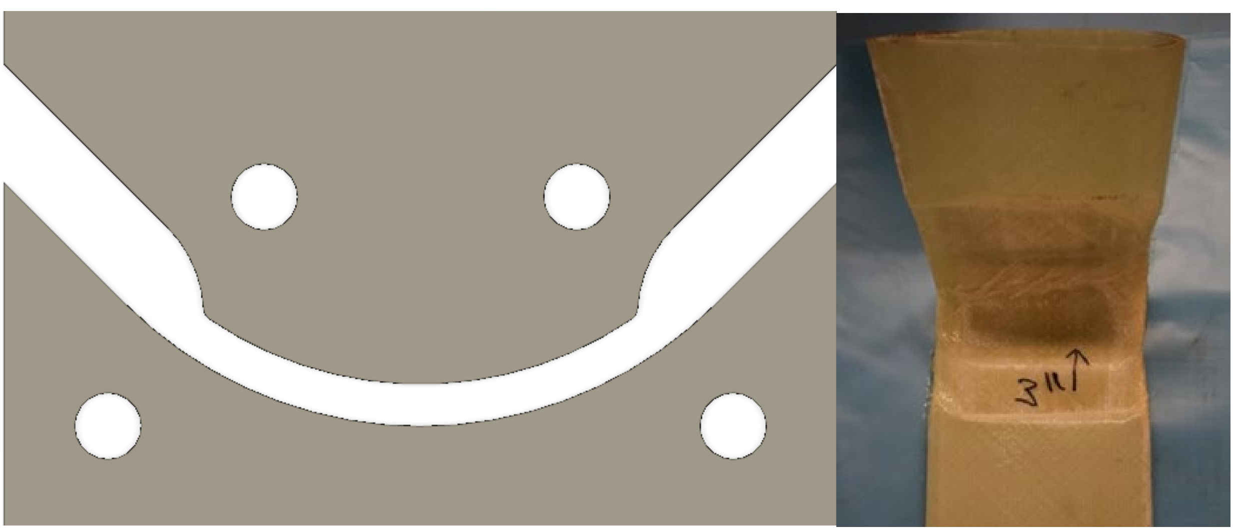


Figure 33: Trial 90 degree matched die set and resulting bend

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 34. 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 generate the mid-point of the bend at the planned location. The blade 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. Thus, between difficulties related to accurate location of the bend and that the geometry was becoming far more complex than a simple 90 degree arc, an alternative bending approach was developed for the final VAWT demonstrator unit.

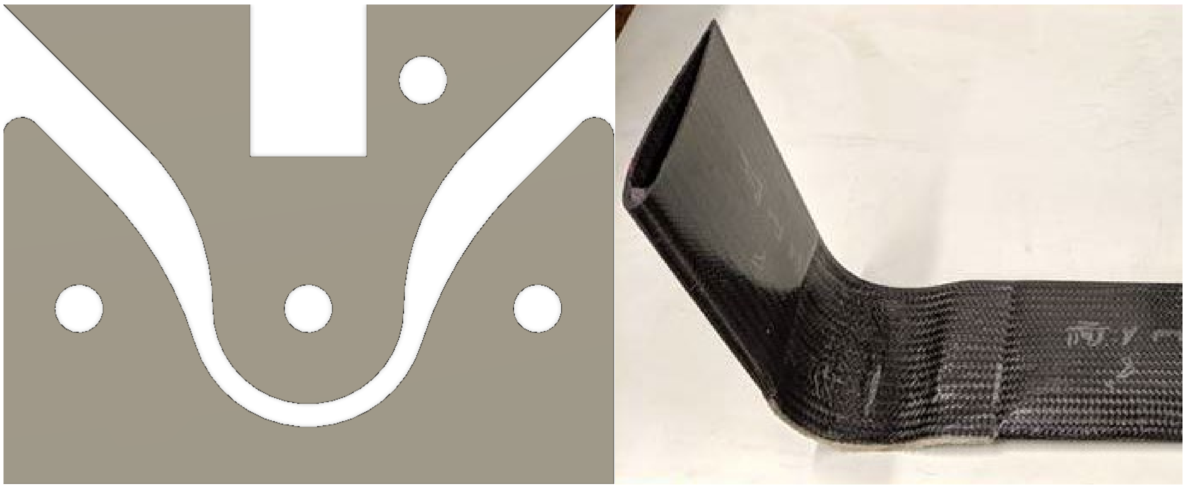


Figure 34: Matched bend die design with equal inner and outer fiber lengths.

The final design for a bending fixture was based on the concept of a wiping die, or tube bender. The key components, two cylinders, are shown in CAD in Figure 35 (left) and in trial application in Figure 35 (middle). Figure 35 (right) shows a short section of carbon fiber reinforced Elium® 150 hollow airfoil with end fittings and the two bends formed using the final bending approach.

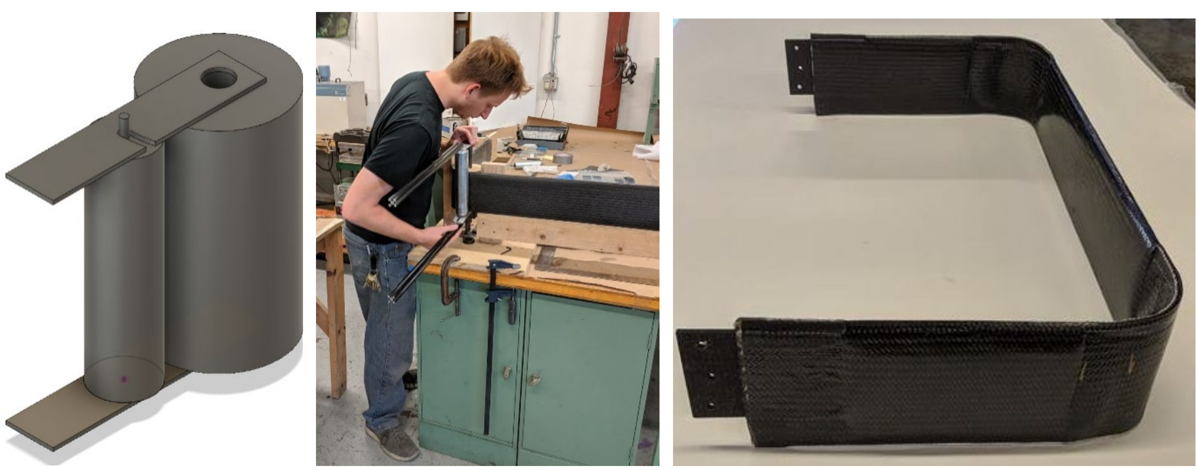


Figure 35: Wiping die set and resulting double bend test article

With this approach the smaller outside roller rotates around the inner (fixed) cylinder and is set to maintain a consistent, controlled radial gap. That radial gap is set based on the thickness of the flattened airfoil and is nominally 0.25”. This wiping, or ironing, action around the outer surface of the blade and the relatively stationary nature of the inner surface resulted in acceptable and reproducible bends. In addition, a key factor of this design is related to fixturing the end plate of the blade, 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.

Subtask 4.5.5

Characterization of Mechanical Properties of Carbon Fiber Reinforced Thermoplastic

A combination of mechanical testing, metallographic inspection and thermal analysis was utilized to quantify the processed composites, and as a basis for the manufacturing process development. Testing was performed in accordance with the appropriate ASTM standards whenever possible. The mechanical test results measured for the thermoplastic composite materials were recorded, to be presented in the characterization database of Milestone 4.5.5.1. Uniformity of the processed composite, across various sections of the blade geometry, was also of interest. The study of uniformity of cure condition was primarily undertaken utilizing a suite of thermal analysis techniques to investigate state of "cure", mass stability and fiber-matrix interface performance and void content. This was important with regard to understanding the sensitivity of mechanical test results to variation in process conditions.

With the increased interest in thermoplastic matrix material for fiber reinforced composites, there has also been significant concerns related to the interface strength. In the fiber industry, especially in the past 5 years, there have been many efforts undertaken to develop thermoplastic-specific fiber sizings to generate acceptable wetout and fiber-matrix adhesion. During this subtask, a degree of understanding of the effects of various fiber sizings and their compatibility with the Elium® resin system was gained, primarily through discussions with representatives of Arkema. The desired goal is for cohesive failure modes during mechanical testing, showing a good bond between the reinforcing fibers and the thermoplastic matrix material. Based on information from Arkema, reinforcement materials with appropriate sizings were identified and procured for all testing. Rather than a proprietary thermoplastic sizing, Arkema indicated that sizings more typically used with vinylesters would be appropriate. That led to the choice of an F0E sizing for the majority of testing, while reinforcement material of the final demonstration product used a 'GP' sizing, also based on information from Arkema.

Elium® 150 Process Study

As part of the investigation, the effects of post-cure of the Elium® 150 resin were measured using Dynamic Mechanical Analysis (DMA) testing in a clamped-clamped configuration. Neat resin specimens polymerized with either 1% or 3% of the Luperox® AFR40 initiator were exposed to an 80°C post cure for various lengths of time. Additionally, a set of specimens were aged in a desiccator for 11 days prior to being tested. Table 1 summarizes the results of the study, showing the average values measured and the associated standard deviation for glass transition temperature (T_g), maximum Tan Delta, and storage modulus (E'). As can be seen, the storage modulus and the glass transition temperature showed a general trend of increasing with increased post cure. The specimens polymerized with 1% Luperox® and post-cured for 4 hours demonstrated the highest T_g of 119.6°C, while the specimen polymerized with 3% Luperox® and post-cured for 4 hours resulted in the highest measured Tan delta and storage modulus.

Table 1: Summary of DMA results showing effects of secondary cure on Elium® resin

	% Luperox®	Tg (°C)	Max Tan Delta	E' @ 20°C (GPa)
No Post-Cure	3	108.84 ± 1.14	518.09 ± 56.36	2.84 ± 0.27
Aged No Post-Cure	3	95.24 ± 2.03	356.35 ± 25.65	3.09 ± 0.33
2 Hour Post-Cure	3	107.66 ± 0.40	378.75 ± 29.97	3.48 ± 0.33
4 Hour Post-Cure	3	113.85 ± 0.34	717.19 ± 9.85	3.93 ± 0.14
4 Hour Post-Cure	1	119.60 ± 0.42	678.71 ± 54.9	3.05 ± 0.60

Carbon Fiber/Elium® 150 Mechanical Testing

Detailed efforts involved the manufacture, testing and evaluation of resin infused carbon fiber reinforced Elium® 150 thermoplastic matrix composite panels. This initial round of mechanical testing was based on ASTM D3039, "Tensile Properties of Polymer Matrix Composite Materials" and ASTM D3518, "In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate".

Mechanical Testing, Material Processing

Resin infusion formed the basis for composite processing utilizing the Arkema Elium® system. Arkema's Elium® is a 2-part system that when mixed transforms, with time, from a low viscosity liquid to a thermoplastic polymer of the acrylate family. A principal benefit is that processing techniques common to liquid thermosets can be utilized with Elium® to create advanced thermoplastic matrix composites with high fiber volume fraction. Modifications to the rate of reaction of Elium® 150 were evaluated. During all processing steps, monitoring of the exothermic heat generated during polymerization took place using thermal data acquisition.

For the manufacture of the composite plates to be used as the basis for mechanical testing, the typical resin infusion process was modified in an attempt to create two surfaces with equivalent texture. The approach utilized a glass caul plate over the laminate and only peelply on the bottom and top surfaces, immediately against the dry fabric stack. Typical panels used to cut the test coupons from were nominally 12"x12", and thus infusion distances were relatively short. Only the very low viscosity (100 cps) of the Elium® 150 resin made this infusion, with no conventional flow media, possible. This approach to infusion was undertaken with the expectation of improved test coupons and better ability to get consistent strain gage application on both surfaces of the test coupons. These flat plate resin infusion trials also were used to gain experience with the Elium® resin. (Figure 36)

Figure 36: Flat plate trial infusion with Arkema Elium® 150 resin system

The resin infusion molding process was first investigated using 4 plies of plain weave reinforcement (Toray T700 300 gsm with F0E sizing) to fabricate flat panels for test coupons. During those initial trials, significant exothermic events were noticed during the polymerization process. Temperatures were recorded using both thermocouples and FLIR C2 infrared camera measurements, both of which indicated that temperatures exceeded 40°C in the thin flat panels (~0.1" thickness) and temperature over 200°C were recorded in larger quantities of resin. (Figure 37) The measured exotherm temperatures could present some risk for thermal degradation during processing if not adequately accounted for.

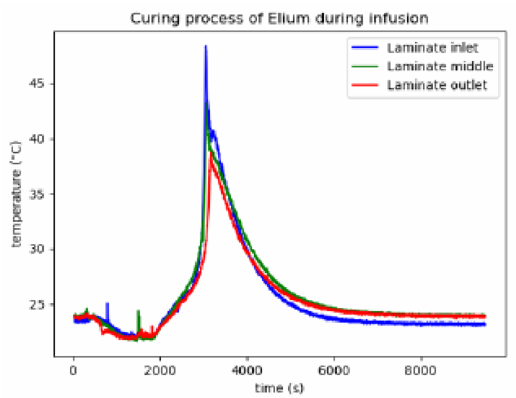


Figure 37: Temperature record (left) and thermal imaging (right) during infusion of Elium® resin

Ultimately, sufficient experience was gained in the flat plate infusion process, using caul plates, to produce tensile coupon material. All test coupons discussed in the mechanical testing section were infused in this nature.

Mechanical Testing, Phase 1 – Woven Fabric Reinforcement

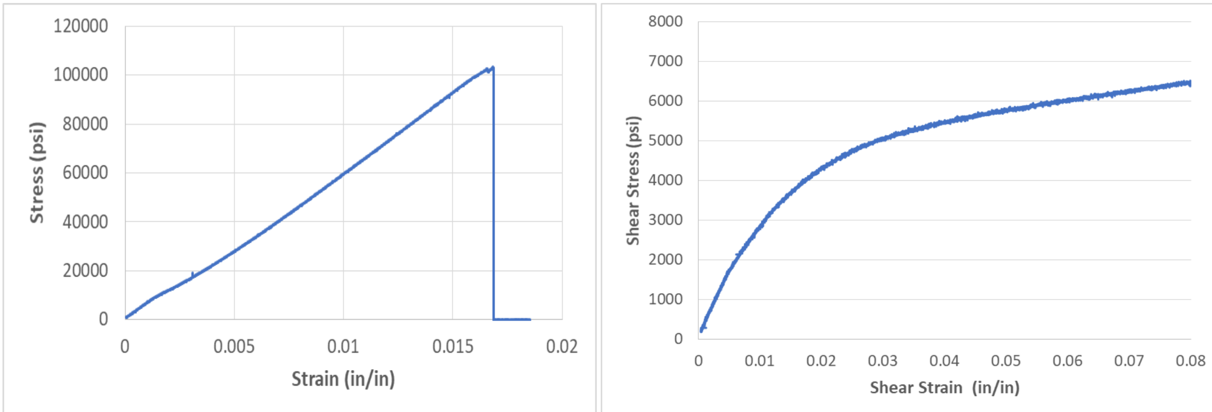
During preliminary discussions with team members regarding the appropriate choice of carbon fiber reinforcement for the Elium® 150 resin, Arkema indicated that the preferred fiber sizing was that normally targeted for vinyl ester resins, and from the choices available the team decided on Toray T700 with an F0E sizing. Obtaining this fiber and sizing posed a challenge which resulted in the use of a Toray T700SC-12K-F0E 300gsm (8.8oz/yd^2) underfilled plain weave fabric as this was the only form of the selected reinforcement available, at that time, in North America. The underfilled weave limited the fiber volume fraction of the test panels, with a maximum volume fraction of 50% achieved. Numerous infusions were performed to develop a repeatable process for making test panels with two high quality surfaces for improved strain gage mounting. Tensile coupons of (0/90) and (±45) configurations were prepared, with (0/90) specimens of 4 and 8 plies and ±45 coupons of 6 and 8 plies. The 4 and 6 ply specimen plates were prepared using a lower vacuum which resulted in a fiber volume fraction (V_f) of 38%, while the 8-ply specimen plate was prepared using an alternative vacuum system which resulted in greater pressure and a fiber volume fraction (V_f) of 50%. The 8 ply laminate was produced, after all initial testing was completed, for the purpose of improved transverse strain measurement, as results indicated excessive out-of-plane distortion in the thinner specimens. Even after the preparation of the thicker 8-ply laminate, difficulties with transverse strain measurement hampered the generation of acceptable Poisson's Ratio data. This seems to be related to the use of strain gages mis-sized for the large tow size and spacing of this underfilled weave.

Test results consistently demonstrated the effectiveness of the F0E sizing in that the modulus results closely followed "Rule of Mixtures" predictions, suggesting a good interfacial bond was achieved. A modulus of 6.33 Msi was measured for the 4-ply, 38% V_f specimens and 7.96 Msi for the 8-ply, 50% V_f

specimens. Considering the crossply weave and these volume fractions, and utilizing rule of mixtures, a fiber modulus of approximately 33.3 Msi is backed out from the 4-ply laminates and a fiber modulus of 31.8 Msi from the 8-ply laminate. Given that T700 has a quoted fiber modulus of approximately 34 Msi, these measured values are consistent with a strong interfacial bond. Tensile strengths measured showed acceptable levels of variation, with an average strength for the (0/90) coupons with V_f = 38% of 103.9 ksi and a strain-to-failure of approximately 1.64%. The shear strength was measured for the 6-ply ±45 specimens with V_f = 38% as 5.78 ksi at 5% shear strain as specified by ASTM D3518 and the total shear strain at failure was greater than 20%. These results are shown in Table 2.

Table 2: Preliminary Mechanical Test Data Summary – Plain Weave

Test	Units	V_f (%) D3171	# plies	Nominal Thickness (in)	Mean	Std Dev
ASTM D3039 (Moduli from extensometer)						
Ultimate Tensile Strength	ksi	38	4	0.061	103.9	4.6
Ultimate Tensile Strain	%	38	4	0.061	1.64	0.1
Modulus of Elasticity	Msi	38	4	0.061	6.33	0.4
	Msi	50	8	0.109	7.96	0.1
Poisson's Ratio		38	4	0.061		
		50	8	0.109		
ASTM D3518						
In-plane Engineering Shear Strength	ksi	38	6	0.095	5.78	0.17
In-plane Shear Modulus	Msi	38	6	0.095	0.430	
In-plane Shear Modulus	Msi	50	8	0.109	0.566	
Glass Transition Temperature *(DMA)*	°F/°C				247/119	



Representative Stress-Strain Plot (0/90) 4-ply test to failure

Representative Shear Stress./Shear Strain (from 6-ply ±45 specimen)

Figure 38: Representative stress-strain curves

Figure 39: Representative failure modes of tensile specimens showing good cohesive failure at left with poor fiber interface pictured at right

Note that the sample strained, through fabric scissoring to a value greater than 20% shear strain. ASTM D3518 requires quoting maximum shear stress at a shear strain of 5% when significant matrix "ductility" is present.

Thus, the results of the preliminary round of mechanical tests indicated that the carbon fiber reinforced Elium®, with the F0E sizing, performed in a manner consistent with epoxy matrix composites, with the exception of the substantially higher strain-to-failure in the non-fiber dominated, shear mode.

Mechanical Testing, Phase 2 – Stitched, Non-crimp Fabric Reinforcement

Once the effectiveness of the F0E sizing was verified, a 300gsm, 3k T700SC F0E biaxial stitched carbon fiber fabric with a F0E sizing, manufactured by Saertex, was procured. Two 200 x 400 mm laminates were manufactured using a resin infusion molding process: an 8-ply $[\pm 45F]_{4s}$ and a 4-ply $[0/90F]_{2s}$. Mechanical testing specimens purposed for elastic modulus and tensile strength determination were cut from the 4-ply laminate using a precision water cooled diamond abrasive blade to the specifications listed in ASTM D3039. Specimens purposed for in-plane shear modulus and in-plane shear strength were cut from the 8-ply $[\pm 45F]_{4s}$ laminate in accordance to ASTM D3518. EA-13-125RA/E strain gage rosettes were mounted to either face of the elastic modulus and in-plane shear modulus specimens and were used to determine the principal strains experienced by the samples when elastically deformed. The axial principal strains were compared to values measured using a clip-gage extensometer mounted on the edge of each specimen during modulus testing to assess any differences in strain readings via the two techniques. Only the extensometer was used in tests to failure. (Figure 40)

Figure 40: Examples of mechanical testing samples. In-plane shear modulus specimen with strain gages and clipgage extensometer mounted (left), In-plane shear strength (middle), and Tensile strength (right)

Supplemental specimens purposed for constituent content determination were also cut from each laminate. Constituent content testing to determine fiber volume fraction and void content was conducted in accordance with ASTM D3171, using the procedure of matrix carbonization in a nitrogen purged furnace. The constituent content specimens were held in a nitrogen environment at 600°C for two hours to ensure full matrix pyrolysis while preventing significant oxidation of the reinforcement. The results of the mechanical testing and constituent content testing are summarized in Table 3.

Table 3: Summary of Tensile and Shear strengths of carbon fiber reinforced Elium® 150 composites

	4-Ply $[0/90F]_{2s}$				8-ply $[\pm 45F]_{4s}$			
	Elastic Modulus (D3039)	Tensile Strength (D3039)	Fiber Volume Fraction (D3171)	Void Content (D3171)	Shear Modulus (D3518)	In-plane Shear Strength (D3518)	Fiber Volume (D3171)	Void Content (D3171)
Average	8.29 Msi (57.16 GPa)	114 KSI (786 MPa)	51.06 %	0.94 %	560 KSI (3.86 GPa)	7.05 KSI (48.64 MPa)	52.01 %	1.69 %
Standard deviation	0.12 Msi	12.3 ksi	0.77 %	0.40 %	9.3 KSI	0.67 KSI	0.40 %	0.23 %

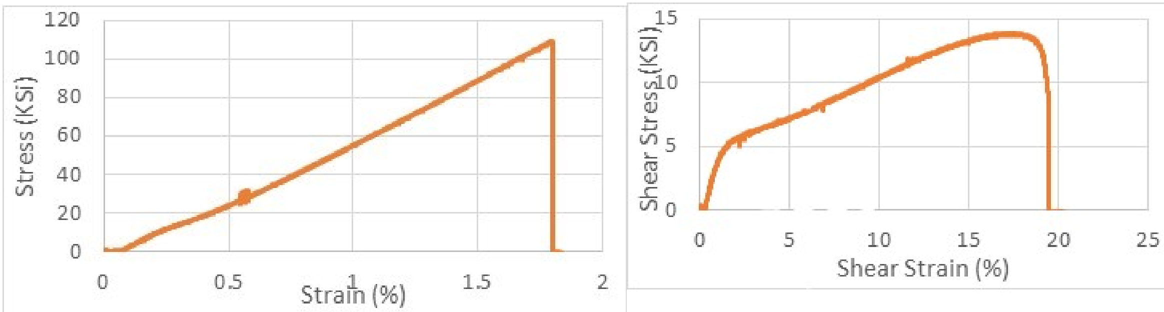


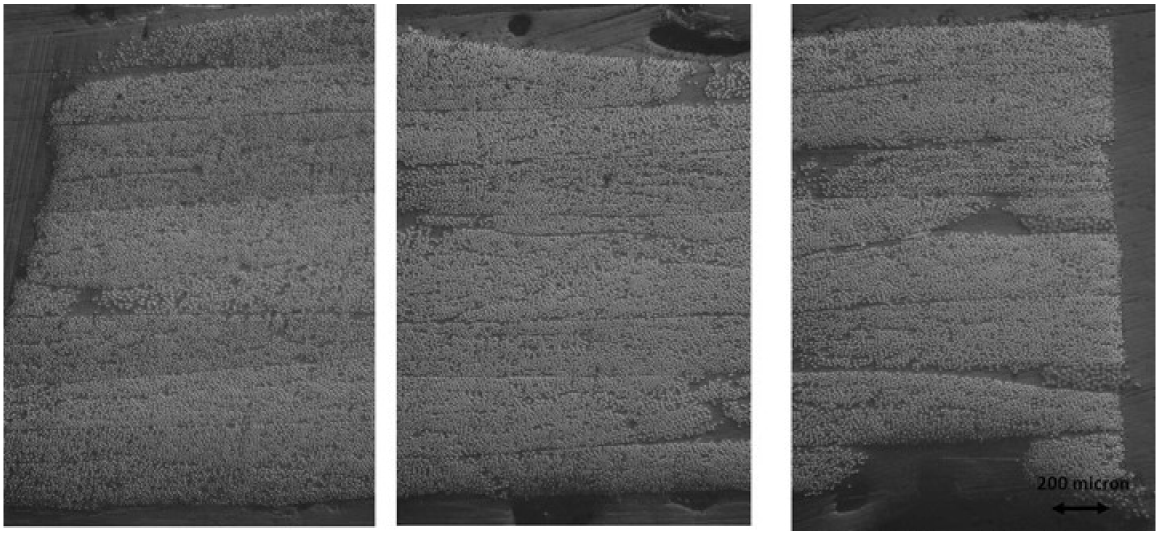
Figure 41: Stress vs Strain response of 4-ply 0/90 tensile strength specimen (left) and the 8-ply ±45 in-plane shear strength specimen (right)

The constituent content testing determined fiber volume fractions near the targeted 50% for both laminates as well as a sub 1% void content for the 4-ply specimen, and a 1.69% void content for the 8-ply specimen. Test results consistently demonstrated the effectiveness of the F0E sizing in that the measured elastic modulus of 8.29 Msi closely follows the "Rule of Mixtures" prediction of 8.52 Msi. The agreement between measured and predicted values suggests a good interfacial bond was again achieved. Additionally, the tensile strength and shear modulus measured from the thermoplastic composite are comparable to carbon fiber reinforced epoxy composites found in literature. The in-plane shear strength measured for the thermoplastic composite is lower than in-plane shear strengths typically measured for carbon fiber reinforced epoxy; however, ASTM D3518 defines shear failure as the lesser value of either catastrophic failure or 5% shear strain. This measurement of in-plane shear strength is highly applicable to thermoset matrix composites that typically fail at less than 5% shear strain yet may not adequately represent the thermoplastic composite tested in this study as it repeatedly reached shear strains around 20%. This significant shear strain prior to failure indicates the increased toughness demonstrated by thermoplastics, and results in an ultimate in-plane shear strength almost double the reported in-plane shear strength value.

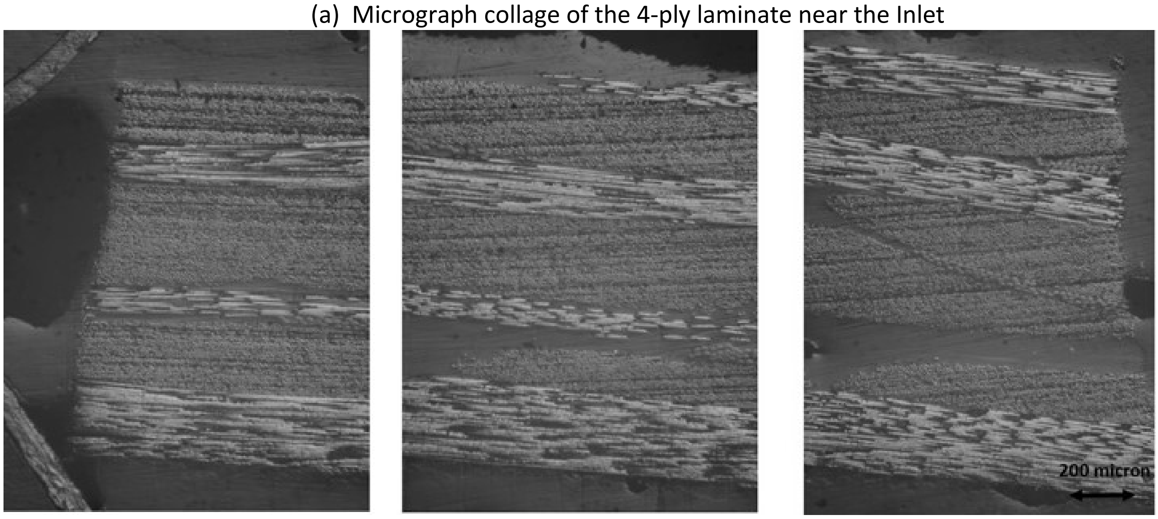
Metallographic Investigation of Laminate Quality

Optical microscope images of the 4-ply and 8-ply stitched non-crimp fabric specimens are included as they are directly related to the mechanical test specimens evaluated in this sub-section. The micrographs provide a visual representation of the composite quality and can be used to better understand the relative size and location of resin rich areas and voids. The specimens used for metallographic imaging were cut from the crossply laminates. Metallographic specimens for both the 4-ply and 8-ply specimens were taken at various locations relative to the resin infusion flow patterns as a cursory evaluation of quality across the manufactured test panel. Three separate locations, (a) near the resin inlet port, (b) near mid-flow, and (c) near the vacuum port/end of flow, are shown for representative cases of both the 4-ply and 8-ply laminates. (Figure 42 and Figure 43)

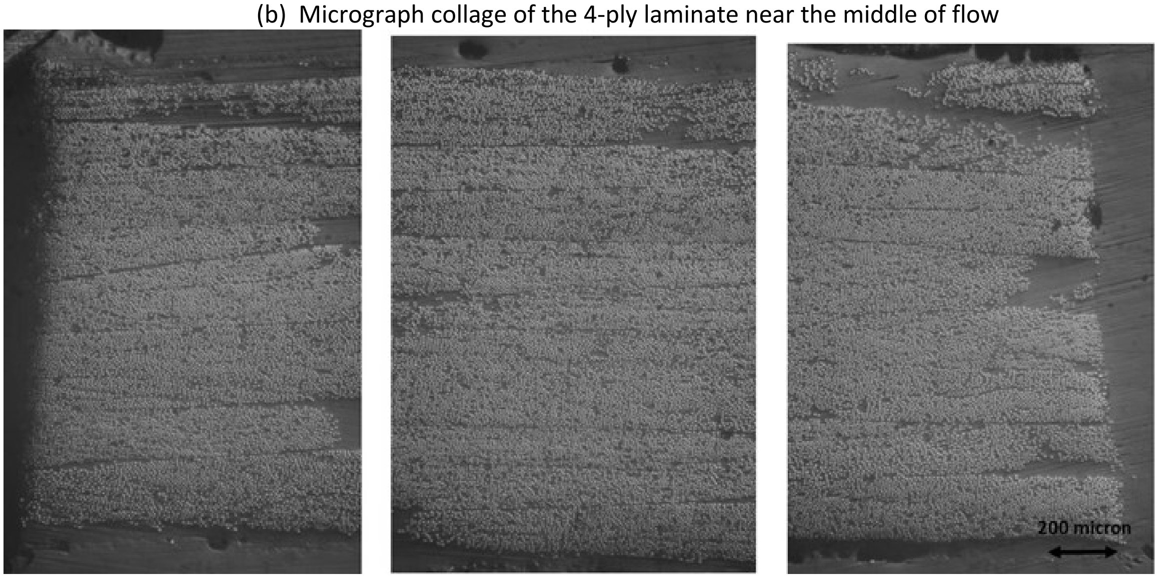
The 4-ply laminate shows small resin rich regions and no large voids. The 8-ply laminate shows relatively larger resin rich regions and some larger voids, especially near the end of infusion, as seen in Figure 43(c). The resin rich areas are typically located near the polyester stitching for both laminates. The average thickness per ply of the 4-ply and 8-ply laminates were 0.015"/ply and 0.013"/ply respectively. The increased consolidation of the 8-ply laminate allowed a similar fiber volume fraction as the 4-ply laminate even though the 8-ply laminate showed a higher void content and larger resin rich regions.



(a) Micrograph collage of the 4-ply laminate near the Inlet

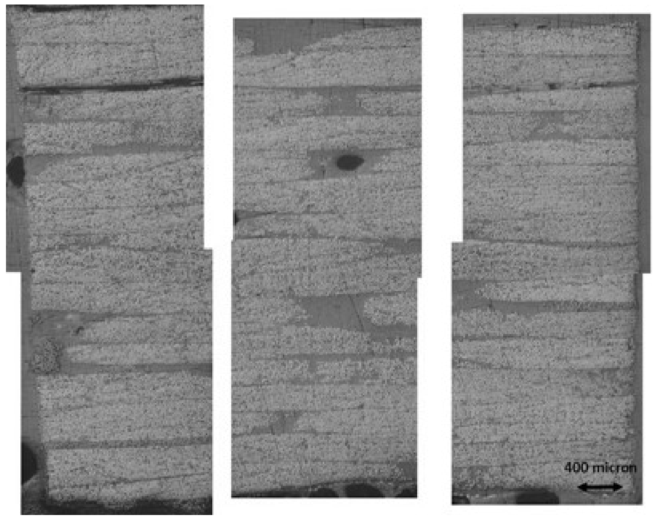


(b) Micrograph collage of the 4-ply laminate near the middle of flow

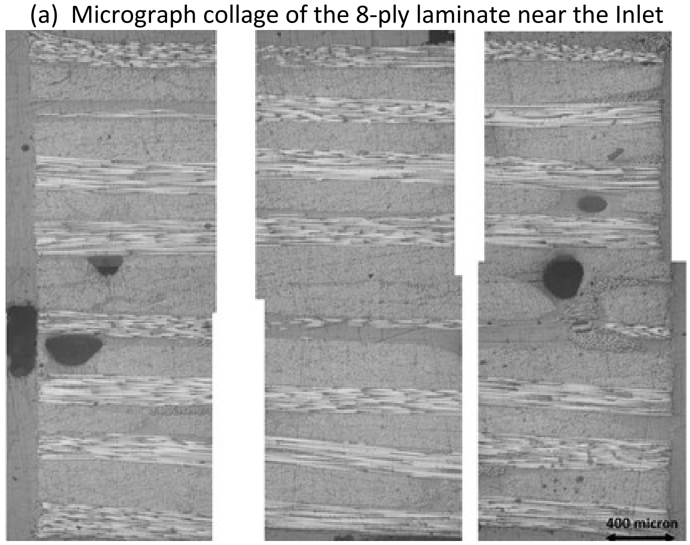


(c) Micrograph collage of the 4-ply laminate near the outlet

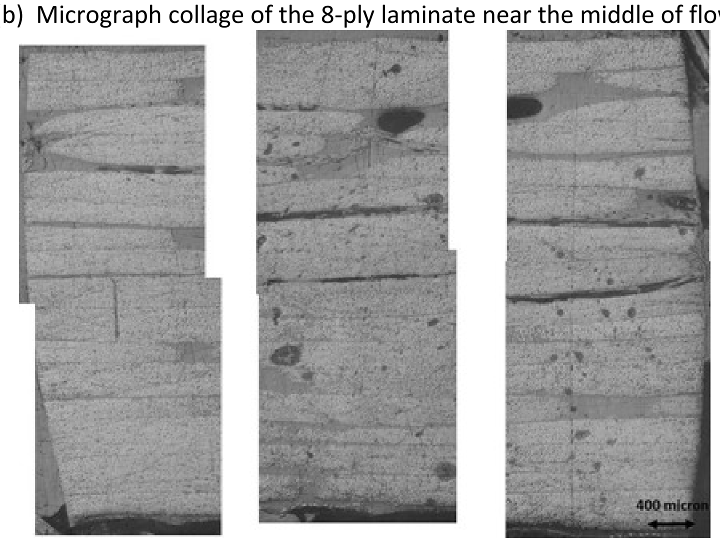
Figure 42: Metallographic images of 4-ply stitched, non-crimp specimens



(a) Micrograph collage of the 8-ply laminate near the Inlet



(b) Micrograph collage of the 8-ply laminate near the middle of flow



(c) Micrograph collage of the 8-ply laminate near the Outlet

Figure 43: Metallographic images of 8-ply stitched, non-crimp specimens

Mechanical Testing, Phase 3 – Combined Braid and Stitched Uni-directional Reinforcement

As the project progressed, it became clear that a combination of braided and unidirectional carbon fiber would be used to create the preforms to be used in the demonstration article blade manufacturing process. During the project, under a separate effort, Arkema had continued to evaluate the effects of sizing on the mechanical performance and had determined that GP sizing performed in a very similar fashion to the F0E sizing. This resulted in a wider range of available reinforcements and reinforcement architectures. With this knowledge, a combination of carbon fiber braided sleeve and stitched unidirectional carbon fiber fabric were able to be specified, with GP sizing, for the final demonstration article. To obtain a more direct set of mechanical allowables for the proposed layup sequence planned for the demonstration article blades, a final round of mechanical testing was performed on specimens representative of the demonstration article VAWT blades. The final materials tested were a biaxial braided carbon fiber sleeve, C400-15, with a GP sizing procured from Highland Composite, and a stitched UD fabric with a glass veil flow media, C-LA-0912, manufactured by Vectorply, which uses a Formosa T-35 carbon fiber and GP sizing.

Three plies of the stitched uni-directional material were placed inside a section of braided sleeve and infused with Elium® 150 to create the laminate. Tensile coupons, nominally 0.106" thick and 0.90" wide, with a [±45,0_3, ±45] stacking sequence were cut from the flat laminate manufactured using these same materials and consumables as planned for the demonstration article. Additional specimens were cut from the laminate, as well as from the ends of the finished prototype blades to determine the fiber volume fraction using the Archimedes method. Fiber volume fractions of the flat laminate and the prototype airfoils were measured to be 42.3% and 41.61% respectively. The fiber volume fraction of the composites processed using the carbon fiber braid and UD carbon fiber had a lower fiber volume fraction than those processed from the stitched biaxial nonwoven carbon fiber, most likely due to the fiberglass veil flow media on the UD material, and the resin rich surface texture that resulted from the use of the Compoflex RF3 flow media. The tensile specimens were tabbed and loaded to failure in order to measure the elastic modulus, and tensile strength. The mechanical properties measured for these laminates, of which the UD plies only account for about 40% of the laminate thickness, are consistent with expectations and are listed in Table 4. The failures observed, Figure 44, are consistent within this laminate stacking sequence, and were consistent throughout this set of specimens. The values obtained from these tests were available to be used in final design considerations.

Table 4: Mechanical properties measured for the final materials and stacking sequence

	[±45,0_3, ±45] flat laminate			Demonstration Article
	Elastic Modulus (D3039) Msi	Tensile Strength (D3039) ksi	Fiber Volume Fraction (%)	Fiber Volume Fraction (%)
Average	6.45	80.6	42.4	41.6
Standard deviation	0.15	7.54	0.54	1.77

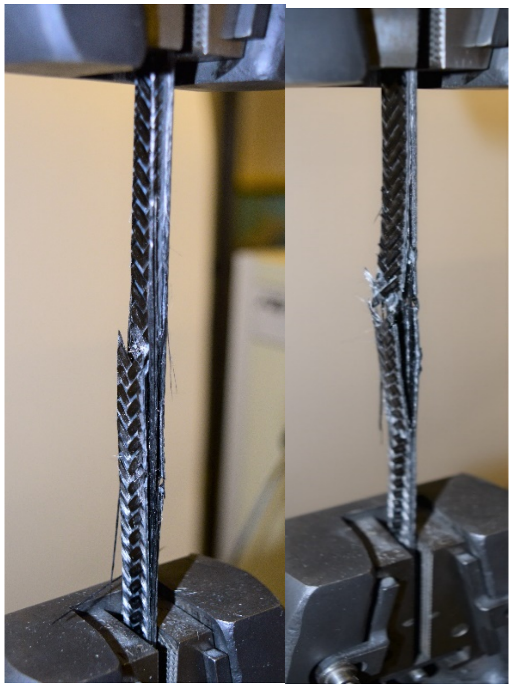


Figure 44: Tensile strength testing of a [±45,0_3, ±45] laminate representative of the final materials used in the prototype VAWT

Subtask 4.5.6

Fabrication and Assembly of a Prototype VAWT

Design concepts identified during Subtask 4.5.3 were used as the baseline design for the VAWT rotor assembly. Those initial designs considered blade joining techniques that are more applicable to traditional thermoset composite materials, such as affixing metal brackets to join vertical airfoil sections to the horizontal blade spreaders. An example of this bracket concept is shown in Figure 45 where the composite airfoil would be drilled (and reinforced) to match the bolt pattern of the inner metal bracket.

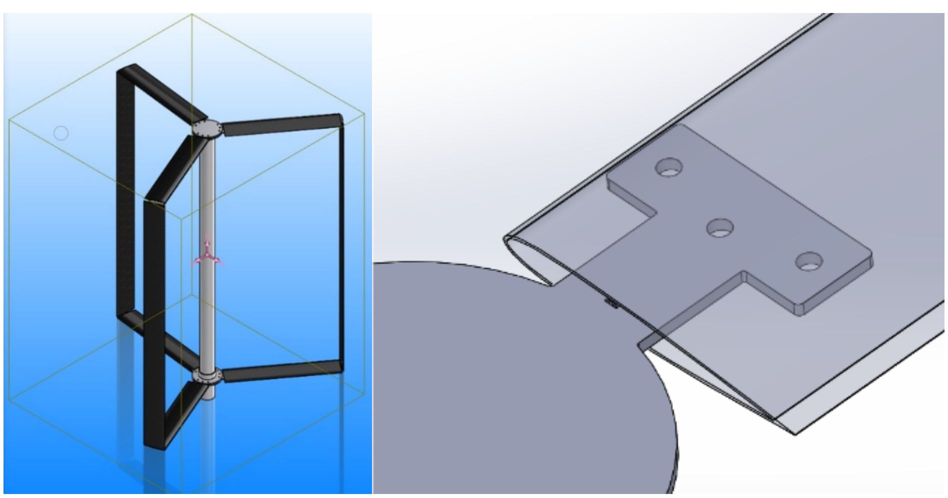


Figure 45: Baseline rotor assembly with metal mounting bracket detail

Figure 45

The rotor assembly mass of this baseline design was estimated to be 47.7 lbs based on the CAD model (Figure 45) using defined material properties for all metal components as well as the carbon fiber composite airfoils.

During the continued material processing investigation conducted under Subtask 4.5.4, the post-processing characteristics of the Arkema Elium® thermoplastic resin were better understood. That post-processing advantage led to improvements and part count reduction in the rotor assembly fabrication through two main areas: (1) integrated blade mounting tabs for central hub connections, and (2) 90 degree bend from vertical blade to horizontal spreader.

Fusion bonding of two separate thermoplastic composite features allowed the mounting tab between rotor airfoil and central hub to be integrated directly into the rotor assembly. By integrating the mounting tab, local composite considerations are minimized since the reinforcement that would have been required to support the bearing load on the airfoil cross section is no longer necessary at that location. Instead that load is handled by shear forces through the fusion bond which was shown to have sufficient strength to withstand the expected loads.

At the 90 degree junction between vertical blades and the horizontal spreaders, post-process bending of the composite airfoil cross section was successful in eliminating the need for any additional brackets. The airfoil was heated then deformed around a mandrel to create a crimped bend. This post-processing approach clearly demonstrated the potential for reforming the Elium® thermoplastic after initial manufacture, opening up a range of possible approaches for mass manufacture of simple geometries that would then be post-processed into their final forms.

More details of the preliminary developments related to airfoil fabrication steps, including the bending and fusion bonding, are presented in this report under Subtask 4.5.4.

Hollow 129” Airfoil Manufacture

The manufacture of the hollow airfoil sections for the VAWT prototype followed the infusion parameters developed in the 64” mold study. Given the success of fusion joining trial for incorporating the tower to blade attachment plates and the post-mold reforming, a hollow airfoil section approximately 129” long was required to fabricate a complete, one piece blade that would include the vertical airfoil, as well as the horizontal spreaders at both top and bottom of the rotor assembly. To manufacture these long hollow airfoils, a high quality, high stiffness mold set was required.

Mold Manufacture

A tool, nominally 92” long, made from machined 40 lb/ft^3 urethane tooling board with a thin epoxy surface coating was procured. The tooling was designed with ‘O’-ring grooves along the length, one near the leading edge and the other near the trailing edge of the airfoil geometry to better contain the low viscosity Elium® 150 resin during infusion. Also, for the purpose of aligning the top and bottom mold halves, 0.5” hemispherical cavities were machined into the flange area of the master to allow 0.5” diameter ball bearings to be used as alignment features in the resulting molds. Aluminum side and end plates were added to the master as seen in Figure 46(a). These were to enable vertical stiffeners to be included as part of the final mold and increase the stiffness without excessive weight. The end flanges were included to stabilize the mold cavity geometry, but were also used in the assembly of the molds, since the tooling master was only 2/3 the length of the required molds. The tool was coated with 5 coats of Releasomers

XK-22 LV.5 (G471) from Stoner. This low viscosity, wipe on mold release does not require an elevated temperature cure, which was necessary given the urethane tooling board chosen.

Carbon fiber was selected as the reinforcement for the molds to take advantage of the higher thermal conductivity than glass fiber, thus better facilitating the removal of excess heat generated in the exothermic polymerization of the Elium® 150. In addition, the increased stiffness provided by the carbon fiber reinforcement was desirable given the dimensions of the mold set. Vectorply supplied non-woven C-4QX 9400, 94.52oz stitched Quadraxial fabric and C-WV-0600, a 6oz/yd^2 twill fabric for the molds. The finer twill weave was used at the tool surface to ensure a finer finish on the airfoil surface, and the Quadrax was used to build thickness and structure. One layer of the Quadrax was used on top of the twill weave. Additionally, along the length of the mold flanges, Lantor Soric LRC 3 was used as a 0.125" thick core between 2 layers of Quadrax to increase mold stiffness. To ensure adequate replication of the square 'O'-ring channel, additional strips of fine fabric were applied between the airfoil feature and the 'O'-ring channel. All the reinforcement material was placed dry and the composite was created through a resin infusion approach.

The 3 - 92" long mold halves were infused using Rhino 1411/4111 epoxy resin at nominally room temperature followed by a freestanding postcure of 2 hours at 100°C. The 92" mold section was the longest that could be accommodated in the available walk-in oven. The Rhino resin was chosen based on familiarity with the processing parameters, even though the final glass transition temperatures (Tg) of 90°C was lower than peak exotherm that had been measured during the processing of the Elium® 150. Choosing the Rhino epoxy over a higher temperature capable infusion resin meant that the final mold set would need to be cooled once the Elium® resin reaction got underway. Each mold section infusion took less than 11 minutes and resulted in molds which were approximately 0.125" thick in the airfoil contoured section and 0.5" thick in the flanges.

To produce the two mold set of the required 138" length, 3 – 92" molded section were produced on the master. Each was postcured and then one of the three was cut in half and each complete 92" mold section was bonded to one of the nominally 46" long halves. This resulted in 2 mold halves of approximately 138" in length which provided just sufficient extra length, over that needed for each blade, for purposes of trimming. Other than the required joining to generate sufficient length, no significant mold rework was required. Figure 46(b), (c) and (d) show steps involved in the mold manufacture.

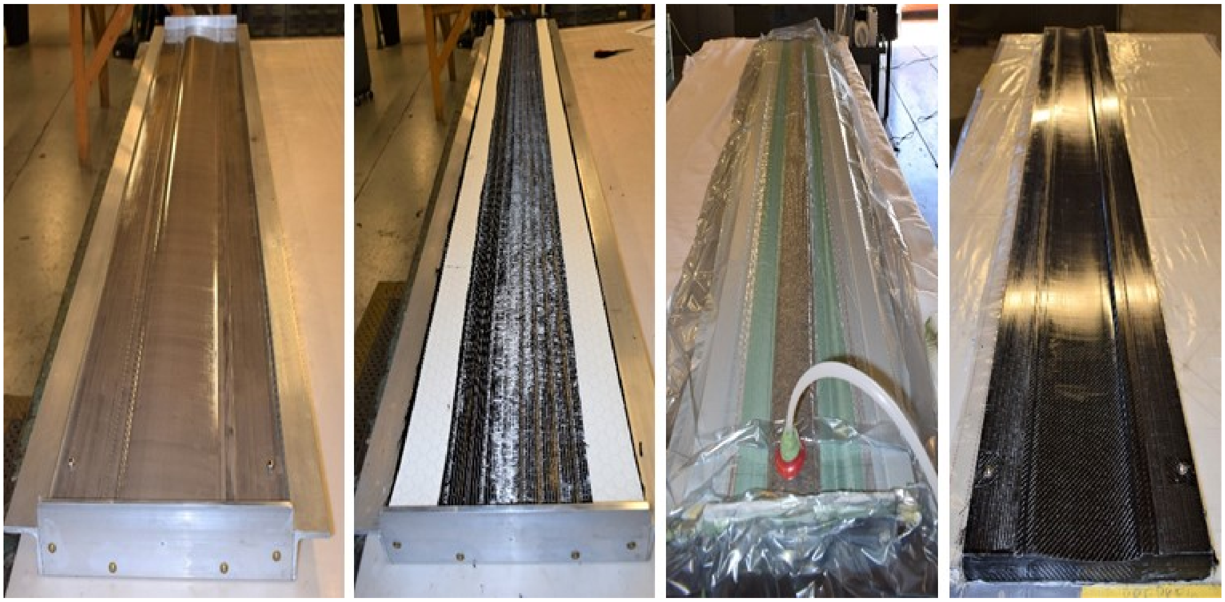


Figure 46: Resin infusion of carbon fiber/epoxy molds. Master with aluminum flanges added (a), partial carbon fiber lay-up showing the foam core flanges (b), Bagged mold (c), bottom surface of mold (d)

Carbon Fiber/Elium® 150 Blade Manufacture

The process used to successfully manufacture the full length 129" prototype VAWT blades required only minor variation in preform set-up and infusion procedure from that used in the 64" trial blade manufacture. The preform again utilized 3 layers of the VectorPly C-LA 0912 stitched 9oz UD carbon fabric with integral 1.2oz chopped glass mat trapped between 2 layers of the 4", 18oz braided carbon fiber, supplied by Highlands Composites (C400-15) and A&P (Z56L400R). This resulted in the final desired stacking sequence [±45,0_3±45] along the top and bottom of the airfoil, and [±45,±45] at the leading edge and trailing edge, where the UD was not positioned. Preform assembly, insertion into the mold and infusion are shown in Figure 47. Note that, from process experience gained in 64" airfoil trials, a length of preform was allowed to extend beyond the ends of the mold. All mold surfaces were prepared with the same Releasomers XK-22 LV.5 (G471) release agent used to release the carbon/epoxy molds from the master.

The first attempt to infuse a full-length airfoil was a success from the perspective of the infusion itself and the performance of the molds. The liquid Elium® 150 resin travelled, in the flow media, down the length of the 138" mold set within 12 minutes and the infusion was complete in less than 20 minutes. Mold surface temperature was monitored with a thermal imaging camera and when the surface temperature reached 50 C bags of ice were applied to the outer mold surface. This approach kept the mold temperature well below the Tg of the Rhino 1411/4111 and also was utilized to stop any possibility of void formation due to boiling of the Elium® resin. The mold set was left closed for several hours to ensure process completion.

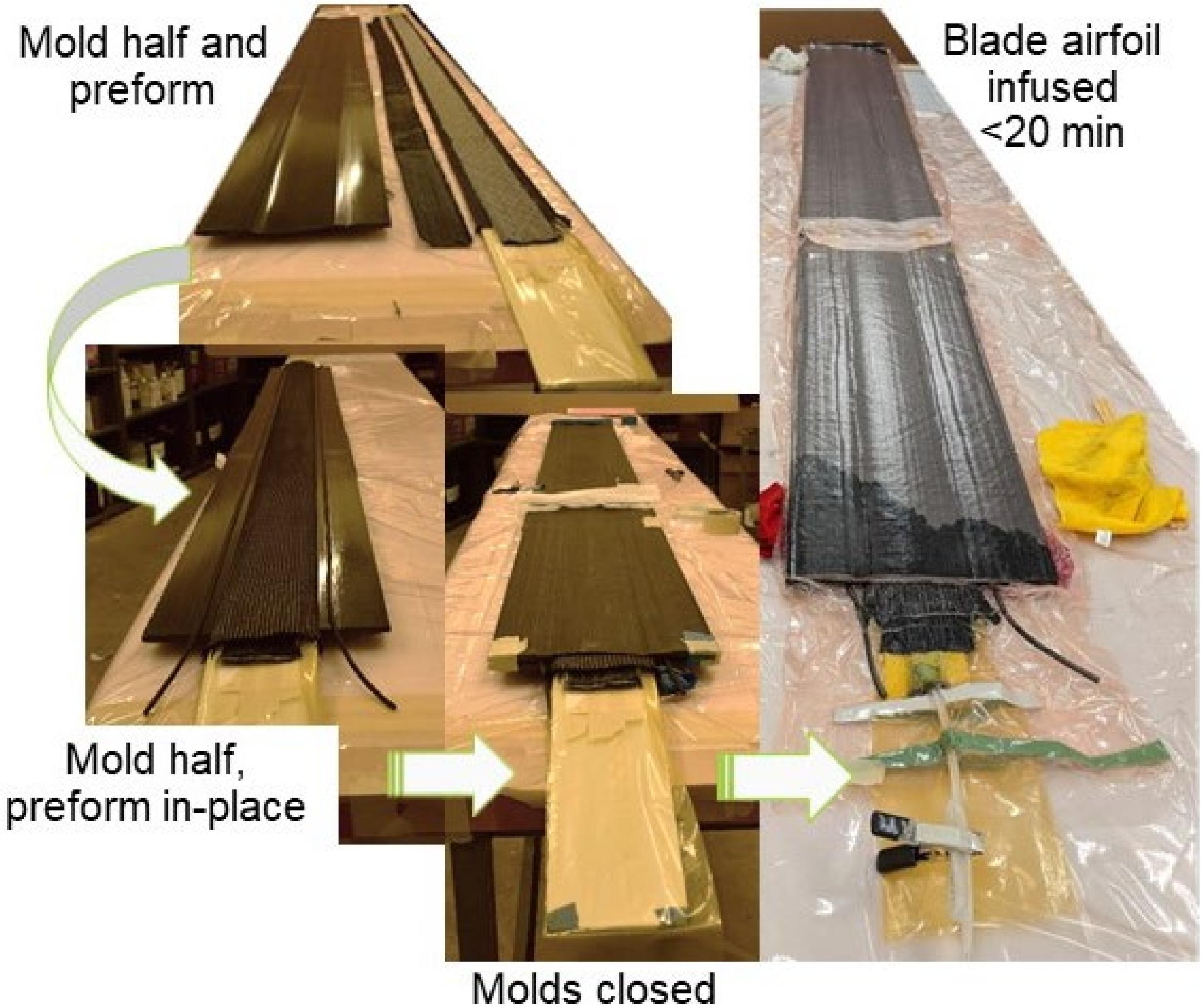


Figure 47: Final manufacturing process 3.35m prototype VAWT blades. Preform set-up (left), preform in the mold (left middle), Closed mold (right middle), infusing the preform (right)

Once the molds were opened the results of infusion could be examined. In this first trial of a full-length infusion, the complete airfoil section had successfully infused and the reinforcement preform had fit and filled the mold cavity, resulting in what should have been an excellent example of a carbon fiber/Elium® 150, 138" airfoil, with the exception of several small dry spots along the center of the lower surface. Unfortunately, it was also clear that only partial polymerization of the Elium® resin had taken place. This had not been a problem encountered during the 64" trial blade infusions; however, it was a result that had been noted before in cases where the process vacuum was compromised, and air came in contact with the Elium® resin prior to completion of polymerization. Since it is known that the Elium® 150 polymerization is sensitive to air, leading to incomplete polymerization which cannot be advanced through post process treatments, the research team had gone to great lengths to ensure that the vacuum was not compromised during infusion. Yet, the resulting lack of complete polymerization clearly indicated the presence of air. Given the limited amount of time available to fully research the contributing factors, an extended debulk was added to the infusion procedure to ensure that air and moisture were removed from the fiber preform prior to infusion. All materials, expendables and reinforcements, were also dried prior to any following infusions and maintained in a dry environment prior to use. The small dry spots along the bottom of the airfoil, considered to be related to the relatively high rate of resin transfer through the flow media, were mitigated by reducing the width of the flow media at the outlet (see Figure 48) from 4" to 2".

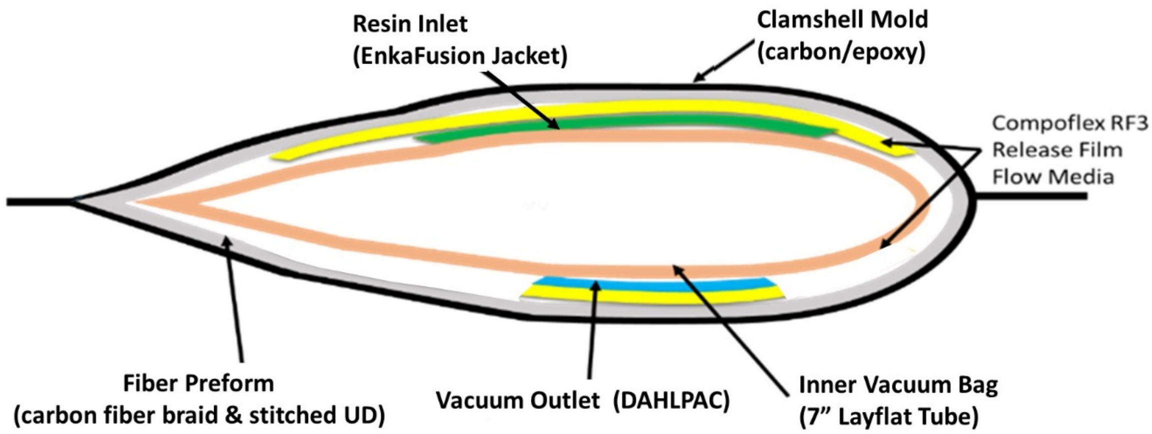


Figure 48: Cross-section schematic of the infusion set-up for the 138'' airfoils

Five more 138" hollow carbon fiber/Elium® 150 were infused and the best 3 were chosen for the VAWT prototype. The reduced amount of internal consumables (flow and vacuum media) notably reduced the effort required to remove the materials from inside the airfoil. Untrimmed ends with internal consumables still in place are apparent in Figure 49.

Figure 49: Untrimmed, as molded, 138'' blades

Conversion of Hollow Infused Airfoils to Installation-Ready VAWT Blades

With a sufficient number of 138" hollow carbon fiber/Elium® 150 airfoils completed, and with confidence in processes developed for end-fitting fusion joining and post-process bending, as described in Section 4.5.4, all the pieces were ready to bring together to complete the blade set for the VAWT prototype. 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 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 129”. The end-fittings were fusion bonded into each end of the 129” airfoil section using the aluminum tooling described in Section 4.5.4 and shown in Figure 50.

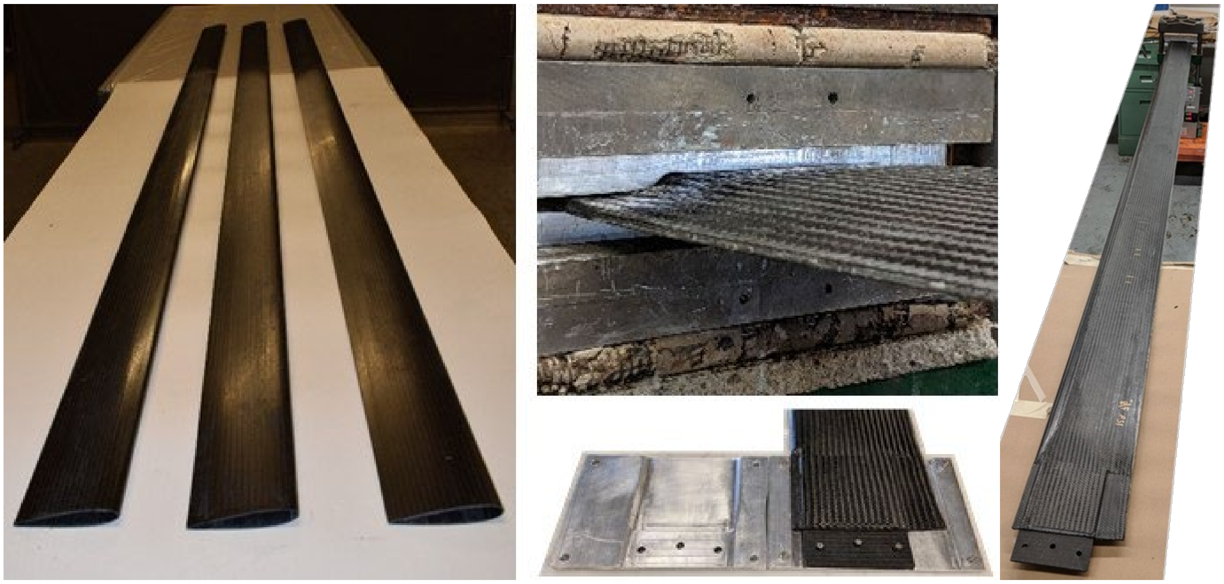


Figure 50: Trimmed 129’’ blades (left), Thermoforming of the mounting tab (middle), straight blades with integrated mounting tabs (right)

The blade section was supported while each end was fusion bonded in the aluminum matched molds, in the heated platen press, at 200°C, as seen in Figure 51.

Figure 51: End-fitting Plates being fusion bonded to the Trimmed 129’’ blades

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 shown in Figure 52. 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 52: Post-process bending in-progress using the wiping die-style system

Figure 53 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 to reduce the likelihood of sagging or twisting and a resultant misalignment.

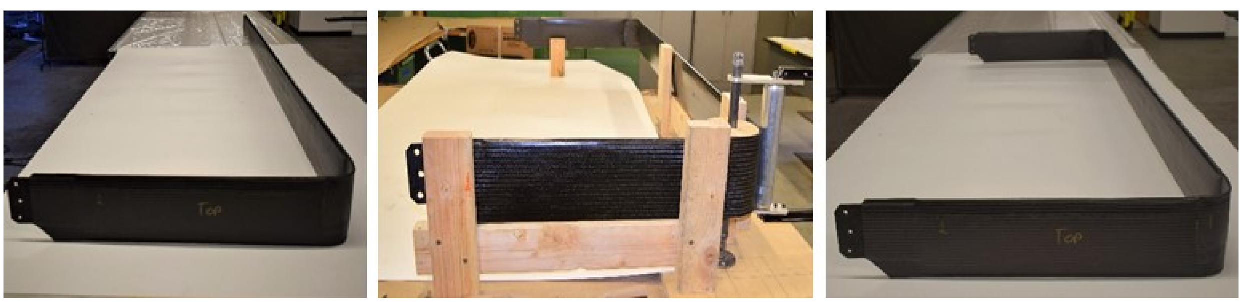


Figure 53: Post-process bending procedure of the 129’’ airfoils

Once the two bending operations were performed the blades were coated with a thin layer of enamel clear coat before being lightly sanded with 1500 and 2000 grit sandpaper to generate a glossy finish for aesthetic purposes. The as-molded versus glossy coated surfaces are compared in Figure 54 and the three completed blades are shown in Figure 55.

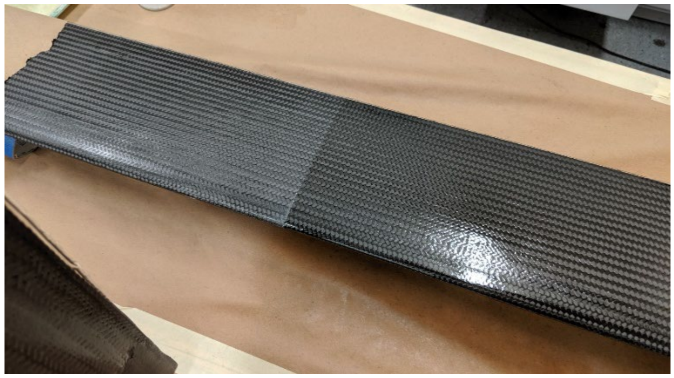


Figure 54: As molded finish on left and glossy finish shown on right

Figure 55: The completed 3 blade set

Assembly of the VAWT Prototype

The full-scale VAWT rotor assembly was fabricated and assembled for display at the July 2019 IACMI Member's Meeting in Denver, CO as seen in Figure 56. That rotor assembly incorporated machined components for the mast, central hubs, and bearing housing as well as the composite airfoil sections. The rotor assembly mass of this baseline design was estimated to be 47.7 lbs based on the CAD model (Figure 45) using defined material properties for all metal components as well as the carbon fiber composite airfoils.

Figure 56: Full-scale VAWT rotor assembly

Applying the design changes representing the bent airfoil and integrated mounting tabs into the CAD model, the updated mass was estimated to be 42.1lbs, suggesting a 12% reduction in mass from the baseline design. This theoretical estimate differed slightly from the as-fabricated mass, where each airfoil section weighed approx. 7.5lbs as opposed to the CAD estimate of each airfoil section at 5.1lbs. This difference is not unreasonable as the design estimates did not factor any thickness differences or resin content variation from the initial theoretical estimates.

The fabricated rotor assembly weighed approximately 50lbs. This assembled weight matched closely with the baseline design target of 47.7lbs, and fell within the 10% tolerance defined for this Go/No-Go metric.

6. BENEFITS ASSESSMENT

One of the primary benefits of this program is the preliminary design of a VAWT with very few parts in its bill of materials that would provide the ability to generate local, distributed energy for mobile and rural industrial applications with relatively low power demands. Beyond the manufacturing advancements that were proven during this prototype manufacture effort, there are also major benefits of using a thermoplastic material in a fiber reinforced composite. The thermoplastic provides an opportunity to recycle and reclaim the separate constituents of the composite material, preventing the blade materials from being discarded into a landfill. This advantage could have massive implications if this material strategy were to be employed in larger scale turbines, which have been making news lately due to their end of life landfill space requirements.

7. COMMERCIALIZATION

Steelhead Composites is partnered with Daedalus Composites, a company that produces high-end, zero-emissions yachts. These yachts harness multiple sources of renewable energy, including wind power through the installation on each yacht of 2 or 3 turbines, each rated at approximately 200-500 Watts. Since wind power is not the primary source of energy, the main requirement for any wind turbine installed on the vessel is not necessarily maximum power generation, but rather modest power generation, with emphasis on aesthetics, small form factor, low noise, negligible vibrations, and providing power at low wind speeds. This specific installation opportunity is an indicator of interest within the marine sector.

Beyond the marine sector, there are commercial opportunities that have been identified with very similar technical requirements as the list above, that would also benefit from a deployable structure, making the inherently small form factor even better suited for packing and transport. Specifically, disaster response efforts could benefit from a low-cost solution such as this that could be distributed to far reaching areas where the return of power will be delayed. A small VAWT could provide an additional power source that would allow for basic electrical requirements (e.g., lighting, cell phone charging) to be met. Other potential market opportunities lie within recreational campers including tent, recreational vehicles, and off grid enthusiasts, as well as exploratory science and military uses. Applications for these turbines, or scaled versions, could also be to supplement power to cell phone towers (especially in developing regions), at oil and gas wells, and in sustainable building complexes in both rural and urban environments.

According to the 2016 Distributed Wind Market Report (August 2017 per DOE contract DE-AC05-76RL01830 PNNL-26540, available at (https://www.energy.gov/sites/prod/files/2017/08/f35/2016-Distributed-Wind-Market-Report.pdf), Primus Wind Power, a US-based small wind turbine manufacturer, experienced record sales of their 160-400 Watt turbines during the year 2016. The main customers for these small turbines were within the oil and gas and telecom industries, as well as domestic and international remote military installations. Per that same report, it is estimated that 95% of sub 10 kW turbine installations during 2016 went into remote, off-grid locations. That general trend supports the increased sales volumes of small turbines (200-500 Watts), indicating a market interest.

The goal of this project was to develop a preliminary design of a VAWT that can now be used to better explore market potential. The proposed technology is intended to stand apart from the currently available products through its unique combination of lightweight thermoplastic composite materials allowing for recyclability at end of life. This VAWT offering will provide more consumer options when aesthetics and ease of deployment are required.

While this project strictly focused on the conceptual design of a VAWT, the long-term goal is to develop a product to be certified to national standards, which is a direct goal of the DOE Competitiveness Improvement Project (CIP).

8. ACCOMPLISHMENTS

A large accomplishment that came out of this program was on display at the July 2019 IACMI member's meeting in Denver, CO. The full-scale prototype VAWT rotor assembly was standing prominently in the entryway and received a lot of positive attention. There was also a presentation given by the project team covering the technical details of the design, analysis, material characterization and process studies performed.

Physical demonstration and quantification of two unique approaches for composite blade sections was another major accomplishment during this program. Fusion bonding of reinforced composite components is a process that provides a solution to many composite joining challenges. The post-process reforming of a reinforced composite structure also opens new avenues to large-scale manufacturing of complex geometries.

The material characterization conducted under this program also generated the first reported quantification of secondary cure property changes of the Elium® 150 resin system.

Additionally, a graduate student thesis at Colorado State University will come directly from the efforts of this program.

9. CONCLUSIONS

This program investigated the feasibility of an ideal VAWT candidate design for decentralized energy generation installations in urban and residential areas. The project team including Steelhead Composites (SHC), Colorado State University (CSU), National Renewable Energy Laboratory (NREL) and Arkema Inc. designed and fabricated a VAWT rotor assembly incorporating thermoplastic composite blades using novel infusion and fabrication techniques. This full-scale VAWT rotor assembly was designed for a rated power output of 0.5-1 kW, as estimated through analytical computational fluid dynamics (CFD) methods.

Much of the emphasis of this program was to characterize the recyclable thermoplastic material. This IACMI program has allowed for more in-depth material characterization than previously reported for a liquid thermoplastic resin system – Arkema Elium® 150 – as a matrix material for continuous carbon fiber reinforced composite structures.

Additionally, this project examined the potential of thermoplastic resin systems to transform the way VAWT rotor assemblies are joined both in the factory in in the field, by utilizing thermally welded joints to minimize field failure. The infused composite blades manufactured during this program are an excellent example some of the benefits made possible by the liquid thermoplastic resin system.

There are many advantages of this type of thermoplastic composite material including its unique post-processing potential, durability, recyclability, and overall strength to weight. The manufacturing techniques utilized for this prototype fabrication show a lot of promise for the manufacturability of similar part geometries.

It was determined that the current approach does not show a favorable economic return on this VAWT design when comparing this approach to currently available competitive products. Further investigation into both optimized aerodynamic performance as well as higher throughput manufacturing techniques would be required to set the stage for commercialization.

10. RECOMMENDATIONS

As discussed in the sections of this report, all performance and economic analysis were based on initial estimates that may or may not accurately reflect the actual performance of this VAWT design. An important step to take in the near future would be to verify and validate turbine performance through physical testing. Wind tunnel testing to understand the torque generated by this rotor design would inform the potential for design optimization and would also corroborate the estimates to better specify the balance of plant components for actual operating characteristics.

Additionally, there would be value in a more detailed assessment of cost reduction strategies for the blade sections themselves. One avenue for reduced cost would be to employ low cost carbon fiber, which may require additional material within the structure to compensate for lower mechanical strengths. Another important avenue to explore is mass manufacture approaches (e.g., pultrusion) for thermoplastic reinforced composite airfoil sections. Finding new means to process the Elium® 150 system could substantially reduce costs over the current VARTM process used for prototype manufacture.

11. REFERENCES

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12. APPENDICES

Appendix A: TE model example calculations

Table A.1: Turbine Assumptions and Specifications

Peak Power	1500	W
Rated Power (AWEA Standard at 11m/s or 24.6 mph)	700	W
OEM Rated RPM	450	RPM
Tip Velocity at Rated	47.1	m/s
TSR at Rated	4.3	
Air Density	1.225	kg/m3
Weibull k factor	2	
Wind Speed (Average)	5	m/s
Wind Speed (Rated)	11	m/s
Number of Turbines Manufactured per year	1000	turbines/yr
Number of Blades	3	
Number of Blade Support Arms per Blade	2	
Blade Chord (constant)	0.1524	m
Blade Thickness (max)	0.018542	m
Rotor Height (H-Rotor VAWT)	2	m
Rotor Diameter (H-Rotor VAWT)	2	m
Rotor Swept Area (H-Rotor VAWT)	4	m2
Rotor Equivalent Diameter (H-Rotor VAWT)	2.256758334	m
Rotor Specific Power	175	W/m2

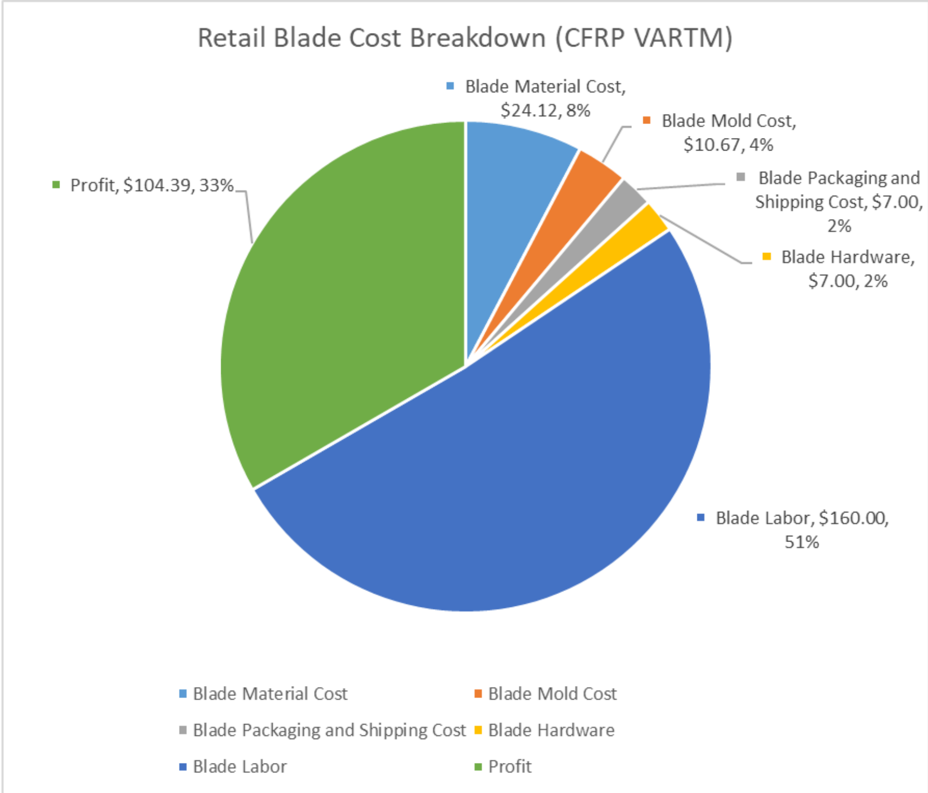
Table A.2: Turbine Projected AEP (20% H-Rotor Losses)

Maximum Possible AEP (Rayleigh-Betz)	3036	kWh/yr
Cp (Rayleigh-Betz)	0.2147	
Gross AEP	1000.0000	kWh/yr
Availability	100	%
Soiling Losses	1	%
Controls Losses	1	%
Collection Losses	3	%
VAWT H-Rotor Losses	20	%
AEP	750	kWh/yr
Average Annual AEP (net)	1071	kWh/kW/yr
Capacity Factor	0.12	%

Table A.3: Turbine Blade Manufacturing Assumptions and Specifications

VAWT BLADE MANUFACTURE-CFRP INFUSION (VARTM)		
Blade Length	2	m
Blade Chord	0.1524	m
Blade Thickness	0.018542	m
Blade Material Volume	0.0003092	m3
Material Cost - CFRP	52.00	$/kg
Material Density	1500	kg/m3
Mold Cost	80,000	$
Plug Cost	16,000	$
Number of pulls from mold	8,000	
Number of turbine manufactured per year	1000	
Number of Blades per Turbine	3	
Number of blades manufactured per year	3000	
Number of Blades Manufactured per day	11.5	
Number of Blades Manufactured per hour	1.2	
Expected lifetime of moulds	2.7	yrs
Tooling Amoritization Period	3.0	yrs

Blade Material Cost	$24.12	$/blade
Blade Mold Cost	$10.67	$/blade
Blade Packaging and Shipping Cost	$7.00	$/blade
Blade Hardware	$7.00	$/blade
Blade Labor	$160.00	$/blade
Profit	$104.39	$
TOTAL Blade Cost	$313.18	$
TOTAL Blade Set Cost	**$939.53**	$



VAWT BLADE MANUFACTURE-INJECTION MOLDING		
Blade Length	2	m
Blade Chord	0.1524	m
Blade Thickness	0.018542	m
Blade Material Volume	0.003092	m3
Material Cost - CCFRP (Chopped Carbon Reinforced Plastic)	5	$/kg
Material Density	1235	kg/m3
Mold/Tooling Cost	569800	$
Number of blades from mold	60000	
Number of turbine manufactured per year	1000	
Number of Blades per Turbine	3	
Number of blades manufactured per year	3000	
Number of Blades Manufactured per day	11.5	
Number of Blades Manufactured per hour	1.2	
Expected lifetime of mold	20.0	yr
Tooling Amoritization Period	3.0	yrs

Blade Material Cost	$19.09	$/blade
Blade Mold Cost	$63.31	$/blade
Blade Packaging and Shipping Cost	$7.00	$/blade
Blade Hardware	$7.00	$/blade
Blade Labor	$40.00	$/blade
Profit	$68.20	$
TOTAL Blade Cost	$204.61	$
TOTAL Blade Set Cost	**$613.82**	$

VAWT BLADE MANUFACTURE-ALUMINUM EXTRUSION		
Blade Length	2	m
Blade Chord	0.1524	m
Blade Thickness	0.018542	m
Blade Material Volume	0.0006184	m3
Material Cost - Aluminum	3	$/kg
Material Density	2700	kg/m3
Mold/Tooling Cost	50000	$
Number of blades from die	100000	
Number of turbine manufactured per year	1000	
Number of Blades per Turbine	3	
Number of blades manufactured per year	3000	
Number of Blades Manufactured per day	11.5	
Number of Blades Manufactured per hour	1.2	
Expected lifetime of mold	33.3	yrs
Tooling Amoritization Period	3.0	yrs

Blade Material Cost	$5.01	$/blade
Blade Mold Cost	$5.56	$/blade
Blade Packaging and Shipping Cost	$7.00	$/blade
Blade Hardware	$7.00	$/blade
Blade Labor	$40.00	$/blade
Profit	$32.28	$
TOTAL Blade Cost	$96.85	$
TOTAL Blade Set Cost	**$290.54**	$

VAWT BLADE MANUFACTURE-GFRP INFUSION (VARTM)		
Blade Length	2	m
Blade Chord	0.1524	m
Blade Thickness	0.018542	m
Blade Material Volume	0.0006184	m3
Material Cost - GFRP	10.2	$/kg
Material Density	1800	kg/m3
Mold Cost	80000	$
Plug Cost	16000	
Number of pulls from mold	8000	
Number of turbine manufactured per year	1000	
Number of Blades per Turbine	3	
Number of blades manufactured per year	3000	
Number of Blades Manufactured per day	11.5	
Number of Blades Manufactured per hour	1.2	
Expected lifetime of moulds	2.7	yrs
Tooling Amoritization Period	3.0	yrs
--		
Blade Material Cost	$11.35	$/blade
Blade Mold Cost	$10.67	$/blade
Blade Packaging and Shipping Cost	$7.00	$/blade
Blade Hardware	$7.00	$/blade
Blade Labor	$160.00	$/blade
Profit	$98.01	$
TOTAL Blade Cost	$294.03	$
TOTAL Blade Set Cost	**$882.09**	$

VAWT BLADE MANUFACTURE-CFRP INFUSION (VARTM)		
Blade Length	2	m
Blade Chord	0.1524	m
Blade Thickness	0.018542	m
Blade Material Volume	0.0003092	m3
Material Cost - CFRP	52	$/kg
Material Density	1500	kg/m3
Mold Cost	80000	$
Plug Cost	16000	$
Number of pulls from mold	8000	
Number of turbine manufactured per year	1000	
Number of Blades per Turbine	3	
Number of blades manufactured per year	3000	
Number of Blades Manufactured per day	11.5	
Number of Blades Manufactured per hour	1.2	
Expected lifetime of moulds	2.7	yrs
Tooling Amoritization Period	3.0	yrs
--		
Blade Material Cost	$24.12	$/blade
Blade Mold Cost	$10.67	$/blade
Blade Packaging and Shipping Cost	$7.00	$/blade
Blade Hardware	$7.00	$/blade
Blade Labor	$160.00	$/blade
Profit	$104.39	$
TOTAL Blade Cost	$313.18	$
TOTAL Blade Set Cost	**$939.53**	$

Table A.4: Turbine System Equipment – CAPEX (CFRP-VARTM)

VAWT-CAPEX WIND TURBINE SYSTEM EQUIPMENT	
Blades and Support Arms	$939.53
Rotor Mast	$1,659.55
Rotor Mast/Blade Connection	$650.00
Alternator	$2,200.00
Electronics (Rectifier/Controller/Inverter)	$1,125.00
Bearings	$137.42
Misc. (e.g. nuts and bolts)	$48.56
Labor	$250.00
Packaging	$50.00
Shipping	$75.00
Turbine Extended Warranty	$0.00
Tower	$500.00
Tower Wiring	$100.00
Total Turbine Capital Equipment Costs	**$7,735.06**

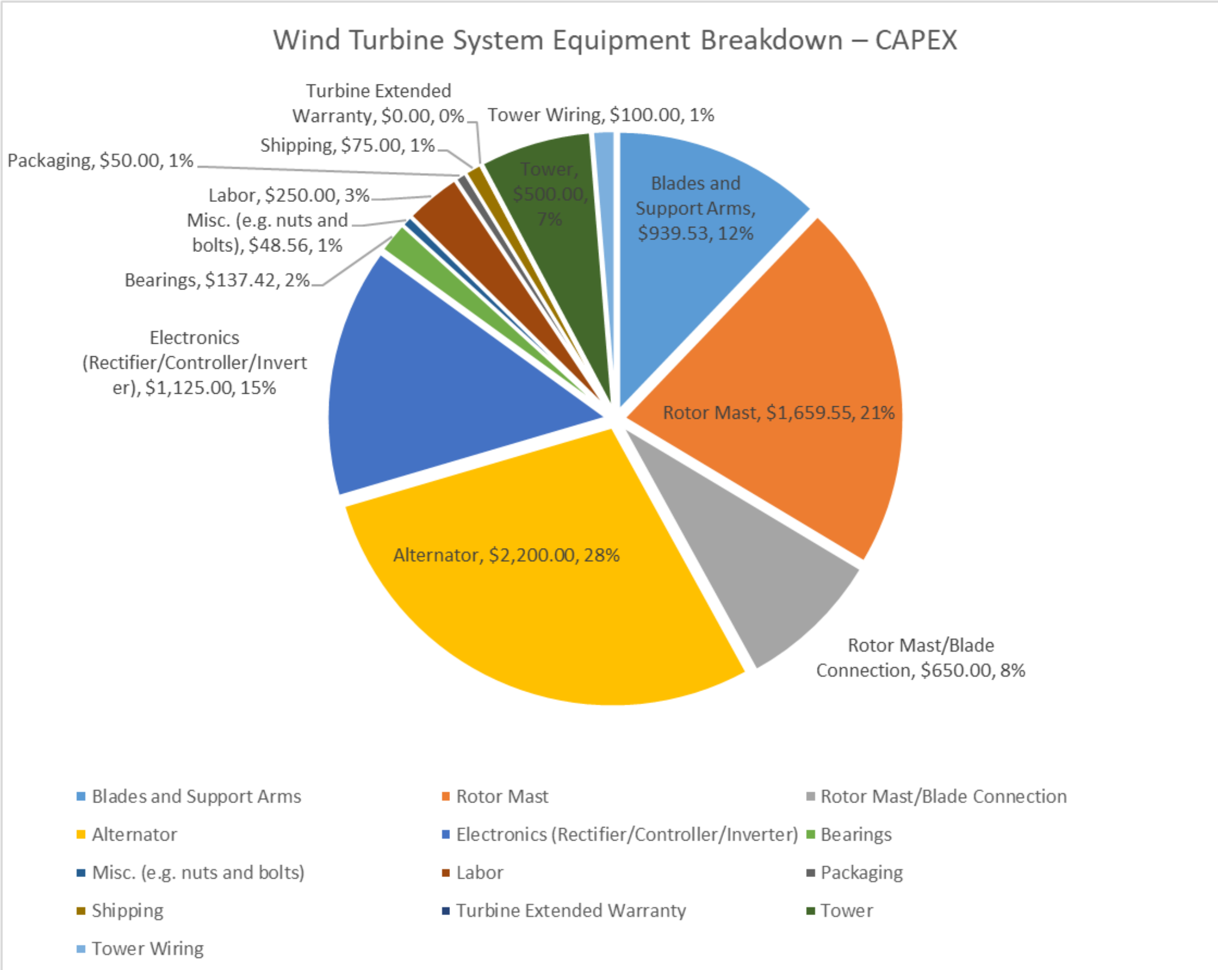


Table A.5: Turbine LCOE Projection (CFRP-VARTM with 20% H-Rotor Losses)

$$\text{LCOE} = \frac{(\text{CapEx} \times \text{FCR}) + \text{OpEx}}{(\text{AEP}_{\text{net}}/1{,}000)}$$

CAPEX-Wind Turbine System Equipment	7735.1	$
CAPEX-Balance of Station (BOS)	450	$
OPEX	109.35	$
AEP-net	1071	kWh/kW/yr
FCR	5	%
LCOE	**0.48**	**$/kWh**