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Development of a fabric winding system for the automated manufacture of prefabricated wind turbine blade roots

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Development of a fabric winding system for the automated manufacture of prefabricated wind turbine blade roots

by

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Abstract

In the rapidly expanding wind energy market, manufacturing processes of composite components must be continually improved to keep up with high demand and increasing part size. This research focuses on improving the offline production of the root section of wind turbine blades. In this research, a system is developed and tested to replace the two-part manual layup of the prefabricated root with an automated fabric winding machine. The system is designed to wind a limited number of long, stitched plies semi-helically around a male mold at a lower cost and higher quality than current processes. A prototype machine is created that pulls two types of Non-Crimp Fabric from supply rolls onto a rotating mandrel that matches the interior surface of a scaled down blade root. The prototype system proves Non-Crimp Fabric plies can be wound and a male mold can be used as a suitable replacement for a female mold by creating several successful prototype root sections. Process times and labor costs between the current manual layup and the winding method are also compared and show a significant reduction in glass layup, further proving the feasibility of the new system.

Introduction

Around the world, renewable energy is becoming the main goal for new energy production, and wind is quickly emerging as the most viable renewable energy source. In July of 2008, the U.S. Department of Energy published a report describing a scenario where 20% of America's energy could be provided by the year 2030 [1]. While this scenario is theoretically attainable, it does require ever-increasing installations which, in turn, require faster manufacturing of wind blades and their components.

Ramping up production of wind turbine blades is not as simple as increasing most manufacturing processes. Wind blades are extremely large and are continually increasing in size. Blades on the smaller end of megawatt scale wind turbines are now at 40+ meters long and require a significant amount of material and labor.

This paper focuses on improving the manufacture of one large subcomponent of wind turbine blades, the root section. The root of a wind blade, shown in Figure 1, is the thick base that attaches to the hub. Depending on blade length and manufacturer, the root section of a blade can be in excess of 60mm thick, requiring many layers of fiberglass and a significant amount of labor to manufacture. Because of the amount of material, time, and labor that goes into this section of the blade, it is often prefabricated as a separate component offline and later infused into the blade. The large thickness difference between the root and the rest of the blade material could also cause thermal issues from the exothermic cure if they are infused simultaneously. It is the goal of this paper to investigate and develop a new automated method for creating these root preforms.

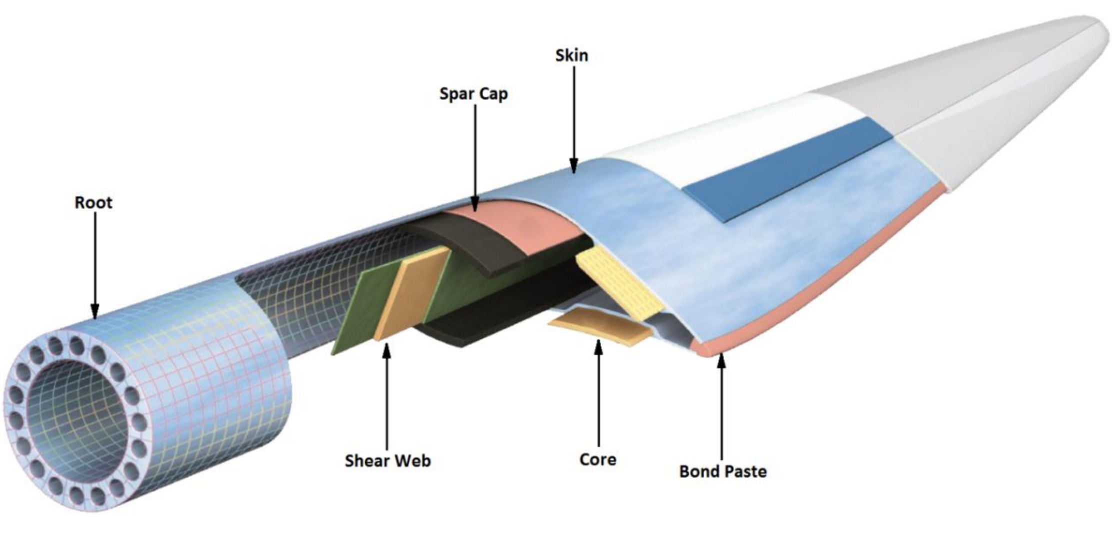

Figure 1: Wind Turbine Blade Components [2]

Because this research focuses on manipulation of composite fabrics to create the root preforms, a basic review of composite manufacturing must first be discussed. In general, engineered composites are two or more materials that remain discernible after combined, usually as a matrix material and a reinforcement material. The root preforms investigated in this research are made from composites comprised of high strength fiberglass reinforcement and a bonding polymer resin matrix to hold the preform shape and transfer load throughout the reinforcement material.

Fiberglass can be deposited in or on molds in many ways. The glass is manufactured as individual glass fibers that are bundled into tows. The tows can then be used alone, turned into tapes, which are a flat grouping of aligned tows, or plies where the tows are woven or stitched together in a sheet. Each of these types can either come as dry fiber that is later infiltrated with resin or as a prepreg where the resin is pre-impregnated into it. Tows are often used in a pultrusion technique where the glass is pulled through a vat of resin before being deposited on or in a mold. The tows can then be laid loosely into a mold or they can be wound tightly around a male mold with a process like filament winding. Tapes commonly come as prepregs that must conform to a mold surface either manually or with multi-axis deposition heads. Fabric plies most commonly come as dry sheets that are laid in molds by hand. If this is done, the operator can manually apply resin to the fabric to perform a wet layup or the glass can be mechanically infused using a vacuum to pull the resin through the glass or a pump to push the resin through the glass.

There are many variations of composite fabric plies. The tows can either be woven or stitched together in many orientations. Stitched fabric, known as Non-Crimp Fabric (NCF), is made up of multiple layers of fiberglass, each containing tows of one orientation, and the layers are held together by stitching that runs the length of the fabric. Woven fabric has no stitching and the tows are held together in the ply by weaving through each other. These two ply styles are shown in Figure 2. NCF is becoming more prevalent in composite manufacturing because the straight tows provide better properties than the inherently wavy woven tows [3, 4].

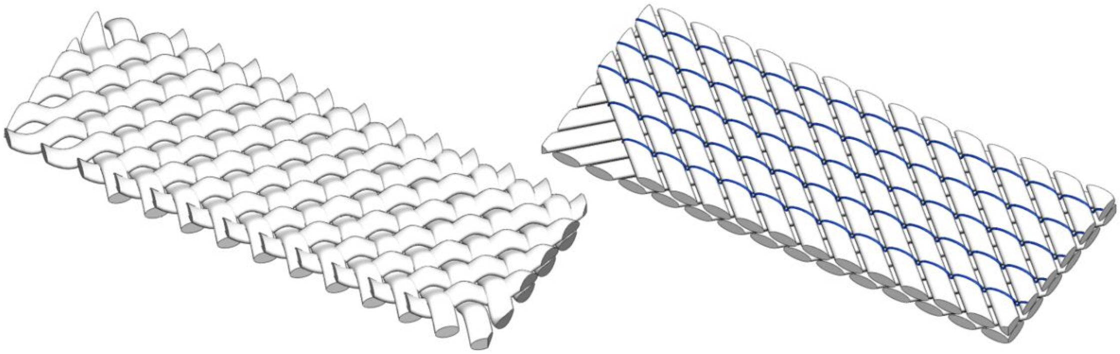

Figure 2: Woven fabric vs Non Crimp Fabric

The main benefit of fabric plies is the ease of depositing a full layer of mechanically aligned fiber tows all at once in the form of a sheet. The tows within fiberglass plies can be aligned in any orientation for different strength properties. Two common orientations used in wind turbine blade manufacturing and in this research are unidirectional and double biased. In unidirectional fabric, all of the load bearing tows are aligned in one direction and serve to provide strength in that direction only. Unidirectional fabric works well for features of turbine blades designed to handle high tensional loads, including the root and spar cap. In most unidirectional fabric, the tows run the length of the fabric, also considered 0° or the warp direction. However, for certain special applications the unidirectional tows can run at 90° to the length of the fabric, or the weft direction, these are referred to as weft-uni's. Another common orientation, double biased (bias), is made of tows running at ±45° to the warp direction. This fabric makes for a conformable reinforcement material that provides torsional strength for components. An example of these three fabric types are shown in Figure 3.

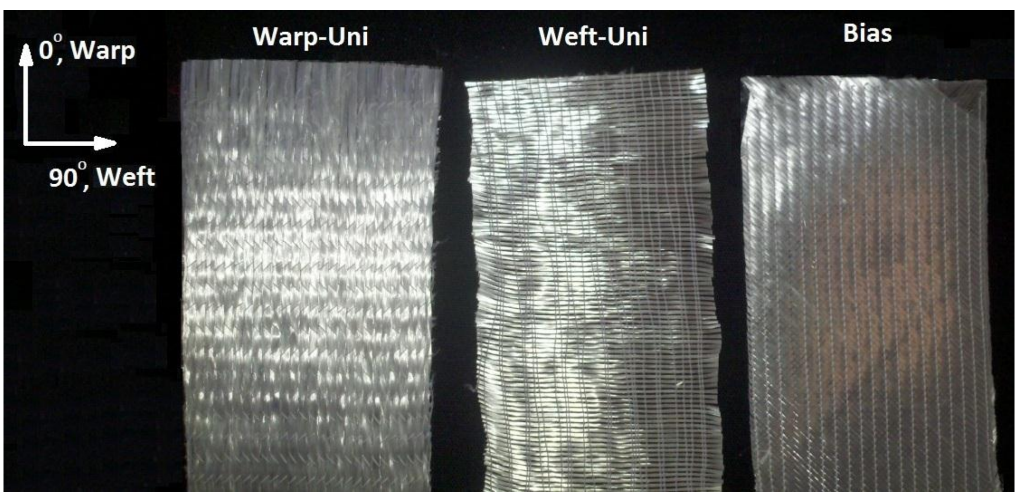

Figure 3: Tow orientation of warp-uni, weft-uni, and bias fabric

Layups in this research will use vacuum pressure to infuse the fiberglass with a variant of Vacuum Assisted Resin Transfer Molding (VARTM) called the Seemann Composites Resin Infusion Molding Process (SCRIMP) patented by TPI Composites [5]. The VARTM process pulls resin into a one sided mold with a vacuum pump and atmospheric pressure conforms the glass to the mold. The SCRIMP process adds resin channels and a quick infusion layer that pulls the resin over the part first and then down through the layers.

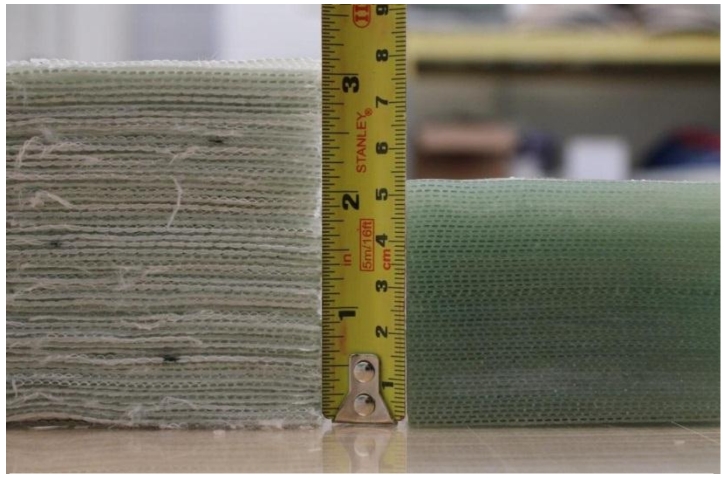

Figure 4: 100 plies before and after infusion

One concern when using the VARTM process are waves induced by the compression of the fabric. Figure 4 shows the compression induced in 100 alternating layers of 490.3gsm and 425gsm fabric by vacuum infusion. This amount of compression can cause the fabric to shift over itself and any restriction to movement can result in waves or wrinkles from cinched fabric. Waves in fiberglass components are measured by their aspect ratio which is quantified by the length of the wave (L) over the height (a), pictured in Figure 5. Larger aspect ratios are preferred as there is less concentrated deviation from the desired surface and less structural compromise [6]. The amount of compression can also vary depending on fabric used. For instance in Figure 4, the layup is a 1:1 ratio of bias and weft-uni plies of roughly equal weight. This layup compressed to nearly 70% of its dry height. If the layup were changed to 1:2 bias to weft-uni, the compression or overall heights may be lower as the unidirectional tows are able to settle into each other and compression would need to be remeasured.

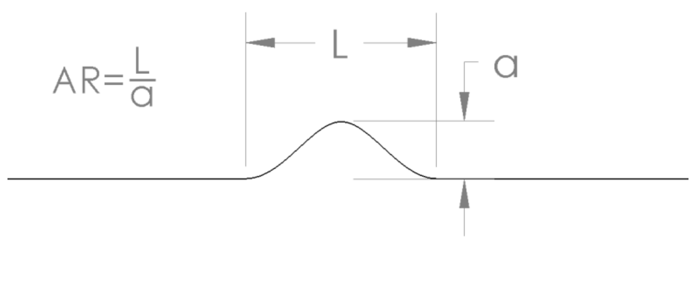

Figure 5: Aspect ratio of fiberglass wave

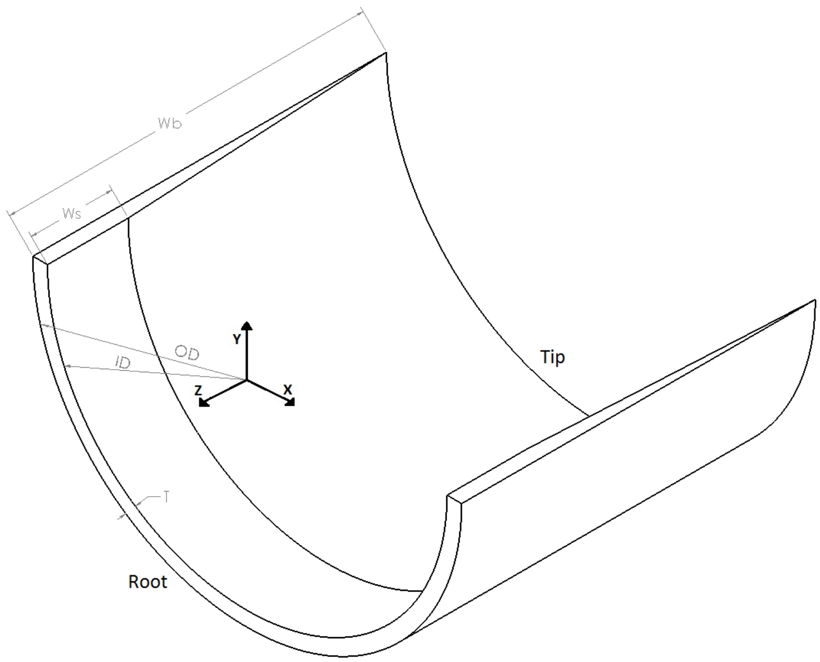

Figure 6: Root preform variables

At this point, an overview of current root preform hand layups must be discussed. Figure 6 shows a preview of the root preform and some of the variables and nomenclature used in this research. The labels for each end of the root preform correspond with the generic labels of a full blade, the root end is attached to the hub and the tip end extends towards the tip of the blade. The origin sits at the root face with the negative z-axis extending through the center of the blade. The variables used to describe the preforms include:

- OD: Outer diameter
- ID: Inner diameter of uniform thickness section
- T: Max thickness
- Wb: Z dimension of preform from root to tip
- Ws: Z dimension of uniform thickness section
- P: Number of plies in the root preform
- f: Infused fabric ply thickness

For confidentiality reasons, the true dimensions of the root preforms studied for this research cannot be disclosed. To give readers a concept of size and to give this research values to use in later calculations, artificial dimensions are created to represent the actual size of a root preform. These values are represented in Table 1 in millimeters along with approximations for number of layers and fabric thickness.

Table 1: Theoretical Root Preform Dimensions (mm)

OD	ID	T	Wb	Ws	P	f
2000	1850	75	1750	500	100	0.75

Figure 7 shows the layup sequence used to create the desired root preform shape. The plies are lowered into a half cylinder mold and smoothed from the center to the edges allowing any waves to be pushed from the fabric. Under this layup scheme, the first ply in the layup covers the entire mold. Each subsequent ply remains against the root end but has a slightly shorter z length. The decrease in ply length has been determined by design specification to build up the root end while tapering the tip end so the preform can later be transitioned into the rest of the blade with a scarf joint to provide a large bonding surface and avoid a large drop in fiberglass.

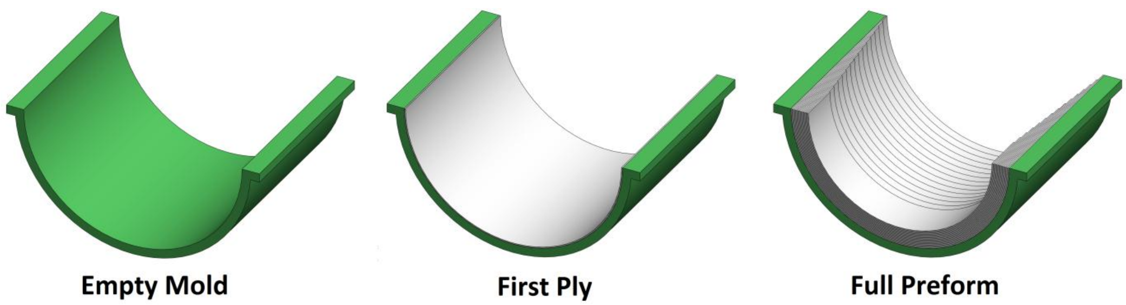

Figure 7: Manual Root Preform Layup Sequence

An extension can also be included on the each side of the preform mold to build up excess fabric vertically along the edge that can later be used to transport the preform to the blade mold. Because the edges of the preform mold end vertically, a spray adhesive is applied under each layer in this area to keep the fabric from falling back down into the mold. However, the use of

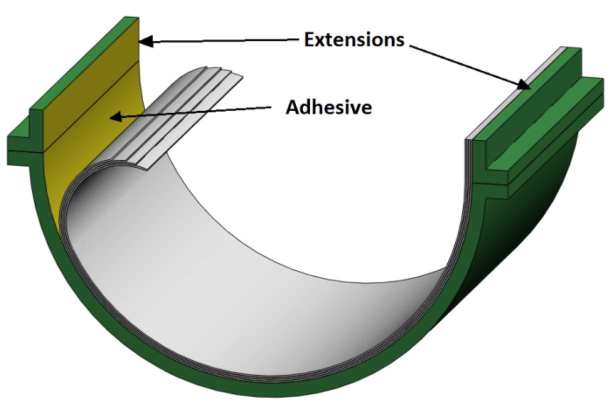

Figure 8: Extension, adhesive, and peeling layers

spray adhesive has been shown to inhibit resin flow in infusions [7, 8]. Figure 8 shows the vertical extensions on the mold, the location of the spray adhesive application, and how the fiberglass layers would fall into the mold if the spray adhesive weren't used.

After layup, the part is infused and cured and is ready to be integrated into the blade halves. Most wind blade facilities create blades in two halves in a clamshell mold similar to the one pictured in Figure 9. The root mold surface matches that of the blade mold surface so a preform can be lowered into each blade half.

Figure 9: Blade Clamshell [9]

After combined with the blade halves, the sides are cut to create a flush mating surface with each other. Finally, after the blade has been assembled and cured, the root face is milled for a uniform mounting surface to the hub and bolt-holes are drilled in the face.

The quality of the root preform layup is critical to the quality of the whole blade. The root section is the connection point of the entire blade to the hub, so if it is not made to high standards, catastrophic failure could occur. An acceptable root preform must not have waves with failing aspect ratios or dry fabric to be able to withstand the forces seen by a wind turbine blade.

Although the current layup style is simple and easy to follow, it is also labor intensive. Root sections use large plies and can be over 100 layers thick, requiring several workers and high cycle times. The goal of this research is to create and test an automated system that will manufacture root preforms with a similar physical makeup as the current process, but at a lower cost in terms of throughput and manufacturing costs and of equal or better quality in terms of dimensional control and flaw reduction. The system proposed to accomplish this will wind fiberglass around a male mold to make two preforms in one automated layup. The new process will be supplied by a limited number of long, stitched plies instead of workers laying many individual fiberglass plies into a female mold.

Literature Review

Automated systems offer several improvements over traditional manufacturing methods, most importantly speed and precision. Automation helps reduce cycle times by systematically completing operations without waiting for operator judgment or availability. It reduces labor hours of a process if tedious or repetitive work needs to be carried out by one or more skilled laborers. It also has the strong potential for increasing product quality by improving repeatability and process control.

The proposed system of winding large amounts of fabric plies around a mandrel is a new idea that uses aspects of several automated composite manufacturing methods. Benefits and drawbacks of the processes that inspire this system are reviewed in this section.

When creating cylindrical, composite structures, automation often turns to filament and tape winding. The filament winding process uses tows or tapes of composite fibers, usually glass or carbon fiber, and winds them around a rotating mandrel. This process has been used effectively for over 60 years to quickly and precisely make parts of a wide range of sizes that are able to rotate around a longitudinal axis [10].

Filament winding machines can use dry, wet, or preimpregnated (prepreg) fibers to create parts depending on the system used. The fiber is pulled from a supply roll and is run through a carriage that moves back and forth over the length of the part, covering the mandrel in a specified pattern. Figure 10 shows an example of a simple mandrel and standard filament winding paths that can be used for differing strength properties [11]. Depending on the complexity of the mandrel and the fiber orientation, these machines can be as simple as a lathe-type machine with a rotating mandrel and a sliding head [12] to deposit single filaments or a several axis head laying multiple tows or wider tapes around more complex curvatures.

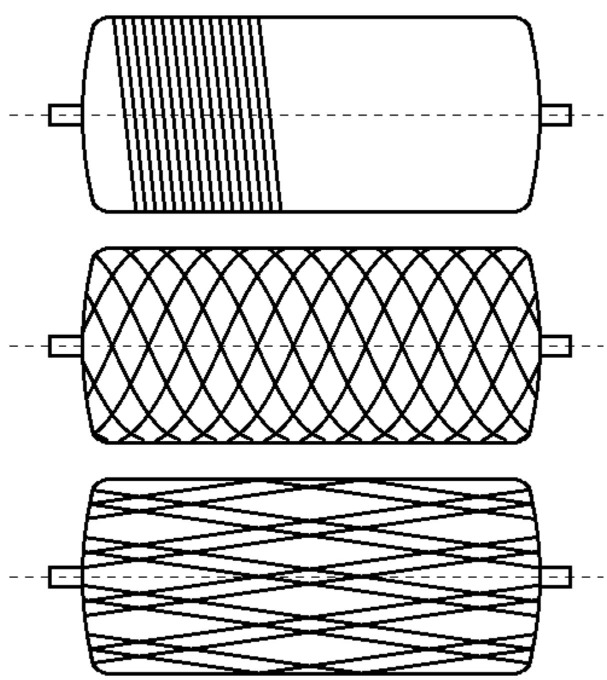

Figure 10: Filament Winding patterns. Top to bottom: Hoop, Helical, Polar Winding

A common focus of filament winding research is on the effects of fiber tension [13, 14, 15]. Mertiny gives a comprehensive overview of fiber tension and how it influences the properties of filament wound components. In their experiments, tubular specimens were made and loaded under varying conditions to prove that the degree of tension directly influences the part strength. Mertiny's research concludes that higher tension improves strength in components under fiber dominated loading but the reverse is true for matrix dominated loading.

Polini discusses the deviations in actual winding tension from planned tension caused by error in robot deposition paths and methods to estimate and compensate for the error. Polini points out that if actual winding is too loose, waves in the deposition direction, called marcels, may occur, whereas too tight of winding can damage the fiber and cause irregular compression in the part. Filament winding tension research is partially related to the proposed root winding research in that fiberglass is tightly wound around a mandrel, however, in filament and tape winding, the tension is applied directly to the fabric but the tension is applied to the stitching when pulling NCF.

Residual stress is another common research topic in filament winding [15, 16, 17, 18]. Casari's research created thick filament wound tubes using three different composites and three winding angles. Their research found that significant strains are revealed after cutting the samples and these stresses need to be accounted for during manufacturing.

Lu conducted research on the stress induced by different amounts of tension applied during tape winding. Lu concluded that radial stress in wound parts can be tensile or compressive depending on if tape tension is increased, decreased, or kept constant throughout the layup.

Lee attributes residual stress to curing and experimented with two different "smart curing" methods [Figure 11] for thick composite flywheels. The results showed that both keeping the inside and outside ambient temperatures equal and heating from the mandrel produced lower stresses than the conventional cure from the outside only.

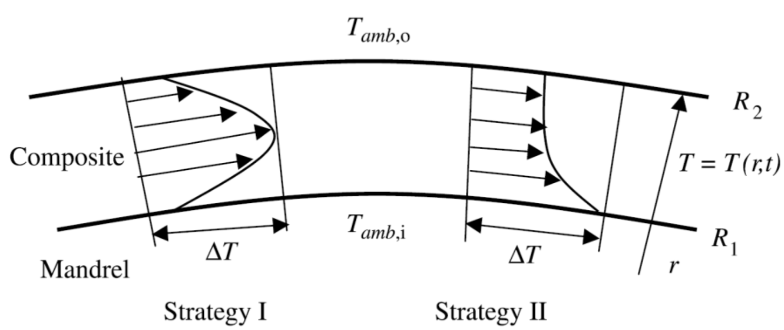

Figure 11: Thick composite curing strategies [17]

Filament winding is able to wind fibers in precise paths because it uses a computer numerically controlled deposition head. This creates very uniform parts with little handling and high process control [10]. With the tight fiber placement control and use of continuous fibers, filament winding can create parts with both high hoop and longitudinal strength depending on part geometry and winding path. Along with the benefits of computer and robotic control, comes complexity compared to traditional layup methods. Filament winding machines require path planning programming and many are equipped with multi-axis deposition heads depending on path and material. Many recent papers have been published about improvements in robotic equipment and programming for filament winding [14, 19, 20, 21].

Scholliers researched quality control for both a simple two axis filament winding machine and a robotic tape winding machine. Research is also continually being conducted to improve the path optimization and collision control of filament winding [19, 21, 22]. While improvements in filament winding over the last half century has made the process common practice for many tubular applications, the technology involved in filament and tape winding is not applicable for the root preform winding application.

Another drawback filament winding has in creating root preforms, is the restraint on longitudinal fiber. The root section of a wind turbine blade requires a significant amount of fiber aligned with the z axis to provide axial strength and resist bending at the base. Although filament winding can lay fibers nearly concentric to the z axis [23], seen in Figure 12, the fibers must run the length of the mandrel and wrap around the ends to create the friction required for winding [11, 24, 25, 26]. However, the tapered inner surface of the root requires longitudinal fibers that do not run the length of the mandrel. Because of this, filament winding cannot be used to build up the root end of the preform with longitudinal fibers.

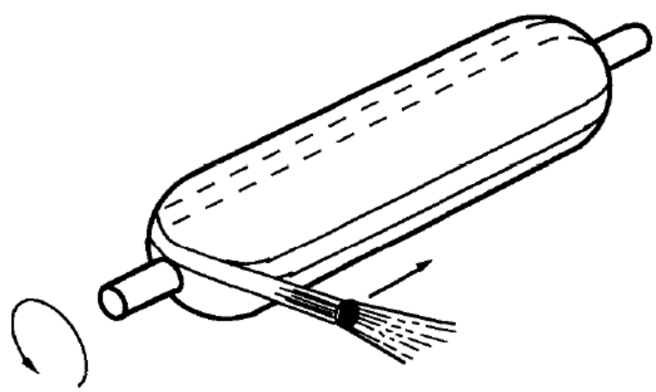

Figure 12: Polar Filament Winding [23]

Another automated fabric system is automated tape laying (ATL) and the slightly more versatile automated fiber placement (AFP) shown in Figure 13. Similar to filament winding, these systems pull fiber from a supply system and a controllable head deposits the fiber in the desired locations. Fiber placement machines do not necessarily require a rotating mandrel, however, and instead use multi axis robotic heads to conform the fabric to the mold.

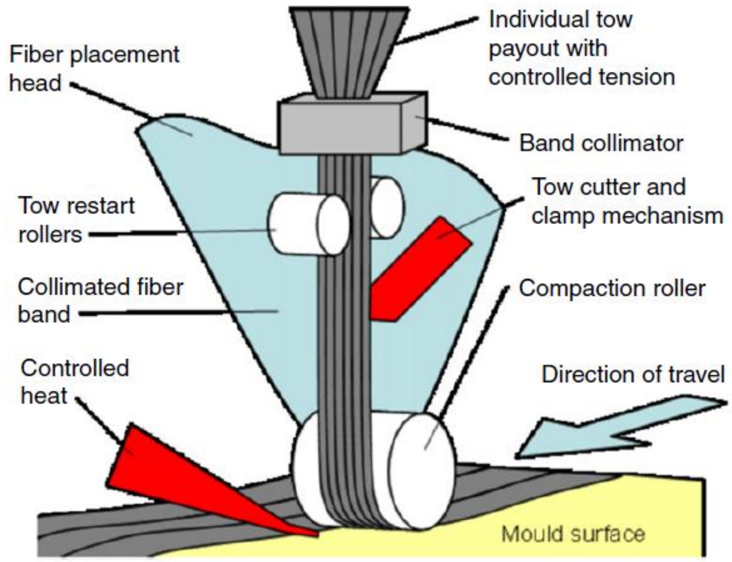

Figure 13: Automated Fiber Placement [27]

ATL places a single prepreg tape made of many tows onto low curvature surfaces and AFP uses many small prepreg tapes and is able to conform to more complex surfaces [27]. The fiber placement machines are able to cut the fabric during layup and change positions to start again [25]. Because of this, ATL or AFP machines would physically be able to make root preforms on a mandrel with the same fiber orientation as current preforms. However, these machines are again more complex and expensive than necessary for such a simple operation. Creating root preforms with a tape laying machine would be very time consuming taking several thousand tape strips even with a wide tape.

In structural fiberglass components, the glass tows are specifically aligned to create strength in the desired direction. Winding and fiber placement machines align the tows individually during layup, but manufactured plies eliminate the need for complex machinery. In fabric sheets, large quantities of fiber tows are aligned as necessary within each sheet in many combinations of orientations. Depending on layup area, thickness, and fiber orientation required, a few NCF plies could replace hundreds of strips of fiber tape. In addition, complex layups would require advanced path planning and robotic control of fiber placement machines where a fabric ply need only be placed in the mold and smoothed out. Using fabric plies could potentially increase deposition rates by providing structure in premanufactured sheets [28], however, they are currently limited almost entirely to hand layups.

The physical properties of fiberglass plies make them difficult for an automated system to manipulate [29, 30]. The plies often come in large sheets, especially in the case of wind turbine blades, and they can be difficult to handle and adjust appropriately. Getting a machine to hold, deposit, and smooth material of this size in even slightly complex molds is a challenging task. In addition to size, fabric plies are flexible, making them difficult to grasp and manipulate and promoting deformation. If the fabric is allowed to shift within an automated system, the tows can become misaligned and the fabric misshapen, defeating the purpose of the original ply design.

There have been several conceptual stitched fabric layup automation machines in recent research. MAG has designed a Rapid Material Placement System (RMPS) that can theoretically unroll fabric over great distances at speeds up to 3m/sec [31]. The RMPS uses a gantry system able to clamp, unroll, and smooth fabric the length of a wind turbine blade. This system is still in testing.

Various systems are also being investigated to grip, transport, and place composite fabrics [32] or looking into the draping effects of these fabrics [33, 34]. Kordi designed a system, shown in Figure 14, to grab smaller plies of fabric using various gripping elements and a moveable frame to conform to mold surfaces. Many of the gripping systems investigated in fiberglass pick and place machines are adopted from textile robotic research [35, 36]. If a fabric manipulation machine similar to Kordi's was made large enough to handle the root preform plies, it could potentially build a root preform in the exact style as the current layup. Unfortunately, many of these gripping systems can be damaging to fiberglass where the quality of the fabric is more critical than in textiles. A machine of this style would also be considerably expensive to purchase and program especially if several were needed to operate multiple molds to keep up with production.

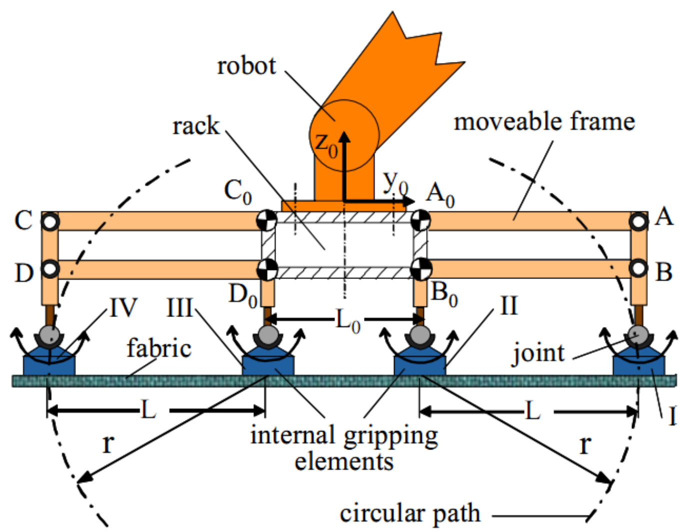

Figure 14: Robotic pick and place machine [32]

The design of the root preform winding machine is based on using the best aspects of several composite layup techniques while excluding the drawbacks of each. Like other winding systems, this is an automated approach to composite layup by winding fiber around a mandrel, but it will need to overcome filament winding's inability to provide variable length fibers aligned with the winding axis. It is a nearly hands-free operation designed to provide a fast, precise layup, however, it will not require a complicated CNC deposition head. Similar to hand layup, this system will use NCF to take advantage of the pre-aligned fiber orientation of the fabric plies, but the plies will no longer require operator layup or a robotic pick and place machine.

Solution Methodology

Winding long NCF plies can make root preforms faster, cheaper, and better than current processes. To prove this hypothesis, a machine must be created capable of winding large amounts of NCF semi-helically around a mandrel and a fabric scheme needs to be prepared to create parts of the correct size and physical makeup. The proposed winding process must be capable of creating parts equivalent or better in cost and quality compared to the current layup process.

Root Preform Winding Machine

This research proposes to create a root preform winding machine designed to automate the entire root preform fiberglass layup. The new method will convert the current layup of manually dropping hundreds of plies into two female molds to automatically winding a limited number of plies around a single male mold. Workers would still be required for loading and unloading the machine and the infusion setup, but the majority of work currently being done would be hands free and done at a much faster pace. Ideally, the new winding process will turn layup times from hours to minutes and nearly eliminate labor.

The machine is comprised of a rotating mandrel that pulls fabric from continuous fabric supply rolls. The mandrel shape is designated by the interior surface of an existing prefabricated root section in current production. This shape includes the straight section of the current built to aid in handling. By keeping the same surface for the mandrel shape, the goal is to create a root preform with the exact dimensions of a current root so it can be seamlessly incorporated into the current build. This idea can be seen in the cross-sectional drawing of both mold types shown in Figure 15. The mold surface for creating the root preform changes from the OD to the ID, but as Figure 15 shows, the shape of the glass remains identical.

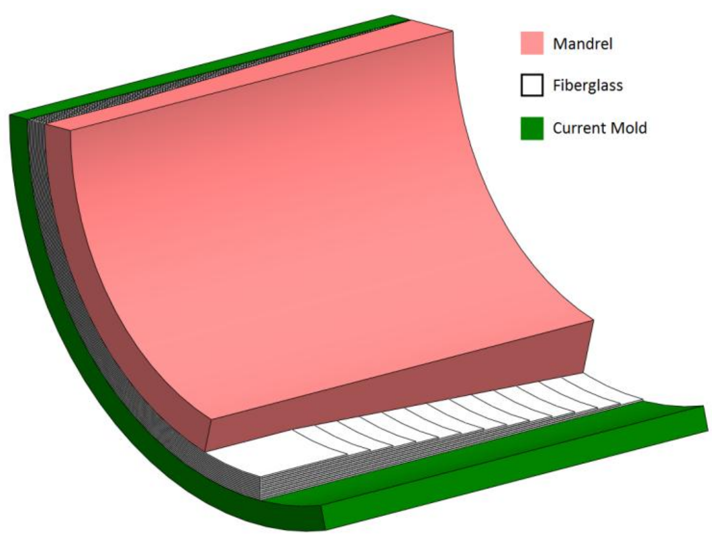

Figure 15: Comparing Mold Surfaces

To test the design considerations of the root preform winding method, a prototype machine was made to wind preforms scaled down from a wind turbine blade root currently in production. The goal of the experimental machine is to determine the feasibility of the root preform winding process. Figure 16 gives the design plans for the prototype machine and Table 2 gives the dimensions in millimeters of the root preforms the experimental machine is designed to make.

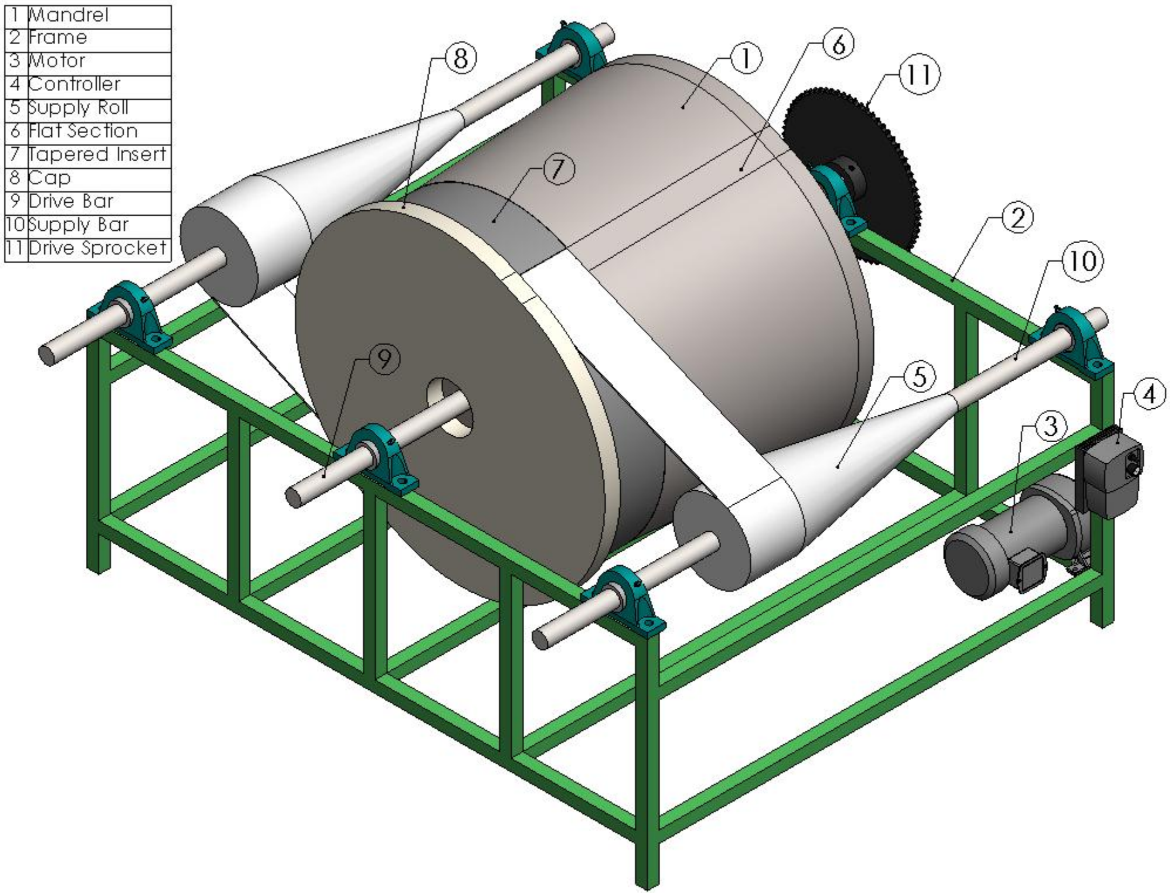

Figure 16: Prototype Machine Features

Table 2: Prototype Root Preform Dimensions (mm)

OD	ID	T	Wb	Ws
942.5	878.2	32.15	777.5	177.5

Fabric scheme

Presentation of fabric is one of the main differences between the proposed root preform process and the current one. In the existing process, operators lay approximately 100 precut fabric plies into a mold for each half of the root where the new process will only require one long ply for each supply roll. In order to get plies of NCF to wind around a mandrel from a limited number of supply rolls and build up an axisymmetric part of non-uniform thickness, they must be prepared to strict specifications.

To minimize human intervention, manufacturing time, and material waste, the supply fabric plies should be kept as long as possible. If the fabric isn't long enough to wind the whole part, the process would need to be interrupted to reload the supply rolls so it would be beneficial if the machine would only need to be set up once and allowed to wrap the entire root.

The finished preform has a cylindrical outer surface, but the mandrel it is being created on has an increasing diameter. To make the mandrel shape work, the fabric used to create the preforms must build up the root end to the full thickness and taper down to a single ply at the tip end while keeping the outer surface of each layer concentric cylinders. Figure 17 shows the general shape of the winding supply fabric plies that will be able to create the desired root preforms. Also shown in Figure 17 is a representation of the fabric used in a current manual layup in female molds to show how the fabric design changes between the two processes. It should be noted that this figure is provided for the benefit of the reader and is not drawn to scale as the angle of the winding fabric can be as low as 0.1° and the manual layup fabric has 100+ plies.

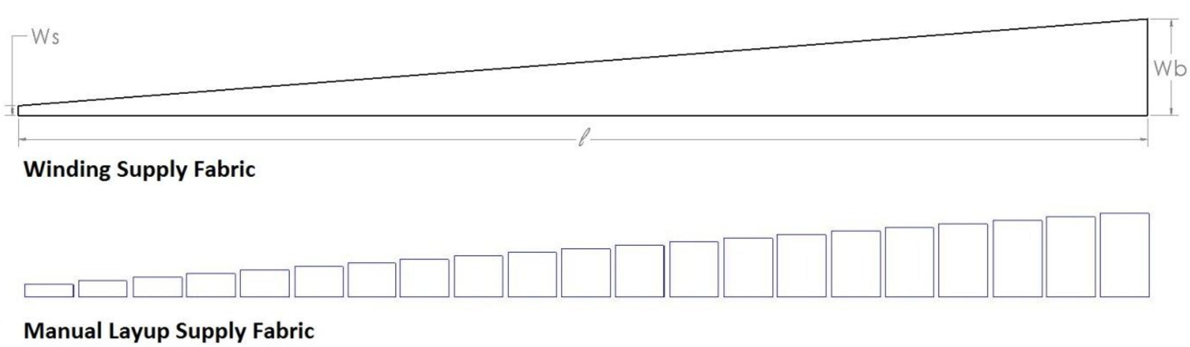

Figure 17: Representation of supply fabric (not to-scale)

The fabric will wind from the smaller end (w_s) to the larger end (w_b), and the straight edge of the fabric will remain against the root face during the winding process while the opposite edge will increase helically towards the tip end of the mandrel. With this pattern, each wrap will add a layer to the root end and extend the fabric farther towards the tip where it will eventually end with a thickness of one layer. This winding process is referred to in this research as semi-helical winding.

The fabric will come from supply rolls pre-wrapped around supply bars that sit concentrically around the rotating axis unwinding onto the mandrel. In order to account for compression of the vacuum infusion, the fabric will need to be wound onto the mandrel under tension. If the fabric is wound as tight as it would be compressed by atmospheric pressure, it cannot be forced into a smaller space so it will not deform and waves will not appear. However, when a vacuum is pulled on loosely wound fabric, the inner layers would pull tight against the mandrel, and as the layers increase, there is more room to compress and the large diameter is forced into being a smaller diameter which collapses the fabric and forms waves. Figure 18 gives a visual explanation of this issue. At the same time, it would also be desirable to not wind too tightly in the case that it would inhibit infusion, add unnecessary residual stress, or create an undersized part. The physical limit of the applied tension is set by the strength of the fabric stitching. For fabric without warp tows, all tensile force in the warp direction of the fabric is applied to the stitching so extreme tension would destroy the fabric.

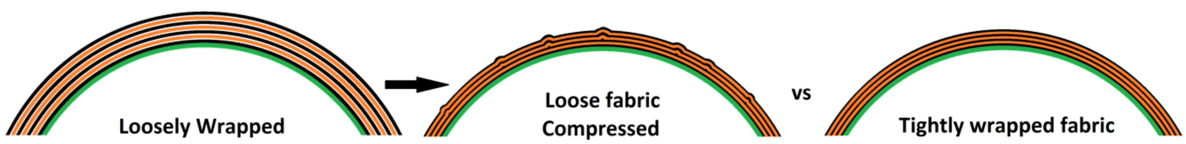

Figure 18: Compression of fabric layers around a mandrel

To be able to replace the manual root preform process, the winding machine needs to create parts of the same dimensions as current preforms for proper incorporation into the rest of the blade. The critical dimensions of the root preforms are the OD and T. Figure 19 examines four scenarios of a root preform seating into a blade mold viewed from the root end of the mold and how variations of the OD affect the assembly. By winding around a mandrel, the interior surface will not change between preforms, however too much or too little fabric will cause the OD to not match the blade mold surface as shown in scenario 2 and 3 of Figure 19. Scenario 4 shows how cylindricity of the preforms must also be kept accurate for proper seating and alignment in the blade mold.

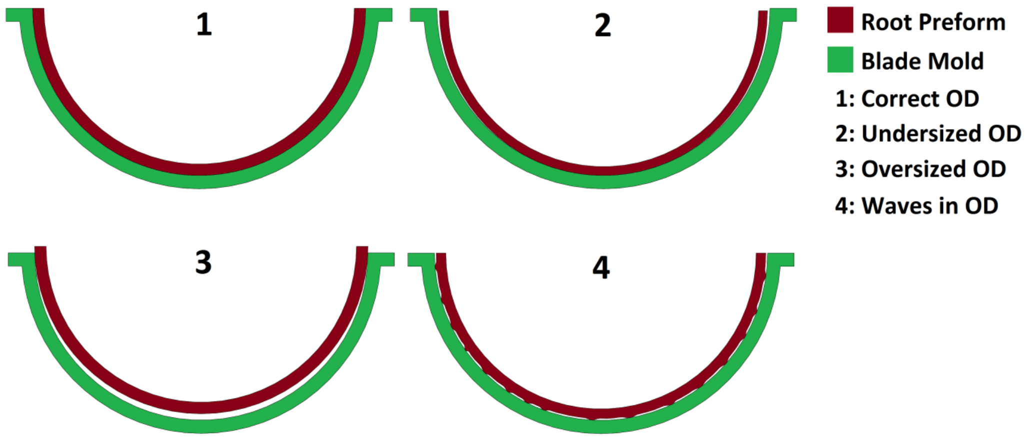

Figure 19: Effects of poor preform dimensions on placement into the blade mold

To determine the ply dimensions, several decisions, measurements, and calculations must be made, the first of which is the fabric being used. To keep the same longitudinal and torsional strength properties as current production, the prototype machine will also use plies with tows aligned at ±45° and 0° to the z-axis of the blade. Because the fabric winds around the z-axis, traditional bias fabric will work for the ±45° tows, but a less traditional weft-uni will be needed to align the unidirectional tows along the z-axis.

The layup pattern of the ply types is determined next. A root preform can use any of several patterns throughout the layup, including all of one type, alternating plies, an unbalanced quantity of types, or a combination of several patterns. The difference these schedules make is the number of supply rolls required to perform the pattern. For example, a root preform using a schedule of 1:1 (UD:Bias) would require one supply roll of each fabric while a schedule of 1:2 (UD:Bias) would have one supply roll of weft-uni and two supply rolls of bias all unrolling at once. If the layup is variable, additional rolls would need to be added to the machine that are fed into the layup intermittently. To show feasibility of the machine design, a layup schedule of 1:1 (UD:Bias) will be used in the prototype experiments. This will allow testing to be done with only two supply rolls, each with one length of fabric.

Because the prototype machine makes parts scaled down from megawatt scale roots, the fabric weight chosen for this testing is also scaled down in an effort to best replicate winding a high number of layers around a male mold. This will better mimic a true root preform and test the capabilities of the machine. The fabric used for initial testing is weft-uni and bias NCF from Vectorply® at weights of 490.3gsm and 425gsm respectively.

Once the fabric type and layup pattern has been chosen, the final infused thickness of each layer needs to be determined. Although fabric manufacturers may provide this information, it is best to find it experimentally to assure accurate calculations. Figure 20 shows how layers can settle differently in different layup patterns. For this reason, the fabric thickness should be calculated for each pattern used in the layup [34]. To find the infused thickness for the experimental fabric, 100 alternating layers of the weft-uni and bias fabric being used were stacked and infused. The thickness of the final infused sample is measured and the average layer thickness is found. Because the prototype machine is using a 1:1 ratio of glass patterns of similar weight, both types are declared to have equal thickness. For the prototype testing, the infused fabric thickness is 0.54mm. Using the fabric thickness and the final part thickness of 32.15mm, the number of layers required for the layup can be found as 59.5, which is rounded up to 60 layers.

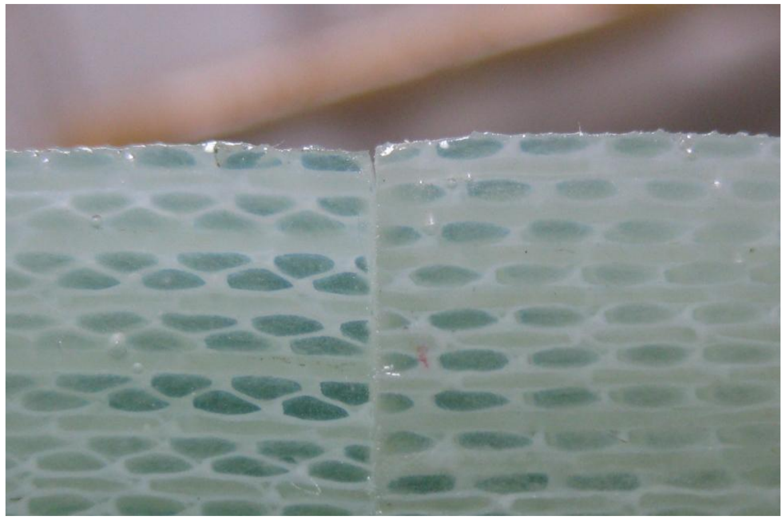

Figure 20: Fabric settling. Left: 2:1, Right 1:1 (UD:Bias)

Based on the number of layers and the size of the mandrel, the length of fabric (*l*) required for the final root alone (excluding the flat section) can be calculated. The total length of fabric is found from combining the circumference of the mandrel as it increases with each layer starting with the ID of the root. This calculation is shown in Equation 1.

$$l = \int_0^P \pi\big(ID + x(2 * f)\big)\,dx \qquad (1)$$

Solving for this equation for the experimental fabric gives:

$$\int_0^{60} \pi\big(878.2 + x(2 * 0.54)\big)\,dx = 171644mm \qquad (1a)$$

The scaled root requires 171.6m of fiberglass. The same equation results in 604.8m of fabric for the full-scale root.

Because of the flat section, additional fabric (r) must be factored into the supply roll length. All growth in the fabric length of each wrap is accounted for with the increase in diameter of the actual preform shape, so the flat section remains the same throughout the layup. The prototype mandrel has a 76.2mm flat section which adds 9144mm of fabric after 60 revolutions, or an additional 4572mm for each supply roll. Additional, non-tapered fabric (s) is also added to the end of each supply roll to provide spare fabric for process control. For the prototype machine, this is set at 3000mm which is slightly more than the circumference of the finished root. The final length (l_i) of each prototype supply roll ends up being over 93m as shown in Equations 2 and 2a.

$$l_i = \frac{l + 2rP}{rolls} + s \qquad (2)$$

$$\frac{171644 + 2 * 76.2 * 60}{2} + 3000 = 93394mm \qquad (2a)$$

Testing the 1:1 layup schedule will determine if the winding process meets the objective of proving that a machine can wind multiple types and many layers of semi-helically wound, woven fabric. The machine needs to demonstrate that it can physically do the task while showing that the parts can be made cost effectively and meet or exceed quality standards. Once this is proven, the full functionality and versatility of the machine can be verified by testing an unbalanced fabric schedule.

Prototype

This section of the paper discusses the design of the prototype winding machine shown in Figure 16 and how it will be operated. The machine is equipped with a ½ HP Bison® gear motor to drive the mandrel and a controller to provide continuous, variable control. The motor controls the mandrel with a 10 tooth drive sprocket connected by ANSI 60 chain to a 70 tooth sprocket mounted on the mandrel drive axis. The motor can spin the mandrel at any speed between 0 and 6.25 RPM.

The mandrel is made of ¾" sheets of Medium-Density Fiberboard (MDF) each machined by a gantry router to create a mold quality smooth surface [Figure 21]. The outer surface was then sanded smooth and coated with West System® epoxy to create a non-porous mold surface. A 2in steel bar is mounted through the center of the mandrel as the drive axis and it is attached by steel plates on the ends of the mandrel.

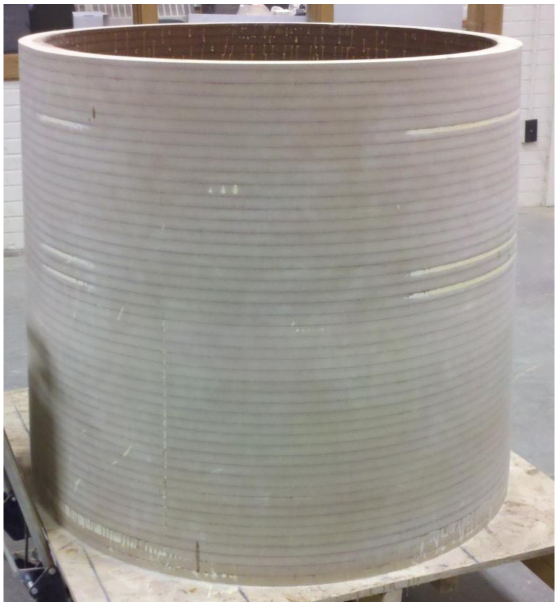

Figure 21: MDF mandrel

Figure 22 shows the features and dimensions of the prototype mandrel. The OD and ID are 942.5mm and 878.2mm respectively, and the length is 828.3mm to allow for w_b and w_s dimensions of 777.5mm and 177.5mm and leave room for sealant tape. Additional features to the mandrel include the flat sections and the insert.

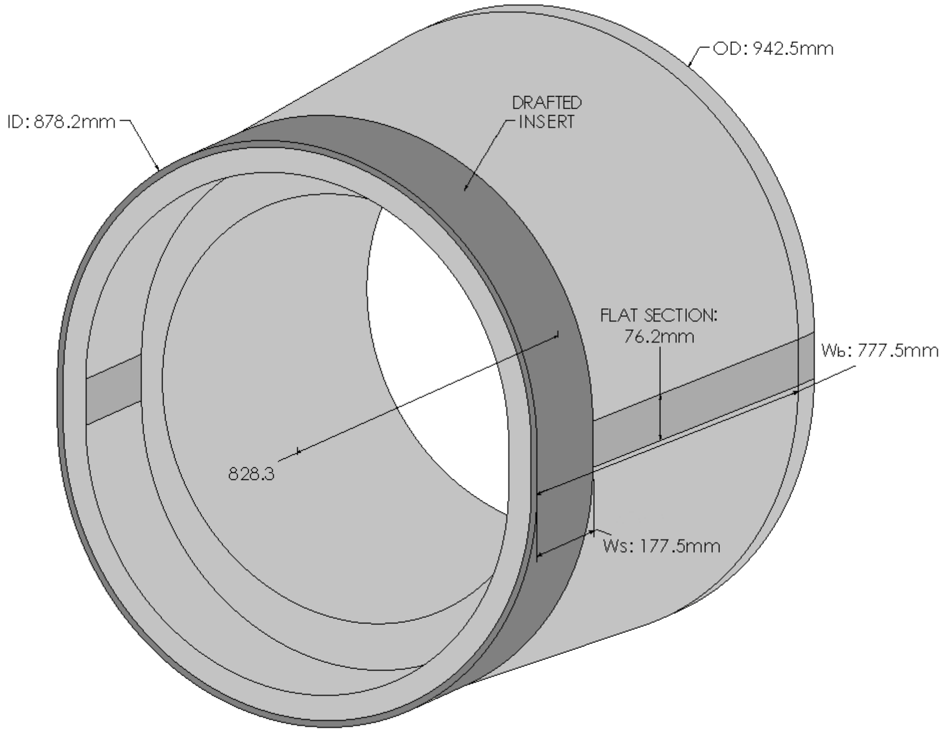

Figure 22: Prototype mandrel design

The first modification to the mandrel design is the addition of two flat sections running down the length of the mandrel on opposite sides The flat section is added to mimic the current layup and give sacrificial edges to the preform to provide an area to cut through without worry of damaging the actual root and aid in handling the preforms. Even though the trial preforms will not be lowered into a blade mold or cut back to half cylinders, a 76.2mm flat section was added to the mandrel to test this feature.

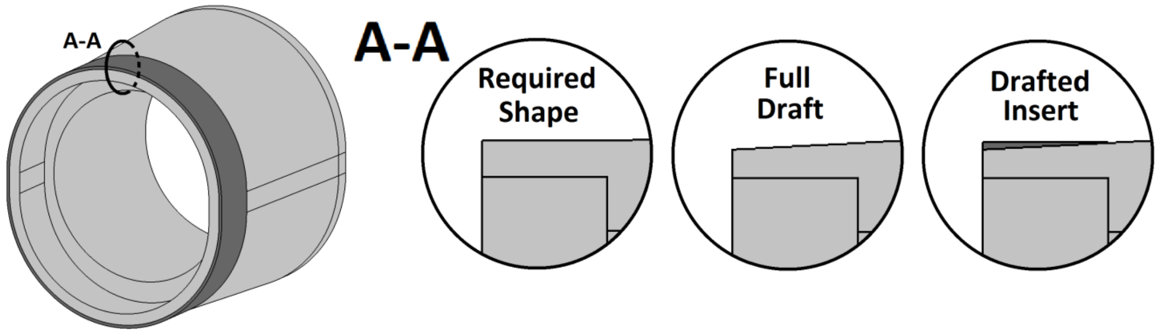

Figure 23: Cross-sectional view of drafted insert and the geometry it is replicating

The second alteration to the mandrel design is to aid in removal of the completed root. The natural draft of the mandrel could aid in removal of the completed root, however releasing the root from the mold may prove difficult with the current design of the mandrel because the uniform section towards the root end has no draft. To account for this, the mandrel design is modified to have a constant taper throughout the entire surface. To recreate the intended preform geometry, a removable insert is added to occupy the space that is removed for the draft (as shown in Figure 23). The insert is designed so it will be pulled off of the mandrel with the root after infusion. Once the root is off of the mandrel, the insert can be detached and reused depending on its condition after removal. The insert will be made with a semi-helically wound warp-uni that is sanded smooth and sealed after infusion so it can be used as a mold surface.

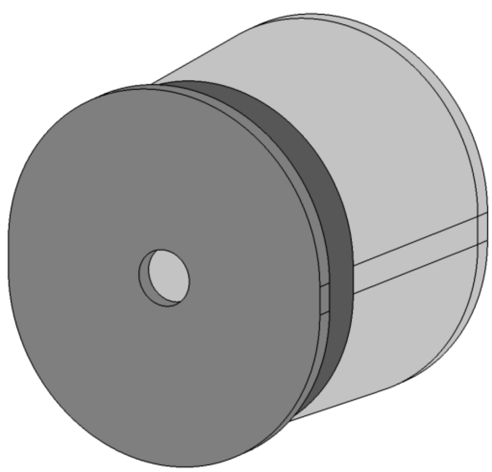

Figure 24: Mandrel with cap attached

A cap is added to the mandrel for winding and infusion to keep the root face square and to provide a surface flush with the outer profile of the wound fabric. The cap also provides a surface that the vacuum bag can attach to. Figure 24 shows the design of the cap and how it matches up to the preform profile. The prototype machine is actually designed with two caps, one for the drafted insert and another for the full preform layup. The insert cap matches the preform ID and the main cap matches the OD. Both caps are also made of MDF and are roughly 50mm thick to provide a wide enough surface for the sealant tape. To use each of the caps, they are bolted directly to the mandrel and sealant tape is inserted at the interface of the cap and the mandrel to keep air out of the infusion.

The prototype machine is equipped with two fabric supply rolls, one holding weft-uni, the other holding bias. The supply fabric will be wrapped around a supply bar starting with the wider end and kept aligned on the supply bar so it will unwind even with the root end of the mandrel [Figure 25]. The supply bars are then mounted to the machine frame by pillow blocks on either side of the mandrel. The fabric needs to be wound even and tight on the supply bar so it comes off in the same way.

Figure 25: Prepared fabric supply roll

To provide the fabric tension required to suppress compression of the wound root, tension is put directly on the supply rolls. To put the tension on the rolls, friction was applied to the supply bars by straps anchored to the machine frame and wrapped over each bar and adjusted by tightening the strap with a turnbuckle. The tension was adjusted during layup so the appropriate settings can be found to eliminate slack in the layup and avoid additional compression of the fabric after the vacuum is applied.

Once everything is loaded onto the machine, the winding is ready to start. The end of the fabric must be attached to the mandrel to start the layup. The attachment is as simple as applying a small amount of spray adhesive on the insert and sticking the fabric to it. After the mandrel starts rotating, the friction around the mandrel will be sufficient for pulling the fabric from the supply rolls.

The fabric continues to wind until the root reaches the desired thickness (T). The supply fabric is designed to reach the end of the semi-helical winding when T is reached. At this point, one supply roll is cut and the end is attached to the wound fabric with spray adhesive. The mandrel will then continue rotating, taking fabric from the last supply roll and causing it to overlap itself, at which point it will also be cut and adhered to the root. Having an outer surface all from one ply adhered to itself will stop the tensioned fabric from unwinding like a coiled spring.

Preparation for infusion can also take advantage of the rotating mandrel by using it to help wrap the infusion material around the layup including peel ply, infusion media, sealant tape, spiral tubing, and vacuum bag. First, a layer of non-sanding peel-ply is wrapped around the fabric. Non-sanding peel-ply gives the fiberglass a textured surface when the ply is peeled off so it doesn't need to be sanded for any future adhesion. Then resin flow medium is wrapped around the mandrel to help resin flow over the fabric during infusion. Spiral tubing for both inlet and outlet resin tubing is wrapped around the mandrel near both ends to allow for resin to flow uniformly through the part from the root end to the tip end. Finally, sealant tape is run around the cap and the tip end of the mandrel and vacuum bagging is adhered. When the vacuum bag overlaps itself, sealant tape is attached between the two layers to finish the vacuum seal. Two resin inlet tubes are fed through the seal and into the spiral tubing around the cap and two vacuum tubes are set in the same way in the opposite spiral tube. This layup sequence is shown in Figure 26.

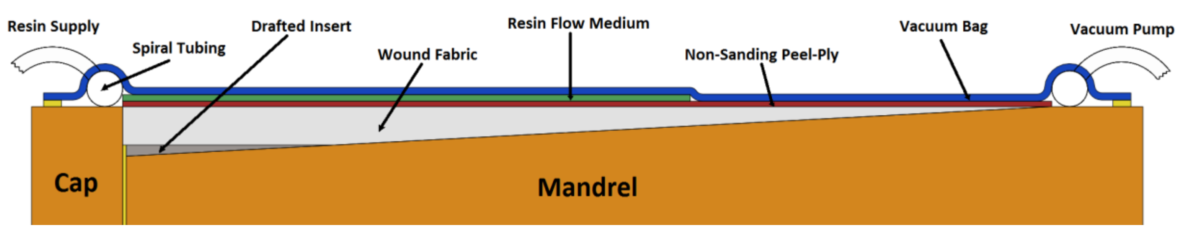

Figure 26: Cross-sectional diagram of infusion

The prototype machine has been designed with a removable mandrel so it can be infused vertically offline. The quantity of resin required for a root section would weigh too much for the part to be infused horizontally. Without a female mold, the weight of the resin would overcome the vacuum force on the underside of the mandrel so the resin would pool at the bottom and possibly deplete the top. To infuse, the root face will be on the lower end of the vertical mandrel and it will be pulled from bottom to top. This orientation uses the vacuum pump to pull against gravity where infusing from top to bottom would combine the two forces and pull resin too directly into the vacuum pump. To perform the infusion, the mandrel is set down vertically on a table that will hold the root and mandrel on the cap without removing the drive axis. An additional advantage of a removable mandrel is that a single winding machine would be able to service several mandrels. Although the prototype machine only has one mandrel, a full-scale machine would be able to wind additional preforms while fully wound mandrels are offline infusing and curing.

After being taken offline, vacuum tubes are connected to the vacuum pump and a drop test is performed to test the airtightness of the infusion. The fabric is then infused using Hexion® Epikote™ epoxy resin and Epikure™ curing agent. After the part is infused and cured, it is removed from the mandrel by being pulled from the root end. After removal, the full root will be cut into the individual preforms and measured with a FARO laser tracker to check their cylindricity and dimensional accuracy.

Testing

After the prototype machine was built and the fabric was cut and prepared, several scaled root preforms were created to determine the feasibility of the new process. The following section describes the individual experiments and their results.

To set the process up, a clean, empty mandrel is loaded on to the machine [Figure 27]. Basic mold setup processes used in the current preform layup would still be required such as mold cleaning and application of release agents.

Figure 27: Setup of winding machine

The cap matching the drafted insert profile is then bolted to the mandrel and sealant tape is used as an airtight gasket. The insert fabric is wound on the mandrel under tension using spray adhesive (3M Super 77®) to start and end the winding. The wound insert and matching cap are shown in Figure 28. The insert was then put under vacuum and infused. After cure, the insert cap was removed and the insert was sanded down to the desired shape and sealed with West System® epoxy to create the sealed mold surface.

Figure 28: Wound drafted insert

The two supply rolls are then mounted equal distances away on either side of the mandrel and the drive bar and supply bars are aligned parallel to each other and the layup cap is bolted on to the mandrel, again using sealant tape to keep air out of the infusion. The start of the supply fabric is adhered to the mandrel on the insert at the flat section, shown in Figure 29. The winding is started at 0.67 RPM and tension set very low so the spray adhesive alone is strong enough to pull the fabric from the supply roll. Once the mandrel makes half a revolution, the fabric begins to overlap itself and the friction is high enough to pull stronger tension. There is no monitoring system for the supply fabric tension so it is simply tightened to the point of keeping the fabric between the supply roll and mandrel tight and the wound fabric nearly incompressible [Figure 30]. The mandrel speed was gradually increased throughout the layup as the winding continued to run without issue, and was maxed out at 2.5 RPM to finish the process at a decent speed.

Figure 29: Start of fabric winding

After the first trial root was done winding, both supply rolls were cut at the same time and adhered to the wound fabric. Because both supply rolls ended at the same time instead of a single fabric making a final wrap, the wound fabric relaxed and the outer layer unraveled roughly a quarter turn and it is unknown how much the inner layers moved. At this point, the fabric still appeared smooth and compact although slightly higher than the cap.

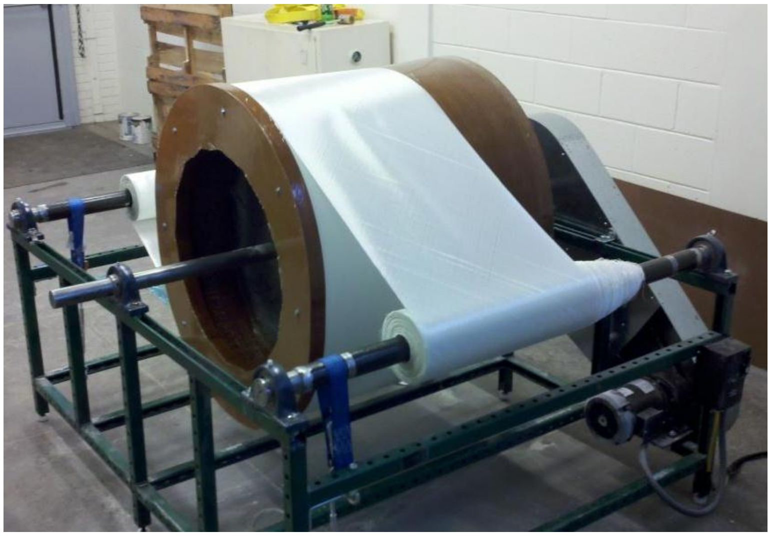

Figure 30: Machine during winding process

The infusion layers and vacuum bagging were then set up and the mandrel was moved off of the machine and tilted up vertically for vacuum infusion [Figure 31]. Unexpectedly, axial waves appeared in the fabric after the vacuum was applied. These waves are assumed to come from too little tension on the supply fabric and from the unwinding after finishing the process.

The root was still infused despite the waves and a thorough infusion was achieved. After cure, the cap was removed and the root was attempted to be removed from the mandrel. The draft alone was not enough for the finished root to slide off the mandrel and being made of MDF, not much force can be applied to the mandrel to assist in pulling the root off. Instead, it was cut down the center of one of the flat sections and after making it through to the mandrel, the root came off easily and the drafted insert remained on the mandrel. Slight damage was done to the mandrel and the drafted insert during the cutting process, but this was easily repaired for the next test.

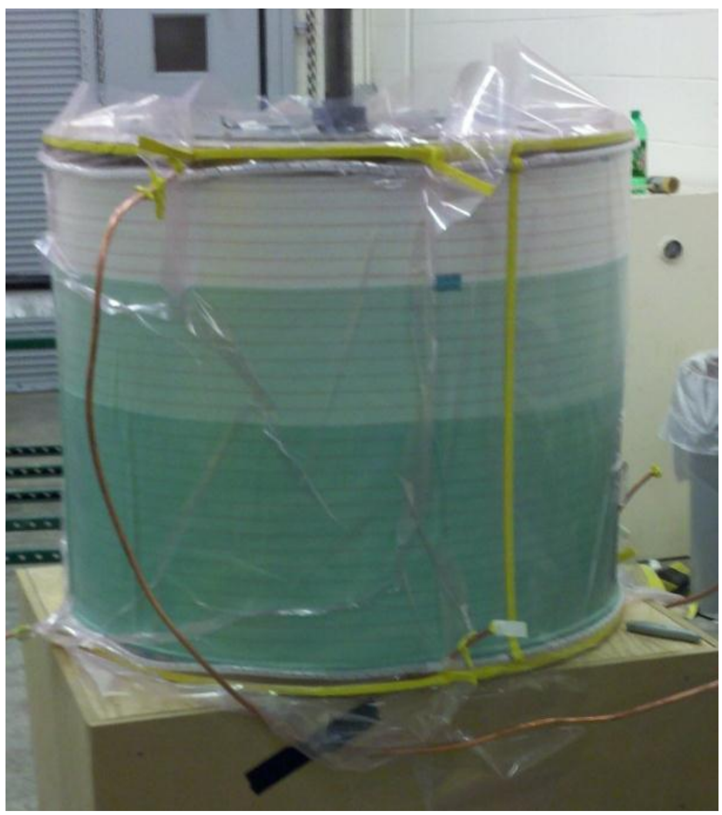

Figure 31: Vertical infusion of wound root

A second trial root was made to confirm that the process is capable of creating root preforms and also to try to remove some of the errors produced in the first trial. The machine was prepared in the same way for the second trial, however, adjustments were made with the fabric preparation and winding.

The first change in the fabric was with the supply roll preparation. It is assumed that if the fabric is wound on the supply bar with high, even tension, it will help provide even tension when winding it from the supply to the mandrel, so the second set of fabric was wrapped much tighter on the supply bar and a larger effort was made to keep uniform tension on the fabric as it was wound on the bar.

The supply bars were mounted much closer to the mandrel for the second operation to avoid pulling the fabric over a long distance. The unrolling tension was also greatly increased for the winding operation. This increased the tautness of the fabric between the supply roll and the mandrel and decreased the compressibility of the wound fabric noticeably compared to the first layup.

The last change in the second layup was with finishing the winding. The bias fabric was cut and adhered to the wound fabric a full wrap earlier than the weft-uni. The final wrap with the weft-uni contained the wound part and stopped the root from unwinding itself. The finished second layup appeared much firmer than the first and it was flusher with the cap.

After the layup was finished, the infusion was prepared in the same way as the first setup. In the second trial, however, no waves appeared in the fabric when the vacuum was applied and the wound fabric retained a smooth exterior through infusion and cure.

Figure 32: Prototype Root Preform

Both wound roots were cut along the opposite flat section to create the preforms for inspection. Figure 32 shows a finished prototype root preform.

Results

To get a closer look at the waves in the first root, one of the first two preforms was dissected through the uniform section to view a cross sectional view of a wave. Figure 33 shows the cross section and some key aspects of one of the worst waves. The height (a) and length (L) of the wave are pointed out equaling 7.2mm and 28mm, respectively, making an aspect ratio of 3.89. This would be too large of a wave and the part would be rejected. The depth of the wave is also marked in the figure, showing that it erupts about ¼ of the way through the layup. Because the second preform had no waves, it was not dissected.

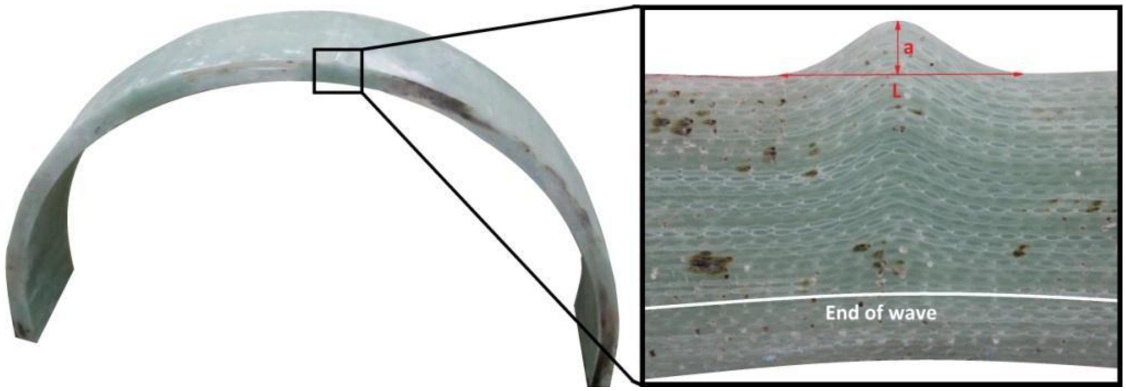

Figure 33: Wave Dissection

To quantify the prototype quality, the three main features of the preforms (OD, ID, and internal taper [displayed in Figure 34]) were measured with a FARO laser tracker. The first two preforms were measured only after the root was removed from the mandrel and cut apart, but the second root was also measured while it was still on the mandrel to check how the dimensions change without support from the mold. The preforms are also labeled A and B according to which half of the mandrel they were made on. Several hundred points were taken of each feature to compare them to a nominal shape and also measure the deviation from that shape. The OD and ID are measured as cylinders and the tapered section takes the shape of a cone. These values are presented in Table 3.

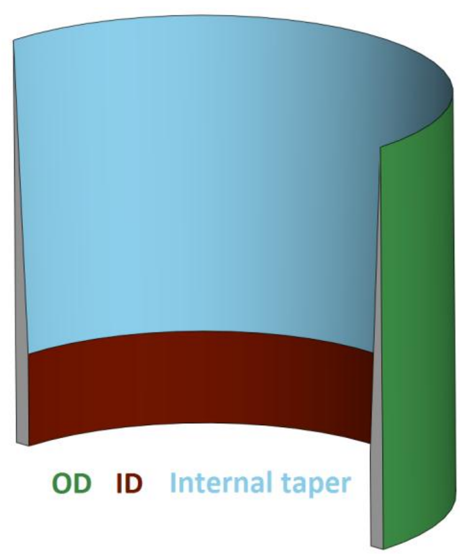

Figure 34: Preform features measured by FARO laser tracker

Table 3: FARO Measurements (mm)

		Trial 1		Trial 2	
		Preform A	Preform B	Preform A	Preform B
On Mandrel	Diameter	-	-	937.69	939.79
	Cylindricity	-	-	3.55	3.48
Off Mandrel	OD	929.02	946.91	923.84	942.12
	OD Cylindricity	2.21	1.49	2.55	2.02
	ID	871.86	876.43	873.25	875.79
	ID Cylindricity	2.56	2.17	2.97	1.89
	Taper Aperture (deg)	6.32	6.35	6.58	6.47
	Conical deviation	2.06	2.35	2.50	2.21

The most critical value presented in this data set is the OD Cylindricity. The measurements found an average cylindricity of 2.06mm over nearly a 1 meter diameter part, supporting the capabilities of the machine. Another value of interest is the discrepancy in OD measurements between side A and side B. Preforms 1A and 2A have similar OD values as do 1B and 2B, however there is an average 18mm difference in OD between the two sides. These values were presented to Steve Nolet, principal engineer at TPI composites and received positive feedback about the overall quality of the preforms[1].

Cost Comparisons

The new root preform machine design must be economically feasible for blade manufacturing facilities to consider replacing their current layup procedures. This will need to be tested by any facility considering changing to the new process or preparing a new blade line by comparing all the costs and savings associated with winding root preforms including: material cost, time and labor savings, and machine cost.

Material costs will be similar for both hand layups and mandrel wound layups. Because the new system proposes to create essentially identical root preforms, any difference in fabric will be negligible. Infusion materials will also have little to no change. The main change in material costs will be in material preparation and presentation. The supply rolls of the new system will need to be loaded both precisely and tightly where the current fabric is simply stacked up for operators to pull plies from. However, to make two traditional preforms, 200 plies must be cut, stacked and brought to the layup and the new machine will use one long ply for each supply roll.

[1] Personal communication 3/28/2011

The main benefit of the new system is in the time and labor savings. In the experiments, winding took under 30 minutes for 60 layers at a very slow, deliberate pace with a relatively small motor. In full production, a layup of 100 layers with 2 supply rolls is estimated to take roughly 15 minutes at a still conservative 3.3 rpm. The time required for infusion material setup, infusion, and cure for a fully wound root are expected to be nearly equal to that of each current preform. The system is also automated to the point that only one operator is required to monitor the machine and perform the loading and unloading.

The labor savings of the new system will have to compensate for the cost of the machine. While this is not a complex system, it certainly has more components than the current stationary female mold. Similar to the current process, there will need to be several molds to keep up with production. The current and new molds are made with similar materials and precision and therefore are expected to have similar costs. Additional machine costs for the new process include the drive system for the mandrel, the tensioning rollers, supply bars and mounts, and the process control switch system.

Although the machine cost is not specifically calculated, it appears that the time and labor savings of the new process will easily justify converting to the proposed system.

Full-scale considerations

Although the prototype machine has proven itself feasible, some of the final machine features still need to be investigated before a full-scale machine can be constructed and put into production.

The full-scale mandrel needs to be made of a mold quality material, most likely fiberglass. To aid in curing the root and mitigation of residual stress, heating elements should also be embedded in the mandrel.

The next item to test is the removal of the drafted insert. This design adds both another layup step and variability in the design and the concept failed in the prototype testing. Two alternative processes are proposed to eliminate the need for the drafted insert. One option is to cut the root from the mandrel. As a means to circumvent cutting the mandrel itself, highly visible sacrificial guards would be inset in the flat section that would both protect the mandrel and notify the operator when the root is fully cut through. The damaged guards can be replaced for each layup. A second option would be to use a collapsible mandrel that the root could be pulled from. For short-term research, the sacrificial strip would be simpler and less expensive to test.

For the full-scale system, more advanced fabric types and layup schemes can be tested to prove the versatility of the machine. An example fabric to test is triaxial fabric (triax) which has fiber tows aligned in three orientations. If a turbine blade manufacturer wanted to simplify a 1:1 (UD:Bias) layup further, the two supply rolls could be replaced with a single transverse triax (90°, +45°, -45°) and achieve the same strength characteristics. Because the current preforms use a manual layup to create a very thick part, the plies used for the layup are often chosen more for deposition rates than for quality. The deposition rates of the new winding machines are expected to be high enough that the marginal cost per layer will be almost negligible, and thinner fabrics of higher quality can be investigated. Whether by an increase in layup quality, or by using better fabric, there is potential for a decrease in the preform thickness safety factor. The thickness of the current preforms is set large enough to contain the stresses provided by the interaction of the blade and the T-bolts. If the root quality was increased, there would be less need to overbuild the root.

Another item to be tested is a changing ply schedule within a layup. Machines running a variable layup require additional rolls that are fed into the layup intermittently. The calculations for a layup using an unbalanced schedule are slightly more complex than an even schedule. To determine the design of the supply fabric, the length of fabric required for each section of a single pattern must first be calculated. Each pattern section is then divided by the number of supply rolls required for that pattern to give the length of each section of each supply roll. Equation 3 gives the length of each section of any ply.

$$l_i = \frac{\int_{0_i}^{P_i} \pi\big(ID + x_i(2 * f)\big)\, dx_i + layers * flat\ section}{supply\ rolls_i} \tag{3}$$

An example of supply fabric for a full scale wound root with a schedule alternating every 25 layers of 1:1 and 1:2 glass ratios is calculated to show how fabric for this type of layup would look. Equation 3a shows the length of the second section of this layup.

$$x = \frac{\int_{25}^{50} \pi(1850 + x * 2 * 0.75)dx + 25 * 304.8}{3} = 52446mm \tag{3a}$$

The cut fabric is shown in Figure 35, with lengths shown in millimeters. During winding, the two longer plies would start simultaneously. As these plies reached the second section, x, the third ply would need to be attached. At the end of section x, the shorter ply is cut and adhered to the mandrel, and section y is wound. Once section y is finished, the shorter ply would be attached again, and all three plies would be wound to completion.

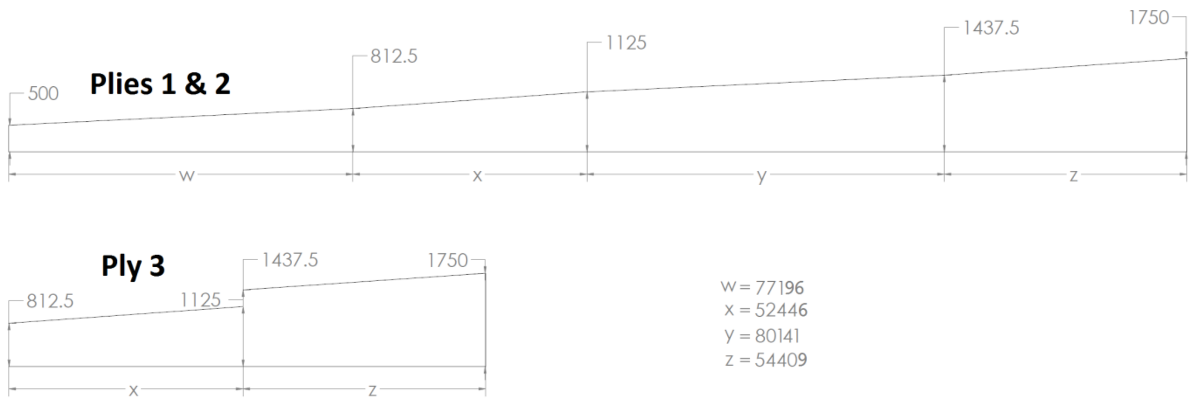

Figure 35: Unbalanced Schedule Ply Representation (Not to-scale)

An alternative system is proposed for applying more controlled tension to the supply fabric. Simply restraining the supply fabric from unrolling was easy to set up and test, but it had some complex implications. With tension on the supply bar, the supply fabric tightened up on itself causing choppy unwinding and spontaneous relaxation. The force on the supply roll also decreases with its decrease in diameter, and the length between the supply roll and the mandrel increase over time. A better option to provide tighter tension control and require less strict supply fabric preparation would be to apply the tension off of the supply roll, as close to the mandrel as possible. This could be done using sandwich rollers mounted close to the mandrel that apply appropriate, controllable tension to the fabric (shown in Figure 36). While this is a more complex setup, there are less resulting variables and less preparation of the supply fabric. The fabric is fed through the rollers and attached to the mandrel in the same way as in the prototype testing and the pinch rollers are tightened when there is enough friction to pull the fabric from the supply rolls.

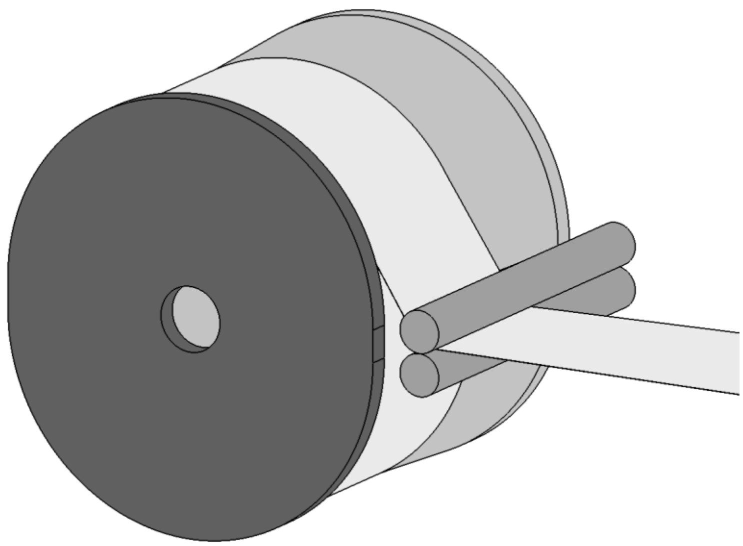

Figure 36: Tensioning sandwich rollers

Figure 37 depicts the critical forces concerning the alternative tensioning system. It shows that torque applied by the rollers (τ_R) acts against the torque from the rotating mandrel (τ_M). This puts tension (T) on the fabric which compresses it against the mandrel. To eliminate waves in the preform, the compression created by the tensioning system must be equal to that of the compression caused by atmospheric pressure under vacuum (F). The amount of torque applied by the rollers will also need to be adjustable for different fabric types and widths requireing more or less tension.

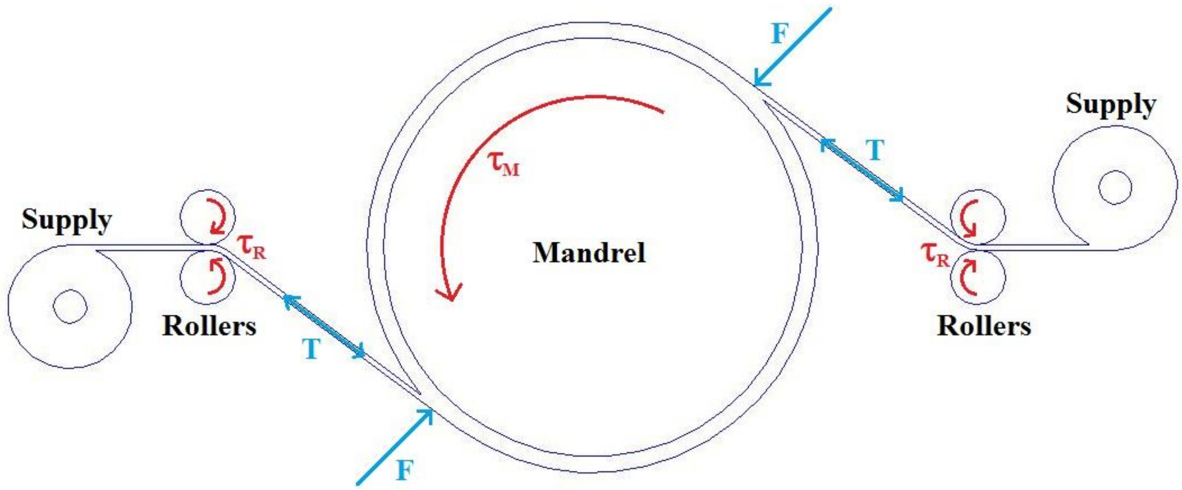

Figure 37: Forces on tensioning sandwich rollers

The supply fabric should be designed to correctly end at max thickness (T), however, process control is necessary to be certain the preforms aren't created too thick or too thin. A height sensor needs to be added to the final machine that stops the winding when it reaches T. Additional fabric will be added to the end of the supply rolls so if the fabric is wound tighter than the original design, the mandrel will keep rotating or if thickness reaches T earlier than expected, the sensor will trip and the winding will stop.

Advantages

In this research, an automated system capable of manufacturing root preforms cheaper and of higher quality than the current root prefab layup was designed and a scaled prototype machine was created to test the concept. The machine was successfully able to wind two stitched plies semi-helically around a mandrel to replace the current layup of several operators laying many individual fiberglass plies into a female mold. This system has many advantages over the current system, some of which include:

- The automated winding system takes significantly less labor
- Each winding operation creates two traditional preforms at once so setup, layup, infusion, and cure only need to be done once per blade
- The speed of the winding provides opportunities for design for manufacturing such as the ability to test more precise fabric patterns
- Winding replaces approximately 200 individual plies with one long ply for each supply roll, greatly reducing the cutting and handling of fabric
- The new process nearly eliminates spray adhesives for a better infusion
- The removable mandrel allows the roots to be infused and cured offline so the machine can service multiple mandrels
- Winding under tension reduces the variability of vacuum compression and the gain in quality could result in a reduction of the safety factor required by the manual layup
- Making the root as a single piece provides the opportunity to bond the full root in the blade shell instead of splitting it infusing a preform in each half
- Winding NCF is the best option for automated winding of root preforms. Filament winding can't deposit the necessary fiber orientations, and winding NDF is less complex, cheaper, and faster than ATL or AFP

References

[1] National Renewable Energy Laboratory, and American Wind Energy Association. *20% Wind Energy by 2030*. Rep. U.S. Department of Energy, July 2008. Web. 20 Jan. 2010.

[2] Gurit. "Breakdown of a Turbine Blade." *Wind Energy*. Web. Mar. 2010. <http://www.gurit.com/breakdown-of-a-turbine-blade.aspx>.

[3] Karahan, Mehmet, Stepan Lomov, Alexander Bogdanovich, Dmitri Mungalov, and Ignaas Verpoest. "Internal Geometry Evaluation of Non-crimp 3D Orthogonal Woven Carbon Fabric Composite." *Composites Part A* 41 (2010): 1301-311.

[4] Mandell, John F., Daniel D. Samborsky, Lei Wang, and Neil K. Wahl. "New Fatigue Data for Wind Turbine Blade Materials." *Journal of Solar Energy Engineering* 125.4 (2003): 506.

[5] TPI Composites. "SCRIMP(R) in Detail." *Innovation*. Feb. 2011. <http://www.tpicomposites.com/innovation/patents.aspx>.

[6] Yerramalli, Chandra S., Thomas Miebach, Karthick Chandraseker, and Shu C. Quek. "Fiber Waviness Induced Strength Knockdowns in Composite Materials Used in Wind Turbine Blades."

[7] Estrada, Gonzalo, Celine Vieux-Pernon, and Suresh Advani. "Experimental Characterization of the Influence of Tackifier Material on Preform Permeability." *Journal of Composite Materials*36.19 (2002).

[8] Shih, Chih-Hsin, Qingfang Liu, and L. James Lee. "Vacuum-assisted Resin Transfer Molding Using Tackified Fiber Preforms." *Polymer Composites* 22.6 (2001): 721-29.

[9] Nolet, Stephen C., and TPI Composites. "Manufacturing of Large Scale Wind Turbine Blades." Iowa State University, Ames. 10 Mar. 2010. Lecture.

[10] Grove, C. S. *Filament Winding: Its Development, Manufacture, Applications, and Design*. By D. V. Rosato. New York: Interscience, 1964. 113-44.

[11] Lossie, M., and H. Vanbrussel. "Design Principles in Filament Winding." *Composites Manufacturing* 5.1 (1994): 5-13.

[12] Abdalla, F., S. Mutasher, Y. Khalid, S. Sapuan, A. Hamouda, B. Sahari, and M. Hamdan. "Design and Fabrication of Low Cost Filament Winding Machine." *Materials & Design* 28.1 (2007): 234-39

[13] Mertiny, P., and F. Ellyin. "Influence of the Filament Winding Tension on Physical and Mechanical Properties of Reinforced Composites." *Composites Part A: Applied Science and Manufacturing* 33.12 (2002): 1615-622.

[14] Polini, W., and L. Sorrentino. "Estimation of the Winding Tension to Manufacture Full Section Parts with Robotized Filament Winding Technology." *Advanced Composite Materials* 14.4 (2005): 305-18.

[15] Lu, H. "Effects of Tape Tension on Residual Stress in Thermoplastic Composite Filament Winding."*Journal of Thermoplastic Composite Materials* 18.6 (2005): 469-87.

[16] Casari, P., F. Jacquemin, and P. Davies. "Characterization of Residual Stresses in Wound Composite Tubes." *Composites Part A: Applied Science and Manufacturing* 37.2 (2006): 337-43.

[17] Lee, D., S. Kim, W. Lee, S. Ha, and S. Tsai. "Smart Cure of Thick Composite Filament Wound Structures to Minimize the Development of Residual Stresses." *Composites Part A: Applied Science and Manufacturing* 37.4 (2006): 530-37.

[18] Meink, Troy E., and Steven Huybrechts. "Processing Induced Warpage of Filament Wound Composite Cylindrical Shells." *Journal of Composite Materials* 36 (2002).

[19] Koussios, S., O.K. Bergsma, and A. Beukers. "Filament Winding: Kinematics, Collision Control and Process Optimisation through Application of Dynamic Programming." *Composites Part A: Applied Science and Manufacturing* 37.11 (2006): 2088-104.

[20] Scholliers, J., and H. Vanbrussel. "Computer-integrated Filament Winding: Computer-integrated Design, Robotic Filament Winding and Robotic Quality Control." *Composites Manufacturing* 5.1 (1994): 15-23.

[21] Polini, W., and L. Sorrentino. "Actual Safety Distance and Winding Tension to Manufacture Full Section Parts by Robotized Filament Winding." *Journal of Engineering Materials and Technology* 128.3 (2006): 393.

[22] Decarvalho, J., M. Lossie, D. Vandepitte, and H. Vanbrussel. "Optimization of Filament-wound Parts Based on Non-geodesic Winding." *Composites Manufacturing* 6.2 (1995): 79-84.

[23] Shen, F. "A Filament-wound Structure Technology Overview." *Materials Chemistry and Physics*42.2 (1995): 96-100.

[24] Peters, S. T., W. D. Humphrey, and R. F. Foral. *Filament Winding Composite Structure Fabrication*. Covina, CA: SAMPE International Business Office, 1999.

[25] Beckwith, Scott W. "Filament Winding vs. Fiber Placement Manufacturing Technologies."*SAMPE Journal* 44.2 (2008): 54-55.

[26] Koussios, S. "Friction Experiments for Filament Winding Applications." *Journal of Thermoplastic Composite Materials* 19.1 (2006): 5-34.

[27] Debout, Pierre, Helene Chanal, and Emmanuel Duc. "Tool Path Smoothing of a Redundant Machine: Application to Automated Fiber Placement." *Computer-Aided Design* 43 (2011): 122-32.

[28] Bogdanovich, Alexander E., and Cristopher M. Pastore. *Mechanics of Textile and Laminated Composites: with Applications to Structural Analysis*. London [etc.: Chapman & Hall, 1996.

[29] Robertson, R., T. Chu, R. Gerard, J. Kim, M. Park, H. Kim, and R. Peterson. "Three-dimensional Fiber Reinforcement Shapes Obtainable from Flat, Bidirectional Fabrics without Wrinkling or Cutting. Part 2: a Single N-sided Pyramid, Cone, or round Box."*Composites Part A: Applied Science and Manufacturing* 31.11 (2000): 1149-165.

[30] Long, A. C. *Design and Manufacture of Textile Composites*. Cambridge: Woodhead, 2005.

[31] MAG. *Automated Systems for Wind Blade Manufacturing*. MAG, 2010.

[32] Kordi, Tarsha M., M. Hüsing, and B. Corves. "Development of a Multifunctional Robot End-Effector System for Automated Manufacture of Textile Preforms." *IEEE* (2007).

[33] Rozant, O., P. Bourban, and J. Manson. "Drapability of Dry Textile Fabrics for Stampable Thermoplastic Preforms." *Composites Part A: Applied Science and Manufacturing* 31.11 (2000): 1167-177.

[34] Potluri, P., and J. Atkinson. "Automated Manufacture of Composites: Handling, Measurement of Properties and Lay-up Simulations." *Composites Part A: Applied Science and Manufacturing* 34.6 (2003): 493-501.

[35] Sahari, Khairul, Hiroaki Seki, Yoshitsugu Kamiya, and Masatoshi Hikizu. "Clothes Manipulation by Robot Grippers with Roller Fingertips." *Advanced Robotics* 24 (2010): 139-58.

[36] Zacharia, P., I. G. Mariolis, N. Aspragathos, and E. S. Dermatas. "Robot-handling Fabrics with Curved Edges Based on Visual Servoing and Polygonal Approximation." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*222.10 (2008): 1263-274.