COMPOSITE MANUFACTURING OF SMALL WIND TURBINE BLADES

UTILITY SCALE METHODS APPLIED TO
SMALL WIND

A Thesis

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ABSTRACT

Composite Manufacturing of Small Wind Turbine Blades- Utility Scale Methods Applied to Small Wind

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Cal Poly, San Luis Obispo's first wind turbine explores the methods and processes that are employed to manufacture utility scale wind turbines, and applies them to small scale wind turbines. The primary objective is to promote the development of small scale wind turbine blades in ways that resemble, as closely as possible, the construction and methods of utility scale turbine blade manufacturing. Vacuum infusion is employed to create a hollow, multi piece, lightweight design using carbon fiber and fiberglass with an epoxy based resin. A "rapid prototyping" method is developed using high density foam molds that allows short cycle time between design iterations of aerodynamic planforms. A production run of eight blades is manufactured and key components of the blade are tested to determine the appropriateness of the design.

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Abbreviations

HAWT: Horizontal Axis Wind Turbine

PCF: Pounds per Cubic Foot

FRP: Fiber Reinforced Plastic

VOC: Volatile Organic Compound

SWT: Small Wind Turbine

EOG: Extreme Operating Gust

AWEA: American Wind Energy Association

IEC: International Electrotechnical Commission

CTE: Coefficient of Thermal Expansion

HD: High Density

C_t: Coefficient of Thrust

ASTM: American Society for Testing and Materials

T_g: Glass Transition Temperature

UV: Ultra Violet

MEKP: Methyl Ethyl Ketone Peroxide

Terms and Definitions

For the purpose of this document, the following terms and definitions apply.

Wind Turbine Definitions

Pitch regulated: A wind turbine that rotates the blade along the axis of the span to regulate the speed the rotor turns.

Stall regulated: A wind turbine that uses the properties of the airfoil to slow the rotor down once the rotor speed reaches a certain RPM.

Tip to wind speed Ratio (λ): The speed of the tip of the blade to the incoming wind speed.

Resonance: A phenomenon appearing in an oscillating system, in which the period of a forced oscillation is very close to that of free oscillation.

Rotor speed: Rotational speed of a wind turbine rotor about its axis.

Horizontal axis wind turbine: Wind turbine whose rotor axis is substantially parallel to the wind flow.

Hub: Fixture for attaching the blades or blade assembly to the rotor shaft.

Gust: Sudden and brief increase of the wind speed over its mean value.

Load case: Combination of a design situation and an external condition which results in structural loading.

Small Wind Turbine: A system of 200 m² rotor swept area or less that converts kinetic energy in the wind into electrical energy.

Swept area: Projected area perpendicular to the wind direction that a rotor will describe during one complete rotation.

Wind speed: At a specified point in space, the wind speed is the speed of motion of a minute amount of air surrounding the specified point.

Wind velocity: Vector pointing in the direction of motion of a minute amount of air surrounding the point of consideration, the magnitude of the vector being equal to the speed of motion of this air “parcel”.

To define the directions of the loads, the system of axes is shown in Figure 1 is used. Note that blade coordinate system follows the right-hand convention for a rotor that

spins clockwise and the left-hand convention for a rotor that spins counterclockwise when viewed from an upwind direction

Figure 1

System of Axis for Horizontal Axis Wind Turbine

Composite Definitions

Composite: see definition for Fiber Reinforced Plastic

Fiber Reinforced Plastic (FRP): a composite material containing a thermosetting resin and fibers. "Thermoset resins have the properties that they do not melt but decompose upon heating. Once solidified by a cross linking (curing process), they cannot be reshaped. Common examples of thermosetting polymers include epoxides and polyesters."¹

Resin rich: A composite part that has less than the ideal fiber-to-resin ratio.

Resin deficient: A composite part that has more than the ideal fiber-to-resin ratio, i.e. dry fibers in laminate.

Volatile Organic Compound (VOC): Chemicals off-gassed by the resins before and during the curing process.

Coefficient of Thermal Expansion (CTE): The dimensional response to temperature change.

Glass transition temperature: The temperature at which a thermo-set resin's stiffness and strength dramatically drop.

Pot life: Length of time before resin in a pot starts to gel and becomes unusable.

Lay-up schedule: A detailed list of the layers of material the laminate consists of.

Symmetric Lay-up: Laminates which are constructed by placing the laminae symmetrically with respect to the mid-plane.

Airfoil Definitions

See figure #2 for airfoil description

Mean camber line: the locus of points, midway between the upper and lower surface, as measured perpendicular to the chord line.

Leading Edge: Most forward point of the mean camber line.

Trailing Edge: Most rearward point of the mean camber line.

Chord, "c": Straight line that connects the leading edge and trailing edge.

¹ Agarwal, B. D., Broutman, L. J., & Chandrashekhara, K. (2006). Analysis and Performance of Fiber Composites. New Jersey: John Wiley & Sons, Inc. Chapter 2

Thickness, “ t ”: Distance between upper and lower surfaces measure perpendicular to chord.

Span: Length of the blade perpendicular to airfoil.

Relative Wind: Wind velocity vector in the frame of reference of the airfoil section.

Angle of Attack, “ α ”: Angle between relative wind and chord line.

Pitch Angle: Angle between chord line and plane of rotation

Twist: Distribution of chord line pitch angle along span, relative to chord line at blade tip.

Pressure side: Side of airfoil that directly faces oncoming wind.

Suction side: Side of airfoil opposite to oncoming wind.

Figure 2

Geometric airfoil parameters

1.0 Introduction

1.1 Project statement

The future of energy production in the US is rapidly changing. The current trend in energy production industry is renewable sources such as wind and solar. Wind turbines have the potential to be a large portion of the new renewable energy industry.

Cal Poly is beginning its first small wind turbine energy project. The American Wind Energy Association (AWEA) defines utility grade wind turbines for land-based wind farms as units with rotor diameters from about 50 meters to 100 meters. AWEA defines “small wind turbines”, as units with rotor diameters of 8 meters or less and with power production of 100kW or less.

This project consists of a horizontal axis wind turbine and all the systems associated with an off the electrical grid wind turbine. One of the most important components of the wind turbine is the rotor; which consists of the blades, the blade roots and the hub. The proper manufacturing of the blades is a large obstacle that must be overcome before a complete wind turbine can be assembled.

1.2 Project Aim

The aim of this project is to manufacture small scale wind turbine blades using similar methods and materials as the utility grade machine blades and to develop a “rapid prototyping” method for future blade designs.

1.3 Project Scope

The project scope includes the following steps:

- Perform trade off studies for process variations such as material selection and mold design weighing both the advantages and disadvantages of each selection
- Design a blade manufacturing process that closely resembles that of utility grade for small blades
- Improve on the accepted processes and create a way of rapid prototyping workable blades
- Design and fabricate multiple prototype blades, built within the selected manufacturing process, for use with Cal Poly’s first wind turbine project
- Perform qualification tests on key components of the blade including a finished blade.

1.4 Report Organization

The remainder of this report is organized in five major sections

- Background research of composite fabrication of blades, including tradeoff studies of mold design and material selection.
- Design of tooling and prototype blade
- Prototype blade qualification and testing results
- Summary of findings
- Conclusions
- Appendices

2.0 Background and Research

Wind Turbine Specifications

The turbine is a stall regulated 3 bladed horizontal axis turbine with a disk brake system for rotor cut off and a tail vain for wind alignment.

Rated Power: 3kW at 22mph wind speed

Generator: Permanent magnet generator rated at 3kW at 225 rpm

Tip to Wind Speed Ratio (λ): 4

Rated Speed: 225 RPM @ 22 mph wind speed

Cut Off Speed: 300 RPM @ approximately 29 mph wind speed

Tower height: 70 ft monopole

Design and manufacturing requirements and goals

The blade will be manufactured to International Electrotechnical Commission (IEC) 61400-2 standards for small wind turbines

Utility scale machines have blades that are large enough that the resonance coupling between the rotor and the tower can be an issue. The goal is to have the resonance frequency of the prototype blade to be an order of magnitude higher than the tower. This would eliminate issues associated with coupling of forces and frequencies of the rotor and the tower.

The aim of the process selection will be to reproduce and mimic methods and materials used by utility scale wind turbine manufacturers.

2.1 Aerodynamic Planform

Profiles

The profiles were chosen from a publication by the RISO National Laboratory in Denmark. The profiles are detailed in the report, “Design of the Wind Turbine Airfoil Family RISO-A-XX²”. The family of airfoil has a few key characteristics that make them a good candidate for this project.

The first characteristic is that this family of profiles operate well when “dirty”, i.e. their performance is relatively insensitive to leading edge roughness (see Figure 2.1). Their

² (Kristian S. Dahl, 1998)

performance can be assumed to remain constant even after long periods of time in the elements without requiring routine maintenance to maintain a clean surface.

Figure 2.1

Comparison of C_l and C_d predictions with free and fixed transition for RISO-A-18 for Clean and Dirty performance.

The second characteristic is that they can be used for both stall and pitch-regulated rotor designs. This allows the blades to be utilized in a pitch-regulated design in the future as a potential modification for future turbine designs.

The blade uses two profiles from this publication: RISO-A-27 (Figure 2.2) and RISO-A-18 (Figure 2.3). The family RISO-A-XX airfoils have the relation of their thickness-to-chord length in the nomenclature for the profile. For example, the 27 in the name designation signifies that the maximum thickness (t) is 27% of the chord length (c). The aerodynamic planform calls for the blade to start with the RISO-A-27 profile at the root of the blade and transitions into the RISO-A-18 profile.

RISO-A-27

The A-27 was chosen for a few prominent reasons. The large relative thickness can accommodate the root tube easier than thinner profiles. Initial profiles should have a high cross-sectional stiffness to limit overall blade weight and tip deflection. The inboard profiles should maximize lift while having a high lift-drag ratio is of less importance. In other words, the inboard profiles, which are the profiles that are closer to the root, are chosen based on a structural design requirement while trading off optimum aerodynamic properties. The relative large thickness of the A-27 allows these requirements to be met.

Figure 2.2

RISO-A-27 Profile

RISO-A-18

The A-18 profile was chosen for a few main reasons: it has a high lift-drag ratio and the lift coefficient (Cl) is insensitive to leading edge surface roughness. These thinner profiles are located further along the span of the blade as the design moves towards the tip. The structural requirements are of less importance than the aerodynamic performance of the profile.

Figure 2.3

RISO-A-18 Profile

The combination of the two profiles allows for high structural rigidity near the base where the stresses are greatest. Transitioning into the higher lift to drag ratio profile increases overall aerodynamic performance of the blade.

The aerodynamic planform (seen in Table 2.1) calls for the blade to start with the RISO-A-27 profile at the root of the blade and transitions into the RISO-A-18 profile. The first profile starts 10.8 inches from the axis of rotation, leaving room for the root of the blade and the hub. The aerodynamic planform was created by Dr. Patrick Lemieux, Cal Poly San Luis Obispo. This planform was followed to create the solid model of the blade.

Table 2.1

Aerodynamic planform of blade

Physical blade dimensions						
Blade length:		6.00 ft	72.00 in			
Span		Dist. From axis	Pitch Angle	Twist angle	Chord	Thick_max
section	Section Description	[in]	[deg]	[deg]	[in]	[in]
20.00	Risoe-A-18	72.00	-2.64	0.00	4.89	0.88
19.00	Risoe-A-18	68.40	-2.17	0.47	5.13	0.92
18.00	Risoe-A-18	64.80	-1.65	0.99	5.39	0.97
17.00	Risoe-A-18	61.20	-1.07	1.57	5.67	1.02
16.00	Risoe-A-18	57.60	-0.43	2.21	5.98	1.08
15.00	Risoe-A-18	54.00	0.29	2.93	6.32	1.14
14.00	Risoe-A-18	50.40	1.10	3.75	6.70	1.21
13.00	Risoe-A-18	46.80	2.03	4.67	7.13	1.28
12.00	Risoe-A-18	43.20	3.08	5.72	7.60	1.37
11.00	Risoe-A-18	39.60	4.30	6.94	8.13	1.46
10.00	Risoe-A-18	36.00	5.71	8.35	8.72	1.57
9.00	Risoe-A-18	32.40	7.37	10.01	9.37	1.69
8.00	Risoe-A-18	28.80	9.34	11.98	10.08	1.82
7.00	Risoe-A-18	25.20	11.69	14.33	10.85	1.95
6.00	Risoe-A-27	21.60	14.54	17.18	11.55	3.12
5.00	Risoe-A-27	18.00	18.00	20.64	12.24	3.31
4.00	Risoe-A-27	14.40	22.23	24.87	12.66	3.42
3.00	Risoe-A-27	10.80	27.36	30.00	12.44	3.36
2.00	Hub	7.20	-	-	-	-
1.00	Hub	3.60	-	-	-	-
0.00	Axis	0.00	-	-	-	-

To create a solid model, the profiles needed to be digitized into a dimensionless xy format. A computer program, called Grafula, was used to convert pixels on a screen to xy coordinates. Simply digitizing the images isn't hard, but verifying that no skewing of the image has taken place in the digitizing process is key. To verify that no skewing occurred, a grid was placed over the image and verified in the image digitizer program that 10 pixels in the x direction were the same as 10 pixels in the y direction. This is a small step in the process but a critical one. If not done correctly to scale, the profiles being used to make the solid model would be inaccurate.

Once the non dimensional points of each profile were established in Grafula, they needed to be scaled correctly to fit the chord and thickness of the pre-prescribed plan for the airfoils seen in Table 2.1. The non dimensional xy coordinates were scaled into inches in Microsoft Excel. For example, the first profile prescribed is RISO-A-27 and

has a chord length of 12.44 inches and a thickness of 3.36 inches, so the xy file was scaled to fit this chord length and thickness listed in Table 1.1.

All of the following 18 profiles were scaled according to the given chord and thickness in Table 1.1. Each profile is prescribed at 3.6 inch intervals along the length of the blade. In addition to the defined chord and thickness of the profiles, the plan also defines the pitch angle and twist angle. The information contained in Table 1.1 fully defines the lift generating portion of the blade

2.2 Basic Blade Geometry

2.2.1 Overall Blade Dimensions

The overall rotor diameter is 12 ft so each blade is slightly less than 6 ft in span. The hub accounts for the blade being slightly shorter than the 6 ft. The overall blade length is 67" and the hub is 10" in diameter (see Figure 2.4) for blade dimensions.

Figure 2.4

Overall Blade Dimensions

2.2.2 Root Geometry

There are multiple root geometries that are used in blade design today. Root geometries can be rectangular or circular in cross section. Most utility scale wind turbines have circular root geometry (see Figure 2.5) while many small wind turbines

have either rectangular or circular cross sections. In large scale wind turbines the root diameter is larger than the maximum thickness of the first defined airfoil. With all of the available options, root geometry could have been either rectangular or circular.

Figure 2.5

Root and profile detail of 750kW turbine blade, notice large root diameter in comparison to profile thickness

Keeping with the project aim to manufacture a small blade using similar methods to utility scale blades, a circular root section was chosen. In the case of this blade, the decision to keep the root diameter smaller than the thickness of the first defined profile was mainly based on its effect on the hub size. If the root was larger than the max thickness of the blade, the hub would necessarily have to grow to accommodate this increase in size. The root diameter was kept smaller than the max thickness of the blade to keep the hub size down. Therefore root diameter is 3" and the max thickness of the blade is 3.46" as seen in Figure 2.6.

Figure 2.6

Profile of Root, First and Last Defined Profile

2.2.3 Creating the Computer Model of Blade

The lift generating portion of the blade is fully defined by the aerodynamic planform in Table #1, but it was just a list of pitch for a given chord and profile. The profiles had to be turned into a solid model if any molds were to be created from the planform.

AutoDesk Inventor was used to bring in the correctly dimensioned xy files from Excel. Each profile was created and rotated to the defined pitch angle of the planform. Once all the profiles were in Inventor they were lofted to create the solid model (as seen in Figures 2.7 and 2.8).

The decision to make the blade turn counter clockwise was an arbitrary one. The permanent magnet generator used in this wind turbine can be turned either direction without consequence. The blade could have been designed to turn either direction just as easily. Also the leading edge was designed such that all of the profiles lined up to make a straight leading edge. The process of creating the computer model was simplified by allowing the leading edge of all of the profiles to fall on the same line.

Figure 2.7

All defined profiles, blade viewed from the tip down

Figure 2.8

AutoDesk Inventor solid model of blade, pressure side of blade shown

2.3 Blade Manufacturing Process Selection

There are multiple ways to manufacture a new blade. Blades can be made out of wood, plastic, metal or fiber reinforced plastics (FRP), also known as composites. Keeping with the project aim to manufacture small scale wind turbines, using the same materials and methods as the utility scale ones, this blade will be constructed with composite materials. Almost all utility scale blades are made with composite materials.

The manufacturing process of composite parts is highly influential on the quality and repeatability of the properties. Unlike most other manufacturing processes, the properties of the final part can be significantly different. So choosing a process that allows repeatable properties is important.

The stiffness and the strength of a composite piece are influenced by the fiber volume of the final part (see Figure 2.9). The higher the fiber content the higher the strength and stiffness will be. So the ability to control the resin content is a key driving factor in the selection of a manufacturing process.

Figure 2.9

Strength of a composite as a function of fiber volume fraction

There are multiple ways to make a composite part: hand lay-up, hand lay-up with vacuum bag, vacuum infusion and pre-impregnated with vacuum bagging. Each method has drawbacks and benefits that aid in the decision making of which process is best to use.

2.3.1 Hand Lay-up

The hand lay-up technique is the oldest, simplest, and most commonly used method for the manufacturing of both small and large reinforced plastics. A hand lay-up is done by manually adding the resin to the dry fabric with a paint brush. Thickness is controlled both by the amount of layers as well as the amount of resin added to the mold surface. This is an open-mold process with no way of containing VOC's, Volatile Organic Compounds, from the curing resin.

Drawbacks

The hand lay-up method often leads to a high resin to fiber ratio which leads to a low strength-weight ratio. This is because there is no way to remove excess resin from the part, except to squeegee out what you can. A hand lay-up is a very imprecise method of controlling the amount of resin in the part. Also, there is nothing holding the fibers to the mold, so if the mold is complicated, gravity must be relied on to hold the fibers and resin to the surface of the mold.

There is also a race against time to lay all the fabric in the correct orientation and apply the resin before the resin starts to gel. This means that complicated lay-up schedules can be hard to achieve without a large workforce to lay the fibers and apply the resin.

Benefits

The main benefit to the hand lay-up method is its simplicity. There is not extra equipment required to make parts when using the hand lay-up method compared to other methods. The only required equipment is paint brushes and containers for the resin.

2.3.2 Hand Lay-up with Vacuum Bag

The wet lay-up with a vacuum bag is the next level in making reliable and strong FRP parts. This method begins the same way as hand lay-up method described above, but a flexible bag surrounds the parts after the resin has been applied and a vacuum pump sucks the air out of the bag. This exposes the outer surface of the bag to about 15 psi. While this amount of pressure is modest, properly made vacuum bagged parts will have better strength and stiffness than the wet lay-up method.

Drawbacks

Even though this is a large improvement over the previous method, it still has many draw backs. The main drawback is that it requires more equipment to make the same part. A pump, bagging material and sealant tape are all required to make this work. The bagging material must be tough enough to withstand the exothermic reaction from the curing resin as well as not react with the resin. This means that it must release cleanly from the cured laminate. The bag must also be flexible enough to follow the contours of the mold.

The bag must seal the entire laminate from the outside air, meaning that the bag must either fully envelope the mold or the mold must be constructed such that it is air tight and have flanges available for the bag to seal to. This can create a problem if the mold is very large or the mold is a porous material such as wood or foam.

There is also a race against time to do the wet lay-up and fully bag the part before the resin starts to gel. This can be impractical to do on large items such as utility scale

blades. This is especially difficult on complicated lay-up schedules. There is also the possibility that laminate can still be resin rich, as it is still under the control of the person applying the resin into the mold and the fibers. The mold must also be strong enough to withstand the atmospheric pressure it will be subjected to by the bag. This requirement for a sturdier mold can lead to increased tooling costs.

Benefits

Using this method holds a constant pressure along the entire laminate and can squeeze excess resin out into a material to hold the excess resin. The use of a vacuum bag leads to higher specific strength and stiffness laminates because excess resin is removed from the laminate and captured by an absorbent material. This increases the fiber volume fraction which increases stiffness and strength.

2.3.3 Vacuum Infusion

Vacuum infusion is similar to vacuum bagging but the fibers are placed into the mold dry and then vacuum is applied. Once this is done, resin is drawn across the dry fibers through a flow media and this process wets out the fibers. This allows unlimited time to lay the dry fibers in the desired orientation and to bag the part.

Utility grade blades are made using a vacuum infusion method.

Drawbacks

While the same equipment is required to do this process as the vacuum bagging process, it can be much harder to do. Drawing on my four years of experience with this methodology, there is almost an art to getting the resin to flow in the desired direction and to fully wet out the fibers. "Vacuum infusion requires not only vacuum tubes but resin inlets as well, not to mention in-bag extensions of these tubes. Placement of these vacuum and resin lines varies from part to part and there is no one way to set them up... this leads into the next pitfall; it is very easy to destroy a part. Typically, once infusion begins, there is little that can be done to correct any errors. Due to the complexity and the ease of error, VIP should be viewed as a trial and error process. The best mindset to have when attempting vacuum infusion for the first time is that a few parts (or more than a few) will be ruined before getting it right." **Vacuum Infusion-the equipment and process of resin infusion**³

Benefits

The vacuum infusion method is unique in that it allows for reliable material properties to be repeated part after part with little cost increase from the previous methods. Those

³ <http://www.fibreglast.com/documents/361.pdf>

additional materials consist of a flow media, separation material (peel ply), and various tubing, all which are relatively inexpensive. Large parts can be made with this process because it allows unlimited time for the fibers to be placed into the mold. This process leads to correct fiber volumes each and every time a part is made. The parts all weigh the same and the properties of the laminate are very well regulated and predictable.

2.3.4 Pre-impregnated with Vacuum Bagging

The properties of a composite laminate depend directly on the fiber-resin content. Knowing this, the manufacturers of pre-impregnated (pre-preg) composites strictly control the amount of resin placed into the fabric. The fibers are pre-impregnated with resin and then partially cured. Once this initial partial cure happens the fabric is placed into the freezer to slow the rate of the reaction down almost completely. This leaves the end user with a material with pre-prescribed resin content.

Drawbacks

The main disadvantage with pre-preg composites is that an auto-clave is required to use them. An auto-clave is an oven that is also a pressure vessel that can exceed pressures of 180 psi and temperatures of 400° F. This also means that the mold must be able to withstand the curing pressures and temperatures. This leads to astronomical high costs for large parts, as an auto-clave large enough to fit the mold is required. In the case of utility scale blades, the use of pre-preg materials becomes unfeasible as an auto-clave large enough to fit the mold for a blade would be cost prohibitive.

Also the resins used in pre-preg fabrics require a high temperature post cure, which leads to internal stresses in the part when the part cools back down to room temperature. These internal stresses weaken the part's integrity if the unit is not utilized at the curing temperature. An example would be a blade being utilized in freezing temperatures following a high temperature curing method would be subject to the stresses caused by the CTE (CTE is explained further later). Therefore a more robust design is also required increasing costs.

Pre-preg carbon is currently \$159 per yard while the same dry fabric is \$55 per yard from the same online retailer fibreglast.com. This almost three fold increase in cost is a major drawback.

Benefits

The main benefit of using pre-preg is the repeatable material properties. This is due to a constant resin-fiber ratio put in by the manufacturer. There is little danger in having properties vary much from part to part.

2.3.5 Final Selection of Manufacturing Process

After all the options presented were weighed, the vacuum infusion process was selected for the manufacturing of the wind turbine blades. It has the key benefits that are required to make a production run of wind turbine blades. The ability to have repeatable properties is key when it comes to the analysis of the blades. This process dissolves any doubt in the material properties and any variation they will have. If the use of pre-preg materials was selected an autoclave large enough to accommodate the molds would necessarily need to be used.

This method is also what large utility scale wind turbines are made using. Finally, and most importantly; the goal of Cal Poly's first wind turbine project is to make a small scale wind turbine using the same methods that large utility scale turbines are made. This allows the same manufacturing method to be used to make the small scale blades that the utility scale blades are made.

2.4 Mold Making Process Selection

2.4.1 Background

The mold (or tooling) is one of the most important parts in composite manufacturing. The quality of the mold directly correlates to the quality of the finished part. The surface of the mold correlates directly to the surface quality of the finished part. A mold has to survive the part making process which can be very long and harsh.

There are four basic types of molds that are used in composite manufacturing: male, female, compression and multi-piece molds. Each has their advantages and all are used in high numbers in composite manufacturing today. The mold type for a specific application almost chooses itself by the geometry of the desired final part. This is because the surface of the finished part that is in contact with the mold surface will be the finished surface. The surface not touching the mold will be rough and somewhat undefined.

2.4.2 Male Molds

Male molds have the finished surface that is convex and produces a part that has a concave finished surface. A good example of a male mold product is a bathtub. The surface of the tub is finished while the back side is rough. In relation to airfoils, the finished side would be on the inside of the blade and the surface exposed to the wind would be rough. This is obviously not the way to make a smooth wind turbine blade.

2.4.3 Female Molds

Female molds are the most often used molds in composite manufacturing; they leave the outside of the part a smooth finish. Female molds are concave and make parts that

are convex. The main drawback to a female mold is releasing the part from the mold. The mold must be made with sufficient draft so the part can be removed from the mold.

The main advantage of using a female mold is that the outside of the finished part will be the smooth part. This means that the final part surface can be prescribed by the mold and little hand work will be required to finish the part.

2.4.4 Compression Mold

A compression mold uses both a male and female mold to compress the fibers and resin together and produces parts with two smooth surfaces. The mold must be made with the correct tolerances to leave enough room for the fibers. Unless two prescribed surfaces are needed then a compression mold is unnecessary.

2.4.5 Multi-Piece Mold

For anything but the simplest of geometries, a multi-piece molds must be used. Multi-piece molds have removable pieces that allow the final part to be released. This allows complex geometry to be made while still retaining the ability to remove the part from the mold. The only drawback is the complexity of the mold. The mold must have ways of piecing together and staying together during the part making process. This means that the mold pieces must be indexed to match up with sometimes very tight tolerances.

2.4.6 Final Selection of Mold Geometry

After exploring all types of mold geometries, the final selection for the type of mold used for the manufacturing of the blades is a multi-piece design. The blades will be made with an internal flange to piece the two halves of the blades together, and to get this flange a multi piece mold must be made. The geometry dictates the multi piece design for the mold, so the blade half can be released. The molds will be female molds so the finished surface is the outer surface of the blade (see figure 2.10).

Figure 2.10

Cross section of top and bottom female molds

2.5 Material Selection for Mold

Molds can be made from any type of material but some materials are better suited for composite construction. A mold must be tough enough to survive the part making process. It must be stiff enough to not deform under the stress of a vacuum bag if one is used. It must be able to take the heat and pressure of an autoclave if pre-preg materials are used. It also must be chemically compatible with the resin system being used.

With all of the strict performance criteria for a mold to meet, the selection of the mold material is very important. There are materials made specifically for mold construction made by many manufacturers, and there is a whole industry of chemicals and materials used for tooling applications. There are a few materials that are commonly used for tooling applications: metal, wood, plaster, FRP and high density foam.

2.5.1 Metal Molds

Metal molds are used extensively in aero-space applications and where high production numbers are needed. Metal molds are the toughest and most robust molds available. They can withstand the heat and pressure of vacuum bagging and autoclaving without many issues. Their main drawback is the cost of the raw material along with the

machining costs. A metal mold this size also presents a problem of simply moving it around and working with it because of its weight.

2.5.2 Wood Molds

One of the cheapest ways to make a mold is to make it out of wood. This option should only be reserved for low or single part production runs. They cannot survive a cycle through an autoclave, so the use of pre-preg materials is generally not compatible with wood molds. Wood also cannot be machined very cleanly without tear outs, but wood can be shaped by hand easily which is why it is still used in some applications. The precision needed to build a blade of this size exclude the possibility of hand carving a mold for a blade of this size.

2.5.3 FRP Molds

An FRP mold can be made of the same materials that the finished part is made of. A common mold used by manufacturers of composite parts is a gel coat surface fiberglass reinforced tool. The gel coat used is a specifically formulated polyester resin to have a high toughness and hardness to survive the part making process. The fiber reinforcement can be any material desired to match the coefficient of thermal expansion (CTE) of the part being manufactured. If a carbon/epoxy part is being made in an autoclave a carbon/epoxy mold can be used to eliminate issues with CTE encountered during the large temperature swings in that environment.

The main drawback to a FRP mold is that a plug must be created first before the mold can be made. This can just add another step in the process and may be unnecessary and if the plug has to be machined. If effort is being taken to machine a plug, it makes sense just to have the mold machined out of a material that can be utilized as the mold itself.

2.5.4 High Density Foam Molds

The use of high density foams for molds is relatively new and very specific to composite construction. Foams of densities from 10-100 pounds per cubic feet (pcf), are available from many manufacturers. These foams are easily machined with any standard Computer numeric controlled (CNC) mill. Their cost is lower than metal molds but higher than other options. Aside from cost there are no drawbacks to using high density (HD) foam for a mold. If a density high enough is chosen, the mold can be used for a high production run. The mold surface must be finished with a sealing agent, but sealing the surface is required with almost all methods of mold making.

2.6 Blade Material Selection

The material selection for the construction of the blade is somewhat independent of the manufacturing process of the blade. But certain properties of the fibers and the resin system make them better suited for vacuum infusion.

2.6.1 Resin Selection

There are three common types of resins available to choose from. Polyester based resins, Vinylester based resins and Epoxy based resins. Utility scale blades are constructed using epoxy based resin systems.

All resin systems can, in theory, be infused to make a part, but there are certain properties that make some resins better than others for vacuum infusion. In fact many manufacturers make resin systems designed specifically for vacuum infusion. The two main properties dictating a good infusion resin are viscosity and pot life. The lower the viscosity and the longer the pot life the better when it comes to choosing a vacuum infusion resin.

Other properties such as glass transition temperature are very important in the selection as well. This temperature changes with the post curing of the resin so the post cure cycle must also be chosen when selecting the resin.

2.6.2 Polyester

Polyester based resins are very common and used in many other applications including surfboards and bathtubs. They do not have very good strength properties when compared to Vinylester and epoxy based resins.

Advantages

The main advantage of polyester resins is that they are very easy to work with. They are low in viscosity which makes them easily poured, pumped and mixed. Also the rate of cure can be adjusted over a wide range by simply adjusting the amount of catalyst. They can also cure at room temperature and are the cheapest of the three main types of resins. They are also chemically compatible with polyester gel coats the importance of this will be explained later in further detail.

Drawbacks

The main drawback to using polyester resins is their strength properties and impact resistance. Polyester resins also shrink more when compared to epoxy based resins. They also have a high VOC content and can be hazardous if the proper precautions are not taken.

2.6.3 Vinylester

Vinylester based resins are similar in chemistry to polyester based resins and have improved strength and impact properties compared to polyester resins.

Advantages

The main advantage to using vinylester resins is their resistance to the elements. They use the same catalyst and generally have a lower viscosity than polyester resins. They have much better strength properties over polyester resins but fall short when compared to epoxy resins and shrink less during the curing process compared to polyester. They too are compatible with gel coats.

Drawbacks

The drawbacks to using vinylester resins are the same as polyester resins. The same issues with inferior strength and impact resistance compared with epoxy exist.

2.6.4 Epoxy

Epoxy based resins are at the top of the ladder when compared to polyester and vinylester based resins. They exhibit superior strength and impact properties compared to the previous two resins.

Advantages

Epoxy based resins can exhibit better properties even at higher temperatures. Stiffness, strength and toughness are all better when compared to the previous mentioned resin systems.

Drawbacks

Most epoxy resin systems are 3-5 times more expensive than polyester resins. Also if careful attention is not paid to the mixing ratios of the resin and hardener, the resin may never fully cure and the whole part can be wasted. Epoxy resins are not chemically compatible with gel coat unless the gel coat is modified for use with it, thus adding to its cost and complexity.

2.6.5 Gel Coat

While some resins have good properties when it comes to weather resistance, they should not be used as protection from the elements. Gel coats can be used to protect the part from the elements. They prevent moisture and UV from getting to the resin. Gel coat is a polyester based resin that has additives to change the properties to suit the application. In general, gel coats have a higher viscosity to keep it in place during its application to the mold. The gel coat becomes the outside surface of the final part. The gel coat can significantly increase the quality of the appearance and surface of the

part being made. Air bubbles and voids on the surface of the final part are a big problem with manufacturing composites, using a gel coat eliminates any chance of voids or bubbles on the surface. A disadvantage to adding gel coat is the added weight to the part because of the added gel coat.

The chemistry behind gel coats is similar to that of polyester and vinylester based resins, but it has a characteristic that does not allow it to fully cure unless oxygen is cut off from any exposed surfaces. This is called the “Stage B”. This allows the resin that is to be applied to chemically bond to the uncured gel coat. This is a benefit for both vinylester and polyester based resins, they chemically bond to the recently applied gel coat. If an epoxy based resin is used an additive must be added to the gel coat before application to fully cure the gel coat so that the epoxy resin can be compatible with it. If this step is not done, the epoxy resin will be applied over an uncured gel coat surface. Instead of chemically bonding to the gel coat, the epoxy resin must rely on its bonding strength. This blade prototype will not be the first time an epoxy resin has been used with a gel coat and there are many manufacturers that make additives that make the two components compatible.

Gel Coat Application and equipment

Gel Coats can be applied in two main ways

1. Brushing directly onto the mold. This is the simplest method and requires the least amount of equipment. But it is very hard to control the thickness of the applied gel coat.
2. Spraying the gel coat onto the mold. Spraying allows for an even thickness to be applied over the entire. Spraying also allows for large parts to receive the coat at a high rate of application. This requires a special sprayer that can handle the high viscosity of the gel coat. Also like with anything that is sprayed, some technique is required to perfect the method.

2.7 Fabric Selection

There are many different types of fibers that can be used in the construction of composite parts. There are a group of fibers that have become commercially available of the past few decades that offer superior strength and stiffness when compared to high performance metal alloys. Carbon Fiber and Kevlar (made by DuPont) are some of the newest of these high performance fibers to become available. These fibers in composite form have very high specific strength and modulus when compared to other high performance metals and fibers. See figure 2.11 & 2.12 for comparisons of composite materials and metals.

Kevlar

Kevlar has very good specific strength and stiffness but has low compressive strength. Some Kevlar fabrics have compressive strengths that are about 1/8th their tensile strengths. Also ultra violet rays deteriorate Kevlar at a molecular level. These properties do not make it a good candidate for a blade that is going to be exposed to the

elements for years to come. These shortcomings in relation to material properties desired for blade construction eliminated it from consideration of the blade being manufactured here.

Figure 2.11

Graphical Representation of specific strength and stiffness of various composites and metals

Material System	Su (ksi)	E (msi)	Weight Density (lb/in ³)	Su/Dens 10 ³ in	E/Density 10 ⁶ in
Steel					
4130 (Normalized)	90	29	0.283	318	102
Aermet 100	280	28	0.281	996	100
Aluminum 7075-T6	75	10.3	0.101	743	102
Titanium (6AL-4V)	150	16	0.16	938	100
Carbon (graphite)/ Epoxy					
High Modulus (Long)	170	40	0.055	3091	727
High Modulus (Trans)	3.5	0.9	0.055	64	16
Int Modulus (long)	350	27	0.06	5833	450
Int Modulus (trans)	8	1.35	0.06	133	23
AS4 Quasi-Iso	---	13.8	0.06	---	231
S2 Glass/Epoxy (long)	220	5.6	0.07	3143	80
S2 Glass/Epoxy (trans)	5	1.5	0.07	71	21
Nylon (30% Glass)	25	1	0.05	500	20
Nylon	11	0.175	0.04	275	4
Sitka Spruce	7	1.57	0.015	467	105

Figure 2.12

Properties of various metals and composites

2.7.1 Carbon Fiber

Utility grade blades do not use carbon fiber in their construction. This is mainly due to an issue of cost. Using carbon fiber in their construction would cause the cost of a blade to be about 4-5 times that of using fiberglass. The small scale nature of this project allows the use of carbon fiber to not be cost prohibitive.

Carbon comes in many different forms including weave, style and weight. The different types are broken up into different categories to describe the fabric style.

Tow - The number of filaments in each strand. This is listed in thousands of filaments. 3k, 6k, 12k are the normal tows available.

Weave - The style of weave is also an important parameter that is listed by the manufacturer. There are many different types of weave that all have their advantages and drawbacks. Common weaves are plain, uni-directional, twill, and satin harness.

Uni-directional fabrics have higher strength and stiffness when compared to woven fabrics. This is because the fibers are straight and uninterrupted, allowing the load to travel through the composite in a straight fashion.

Woven fabrics are generally better when high production numbers need to be made of composite parts. In the case of the wind turbine blades a woven fabric speeds up the manufacturing process simply because they are easily worked with. Dry uni-directional fabrics can be hard to work with because they have a tendency to separate as they are not woven together.

Weight – The weight of the material is given in an ounce per square yard figure. This almost always correlates to the tow of the fabric. The higher the tow of the fabric generally corresponds to a higher weight of fabric. There are exceptions of looser fabrics that have a high tow count but a low fabric weight.

Carbon Type- There are multiple ways to make carbon fibers. Many manufacturers make different types of carbon fibers. Some fibers are high stiffness while others are considered high strength. The manufacturer releases published data of the fiber properties only, that is, not in composite form with resin.

AS4 carbon is a fiber offered by more than one manufacturer. It has a pure fiber breaking strength of 550 ksi in tension.

The carbon fiber chosen was an AS4 fabric in 6k tow, 2X2 twill weave which is .012" thick and weighs 11 ounces per square yard. It is a commercially available material made by Mitsubishi Rayon Group under the name Graphil Carbon Fiber in the United States. The 6k tow size gives good build up thickness without sacrificing too much

preciseness to build the laminate thickness. The 2X2 twill weave is easy to handle and keep straight and drapes easily to most compound curves.

2.7.2 Fiberglass

The blade will have both carbon and glass in its construction and each fabric has specific properties that make them useful. Fiberglass is used in the blade construction for its properties during impact. The fiberglass/epoxy composite will offer impact protection while the carbon fiber will be relied on for the strength and the stiffness of the blade. The high strain rate to failure of fiberglass makes it an ideal candidate for use in impact protection on the blade. While carbon has an average strain to failure of 1%, fiberglass has a strain to failure of 4%. This allows the material to absorb more energy before fiber failure occurs.

Many different types of fiberglass are available on the market today. Two main types of fiberglass are available on the commercial market: S-glass and E-glass.

S-glass has superior strength and stiffness when compared to e-glass. The cost of s-glass is around 30-50% higher than that of e-glass. S-glass is used in high performance applications where the cost of carbon is prohibitive.

E-glass is a lower cost, lower strength and stiffness, fiberglass fabric. Its specific strength and stiffness are still higher than that of aluminum and steel. E-glass is used to make boat hulls and surfboards as well as body panels on race cars.

3.0 Blade Manufacturing

3.1 Introduction

Load Cases for Analysis

The blade is designed to follow the IEC 61400-2 standards. These standards encompass the design requirements for small wind turbines. There are two load cases that the blade will be analyzed for.

The first case is the normal operating condition where the blade is making rated power. This condition equates to a wind speed of 22 mph when the turbine is making 3kW of power. The rotor is spinning at 225 rpm during the rated power condition. The three blades make 105 lb-ft of torque during normal operation.

The second case corresponds to an Extreme Operating Gust (EOG) as defined by the IEC 61400-2 standard for small wind turbines as seen in figure 3.1. The forces in this analysis for the condition correspond to a Coefficient of Thrust (C_t) of 2.

Figure 3.1

Example of Extreme Operating Gust as defined by IEC 61400-2

The loads the blade sees can be broken down into edgewise and flapwise loads. Edgewise loads are loads that act parallel to the plane of rotation of the rotor, while the

flapwise loads are perpendicular to the rotor plane (see Figure 3.2). The flapwise force is the larger of the two forces and drives the analysis of the blade.

Figure 3.2

Edgewise force and flapwise force in relation to airfoil

The normal operating case produces a total flapwise force of about 114 lbf and a moment of about 5250 in-lbf. The breakdown of the normal operating load over each section is detailed in Table 3.1. The EOG case corresponds to a total flapwise force of about 680 lbf and a moment of about 33,000 in-lbf. The EOG case was used by Devin Gosal another MS student on the wind energy project, to perform the structural analysis, and this case is what drives the laminate schedule.

Table 3.1

Normal Operating Load Condition			
Span		Blade section load	
section	Section Description	[N]	[lbf]
20.00	Risoe-A-18	28.907856	6.49874619
19.00	Risoe-A-18	28.907856	6.49874619
18.00	Risoe-A-18	36.8446748	8.28301449
17.00	Risoe-A-18	39.971429	8.98593699
16.00	Risoe-A-18	40.6018532	9.12766202
15.00	Risoe-A-18	39.1601443	8.80355287
14.00	Risoe-A-18	37.7863548	8.49471264
13.00	Risoe-A-18	35.7928681	8.04655888
12.00	Risoe-A-18	33.2089133	7.4656626
11.00	Risoe-A-18	30.5299396	6.86340519
10.00	Risoe-A-18	27.7960185	6.24879511
9.00	Risoe-A-18	25.030758	5.62713966
8.00	Risoe-A-18	22.2482046	5.00159662
7.00	Risoe-A-18	19.4568101	4.37406601
6.00	Risoe-A-27	16.6616531	3.74568958
5.00	Risoe-A-27	13.8654834	3.11708545
4.00	Risoe-A-27	11.0688837	2.48838467
3.00	Risoe-A-27	16.4941677	3.70803736
2.00	Hub		
1.00	Hub		
0.00	Axis		
	Total load:	504.333868	113.378793

3.2 Overall Blade Construction

There are a few methods to manufacturing wing profiles. One of the methods is to make a single piece design of the entire blade. This has better strength characteristics but is very difficult to manufacture. The other method is to manufacture pieces of the blade and attach them together. This method is easier in respect to manufacturing the pieces but it creates issues with attaching them together. This method also creates seams where the pieces are bonded together.

If a single piece design is chosen, the molds need to be machined with very tight tolerances and must fit together. There must also be a way to press the fabric and resin up against the side of the molds if a single piece design is made. This means either a pressure bag or a machined piece of foam must be used to hold the fabric and resin in place during the curing process. Once the mold is closed up the process essentially becomes blind, and there is no way to inspect for a complete wet out of the part during a resin infusion. This is not an issue with pre-preg materials because the fabrics

already have the resin pre-impregnated in them. But if pre-preg materials are used, the same issues of mold integrity and a source of an autoclave large enough to accommodate arise.

The decision to make the blade in multiple pieces was selected based on a few issues. The main one is the ability to see what is going on in the manufacturing process. If the blade is split up into pieces the manufacturing process can be inspected during and after the part is being made. This is important in a composite part because visual inspection is necessary to ensure the part has been fully wet out by the resin. Making the blade in multiple pieces also makes the process simpler. The process can be broken up and if one portion fails, an entire blade is not lost due to the failure.

Again, utility scale wind turbine blades are made in 2 halves and bonded together and the goal is to replicate as many of the processes used by utility scale manufacturers.

The blade will be made in two halves and bonded together. This will allow for each half to be visually inspected during and after the part making process. The blades will have overlapping internal flanges that are glued together along the bond line (see figure 3.3). This internal bond line must be made large enough to allow for sufficiently low stress in the adhesive.

Fig 3.3

Cross section of blade profile halves

The internal flange is made possible by the removable part of the mold. The flange mimics the profile of the other half of the blade but is offset to accommodate the thickness of the other half of the blade. The mold has two removable flanges, one for the leading edge of the blade and one for the section between the root and first profile on the trailing edge. The vacuum bag holds the material to the flange during the

infusion process, even though the flange surface is past vertical and gravity would otherwise cause the material to fall away from the surface.

3.3 Material Testing

Once the manufacturing process and materials were selected, the properties of the materials needed to be characterized and tested. To characterize the composite materials, American Society of Testing Methods (ASTM) specifications were followed for the testing of the materials.

Material properties for composite laminates are not isotropic, i.e. they differ depending which direction the properties are referred to in the material. Properties in the fiber direction are very different from properties perpendicular to the fiber direction. This anisotropic behavior means that the material needs to be characterized in three different directions.

The 1 (longitudinal) direction is the direction that the fibers run while the 2 & 3 (transverse) directions are perpendicular to the fiber direction (see figure 3.4). Properties in the 2 & 3 directions resemble those of the matrix material while the properties in the 1 direction resemble a mix of the fiber and matrix materials. In the case of the woven fabrics used in the blade construction, the 2 direction will have similar properties to the 1 direction because fibers travel in two directions.

Figure 3.4

Material directions on a test sample

Test samples were created by infusing panels of either carbon fiber or fiberglass and cutting them to the desired size. Several different panels were infused with the fiber orientation required for the specific test. Panels of 0°/90° and +/- 45° fiber orientation were infused.

Tests were performed on an Instron model 1331 tensile/compression testing machine (see figure 3.5).

Figure 3.5

Carbon sample mounted in Instron machine for a tensile test

Tests Performed

ASTM D3039- Tensile test of composite 0/90 lay-up

This test is performed on long thin strips to determine the stress strain curve of the given lay-up and composite. This test determines how strong (ultimate tensile strength) and how stiff (modulus of elasticity) the composite is in the fiber direction.

Used to determine:

- Ultimate tensile strength, $\sigma_{1,2tu}$
- Ultimate tensile strain, $\epsilon_{1,2tu}$
- Poisson's Ratio, ν_{12}
- Modulus of Elasticity, $E_{1,2t}$

ASTM D3518- Tensile test of composite +/- 45 lay-up

This test is same in set up as the ASTM D3039 test, except the fibers are oriented in a ± 45 direction as opposed to a 0/90 orientation. This test is used to determine the shear strength of the composite

Used to determine:

- Ultimate shear strength, τ_{12}
- Ultimate shear strain, γ_{12}
- Shear Modulus of Elasticity, G_{12}

ASTM D790 – Short beam flexural test

This test is a 3 point bending test that finds the bending stiffness and strength of the material.

Used to determine:

- Flexural Stress, σ_{1f}
- Flexural Strain, ϵ_{1f}
- Tangent Modulus of Elasticity, E_{1s}

ASTM D2334 – Interlaminar shear test

This test is similar in set up to the ASTM D790 but the samples are much smaller (see figure 3.6). This finds the ability of the resin to transfer load from one layer to the next. This is more a test of the resin system than the fibers in the resin. It is affected by the fiber in the composite so it must be done for both the fiberglass and the carbon.

Figure 3.6

Sample of Carbon in fixture for interlaminar shear test

Used to determine:

- Apparent shear strength, S_H

This combination of tests accounts for all the material properties needed to characterize a composite material. The only property not tested for was compressive properties of the composite. This was not done because the testing fixture required to conduct a compressive strength test was not available for use at Cal Poly.

To overcome this lack of compressive strength properties, the compressive properties of similar materials were substituted. Looking at historical trends of how compressive strength compares to tensile strength was done by Devin Gosal, another MS student on the project.

3.3.1 Testing Validation

The properties of composites are not readily available and even when they are, the properties listed are not of the same resin or fabric as you intend to use. The only solution was to find a similar resin and fabric composite that had properties characterized by another manufacturer. The carbon fiber composite properties were compared to a similar weave and resin system in the Department of Defense Composite Materials Handbook. The carbon fabric itself is the same AS4 carbon but in a different weave.

The other issue encountered was the failure mode of the composite samples. When the tensile test (ASTM D3039) of the composite was conducted, initial failure of the samples was in the grip tabs. Grip tabs are fiberglass samples glued onto the test sample that tapers to aide in the load path. This failure mode is due to the compression of the test machine holding onto the sample combined with the tension. This can lead to apparent lower strength values than the composite can actually take. This would mean the part will be heavier to take the same loads, so getting accurate values for the strength is important on a weight sensitive part.

The solution to the grip tab failures was to build them into the samples by layering the transition with the fabric itself. They let the samples fail in the middle of the lay-up as opposed to in the grip tabs. This gave confidence that the failures occurred due to pure tension as opposed to a combined load case of compression from the grip tabs and the tension.

3.3.2 Material Test Results

Final test results were compiled for statistical analysis and compared with the similar fabric/resin composite in the Department of Defense Composite Materials Handbook. The strengths of the infusion process compared well to pre-preg material chosen for

comparison. This means that the fiber volume created in this process is close to that of a pre-preg method.

The composite strengths of both the fiberglass/epoxy and carbon fiber/epoxy selected are given below in table 3.2.

Table 3.2

Material Properties

	6k Carbon		E-Glass	
	Average	Standard Deviation	Average	Standard Deviation
Tangent Modulus of Elasticity, E_s (ksi) [short beam test]	93.186	0.258	23786.	5.6
Apparent shear strength, S_H (psi) [ILSS test]	6929	396	4670	450
Ultimate shear strength, τ_{12} (psi) [45 tensile test]	9673	**	10500	1200
Ultimate Tensile Force, $F_{1,2t1}$ (lb)	4820	67	1042	137
Ultimate tensile strength, $\sigma_{1,2tu}$ (ksi)	104.6	3.1	40.5	5.5
Modulus of Elasticity, $E_{1,2t}$ (Msi) [tensile test]	10.0	**	3.006	0.117
Poisson's Ratio, ν_{12}	0.0775	0.0030	0.153	0.0156
Max Shear Stress (psi) [tensile test]	27120	287	9040	287
Shear Modulus, G_{12} (psi)	535200	**	521000	1200

Table 3.3

Material Comparison

	6k Carbon		E-Glass	
	Tested	Published	Tested	Published
Ultimate Tensile Strength, $\sigma_{1,2tu}$ (ksi)	104.6	114	40.5	48.3
Tensile Modulus, $E_{1,2t}$ (Msi)	10.0	9.61	3.01	3.39
Ultimate Shear Strength, τ_{12} (ksi)	9.67	12.6	10.5	11.5
Shear Modulus, G_{12} (Msi)	0.535	0.514	0.521	0.758
Poisson's Ratio, ν_{12}	0.0775		0.153	0.115

3.4 Final Lay-Up Schedule

Once the testing was finished, the lay-up schedule (see Table 3.4) could be determined. The overall lay-up analysis and schedule was performed in collaboration with Devin Gosal, another MS student at Cal Poly working on the project. Suggestions of lay-up schedules were made for an ease in manufacturing stand point and the analysis was performed on the suggested schedules. The lay-up schedule was broken up into 3 sections to aide with manufacturing simplicity.

The lay-up for the first section starts at the root and continues to the first defined aero profile. The second lay-up schedule continues from the first A-27 profile and continues 26" inches down the span of the blade. The final schedule goes for the final 10 profiles (or 36") to the end of the blade (as seen in figure 3.7).

Nomenclature for lay-up schedule:

For the purposes of explanation the following nomenclature is defined for the next several paragraphs [# x, n/# x, n.../# x ,n].

is the direction (in degrees) of fiber orientation in relation to blade span. 0 is fibers running down the span of the blade. 45 is fibers running 45° to the span of the blade

X is the material for the layer. C is for carbon fiber and g is for fiberglass

N is the number of layers

The last material listed is the one touching the mold surface, while the first material listed is the one on the inside of the blade.

For example, the lay-up schedule of [0c/0g/45g/0g/0c] has 2 layers of carbon and 3 layers of glass. Carbon is at 0° for the first and last layer, and the glass has 2 layers of at 0° sandwiching a layer of glass at 45°. The laminate is symmetric around the center layer of 45° glass.

Table 3.4

Lay –up Schedule

Section	Lay-up Schedule
Root- 1 st profile	[0g,1/0c,4/45c,1/0g,1/45c,1/0c,4]
1 st -10 th profile	[0c/45g/0c/45g/0c]
10 th - last profile	[0c/0g/45g/0g/0c]

Figure 3.7

Lay-up schedule along span of blade

All of the analysis was done with symmetric lay-ups to avoid any coupling of bending during axial loads and thermal cycling. The first schedule has an added layer of glass as the first layer. This layer acts as a barrier between the steel root and the carbon fiber. This is needed to prevent a chemical reaction between the carbon and steel after

time. While there is a layer of glue to separate the steel from the carbon, this is just another added protection.

The first lay-up schedule is the thickest of the three schedules; it goes from the root tube up to the first defined profile. The root section of the blade has the highest moment and needs to be the stiffest portion of the blade to prevent large tip deflections. The analysis showed that a total of 12 layers are sufficient to handle the loads. The lay-up schedule for the root section is [0g,1/0c,4/45c,1/0g,1/45c,1/0c,4].

The last and thinnest lay-up was chosen to protect against impact and local buckling. A thinner lay-up could be chosen but was not due to these issues. The blade could be made thinner if further optimization was done but the purpose of these blades are for a test bed, so it does not hurt to have a robust design. The lay-up does not have a factor of safety (FS) any lower than 1.8 at any point along the span for a wind gust of 60 mph (as seen in Table 3.5).

Table 3.5

Factor of safety for laminate along the blade span

laminate lay-up	Blade section	length down blade (in)	chord length (in)	max thickness of cross section (in)	safety factor	laminate thickness (in)
[0cw/45g/0cw/45g/0cw]	1	10.8	12.436	3.358	4.4	0.072
	2	14.4	12.662	3.419	4.51	
	3	18	12.244	3.306	4.17	
	4	21.6	11.554	3.120	3.77	
	5	25.2	10.849	1.953	2.34	
	6	28.8	10.084	1.815	2.18	
	7	32.4	9.368	1.686	2.09	
	8	36	8.715	1.569	2.098	
	9	39.6	8.127	1.463	2.203	
[0cw/0g/45g/0g/0cw]	10	43.2	7.599	1.368	1.79	0.062
	11	46.8	7.127	1.283	1.88	
	12	50.4	6.703	1.206	2.12	
	13	54	6.322	1.138	2.56	
	14	57.6	5.978	1.076	3.34	
	15	61.2	5.667	1.020	4.79	
	16	64.8	5.385	0.969	7.74	
	17	68.4	5.129	0.923	13.7	
	18	72	4.894	0.881	16.3	

3.5 Adhesive testing

The blade relies on an adhesive for two main purposes. The adhesive attaches the steel root to the composite and it will also bond the two blade halves together. The two halves will be a carbon to carbon attachment and the root will be an e-glass to steel attachment. The properties of the glue in these two cases were tested. Three different adhesives were tested: 3M DP-460, Loctite E-60HP hysol, and Devcon Plastic Welder II. The 3M product was recommended for testing by Dr Joe Mello a professor at Cal Poly. The final two products were recommended for testing by AeroMech Engineering of San Luis Obispo.

The final properties of the glue depend highly on the surface preparation of the two bonding surfaces. The goal of the surface preparation is to obtain an oil and grease free surface for the adhesive. Secondly, the surface must be rough enough to obtain maximum adhesion of the glue as this glue relies on mechanical bonding as opposed to a chemical bond. A surface prep of alcohol wipe/abrade/alcohol wipe was chosen for simplicity. The simplest most effective procedure is desired on production runs to reduce cycle times. So each surface of the sample was wiped with isopropyl alcohol then sanded with 150 grit sand paper the wiped again with alcohol. The thickness of the glue was .050" and the samples were allowed to cure for seven days at room temperature to ensure a complete cure.

A simple lap shear test to measure the max shear stress the adhesive could handle was performed. All previous calculations assumed a sheer stress of 1000 psi and the bond length of the root section and the internal flange size were sized based on this strength. As long as the adhesive was able to match 1000 psi or greater it was acceptable for use in the current design.

3.5.1 Results of Adhesive Testing

All three adhesives were able to exceed the required 1000 psi. The carbon-carbon samples exceeded 4000 psi for all three glue types. And the e-glass-steel samples all exceeded 2000 psi and the failure mode was failure of the e-glass laminate not the adhesive. The 3M-DP460 was chosen because it exceeded the requirements and is well characterized through the manufacturers published data.

3.6 Impact Testing

Impact tests were performed on samples of the composite that were the thinnest portion of the blade. These tests were performed to measure the damage of an impact on the skin of the composite with the same lay-up schedule and construction as the blade. The sample panels were a hybrid carbon and e-glass with a gel coat surface. The e-

glass is in the blade for impact protection, therefore this is a test to measure the fiberglass' ability to protect against impact as well as the gel coat's ability to remain bonded to the laminate.

The test was performed following ASTM D7136 guidelines for testing composite panels in impact. The panels are flat 4 X 6 inch with a gel coat top surface with a lay-up schedule of [0c,1/0g,1/45g,1/0g,1/0c,1]. The impact piece is 2.55 lb and fitted with a high g accelerometer. The ASTM spec does not specify an energy, but suggests one be chosen to fit the certain application. So the equivalent of dropping the largest wrench used out in the field from 4 feet was chosen. The wrench chosen was an open ended 1" wrench weighing 342 grams. The transferred to dropping the 2.55 lb test piece from 14.5 inches and an energy of 10.22 lb-ft.

3.6.1 Results of Impact Test

The first panel experienced an initial impact 229 g's followed by 122 g's and 101 g's and 81 g's as the mass bounced on top the panel. The second panel experienced an initial impact 213 g's followed by 112 g's and 91 g's and 71 g's as the mass bounced. This 1st panel experienced an initial impact while the mass was traveling about 50 ft/s and the first impact absorbed 2 lb-ft of energy, the rest of the energy was absorbed during the other bounces.

The panels visually showed very little sign of damage and no apparent de-lamination or fiber failure. The gel coat only showed slight damage that was due to the impactor surface having a slight burr on it. If this imperfection in the impact piece had not been there, there would not have been any detectable damage to the gel coat. There was a slight dimple where the impact occurred on the test panel. Total damage of the panel was limited to an area of 1/4 inch diameter. This shows that the panels are resistant enough to an impact and would not affect the performance of blade.

3.7 Root Design

The part of the blade that attaches to the hub for the first set of blades will be steel. Steel Aluminum, plastics and Titanium were considered for use as the root. The two main driving factors for the selection of the root material were strength and a compatible Coefficient of Thermal Expansion (CTE). Plastics were immediately ruled out for their lack of strength. Aluminum was ruled out for a large mismatch in its CTE with the composite. Titanium and Steel were both compatible, however Titanium was cost prohibitive for our use. This means that there will be a composite to steel joint as a major component of the blade. The steel piece slips into the composite root and is bonded to the composite.

The composite root of the blade is 3 inches in Diameter with a thickness of .2 inches. A 1020 mild steel was chosen on a cost bases and designed for the following set up failure criteria:

- FS =1.5 for Failure for a Extreme Operating Gust (EOG) (IEC 61400-2)
- FS=1.5 for Yielding for load half of EOG

The outer diameter of the root is 5 inches and the flange it .5 inches thick. The part that bonds to the composite is 2.6 inches in diameter and .2 inches in thickness (see figure 3.8). The bond Length is 4 inches and Devin Gosal verified the appropriateness of the bond length using a finite element analysis (FEA) model of the root.

Figure 3.8

Dimensions of Steel Root

3.8 Final Mold Material Selection

Foam of density 20 pcf was chosen for the molds of the blades. The Manufacturer recommended a density of 20 pcf as capable of producing the limited production we were seeking. A production run of 8 blades would not harm the mold. Other considerations were cost, as the next higher density foam was 50% greater in price. If the production number was much higher, a higher density would have been chosen or a plug would have been machined, then an FRP mold would have been made. This method also allows for an FRP mold to be made from the foam mold if higher production numbers are needed.

3.9 Final Resin and Cure Schedule Selection

There are multiple manufacturers of epoxy resin. RevChem plastics (a distributor of composite materials) recommended the use of ProSet 117LV/226 epoxy based resin as it is a resin specifically designed for the infusion process. This is the resin used during the material testing phase. Also utility scale wind turbines use epoxy based resins based on their durability and toughness in harsh environments.

The cure schedule of Root Temp X 15 hr + 110° F X 16 hr (see figure 3.9) was chosen based on a few properties. The Glass Transition Temperature (T_g) needed to be high enough that a hot day will not cause the blades to deform in the event a large gust came along. If the T_g was passed and a large gust came, the blade could potentially become deformed permanently. The T_g of 144° F is for Neat Epoxy (without fibers in it), and once fibers are in the epoxy the T_g will be much higher. This eliminates the chance of the blade becoming deformed due to overheating.

Another reason for the cure schedule chosen is to keep the cure temperature close to the temperature the blades will operate at. If a higher cure temperature had been chosen, internal stresses due to the CTE during extremely cold weather could crack the resin.

PHYSICAL PROPERTIES

117LV Resin/226 Hardener

Physical Property	Test Method	Cure Schedule				
		Room Temp.* × 2 weeks	RT* x 15hr + 110°F × 16hr	RT x 15hr + 140°F × 8hr	RT x 15hr + 140°F × 16hr	RT x 15hr + 180°F × 8hr
Hardness (Shore D)	ASTM D-2240	84	84	84	84	84
Compression Yield (psi)	ASTM D-695	14,920	15,741	15,864	15,988	15,423
Tensile Strength (psi)	ASTM D-638	8,234	9,352	10,708		11,683
Tensile Elongation (%)	ASTM D-638	1.9	2.2	3.2		4.8
Tensile Modulus (psi)	ASTM D-638	5.28E+05	5.12E+05	5.08E+05	5.18E+05	4.71E+05
Flexural Strength (psi)	ASTM D-790	13,636	19,747	19,849	20,625	20,884
Flexural Modulus (psi)	ASTM D-790	5.66E+05	5.64E+05	5.57E+05	5.49E+05	5.45E+05
Heat Deflection (°F)	ASTM D-648	129	144	156	166	177
Glass Transition Temperature (°F)**		131	144	154	166	178
Ultimate T _g -second heat (°F)**		167	167	167	167	167
Izod Impact, notched (ft-lb/in)	ASTM D-256	0.31	0.32	0.38	0.39	0.41

* Room Temperature (70°F-75°F)

** Determined using a Differential Scanning Calorimeter (DSC). Value reported is the onset of the glass transition.

Typical values; not to be construed as specification.

Test specimens were neat epoxy (without fiber reinforcement).

Figure 3.9

Manufacturer Material Data Sheet for Selected Resin and Cure Schedules

3.10 Manufacturing the Mold

3.10.1 Cutting the Molds

The programming for the molds was done on CamWorks and the solid model files were developed in AutoDesk Inventor and converted into SolidWorks .prt files.

The mold material is a 20 lb/ft³ high density polyurethane foam that can easily be machined with any router. The foam arrived in a 4'X8'X5" sheet weighing 267 lbs. The sheet was cut down into two 18X76" sheets to be used for the molds. Once the foam was cut down to a workable size they were taken to AeroMech Engineering in San Luis Obispo to be cut on a 5 axis Gimble CNC router (as shown in figure 3.10) capable of a .003" tolerance. Both molds were machined within 8 hours on the CNC router. The quick turnaround time that the foam is capable of, fits into the previously stated objective of developing a "rapid prototype" method for blade development.

Figure 3.10

Photographs of Gimble CNC router

3.10.2 Surfacing the Molds

After the CNC router is finished with the molds, hand work is required to develop a surface suitable for part making. As the molds are made out of a porous material they needed to have a number of surface coatings put on them to smooth out the finish. The finish of the mold correlates directly to the finish on the part coming out of that mold. So it is important to spend an adequate portion of time on making sure the molds have a good surface finish. On molds that are being used for production runs it pays to spend more time on the mold to reduce any handwork that would need to be spent on the blade after the blade has been removed from the mold.

There is no industry standard for how to seal a foam mold, but there are many ways to do it. The goal is to make a hard impact resistant, smooth surface that will bond to the

mold surface and will not react in any way with the resin or gel coat that will contact it during the infusion. Refer to appendix 1 for the surface sealing instructions.

Once the molds have been surfaced they are ready for part making. The surface of the molds should be extremely smooth and if done correctly you should be able to see your reflection (see figure 3.11) in the mold. The molds need to be waxed to allow for the parts to be released. If the mold is not waxed, the part could potentially become bonded to the mold by the resin being used. The wax created a physical barrier between the mold surface and the chemicals that are going to be applied to it later.

Figure 3.11

Finished Surface of mold

3.10.3 Removable Pieces of the Mold

The pressure side mold is a multi piece mold that needs two pieces to be removed before the blade can be released from the mold. These two removable pieces (see figure 3.12) are what makes the internal flange on the pressure side of the blade. The pieces are held in by studs and wing nuts and have the correct offset so the two halves can be pieced together correctly after they are made.

Figure 3.12

Removable pieces of mold

Indexing of Root

To ensure the proper angle of the blade on the root, an indexing system is used. The steel root is manufactured with a small hole that a groove on the root of the blade is required to align with. Upon alignment of these “keys” the blade will have its proper pitch when assembled upon the hub (See figure 3.13). Without this indexing, proper pitch would not be possible.

Figure 3.13

Indexing of root

3.11 Infusing a Blade Half

3.11.1 Making the Infusion Work

Infusing the blade is the most important part of the process up to this point in the manufacturing. If the infusion does not go correctly and only part of the blade wets out,

then the entire blade must be thrown away. Setting up the resin inlet and vacuum outlet is very important to how the resin will flow once the inlet line is opened. Knowing where to place both the inlet and outlet are very important. It takes a well laid out plan and a little luck to get the resin to flow where it is desired the first time. The resin will take the path of least resistance to the vacuum side, and this can sometime leave a part that is not fully wetted out.

Two main things can go wrong with an infusion. The first is that the resin does not go where you intended it to go. The other is the resin can simply stop flowing leaving a portion of the blade not infused.

The first case can happen if the inlet and outlet are improperly placed in relation to each other. For example, if the inlet is placed too close to the outlet on one portion of the mold, the resin could just be pulled straight from the inlet into the outlet leaving the rest of the part dry. This could happen on a blade near the tip where the resin only needs to infuse over about 5" and 5 layers where at the root and first profile it needs to travel over 12" and go through 12 layers.

The second type of problem can happen if the resin starts to gel or if the outlet becomes cut off by the flowing resin. To overcome this issue, "vacuum continuity" must be created. If the vacuum outlet is isolated, the resin will not have a tendency to flow where there is no vacuum. The resin can actually seal itself off from the vacuum. The vacuum should "pull" on the resin evenly across the entire span of the blade. This ensures that the resin will be pulled across the mold evenly.

The goal is to have the resin flow evenly across the blade and to reach the outlet all at the same time. This is achieved by using spiral wrap tubing to evenly distribute the resin across the entire span of the blade. Spiral wrap is just a tube that has been cut spirally along the entire tube length. This allows the resin to flow out along the entire length of the tube.

On the outlet side, spiral wrap along with a breather material is used to evenly distribute the vacuum. The breather material allows the excess resin to be absorbed and to prevent it from going in the outlet tube. The breather material stays in contact with the flow media, and also stays in contact with the outlet spiral wrap. This is the "vacuum continuity" that was previously discussed. The resin inlet also contacts the flow media. A natural path for the flow is created through these means.

An airtight canister should be used to catch any excess resin and to protect the vacuum pump. If any resin gets into the pump and cures, it will ruin the pump. Also, the pump should be vented outside of the area you are working in. If steps are taken to vent the fumes outside, this can create a relatively VOC free work zone.

3.11.2 Setting Up to Infuse

The next step that needs to happen once the mold is ready for a part to be made from is to cut all the materials that are needed to make a blade half. The list of the materials that need to be cut is listed in Appendix 2.

3.11.3 Gel Coating the mold

As previously stated, the blades will have a clear marine gel coat (see figure 3.14) as part of their construction. The gel coat is a form of weather protection for the blade. Gel coats come in multiple colors including clear. A white gel coat could be used but this would not allow for visual inspection of the infusion of the finished surface of the blade. A clear gel coat was chosen to alleviate this issue. (See Appendix 3 for materials and application to the mold.)

Figure 3.14

A mold that has been sprayed with Marine Clear Gel Coat

3.11.4 Laying Down the Fabric

Once the gel coat is fully cured, the fabric can now be “laid” onto the mold (as seen in Figure 3.15). The first layer is applied over the entire surface of the mold and will slightly stick to the gel coat. All following layers can be held in place with a very light spray of 3M spray adhesive. Very careful attention needs to be paid to this process. After years of personal experience working with composite fabrics and various types of molds, I’ve found that the fabric cannot simply be laid in place in the mold; it must be worked into all the compound curves making sure there are no gaps between the fabric and the mold surface. These gaps will be filled with resin only (i.e. resin rich) reducing the strength of the part at that point or worst case, the area is occupied by air,

dramatically affecting the properties of the part. When the additional layers are laid in place, they too must be worked in place so there are no gaps between layers.

When the layup schedule changes the layers must overlap each other and the layers should be staggered from one layup schedule to the next. This means when laying up the fabric, you work down the blade and start over in the same place each time. This prevents five layers from one schedule sitting on top of five layers of another schedule. Instead the layers overlap each other one at a time. This will reduce the inter-laminar shear stress between the two differing lay-up schedules.

Figure 3.15

Adding the layers of e-glass and Carbon to the mold

Once all the carbon and fiberglass are in the mold, the next layer is the peel ply (see figure 3.16 below). The peel ply allows the excess resin and flow media to be peeled off the back of the blade once the part is cured. The peel ply is followed by the flow media. The flow media is the material that allows the resin to flow on top of the fabric in the bag. Without the flow media, the resin would flow a few inches and stop. It is impossible to pull resin through just the fabric more than a very small distance. The goal is to pull the resin across the fabric evenly and swiftly. The flow media allows larger surface area parts to be made by overcoming this issue.

Figure 3.16

Peel Ply and Flow Media Placed on top the Fabric

The spiral wrap and breather material (see figure 3.17) are laid on top of the flow media and the entire assembly is envelope bagged (see figures 3.18 and 3.19). The bag is sealed around the inlet and outlet tubes. Once the bag is sealed vacuum is applied. The vacuum is applied and released several times while all the material is moved into the desired place. Leaks are checked for and if any are found they are sealed with the sticky tape. Personal experience, again has shown that even a hole as small as a pin hole has very detrimental effects on the quality of a vacuum infusion. Once full vacuum is achieved (25-29 in Hg), it is left for 30 minutes to ensure a good vacuum and to de-bulk the material.

Figure 3.17

Spiral Wrap and Breather Material placed on top of flow media

Figure 3.18

Mold and Fabric under Full Vacuum

Figure 3.19

Close up of Root Section under Full Vacuum

3.11.5 Infusing the Blades

Once full vacuum has been achieved the blade is ready to be infused. The ProSet 117LV/226 epoxy resin is mixed according the manufacturer's specifications, 3:1 resin to hardener by volume. This blade half required 40 oz total of resin is mixed together (30 oz of resin, 10 oz of hardener). The resin container is shaken to raise the bubbles to the top and let to sit for 2 minutes to further remove any bubbles. If any air bubbles are left in the resin, they will be drawn into the part during the infusion. This should be avoided to prevent any porosity in the laminate.

The inlet tube is placed into the resin and unclamped to let the resin flow. The resin starts flowing immediately and the entire blade half will be done infusing in under 2 minutes. Once the resin has fully traveled across the blade, the inlet is clamped and the blade is left to cure. The blade is left to cure at room temp for 15 hours and then put into an oven for 16 hours at 110 ° F. This is the cure schedule chosen from ProSet's data sheet. This elevated temperature post cure elevates the T_g, as described in section 3.10.

3.11.6 Removing the Blade Half From the Mold

After the blade half has cured it can be removed from the mold. This is where mold design and surface prep plays an important part. The smoother the surface and the more times it has been waxed, the easier it will be to remove the blade. The bag must first be cut away and the peel ply and spiral wrap removed. Once they are removed the blade can be removed. The blade must be handled carefully so no damage occurs to either the mold or blade during the de-molding process. These molds are foam, so extra attention must be paid to prevent damaging the mold. A putty knife and compressed air are the only tools needed to remove the blade from the mold. The putty knife simply breaks the edges free and the compressed air is blown in to remove the blade from the mold. No tugging or pounding should occur while trying to remove the blade from the mold. Pounding can damage the composite and the mold surface.

3.12 Visual Inspection of Infused Blade Half

After a blade half has been removed from the mold (as seen in figure 3.20) it requires a thorough inspection of the infusion to ensure full wet out of all the fibers has occurred. From the back side there should be no dry fibers or large air bubbles. On the front side there also should be not any dry fibers or large air bubbles. The back side of the part can look fully infused while the front side can have dry fibers present because the resin did not wet out all the layers. This is where having a clear gel coat pays off; visual inspection of the entire part (both front and back) can occur. The root section that has 12 layers total and should be very carefully inspected, as this is a very critical area for structural integrity.

Figure 3.20

A blade half just as it comes out of the mold

3.13 Trimming of Blade Half

As the Blade comes out of the mold it will need to be trimmed to remove the extra flashing that is on it. Because the blade is fairly small in size the majority of trimming can be done with a table saw and a large stationary belt sander. The blade half does not have to be perfectly trimmed during this step because the final trimming will take place after the blade has been assembled together. A grinder is used to thin out the trailing edge and any place where the fabric is stacked too thick. Two halves are pieced together and trimmed more until the fit is satisfactory (see figure 3.21).

Figure 3.21

2 Blade Halves placed together to test trimming

3.14 Gluing and Indexing the Steel Root

The suction side of the blade has a small mark that lines up with a small drilled hole on the root. When these two marks are lined up the root is indexed correctly with the blade (as seen in figure 3.22). The root is glued in to the suction side first and allowed to cure before the blade is assembled. Both the root and the blade are given the same surface treatment of alcohol wipe/abrade/alcohol wipe. The glue is placed onto both the root and blade and the root is clamped into place making sure it is indexed correctly. The assembly is placed in the oven and cured at 110° F for 4 hours as per 3M's specifications.

Figure 3.22

Close up of properly indexed root

3.15 Gluing 2 Halves Together

The two halves are designed to fit together and almost self center themselves, however they still need to be held together for proper alignment during the gluing process. Therefore a Jig and clamps are needed to hold the blade in place while the glue cures. The internal flange of the pressure side (see figure 3.23) fits under the suction side and this is the bond line for the leading edge. The trailing edge is thin enough that no overlapping flange is needed and glue just fills the gap between the two halves.

A jig was created to hold the blade halves in place while the glue cured (see figure 3.26, 3.27 and 3.28). The bottom half of the jig is identical to the mold for the pressure side of the blade, except it is shortened to allow the steel root to fit in place. The lower portion of the jig is fiberglass reinforced with a gel coat surface. The upper portion of the jig is pieces of wood mated to a wood frame that are cut to resemble the contour of the blade. This skeleton profile allows the blade to be observed during the bonding process. The process can be inspected to see if enough glue was added by checking

for excess glue coming out of the seams. Shims are placed between the blade and the wood contours to ensure a tight fit between the two halves.

Figure 3.23

Close up Detail of Internal Flange on Pressure Side

To bond the two halves together, the pressure side is laid into the jig. Both surfaces are prepped the same way as previously described and the glue is laid in place. A bead is applied along all the bonding surfaces and a putty knife (see figure 3.25) is used to evenly distribute the glue on both halves and the root. The two halves are placed together and the top of the jig is put in place. Shims are then placed between all the pieces of contoured wood and the blade (as seen in figure 3.24). The shims are all put in place until excess glue comes out the seam along the leading and trailing edge. Careful attention must be paid here as to not squeeze out too much glue and leave the bond surfaces deficient of glue.

Figure 3.24

Shims being applied to the jig to ensure a tight fit

Once all the shims are in place, the jig and the blade are placed into the oven and left to cure at 110° F for 4 hours as specified by the 3M. After the bonded blade is removed from the jig it is placed back into the oven and left for another 4 hours to ensure the glue has fully cured.

Figure 3.25

3M DP-460 Epoxy Adhesive being applied to suction side of blade

Figure 3.26

Two Halves and a Root laid into Jig

Figure 3.27

Two Halves placed over each other to test fit

Figure 3.28

Top of Jig Laid in Place

3.16 Hand Work on the Blade

3.16.1 Filling the voids

After the blade has been glued together the seam left by the two halves must be worked on to smooth up the leading and trailing edges of the blade. The two halves will have a parting line where they are glued together left by the excess glue or where the two

halves did not fit perfectly together. These seams need to be filled to create a void free and continuous leading edge to maintain the airfoil's aerodynamic properties.

This parting line is filled with an Ultra Violet (UV) curing resin and micro balloons if there are any gaps that need to be filled and sanded smooth (see figure 3.29). The micro balloons allow for easy sanding of the UV curing resin. The mixture has a very thick consistency and will fill any voids easily. This step ensures the leading edge is smooth and free of any voids. Also if any voids along the surface of the blade need to be filled, the same process of filling the voids is followed.

Once the resin and micro balloon mixture has cured it can be sanded smooth. If any voids remain anywhere along the blade, this process can be repeated until the blade is void free.

Figure 3.29

Close up of leading edge after being filled with UV cure resin and micro balloons and sanded smooth

3.16.2 Overwrap of the Root

The root of the blade was designed to be wrapped with fiberglass to handle the hoop stress in the root. Fiberglass is wrapped 8 times around the root section with a Vinylester resin (see figure 3.30). The Vinylester resin is a corrosion resistant resin system made by Composites One Inc. This resin was chosen because it works well with fiberglass and has good resistance to the elements and is often used in marine applications. The ProSet 117LV/226 infusion epoxy used for the construction of the blades was not used because the manufacturer does not recommend use of that particular resin for open molding processes, i.e. wet lay-ups such as the overwrap.

The thickness required for the overwrap was analyzed by Devin Gosal and a total thickness of .02" is sufficient for a uni-directional e-glass with a safety factor of 2. The overwrap was done with the same woven fabric that the blades are constructed with which has a lower strength. The overwrap was applied to a total thickness of .09" to ensure the root could take the large moment and to increase the effective safety factor. The additional thickness was added because it does not represent a significant weight increase to the blade but offers good protection against root failure.

Figure 3.30

Close Up of Fiberglass Overwrap

3.16.3 Painting the Blade

After all of the handwork has finished on the blade, it needs to be painted. The paint will protect the blade from the elements and add another line of protection in addition to the gel coat. Utility scale blades are painted with a durable polyurethane paint to protect the blade from the elements. Again, following the methods of utilized by utility scale manufactures, these blades will be painted with a high grade polyurethane paint

The entire blade needs to be prepped for painting to ensure the paint will adhere to the blade. The entire blade is sanded with 320 grit and all grease and oils is removed with a degreasing soap and a hard sponge. The removal of the grease and oils ensure the paint will stick to the blade for long term adhesion. If the grease and oils are not removed from the surface the paint will not adhere properly and could potentially come off shortly after application.

The first blade is painted with an automotive clear coat and is to be used for testing. All following blades will be painted white (GM 2009 Galaxy White) with Polyurethane

automotive grade paint. The white paint will help prevent the blades from getting too hot on summer days.

4.0 Results

4.1 Introduction

The blade has a variety of safety factors (FS) associated with different components. The design FS's are listed below in Table 4.1

Component	FS operating	FS EOG 1.5 Ultimate	Test Result
Steel Root	1.5 yield	Ultimate	No Failure for EOG Load
Composite Root	N/A	2	No Failure for EOG Load No failure for Modified Operating Load*
Bonded Flange-glue	N/A	2	Load*
Steel-composite bond	N/A	2	No failure for Modified Operating Load*

* Modified Operating Load is 120 lbs placed at tip
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4.2 Root Design Validation

The root of the blade is one of the most important structural components of the blade. It must resist the large moment created by the wind and survive the harsh environment for many years. Because the root is glued in place, a test was conducted to determine the appropriateness of the bonded joint design. A small test piece (see figure 4.2) with the same lay-up and overwrap schedule as the blade was made and bonded to the steel root. This test piece would be subject to a large moment that corresponds to a Coefficient of Thrust of 2 for the blade in a 68 mph wind.

The root is also being tested to make sure the CTE mismatch between the steel and composite portions does not cause the joint to de-bond in severely cold climates. The root is cycled between room temperature and 10°F (representing a cold night) three times. The steel has a higher significantly CTE than the composite. This mismatch could cause the steel to pull away from composite on a cold night, and de-bond the joint.

4.2.1 Test Fixture

The test rig (as seen in figure 4.1) is welded steel and holds the root or a blade horizontally. The test piece had a 3" pipe inserted into it and was jacked upwards at the other end. A load cell was placed in between the jack and the pipe to measure the

force at the end of the pipe. A load of 500 lbs at the end of the bar was applied equating to a moment of 30,000 in-lbs at the root. The load was applied slowly so a quasi-static assumption could be made.

The root was then removed from the test fixture and placed in a freezer and brought down to 10° F. The root was removed from the freezer after verifying it had cooled all the way to 10° F and brought back up to room temperature. This process was then repeated two more times. After the thermo cycling was completed, the root was placed back onto the test fixture where the moment was applied again.

Figure 4.1

Test Rig for Root Test

Figure 4.2

Close up of Root Test Piece

4.2.2 Results of Root Test

The load was applied and slowly removed, during which there was no detectable fiber failures or de-laminations. The bond did not fail and there appeared to be no damage to the composite or the glue. There were no audible cracks or pings that came from the root fixture that would indicate fiber or glue failure. The extreme temperature change did not affect the performance of the bonded joint. If there had been any failure in the glue, the test fixture would have failed after the thermo cycling portion of the test.

4.3 Static Blade Test

The same fixture for the root test was also used for a static blade strength and tip deflection test (see figure 4.3). Operating load on the blade is 114 lbs distributed over the lift generating portion of the blade. The test was done with 120 lbs located at the tip to represent a worst case scenario. The test was repeated multiple times to check for fiber failure. If fiber failure had occurred, tip deflection would change after each failure. The tip deflection did not change after each successive application of the load. Tip deflection for each load case was identical for all four trials.

Figure 4.3

50 lb Load Applied at Tip of Blade

The load was applied gradually in 20-30 lb increments. Starting with 20 lbs and increasing to 120 lbs. Tip deflection was 3 7/8" for 120 lb load applied at the tip. There were a few audible “pings” from the blade during the first application of the load. It was discovered that the sounds were not fiber failures but the overwrap of fiberglass pulling away from the root where the excess resin had stuck to the steel. The following applications of the load had no audible “pings” that would have indicated fiber failure in the blade. Further visual inspection of the blade showed no signs of either fiber or matrix failure anywhere along the blade.

The actual tip deflection of the blade is plotted (see figure 4.4) against the predicted tip deflection as analyzed by Devin Gosal. The actual deflection does not match up perfectly with the predicted deflection. This can be due to a few assumptions made in the analysis that do not quite fit the actual case. The first assumption is that the root section is rigid and does not deflect. If the root section deflects even a small bit this deflection will translate to a very large deflection at the tip.

Figure 4.4

Actual and predicted tip deflection

The other reason that the predicted tip deflection might not be correct is the large stiffness change in the blade that occurs when the blade transitions from the A-27 profiles to the A-18 profiles. The calculations for tip deflection do not include this effect of the real geometry. During the test, all of the deflection seemed to come from this section of the blade. The blade seemed to “hinge” or rotate around this transition. The base seemed to deflect very little up until the large drop off in cross sectional stiffness at

the transition. Further blade designs could benefit from using an intermediate profile such as the A-24 and A-21 profiles of the same RISO family.

The tip deflection does follow a linear curve which does indicate that there was no fiber failure during the course of the test. If any fiber failure or glue failure had occurred the tip deflection would not follow a linear curve and tip deflection would increase more and more with the load applied.

4.4 Replication verification

A way to evaluate the process is to see if the blades are all similar to one another. If the process does not create blades that are all similar in dimension then it would need to be re-evaluated. A good way to check for warping of the blades is to place them back into the mold after a period of time has passed. If either the mold or a blade half has warped, it would be visably noticeable quickly once the half is placed back into the mold. This is where a symmetric lay-up helps. If the lay-up had not been symmetric, the blades could potentially warp and twist as they cool down from the curing temperature. The lay-ups are all symmetric so the issue is so the issue of coupling between bending and CTE is eliminated. All blade halves were periodically placed back into the mold over the course of 2 months to check for any warping of either the mold or the parts. There was no detectable warping to either the molds or the blades.

5.0 Summary of Findings

5.1 Prototype Blade Evaluation

Based on the results of the root and static blade tests, the first production run of these blades has met or exceeded the qualifying tests established as base line minimums for this design.

During the static blade test under conditions far exceeding expected operating loads, the blade tip deflection was minimal. Therefore, under normal operating conditions there would not be enough overall blade deflection to interfere with its assumed aerodynamic properties as modeled.

The low strain levels the blade will encounter, in normal operating conditions, would lead to a long service life. This low strain level was made possible by the high stiffness of carbon fiber composite. Conditions during expected field operations would never approach levels needed to de-bond the root.

5.2 Process Evaluation

The process detailed in this report replicates the exact blade design. A blade can be fabricated to meet a variety of loading conditions and varying sizes as dictated by turbine or environmental demands.

This process is environmentally friendly. Minimal quantities of volatile organic compounds (VOC) are released into the atmosphere during the fabrication of the blades.

One of the main goals in any manufacturing process is to achieve repeatable results. The processes and materials chosen have aimed at achieving a process that is completely repeatable. The infusion process allowed all of the blade halves to pass a thorough visual inspection both during and after the infusion. The fact that there is unlimited set-up time to lay the fabrics in the mold allowed for a high degree of certainty that all the blade halves would be similar in construction and properties.

The goal for a “rapid prototype” process has been met for a few key reasons. If a new design is made for a blade, it would be a matter of weeks before three new blades could be produced. Machining time for the molds is very limited because of this. Molds for future 6 ft blades can be machined in one day if the solid model is readily available. Surfacing of the molds can be achieved in a matter of days, and parts can be made quickly thereafter if a lay-up schedule is known. This would make small aerodynamic changes to the blade very easy to implement.

5.3 Improvements and Suggestions

The design utilized had been well thought out and leaves the ability to change blade design as necessary for differing conditions and requirements. The process to create the blades is the same of that of utility grade manufacturers. There is only a slight divergence in materials in the use of carbon and gel coat. This use of carbon allowed for a lightweight design that also allowed the use of a small root tube.

Further designs could benefit from an improved aerodynamic planform. Intermediate profiles could be added to the blade so that it does not transition directly from the large A-27 Profile to the small A-18 profile. During the testing, this jump in cross sectional area seemed to be the source of most the deflection of the blade. This high strain at the jump appeared to have the highest strain of the entire blade. I would predict if the blade were to fail, it would be in this region.

6.0 Conclusion

With the successful completion and repeatability of this process, I conclude that the aim of this project was met. The ability to manufacture small scale wind turbine blades using similar methods and materials as the utility grade blades are made and to develop a “rapid prototyping” method for future blade designs was accomplished.

Appendix 1

The steps to seal the surface of the molds are as follows:

1. Sand the bare foam with 80 grit surface to remove machining lines left by the CNC router
2. Spray the entire mold (including sides not used for mold surface) with Duratec 707-002 Grey Surfacing Primer
 - 3 full coats were applied, allowing at least 3 hours between coats
 - 2% MEKP catalyst
3. Sand Duratec Grey Surface Primer with 80 grit to allow next agent to be applied
4. Spray the entire mold with a 1:1 mix of Duratec 904-001 Clear High Gloss Additive and Valspar GC132 Black Tooling Polyester Gel Coat
 - The amount of coats varied depending on how well the gel coat filled the still porous mold
 - The additive allows the tooling gel coat to be sprayed through a normal paint sprayer, as opposed to a dedicated gel coat sprayer
 - 2% MEKP catalyst
5. Sand entire mold surface with 80 grit to allow next agent to adhere
6. Spray Duratec 904-045 Clear High Gloss Top Coat
 - Only one coat is applied, and allowed to fully cure overnight
 - 2% MEKP catalyst
7. Wet sand mold surface with 400, 600, 1000 and 1500 grit paper
8. Polish with high speed buffer and 3M Rubbing Compound
9. Finish Polish with high speed buffer and 3M Polishing Compound
10. Wax entire mold with TR Industries High Temp Mold Release wax 10 times

Appendix 2

List of materials needed for an infusion of one blade half

1. A Vinyl envelope bag 31X90 inches
 - The bag needs to be sealed on all edges with General Sealants AT-200Y Double Sided Stick Tape
2. Airtech Green Flow media cut to match the blade profile
3. Airtech Nylon Peel Ply 78X20 inches
4. Carbon Fiber and Fiberglass
5. Strips of Breather Material
6. Spiral Wrap Tubing
7. Inlet and Outlet Tubing
 - Inlet tubing is a flexible ½" OD Vinyl tube and the outlet tube is a hard Polyethylene ½" tube

Appendix 3

Instructions for gel coating mold in preparation for part making

A 1:1 mix of Composite Resource Marine Clear Polyester Gel Coat and Duratec 904-001 High Gloss Additive is sprayed onto the mold. The mix is catalyzed to a 2% by mass with MEKP. It is sprayed in 3 passes, the first is a light pass followed by a 2-3 minute wait for the solvents to flash. This solvent flash prevents trapping any gasses in the gel coat that could cause “fish eyes” for the final two passes. After the 2-3 minute wait is over, 2 passes are sprayed on creating a gel coat that is 12-15 mils thick. The gel coat is then allowed to fully cure for at least 3 hours. The gel coat should be cured enough that if touched with a finger, there is no fingerprint left on the surface.

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(Fibreglast)

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