Evaluation of hand lay-up and resin transfer molding in composite wind turbine blade manufacturing

by Jon Dana Skramstad

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
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Abstract:
Currently, the majority of the turbine blade industry uses the low budget, hand lay-up manufacturing technique to process composite blades. The benefits of hand lay-up include the ability to fabricate large, complex parts with a quick initial start-up. Yet, the drawbacks of the hand lay-up technique suggest that other methods of composites manufacturing may be more desirable in industrial-scale, wind turbine blade fabrication.

Resin transfer molding (RTM) was identified as a processing alternative and shows promise in addressing the shortcomings of hand lay-up in turbine blade manufacturing. The current study compares and evaluates both processes according to fundamental criteria and mechanical performance for a variety of fabric reinforcements, lay-up schedules and turbine blade critical structures. The geometries investigated were flat plates, thin flanged T-stiffeners with skin intersections, thick flanged T-stiffeners, I-beam load carriers, and sample root connection joints. The variables that were explored and compared according to process included laminate thickness, fiber volume, cycle time, and porosity. Flat plates were tested under five typical loading conditions: transverse tension, compression, three-point bending, axial tension, and fatigue. The variety of three-dimensional substructures were also tested mechanically to determine what effects processing might have on structural performance.

In this study it was found that process played an important role in laminate thickness, fiber volume, and weight for the geometries investigated. RTM was found to reduce thicknesses and improve weights for all substructures. In addition, RTM processing resulted in tighter material transition radii and eliminated the need for most secondary bonding operations. These observations were found to significantly reduce weight for complex structures. Hand lay-up was consistently slower in fabrication times when compared to RTM for the manufacturing of the specimens tested in this study. Computed Tomography (CT) technology was introduced as a means to measure porosity for specimens of different processing. However, the current efforts in characterizing porosity via CT suggest further refinement.

Analysis of the mechanical testing results for flat plate specimens demonstrated that vacuum-assisted RTM specimens performed notably better than their hand lay-up counterparts for a variety of properties. Yet, thickness played a critical role in comparing the mechanical test results of flat plate specimens. Variations in thickness had the tendency to bias the structural performance results according to process and as a result, fiber volume normalizing techniques were introduced. Specimen normalization was found to reduce the measurable differences between flat plate test results for specimens manufactured by the different processes. It was also noted that in most cases reinforcement played a more instrumental role in mechanical performance than process. Substructure tests demonstrated that differences in processing methods affected specimen mass and moment of inertia. These properties were greater for the hand lay-up specimens and resulted in improvements in ultimate strength and initial damage when compared to RTM substructures. The current root specimen design does not show significant differences according to process and exceeds all static and fatigue

requirements.

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Jon Dana Skramstad

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

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CHAPTER 1

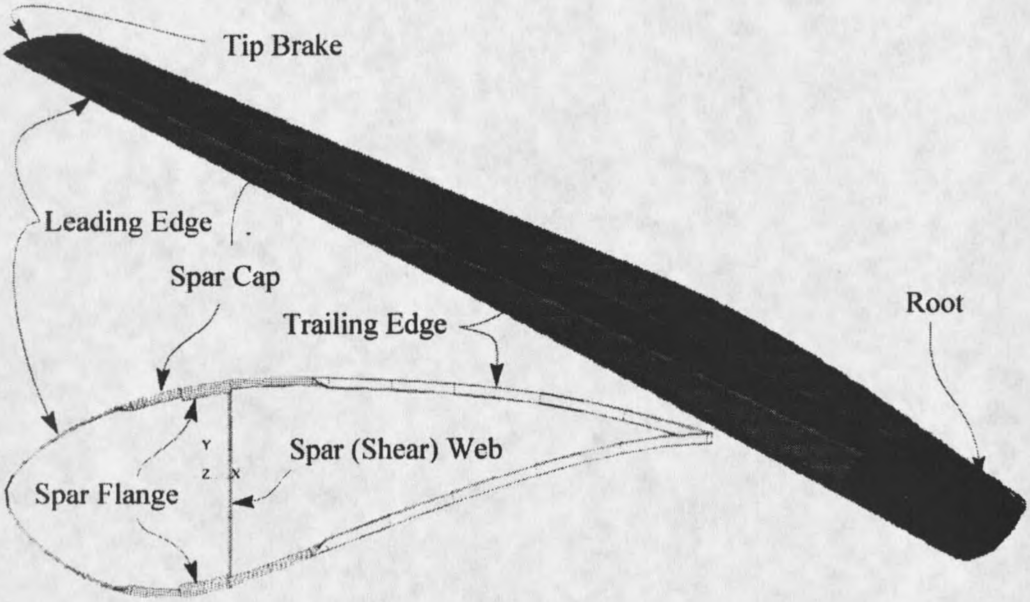
INTRODUCTION

Low cost composites are gaining wider acceptance as a structural material. One form, commonly referred to as "fiberglass", consists of glass fabric reinforcement and a thermosetting or thermoplastic polymer matrix. The aerospace and automotive industries have proven that composites have superior strength-to-weight ratios and excellent fatigue resistance when compared to many traditional materials [1]. Another advantage of composites is their ability to be tailored for different properties using various reinforcement configurations, matrix materials, and manufacturing processes. In addition, fiberglass is relatively inexpensive when compared with other composites, such as carbon-fiber/epoxy, used in aerospace and sporting goods applications [2]. Fiberglass composites, which where once reserved for boat hulls, surfboards and other stiffness dominated applications, are now being driven towards more complicated geometries and critical structures.

Hand Lay-up in Turbine Blade Fabrication

One industry advancing the structural implementation of fiberglass composites is the wind turbine blade industry. The standard method of blade manufacturing employs inexpensive E-glass fabric reinforcement and polyester resin to fabricate complex composite wind turbine blades for electrical power generation. A typical composite wind turbine blade and its components are illustrated in Figure 1. This blade is the current, MSU blade design for the Atlantic Orient Company AOC 15/50 turbine [3]. From this figure it can be observed that the composite blade is composed of skin surface, spar cap, spar web, spar flange and root components. Each substructure provides a well-defined function to the wind turbine blade structure. The leading and trailing edge skin surfaces give the turbine blade its airfoil shape. The spar structures support the large wind induced bending moments on the blade. And the root section transmits the structural loads of the turbine blade to the rotating turbine hub. These turbine blade components vary in thickness and lay-up over the blade's length, as allowances must be made for the blade's tapered, twisted geometry. In Figure 1, Table (b) the lay-ups and thicknesses for the current design can be found for the different blade components at a variety of blade locations.

The majority of the turbine blade industry uses the low budget, hand lay-up manufacturing technique to combine resin and fabric components. In the hand lay-up process, fiber reinforcement is manually inserted into a single-sided mold, where resin is then forced through the thickness of the fiber mats using hand rollers. After the fabric is saturated, excess resin is removed with squeegees. The part is allowed to cure and is finally extracted from the mold. A primary advantage to the hand lay-up technique is its ability to fabricate very large, complex parts with a quick initial start-up. Additional benefits to the process are simple equipment and tooling that are relatively less expensive



(a) graphic display of components in layup schedule

Component	Z Location (inches)	Layup Schedule	Thickness (inches)
Root	11 to 30.5	$[\pm45/0_6/\pm45/0_6/+45]_s$	0.620
	30.5 to 35	$[\pm45/0_5/\pm45/0_5/+45]_s$	0.530
	35 to 43	$[\pm45/0_4/\pm45/0_4/+45]_s$	0.440
Spar Cap	43 to 91	$[\pm45/0_4/\pm45/0_4/+45]_s$	0.440
	91 to 155	$[\pm45/0_3/\pm45/0_3/+45]_s$	0.350
	155 to 219	$[\pm45/0_2/\pm45/0_2/+45]_s$	0.260
	219 to 295	$[\pm45/0/\pm45/0/+45]_s$	0.170
Leading Edge	43 to 91	$[\pm45/0_2/\pm45]_s$	0.154
	91 to 295	$[\pm45/0/\pm45]_s$	0.109
Trailing Edge	43 to 250	$[\pm45/0/\text{balsa}/0/\pm45]$	0.452
	250 to 295	$[\pm45/0]_s$	0.077
Spar (Shear) web	43 to 278	$[\pm45/0_2/\pm45]_s$	0.158
Spar Flange	43 to 295	$[\pm45/0_2/\pm45]_s$	0.154

(b) layup schedule

Figure 1. MSU composite blade design for AOC 15/50 turbine [3].

than required by other manufacturing options. Yet, the drawbacks of hand lay-up suggest that other methods of composites manufacturing may be more desirable in industrial-scale, wind turbine blade fabrication.

Drawbacks Inherent to Hand Lay-up

Hand lay-up's first disadvantage is that the process is labor intensive, which can result in high cycle times and a low volume output of parts. The nature of the hand lay-up process may also result in parts with inconsistent fiber orientations. In other words, the more the reinforcement is handled, the more likely strands will separate or distort from the preform and compromise the mechanical strength of the composite. For the wind turbine blade example, the open molding feature of the hand lay-up process requires one skin to be molded at a time and in the final step, skins, spars, and core are bonded together. Such a sequential process increases the amount of labor required, increases variability between blades, and slows the rate of production. In addition, the method generates a textured finish on the inner surface of the blade skin, which provides a poor condition for bonding between parts. Tight dimensional accuracy and smooth surfaces at the bonding interface are more desirable.

Another drawback inherent to hand lay-up is its yielding of laminates of variable thickness. This raises concerns with bond line thicknesses, uniformity of composites, and blade weights. To allow for the larger deviations in thickness found in hand lay-up geometries, looser tolerances must be allowed at the bond lines where the blade substructures are joined together. This allowance substitutes bonding materials for structural composite and increases blade weight. Variations in laminate thickness also determine the range of fiber volumes in a given composite. This presents a problem in hand lay-up because its dimensional tolerances often yield composites of non-uniform fiber volume and mechanical strength. Maintaining fiber volumes higher than those found for hand lay-up significantly decreases blade mass. For example, a mass savings of approximately 6.3 kg or 10% would result in the current composite blade design for the AOC 15/50 turbine, if a single skin laminate thickness could be compressed by one millimeter over the length of the blade. Lastly, this technique raises environmental and safety concerns with the amount of hazardous volatiles it releases. Hand lay-up is a proven process for constructing composite turbine blades and other structures, but the method's limiting volume output and part inconsistencies motivates research into other manufacturing techniques.

The Potential of Resin Transfer Molding

There exists a wide variety of alternative techniques available for the manufacturing of composites. Compression molding, prepreging, vacuum molding, pultruding, filament winding, and resin transfer molding are just a few of the current options [4]. Candidates of interest to utility-grade wind turbine blade fabrication need to improve fiber volume, lower the blade weight, increase structural reliability, and decrease the overall cost of blade fabrication. Through previous work conducted by the Composites Technology Team at Montana State University and Sandia National Laboratories, resin transfer molding or RTM was identified as a viable process in blade fabrication [5]. Resin transfer molding is a relatively new process that has received a significant amount of attention due to its potential in low budget applications. This process begins with the placement of the reinforcement mat, or preform, into a two-sided closed mold. The resin is then forced through the length and width of the mold by applying pressure, drawing a vacuum, or a combination of the two. After the resin is applied, the part is cured and finally removed from the mold. Resin transfer molding is a very versatile process and can be performed with or without the influences of post-molding heat and pressure [6]. The method has had limited exposure to manufacturing turbine blades, but RTM has many advantages over the hand lay-up technique, even after consideration of RTM's limiting factors.

<u>Concerns Associated with RTM</u>

RTM's first limitation is initial cost. In comparison to hand lay-up, the equipment necessary for RTM is more expensive. In hand lay-up, the minimal equipment required is a one-sided mold, the resin applying rollers and the resin removing squeegees, while RTM requires a two-part closed mold, along with the resin injection equipment. Another challenge facing RTM is that resin flow can be difficult to predict, due to the nature of the closed mold process. Resin flow around corners and through joints is not easily predicted because locally high fiber volumes in these regions can drastically change mold fill behavior. Currently, RTM operators cannot accurately anticipate these effects, nor can they visually verify whether the part has reached full saturation before the injection process is shut down. If the part is not entirely "wetted out", dry spots or voids are introduced, which may require rework or part rejection. Flaws in resin transfer moldings can also be introduced if the operator uses resin injection pressures or flow rates that are too high. In this instance, fibers can be distorted or possibly "washed out" resulting in a part of questionable mechanical strength.

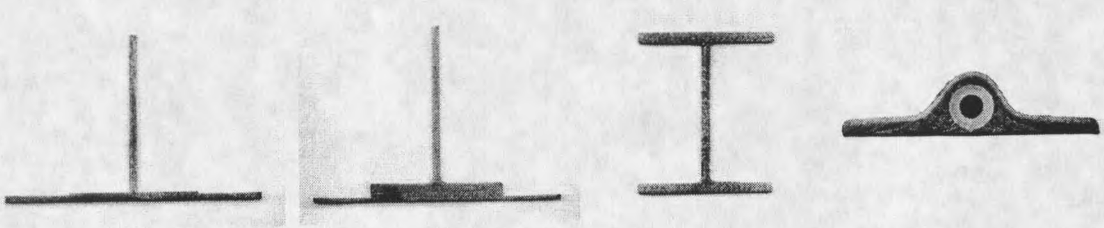
The Advantages of RTM

Despite its limitations, RTM does have many advantages over other methods of turbine blade construction. First, large and complex parts can be fabricated. When compared with present blade manufacturing methods, RTM has much lower cycle times and higher volume outputs. Resin transfer molding also produces parts with a higher degree of repeatability. The structural properties of a hand laid-up blade depend upon the pressure and speed at which the operator physically applies the resin, while in RTM, speeds and pressures remain constant and blades are removed from molds identical to one another [7]. Of all the methods analyzed, RTM is unique in its potential for molding an entire blade in one step. In addition, RTM produces smooth-surfaced parts on both inner and outer mold surfaces. Both methods generate an acceptable airfoil surface but only RTM'd skins have a good surface finish on the interior, which is ideal for secondary bonding. Lastly, RTM's closed mold feature is a more environmentally friendly process because fewer volatiles are released.

Research Evaluation Objectives

Worldwide, wind turbine designs have improved substantially due to composite technology [5]. As composite usage becomes more commonplace, manufacturing efforts will continue to focus on minimizing the time required to fabricate blades while increasing dimensional tolerances, repeatability, fiber content, and affordability. These efforts include advancing current techniques, while exploring other available manufacturing options. The current evaluation between hand lay-up and RTM takes a twofold approach in answering how each process addresses potential improvements in blade fabrication.

First, the physical variables of composite samples were investigated and compared. Laminate thickness, fiber volume, cycle time, and porosity measurement, along with their variability, were measured for five geometries representative of turbine blade structures. These properties are important to a manufacturing comparison because they define the strength to weight ratios, manufacturing speeds, repeatability, and defect levels of composite materials. The geometries investigated were: flat plates (skin sections), thin flanged T-stiffeners with skin intersections, thick flanged T-stiffeners, I-beam load carriers, and sample root connection joints (Fig. 2). The RTM tools used in fabricating these five substructures were compared to determine their benefits and drawbacks in dimensional accuracy, cure time, and ease of manufacture.



a) Thin Flanged T b) Thick Flanged T c) I-beam d) Root

Figure 2. Composite T-stiffener, I-beam, and root critical structures.

Secondly, the mechanical performances of the five composite substructures were compared for each method of manufacturing. This component of the manufacturing evaluation helped to determine any differences between the strength to weight ratios and fatigue cycle lifetimes of hand laid-up and RTM'd structures. Flat plates were tested under five common loadings: transverse tension, compression, three-point bending, tension, and fatigue. Thick and thin flanged T-stiffeners were tested in a stiffener pull-off configuration, while I-beams were loaded under four-point bending in fatigue. The final mechanical tests involved the root specimen in tensile and fatigue loading to gauge differences in the structural performances of hand lay-up and RTM in a thick, complicated geometry.