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Resin Transfer Molding and Wind Turbine Blade Construction

A Final Research Report

Principal Investigator: Doug Cairns, Montana State University, Bozeman

Research Assistant: Jon Skramstad, Montana State University, Bozeman

Sponsor: Sandia National Laboratories, Wind Energy Technologies Department

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Abstract

This report examines Resin Transfer Molding (RTM) and other leading composites manufacturing processes as potential candidates for wind turbine blade construction. Among those methods investigated were hand lay-up, compression molding, prepreg, pultrusion, filament winding and RTM. RTM was selected for an economic evaluation against the traditional composite turbine blade manufacturing process, hand lay-up. In reviewing the RTM fabrication technique, it was found that injection modeling is a necessary requirement for the proper mold fill of complex parts and that this process is advancing in four areas pertinent to turbine blade construction: tooling, core integration, automation and sensors. After comparing the limitations and advantages of each of these processes, we concluded that RTM has significant potential in wind turbine blade construction. Resin transfer molding is capable of producing complex geometries with low porosity in a consistent manner and can accomplish this more economically than traditional methods.

Background

Worldwide wind energy production has grown significantly in the past five years and will play an ever-increasing role in the 21st century. State-of-the-art wind turbines are now producing energy at costs comparable to those of fossil-fuel power generation. Improvements in wind turbine design have decreased the cost for wind-generated power from $0.25 per kWh in the 1980's to approximately $0.05 per kWh today, which is competitive with the cost of new coal-fired electric power [1]. Prospects for the future suggest that wind energy may economically surpass other means of energy production and play an even broader role in utilities worldwide. Presently, the U.S. has approximately 2500 MW of energy capacity from wind power. Wind energy may never become the world's largest source of power, but it continues to be an economical and dependable source of clean energy. Major advancements in making wind energy an efficient and economical power source, thus far, can be accredited to turbines with taller towers and blades with advanced airfoil designs. A central effort in future wind turbine designs will focus on producing turbine blades and other components with advanced materials using automated methods. The next generation of wind turbines, which will bring us the safest and most economical power ever, will be aided by the application of advanced composites technology.

Purpose and Motivation

Composites offer many advantages in wind turbine blade construction. The aerospace and automotive industries have proven that composite structures have superior strength-to-weight ratios and excellent fatigue-resistant properties when compared with many traditional materials. Composites are also unique in their ability to be tailored for different properties using various reinforcement configurations, matrix materials, and manufacturing processes. Wind turbine design has improved substantially due to composites technology, and as composite use becomes more commonplace there exists the need to minimize the time required to fabricate blades while tightening dimensional tolerances and repeatability. Many institutions are investigating and addressing these concerns in an attempt to improve the manufacturability of wind turbine blades. One such institution is Montana State University, where a joint effort exists between the chemical engineering and mechanical engineering departments, in conjunction with Headwaters Composites, to fabricate composite wind turbine test blades using the hand lay-up method. Soon, test blades will be removed from molds and mounted on turbine hubs for the purpose of gathering experimental data. Once the structural components of the blade design are finalized, the next step in MSU’s work will be to reduce unnecessary costs and trim excessive labor during the manufacture of these turbine blades. These cuts require equipment that reduces labor costs and part-to-part variability when compared with the hand lay-up method. Assisting in this area, Sandia National Laboratories has contracted with MSU to explore different modes of composites manufacture, weigh the advantages and disadvantages of each of these processes, and decide upon a direction in which to continue turbine blade research and development. This report discusses and compares the many available methods of composites manufacture: hand lay-up, compression molding, pre-preg, pultrusion, filament winding, and resin transfer molding (RTM). Also included is an update on mold filling software and a review of research on specific advances in RTM that are relevant to blade fabrication. The conclusion of this research evaluates the economics of RTM and outlines how the progress of resin transfer molding technology can strongly benefit wind turbine blade construction.

Hand Lay-up

Hand lay-up is the traditional technique used in producing composite wind turbine blades. In hand lay-up, the fiber reinforcement is manually inserted into a single-sided mold, and resin is then forced into the fibers using hand rollers and squeegees. The part, in this instance the turbine blade, is allowed to cure and then is removed from the mold. The hand lay-up method can be used to make very large, complex parts — such as wind turbine blades - at a low initial expense [2]. Since this process is not typically performed under the influences of heat and pressure, simple equipment and tooling can be used that are relatively less expensive than most other available options. However, this process is very 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; that is, the more the reinforcement is handled, the more likely strands will separate from the mat or preform. In an open mold of the hand lay-up process, one skin is 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. Hand lay-up also yields a textured finish on the inner surface of the skin, which does not provide the best condition for bonding between parts — tighter dimensional tolerances at the bonding surface would be more desirable. Hand lay-up is a proven process for constructing composite turbine blades, but the method’s limiting volume output and part inconsistencies motivates research into other modes of manufacture.

Compression Moldiriq

The compression molding process begins by placing reinforcement and resin matrix into a two-sided mold. The mold is closed, heat and pressure are applied for a specified time and then, the part is removed for postcure before being put into use. Benefits of this process are high fiber volume and low porosity — properties that yield stronger parts. This method also has low cycle times, more accurate tolerances, and excellent surface finishes [2]. Implementing this process in constructing turbine blades does present some significant difficulties, however. Compression molding excels at producing simple composites such as snowboards, but it proves very difficult in making complex parts consisting of skins, cores, and spars as exist in turbine blade designs. Even if the process could be revamped to include complex parts, a two-sided, heated mold that could withstand the pressure applied by a large press over a 20-40 meter span would require a significant capital investment. Compression molding produces parts with high fiber volumes - and consequently, high strength to weight ratios - but has difficulties in molding complex geometries at feasible costs.

PrePreg

The prepreg method borrows its name from the preimpregnated reinforcement it uses. In this process, partially cured resin and reinforcement are placed in a single-sided mold where heat is added to activate and cure the matrix material. Prepreg is occasionally used in bag molding processes under applied pressure loads, as well. The primary advantage of using prepreg material is that the fiber reinforcement remains well aligned during manufacture, thereby creating parts with lower fiber flaws and excellent predicted properties [2]. Carbon fiber prepregs are widely used in the aerospace industry because they can be used to construct complex parts, and the material is readily available. The primary drawback to selecting prepreg for turbine blade construction is cost. This partially cured material is typically 5 - 10 times more expensive than simply purchasing resin and reinforcement [3]. The expense of producing prepreg parts also includes the cost of an autoclave, which is required to activate the resin for high-quality laminates. For producing utility-grade turbine blades, an autoclave of at least 24 feet in length would be required, which necessitates a substantial start-up cost. Because prepreg is typically prepared by manually laying down the individual plys, it is also labor intensive and does not increase the production rate when compared to hand lay-up. Prepreg construction is a sound procedure for building structures with complex features, but is generally too costly for the production of wind turbine blades.

Pultrusion

Pultrusion is commonly used in the production of composites with constant cross section. This automated process draws reinforcement through a resin bath, into a shape preformer, and then out a heated die. The pultrusion of composites has many similarities to the extrusion of metals, the main difference being that the material is pulled, rather than forced through a die. This process excels in producing net shape parts with high fiber volume very rapidly and when compared to the hand lay-up method, has nearly zero variability between final parts [2]. Despite pultrusion’s many benefits, the process does have several drawbacks in wind turbine blade applications. Pultrusion has been successfully used to manufacture VAWT (vertical axis wind turbine) blades and some small, constant cross-section HAWT (horizontal axis wind turbine) blades, but at this time it is not possible to pultrude a twisted, tapered wind turbine blade. I-beams and other solid sections are simple challenges for, the pultrusion process, but hollow parts, including spars and core materials are presently an obstacle for this process. The cost of the large, automated equipment necessary is another concern when considering the application of this process. Due to pultrusion’s current inability to produce complex parts with varying cross section, the method’s high volume output of net shape parts is not easily taken advantage of in wind turbine blade construction. This process does, however, have notable potential in smaller turbine blade applications and in the fabrication of some larger turbine blade components of constant cross section.

Filament Winding

Filament winding is primarily used in the fabrication of vessels and tubes. In this process, continuous strands of glass fiber are dipped into a resin bath and spun around a cylindrical machine-driven mandrel. The filament winding method allows for variation in the tension of the strands, the speed of production, and the angle of the applied strands. This method benefits from its superior control over fiber placement and degree of automation, which provides high production rates. Filament winding is also very versatile in its ability to produce parts of different sizes and thicknesses with high fiber volumes [2]. One drawback when applying this technology to the production of turbine blades is the inability to wind strands in the longitudinal direction of a turbine blade. Typically, only geodesic or cylindrical parts are filament wound. The lack of fiber strands along the length of the blade would produce an inefficient part due to the large tensile and flap bending loads seen in primary service. In addition, the winding of an airfoil cross section is difficult. Filament winding is designed for constructing parts with relatively large radii, and the sharp trailing edge of turbine blades would be a challenge to construct with this process. The aerodynamic performance of the blades made using this method can also suffer from the rough external surface generated by filament winding. Finally, the cost of a machine-driven mandrel and the accompanying computer control would be significant. It is apparent that filament winding serves its purpose in the vessel and pipe industries, but has a number of limitations in wind turbine blade construction.

Resin Transfer Molding

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 into 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 versatile process and can be performed with or without the influences of heat and pressure [2]. The method has limited experience in the turbine blade industry, but RTM is being investigated for potential improvements in blade fabrication.

Limitations

RTM’s first limitation is its 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 squeegees and rollers, while RTM requires two matched mold halves, along with the resin injection equipment. Another challenge facing RTM is that due to the nature of the closed-mold process, resin flow can be difficult to predict. Resin flow around corners and through joints is not well understood, and the operator cannot 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 will occur, requiring the part to be discarded. Flaws in resin transfer molded parts can also be introduced if the operator uses resin injection pressures or speeds that are too high; fibers could be distorted or possibly “washed out,” resulting in a wasted part.

Advantages

Despite its limitations, RTM does have many advantages with regard to turbine blade construction. First, very large and very complex parts are possible. When compared with present blade manufacturing methods, RTM has much lower cycle times and higher volume outputs. Resin transfer molding also produces a higher consistency between parts. The structural properties of a hand laid-up blade depend upon the pressure and speed at which the operator applies the resin, while in RTM, speeds and pressures remain constant and blades come out of the mold identically. Of all the methods analyzed, RTM is unique in its potential for molding an entire blade in one step. In addition, RTM is advantageous over hand lay-up because it produces parts with smooth surfaces on all sides. Both methods generate an acceptable airfoil surface but only skins molded by resin transfer have an excellent surface finish on the interior, which is the best condition for secondary bonding. Lastly, RTM's closed-mold feature is a more environmentally friendly process because of the low amount of released volatiles.

Modeling

An area that has been the focus of significant RTM research is in modeling the resin transfer molding process. Modeling is a critical topic in the advancement of RTM because it addresses a primary drawback — the insufficient knowledge of closed-mold resin flow. In parts with simple geometries and relatively short dimensions, proper mold fill is not a particular challenge because resin flow paths are short and unobstructed. If the part is not wetted out, it must be discarded and changes made to the injection geometry until all dry spots are eliminated. Applying this trial-and-error methodology to the resin transfer molding of large structures, i.e. utility grade turbine blades, would be expensive. However, through the successful modeling of RTM flow, it is possible to predict the flow properties in a complex structure and eliminate the trial-and-error approach. Currently, one of the important facets of MSU's RM composites research has been the development of a practical RTM model to assist in analyzing the flow through difficult areas of the blade geometry.

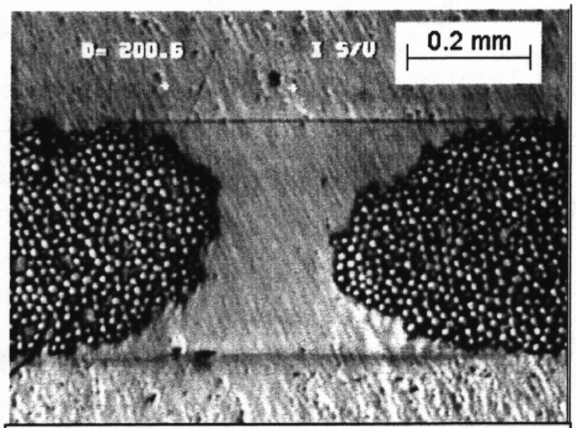
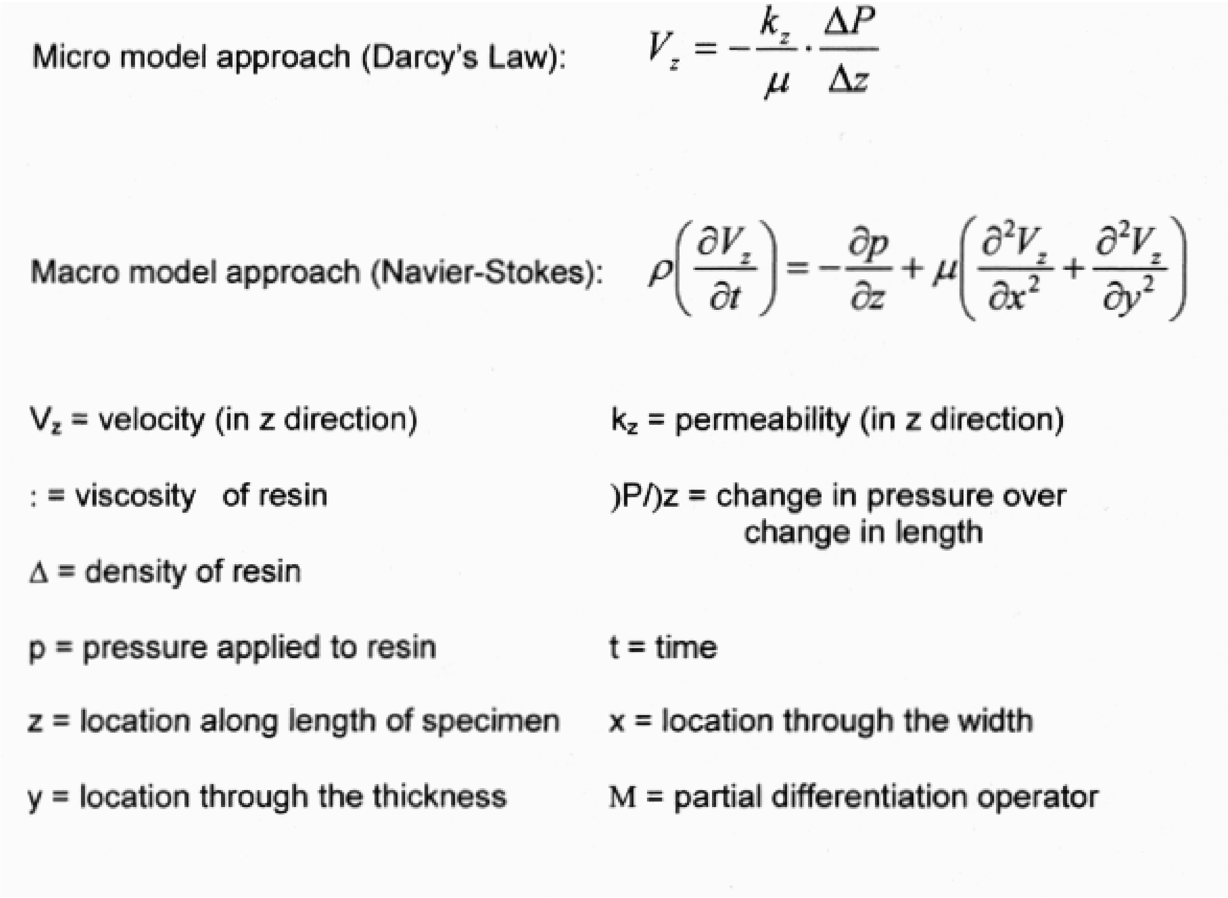


Figure 1 - Composite Cross Section

In the MSU RTM studies, the processing parameters are defined and investigated analytically and experimentally [4]. A basic model has been developed that is based on DArcy's law in fibrous bundle regions and channel flow equations between bundles. The model incorporates a micro and macro approach to account for local architecture and structural geometry. The micro model is important to capture local inhomogeneities as shown in Figure 1. In Figure 1, the edges of tows with a resin-rich channel between them can be clearly seen. The analytical model predicts the wetting out of this cross-section using the following sets of equations:



Micro model approach (Darcy's Law):

$$V_z = -\frac{k_z}{\mu} \cdot \frac{\Delta P}{\Delta z}$$

Macro model approach (Navier-Stokes):

$$\rho\left(\frac{\partial V_z}{\partial t}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 V_z}{\partial x^2} + \frac{\partial^2 V_z}{\partial y^2}\right)$$

V_z = velocity (in z direction)

: = viscosity of resin

Δ = density of resin

p = pressure applied to resin

z = location along length of specimen

y = location through the thickness

k_z = permeability (in z direction)

)P/)z = change in pressure over change in length

t = time

x = location through the width

M = partial differentiation operator

Darcy's Law evaluates the flow through fibrous bundles while the Navier-Stokes equation acts as a field solver that incorporates flow through channels.

Results of model predictions for resin flow through unidirectional, stitched preforms, and multi-layer configurations are shown in Figure 2 and agree well with the experimental results of Figure 3. Experimental results illustrate that incorporating channel flow is important for properly modeling the RTM process. Due to the large difference between permeabilities of the channels and bundle tows, the channels will fill much more rapidly than the fiber bundles. Pressure profiles, resin velocities, and resin flow fronts are predicted accurately and will be further explored in manufacturing process research under a Sandia contract. It should also be noted here that the model results were compared to experimental stitched preform injections.

It was found that although the shapes for resin flow are similar between experimental and analytical results, the stitching affects the permeability so that unidirectional ply data does not accurately capture the times for resin flow. The fabric stitching was found to complicate the modeling of flow through glass reinforcement. At the location of the stitching, the fiber bundle is greatly constricted, which impedes resin permeation and opens up a larger channel for flow

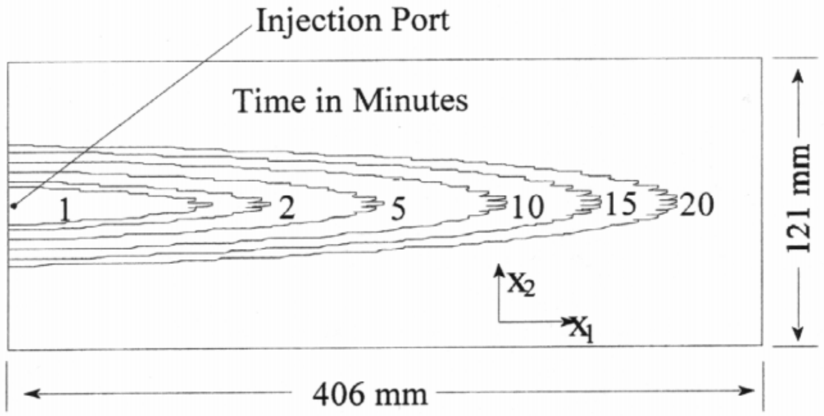


Figure 2 – Single Layer Analytically Predicted Flow Front Position with Time

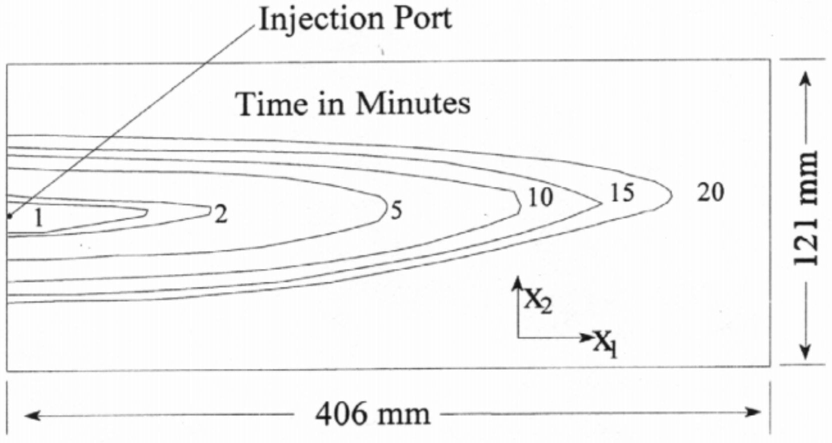


Figure 3 - Single Layer Experimental Flow Front Position with Time

between bundles.

ANSYS flow software and Liquid Injection Molding Simulation (LIMS) software are also being researched. ANSYS contains a field-flow type feature in its finite element model for macro (geometrical) RTM modeling that could yield a commercially available solution to mold filling predictions. The University of Delaware has also developed an interesting three-dimensional finite element package, LIMS, which offers a user-defined scripting language that gives a wide range of control options in modeling the RTM process. Resin flow results from this package for a T-stiffener section are illustrated in Figure 4.

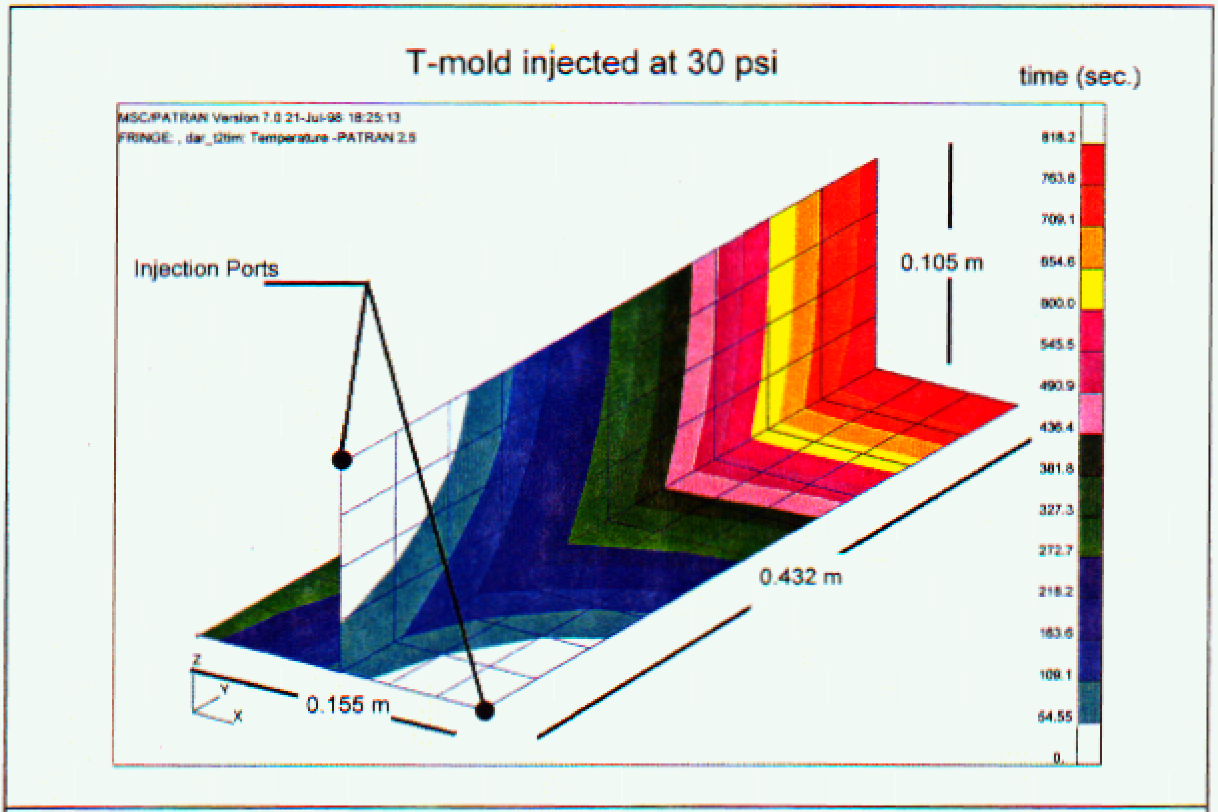


Figure 4 – LIMS Model of T-Stiffener Section

ADplications and Technology

Figure 5 - Commanche Helicopter

The primary motivation behind the background research and evaluation of the RTM process is due to the attention it has received from its successes in other applications. As the use of composite materials continues to grow, the number of RTM applications grows just as rapidly, filling niches that cannot be accommodated effectively by any other process. For example, in recent developments of the Army's Commanche helicopter, a prototype composite keel beam was manufactured, using RTM, that illustrated a few of the method's advantages. By substituting this composite assembly for its metal counterpart, the number of fasteners was reduced from 60,000 to 6,000 and the number of parts making up the beam structure was reduced from 6,000 to 350 [4]. These part reductions facilitated a structure of less material and fewer hours of assembly time. Another example is the case of a commercial jet's exit, which is a spin-off of a development in the F-22 advanced fighter project. Initially this 110-inch diameter jet exit was manufactured from titanium alloys and tipped the scales at 770 pounds. After resin transfer molding the part using carbon fiber reinforcement, the weight was reduced to 470 pounds and the cost by 38% [5].

These successes in RTM manufacturing are encouraging, but they also raise the following questions: can RTM technology and its recent advances be applied to wind turbine blades in a cost-effective manner? Through a literature review of current research, four key areas have been identified that illustrate the potential application of RTM technology to wind turbine blades: mold advances, core integration, automation and sensor technology. The question of economics will be answered in the next section.


Figure 6 – Dodge Viper with RTM body

The first RTM advance that pertains to turbine blade design is mold tooling. Dodge and Aero Detroit Inc. have made advances in this area, specifically in the development of resin transfer molded body panels for the Viper automobile. In 1992 when this car was first introduced, epoxy molds were utilized in the fabrication of 300 cars. In 1993 as demand rose to 3,000 automobiles, Dodge required RTM molds that increased the rate of production ten-fold while maintaining tolerances and longevity. The solution was to implement heated nickel shell molds. By using nickel shell molds at a temperature between 140 — 150 degrees Fahrenheit, Dodge was able to get panel cycle times down to 5 minutes and make its annual quota of Vipers [6]. These heated metal molds also allowed Class-A surfaces to be attained without gel coats, which meant the body panels could be painted right out of the mold. This type of dimensional control is paramount for the demanding aerodynamic performance of wind turbine blades and could allow turbine blades to be painted without secondary resurfacing.

Another applicable RTM technology is that of core integration. The composites group at MSU has been conducting testing into the application of balsa wood core with E-glass composites. Through the procedures developed in its labs, MSU has constructed balsa sandwich panels that provide increased stiffness for thin skin panels threatened by buckling. The research in RTM technology has shown that core integration is not limited to simply balsa core applications. There have been many recent successes with structural foam, syntactic foam and honeycomb — one of which is Rohr engineering's carbon fiber, resin transfer molded engine access door. This part is 12" x 20" and previously was constructed of traditional metals. By using carbon fiber reinforcement and a proprietary process, Rohr has been able to integrate a honeycomb core and gain a 33% cost savings in addition to a 35% weight reduction [7]. Through similar innovative RTM applications, the horizons of lighter weight core materials for wind turbine blade components are broadened.

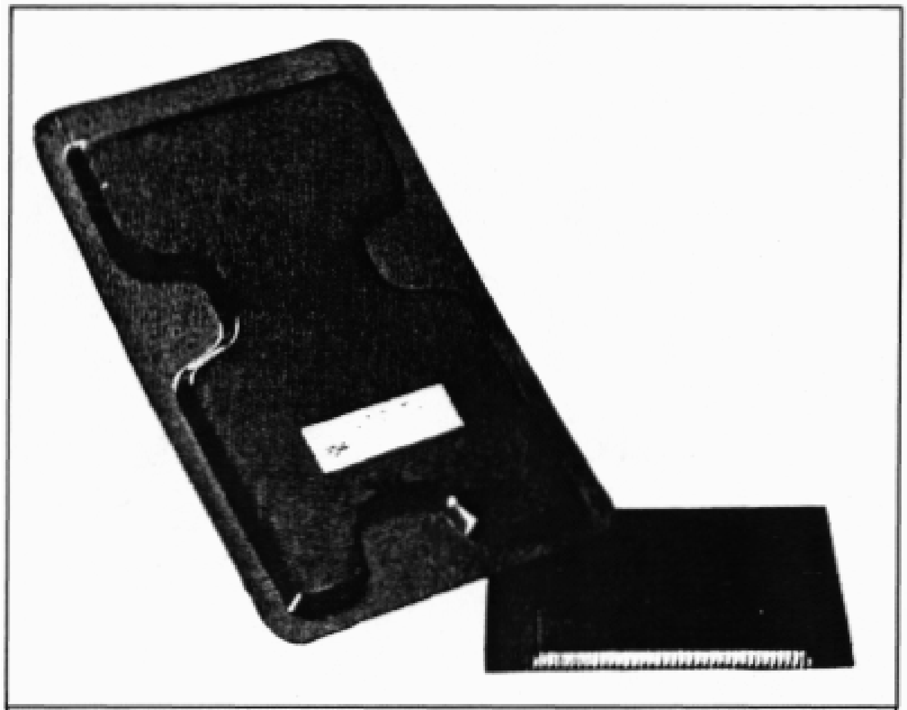
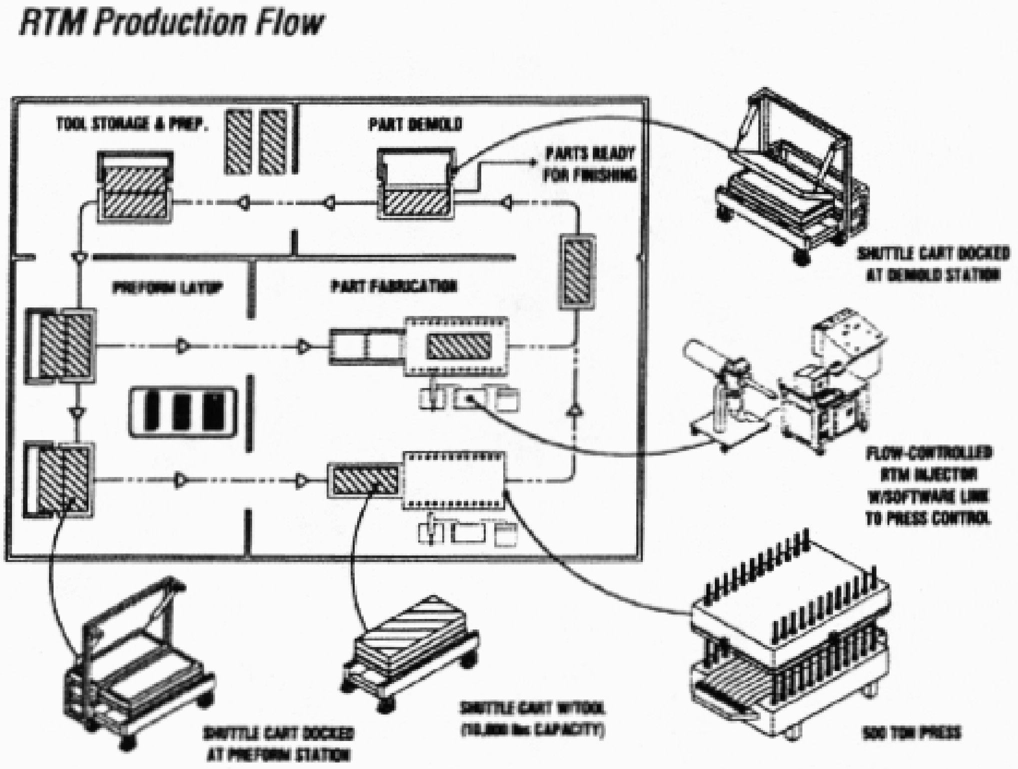


Figure 7 – Rohr Engine Access Door



Source: Radius Engineering

Figure 8 - Boeing / Radius RTM Automation Endeavor

Another emerging area of RIM applications in industry is automation. After visualizing the large potential of RTM in aircraft structures, Boeing subcontracted Radius Engineering to develop an automated system for resin transfer molding. Boeing required the automation of RTM’d commercial jet parts up to 74” x 36” x 30” to be performed under computer control [8]. To meet this challenge Radius developed a system of automation that uses “shuttle carts” to ship the RTM part through different stages of the process. Radius found that to meet Boeing’s production requirements, heated molds would be necessary. Similar automation methods could readily be explored for the production of turbine blades.

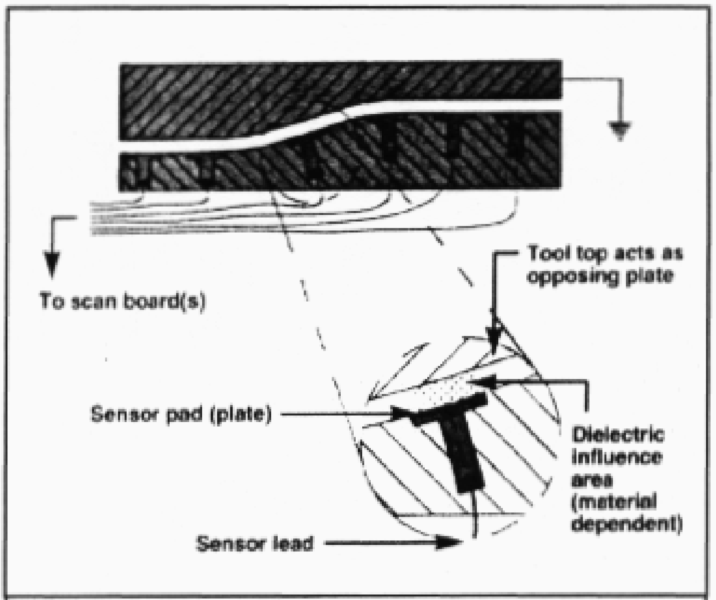


Figure 9 - Radius Flow Position Sensors

Research was also conducted in the area of mold filling. Radius Engineering made another advance in RTM technology by introducing sensors to monitor mold fill. This firm developed new sensors that will monitor state of cure, flow front, pressure and temperature throughout the tooling during resin transfer molding [9]. Another line of products offered by this company is a thermoplastic sensor that provides an inexpensive way to monitor flow positions. Such sensor technology could provide invaluable information into the nature of resin flow through a long mold, such as larger 25-meter long turbine blades.

Economic Evaluation

In the military applications discussed earlier, healthy budgets were allotted to determine whether it was possible to accomplish certain tasks using the RTM process. Wind turbine construction poses a different scenario: every effort needs to be focused on squeezing the most out of the limited time and money available. MSU’s turbine blade work involves a comparison of RTM against a variety of other processes according to structural integrity, overall weight and final cost of a production blade. Discovering reliable cost data for a hand laid-up turbine blade versus one built with the RTM process is difficult. The RTM method has not been applied to commercial turbine blade construction to allow the development of good economic figures. The best that can be offered at this time are outlines of the expected capital and operating requirements for the two methods (see Tables I & 2).

To understand the benefits and limitations of RTM, the initial cost of mold construction and resin applying equipment was investigated. Due to the open mold nature of the hand lay-up process, very low pressures are applied to the resin, which allows for the use of light mold reinforcing and little capital investment. In a brief conversation with Chuck Hedley of Headwaters Composites, he explained that for the hand lay-up of a wind turbine blade, wood would be an excellent candidate for mold reinforcement. RTM, however, uses much higher

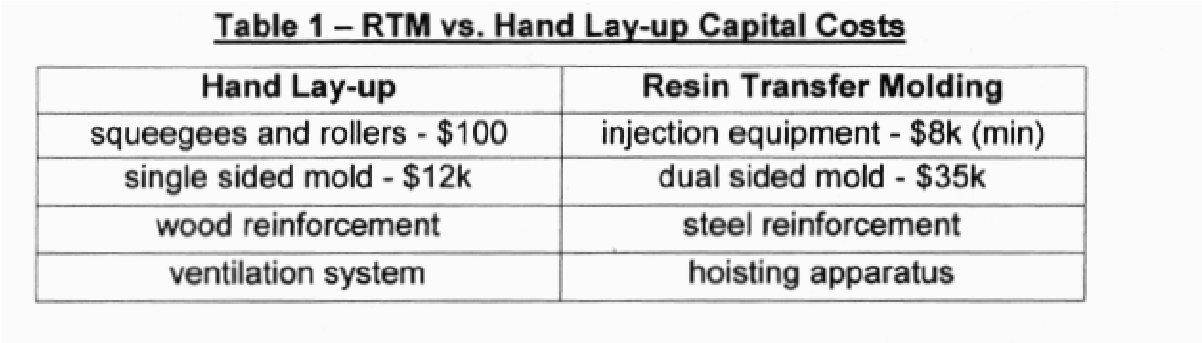


Table 1 – RTM vs. Hand Lay-up Capital Costs

Hand Lay-up	Resin Transfer Molding
squeegees and rollers - $100	injection equipment - $8k (min)
single sided mold - $12k	dual sided mold - $35k
wood reinforcement	steel reinforcement
ventilation system	hoisting apparatus

pressures to force the resin through the process, thereby requiring a much stronger mold reinforcing material, such as steel. For a rough estimate in costs, Hedley suggested that a polyester, hand lay-up mold for fabricating blades 24' in length would cost approximately twelve thousand dollars. He estimated that an RTM mold for a similar part would run about thirty five thousand dollars, almost triple the hand lay-up mold cost, due to the heavier reinforcement material and the hinging or hoisting mechanisms. Yet with hand lay-up, the excessive release of volatiles requires that a ventilation system investment be included in the capital costs. The closed-mold feature of RTM also requires hoisting equipment to open and close the 24' long steel reinforced mold. Indirect costs of the two processes have yet to be made available.

When comparing the start up costs of these two turbine blade manufacturing methods, RTM comes in second place, but when measuring the two according to operating costs, RTM comes out significantly ahead. Both processes require the hand placement of reinforcement into the molds, but in the RTM process the manual application of resin is eliminated, which may double the daily output of blades. Additionally, RTM uses its materials more effectively. For example, in a 24' turbine blade application the RTM process is 100% repeatable and results in only two square feet of excess material; in comparison, fabricating

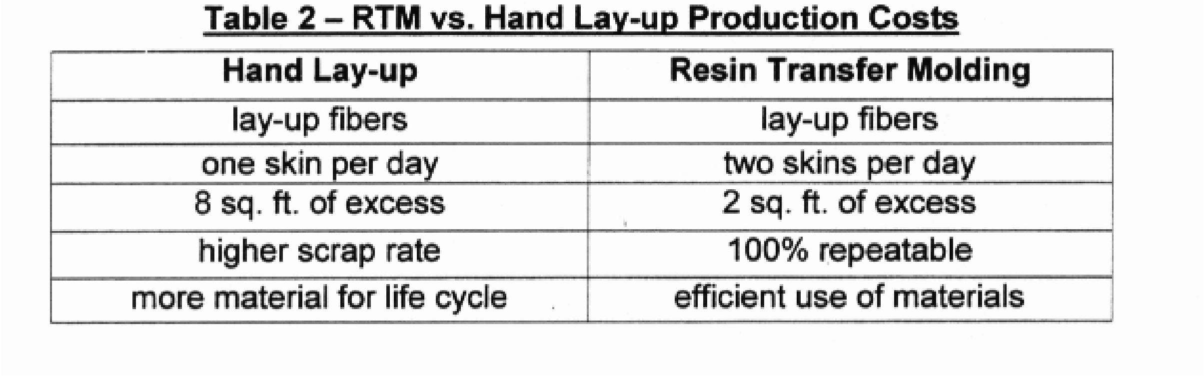


Table 2 – RTM vs. Hand Lay-up Production Costs

Hand Lay-up	Resin Transfer Molding
lay-up fibers	lay-up fibers
one skin per day	two skins per day
8 sq. ft. of excess	2 sq. ft. of excess
higher scrap rate	100% repeatable
more material for life cycle	efficient use of materials

the same blade using hand lay-up would result in eight square feet of wasted material [10]. Due to the natural repeatability of the resin transfer molding process, resin transfer molded turbine blades have higher part consistencies and thus are more reliable in satisfying the requirement of a 30-year life span.

Conclusions

The current research examined the available methods of composites manufacturing and compared their potential for fabricating blades. Resin transfer molding was found to be a promising option due to its advantages in delivering large, complex parts with consistent part properties and excellent surface finishes. One of RTM’s primary challenges, RTM modeling, was addressed and continues to be explored in MSU’s task to develop and apply mold filling software.

RTM applications and technology were also investigated. A series of examples was found, and a selected number of these illustrate the weight and cost savings of the process. Some of the key issues in advancing RTM technology were briefly addressed: tooling, core integration, automation and process sensing. The initial and operating costs of RTM were also weighed against the costs of hand lay-up and found to be competitive. This inquiry into RTM has shown that the process may have advantages in producing blades that are lighter, stronger, more economical and more consistent in properties when compared to the traditional hand lay-up technique.

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