Pressure bag molding : manufacturing, mechanical testing, non-destructive evaluation, and analysis
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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University

Abstract:
It is desirable in the wind turbine industry to use low-cost fiberglass composite materials. However, current manufacturing capabilities for these materials can not keep pace with the increases in size and demands of new wind turbine designs. Process limitations in Resin Transfer Molding (RTM) have been identified that make this otherwise popular process less attractive for wind turbine blades, especially as the size of new blades increases. Other factors such as reliability and maintenance costs also need to ' reduce to allow for the continued competitiveness of these low cost materials. There were three main areas of research addressed in this work which were intended to address these needs.

The first was "pressure bag molding", a variation of RTM which was designed to remedy some of the limitations inherent with RTM. Critical manufacturing process parameters were identified and testing was conducted to compare these parameters for pressure bag molding to those of RTM. Mechanical testing was conducted to compare products of RTM to products of pressure bag molding.

The second area of research was a new non-destructive evaluation method for fiberglass materials. This method involves the transmittance of infrared light through a laminate. This optical evaluation method is described in detail. Several exploratory tests were conducted to gain an understanding of the behavior of this method of evaluation.

Then, a damage accumulation test was designed to compare damage accumulation properties of products of RTM to those of pressure bag molding.

The third research focus was the development of a numerical progressive damage model. Ansys was used to model the complex damage behavior of the layered, angled laminates that were chosen for the damage behavior comparison discussed above.

The process parameter tests showed superior performance for pressure bag molding. Mechanical testing of the products showed similar performance for pressure bag molding products, except for slightly reduced performance in the compressive strength test, which was discussed. The progressive damage model seemed to provide reasonable results. However, it was found (and discussed) that the resolution in the mechanical damage accumulation measurement was not adequate to facilitate reasonable comparison to the Ansys model.

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Master of Science

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Mechanical Engineering

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

January 2004

APPROVAL

of a thesis submitted by

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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

It is desirable in the wind turbine industry to use low-cost fiberglass composite materials. However, current manufacturing capabilities for these materials can not keep pace with the increases in size and demands of new wind turbine designs. Process limitations in Resin Transfer Molding (RTM) have been identified that make this otherwise popular process less attractive for wind turbine blades, especially as the size of new blades increases. Other factors such as reliability and maintenance costs also need to reduce to allow for the continued competitiveness of these low cost materials. There were three main areas of research addressed in this work which were intended to address these needs.

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CHAPTER 1

INTRODUCTION

The use of modern composite materials in critical structural applications has seen significant increase in recent years. The ability to "engineer" a composite material to meet specific design requirements makes them attractive for many applications. One application that has experienced increased use of composite materials is wind turbine blades.

Wind is a potential source of clean domestic energy. Wind generation facilities that convert wind into electricity are increasing in number and generation capacity. Wind generators that are being developed are also increasing in size and capacity. Offshore wind turbines with generation capacities over three megawatts are currently installed in many locations around the world [1, 2]. As the demands on the turbine blades have increased, the use of composite materials for turbine blades has also increased. Typical wind turbine blade construction details are shown in Figure 1.

Composite materials are available in many variations ranging from low cost E-glass fibers combined with thermosetting polyester resins (typically referred to as "fiberglass") to high quality aerospace materials such as metal matrix composites. For some wind turbine blade applications, fiber reinforced plastics have become the chosen materials [3].

Manufacturing Fiberglass Laminates

Currently, there are not many choices for the method of manufacture for structures such as these. Hand lay-up is used for the manufacture of some turbine blades [4, 5]. However, hand lay-up has been shown to have several critical drawbacks [5]. Resin Transfer Molding (RTM) is a relatively recent development for the manufacture of composite structures, and has shown abilities to produce higher quality products while alleviating some of the drawbacks of hand lay-up. Traditional RTM uses low cost glass fabric materials and a net-shape two-sided mold. Liquid resin is injected from one or more locations and flows in the plane of the fabrics until the mold is filled. RTM is considered the "standard" manufacturing method used for comparisons in this work.

Despite distinct advantages to using RTM, it also has been shown to have limitations in process capabilities, especially for larger structures. The in-plane flow mechanism described above is a limiting aspect of RTM. The in-plane flow requires high injection pressures, long injection times, and has limited injected distances and volumes. The limitations inherent to RTM prevent current manufacturing capabilities to keep pace with increasing demands from the turbine blade industry.

Motivation for Work

The cost of energy produced from wind has decreased in recent years. To continue this trend, which is necessary to allow this clean energy source compete well with traditional generation methods, the associated costs need to continue to decline. There are several opportunities to improve the cost-effectiveness of using low-cost fiberglass materials in wind turbine blades:

1. Improved manufacturing methods can result in potential cost reduction when using low cost fiberglass materials in the form of improved structure quality. Wind turbine blades experience widely varying loadings and environments. Failure of a wind turbine blade can be catastrophic to the entire turbine.
2. In the relative absence of an understanding of material behavior in the structural design process, structures are typically overbuilt. This approach is costly and still may not prevent the potential failures that may occur because of failures in local regions. Improved understanding of material behavior in extreme situations may allow for more economical designs.
3. A better understanding of the link between manufacturing process and mechanical performance is likely to improve the economics of wind energy. It has been shown that the manufacturing method affects the final properties of a fiberglass structure [5]. A more complete understanding of material properties resulting from the preferred manufacturing process will allow for more economical designs.
4. Maintenance costs are also a significant factor in the wind industry. Blades that are in service are periodically investigated for early indications of impending failure. Nondestructive evaluation methods are sometimes used to detect damage in structures. X-ray methods and Ultrasonic methods have been used to some success. However, the use of X-rays needs to be done in a controlled environment because of health risks, and ultrasonic techniques frequently result in

ambiguous results [5]. Improved non-destructive evaluation technologies are needed to determine sub-critical damage and will reduce maintenance costs.

It is crucial to the industry to reduce costs while improving product performance. Advancement in these areas will continue to improve wind energy's ability to compete with traditional energy sources.

Research Approach

This thesis approaches these needs in three ways. Although these three areas of research are presented under the single thesis topic, they address the main theme of manufacturing-related cost reduction separately, and could be considered to have intrinsic value individually.

Pressure Bag Molding

A variation of RTM that is designed to remedy some of the limitations of the RTM process when used to produce large structures is introduced. This manufacturing method, "pressure bag molding," is described in detail. Mold construction and process parameters are identified.

Some of the critical molding process parameters are identified and compared with those of RTM. The limiting processing aspect of RTM for increased structure sizes is the in-plane flow mechanism. The pressure bag molding process was designed to reduce the effects of in-plane resin flow. Two critical parameters affected by the flow mechanism were chosen to be compared, injection time and injection distance from the injection port.

Since previous work has revealed a link between manufacturing method and mechanical performance [5], mechanical properties of products of pressure bag molding were compared with those of RTM products. Several mechanical tests were conducted to quantify the resulting mechanical performance of the resulting products of pressure bag molding. Fiber volume content, tensile strength, compressive strength, and short beam shear strength were compared.

Infrared Transmittance Testing

A new nondestructive evaluation method was developed for this work. This method is used in this work to compare damage properties of RTM products and pressure bag molding products, as well as to serve as a laminate "quality" metric.

This method involves the transmittance of light through the fiberglass material. The transmitted light is quantified and output voltage is recorded. A brief discussion of the physics involved in this method followed by a series of exploratory tests is included in Chapter 3.

In addition to the typical mechanical testing described above, a damage accumulation test comparing RTM to pressure bag molding products is described and demonstrated. This test involves two-dimensionally mapping the damage imposed on a chosen geometry of samples from the candidate processes. An X-Y stage apparatus was constructed to facilitate this test. The apparatus and electronics are described, along with the test methodology and results.

Numerical Progressive Damage Model

A numerical progressive damage model was also developed for this work. It was designed to aid in development of the damage accumulation test to correlate with the infrared transmittance technique discussed above, but as mentioned previously, the development of this model may have merit in other applications as well. Ansys was used to model the geometry that was chosen for the damage mapping test described above. Layered shell elements were used. An incremental displacement approach was applied in the model. At each incremental loading step, strains were checked against previously established failure criteria to determine if damage was introduced. If damage was determined to have taken place, the properties were downgraded and the solution at that displacement was reacquired.

The solution algorithm and Ansys code is included along with discussion of assumptions made. Results are displayed in the form of series of images showing Ansys' prediction of the progression of damage along with several other images of selected stress and strain distribution responses as damage accumulated.

Results from this test are compared with the two-dimensional mapping of damage in manufactured samples. The results of this comparison are difficult to interpret due to several factors which are discussed. The damage mapping resolution was found to be inadequate to accurately display damage properties. A failure mode also occurred in the mechanical testing that the progressive damage model did not account for. These limitations are discussed in detail.