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BIO-BASED WIND TURBINE BLADES: RENEWABLE ENERGY MEETS SUSTAINABLE MATERIALS FOR CLEAN, GREEN POWER

A Dissertation Presented
by
RACHEL S. KOH

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

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Mechanical Engineering
BIO-BASED WIND TURBINE BLADES: RENEWABLE ENERGY MEETS SUSTAINABLE MATERIALS FOR CLEAN, GREEN POWER

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Wood, once the material of choice for wind turbine blades, was phased out in the late 20th century as the growing size of blades imposed stricter material requirements and glass- and carbon-fiber composites gained industry popularity. However, the last several years have seen great advances in bio-based composite materials technology, including flax, hemp, and wood composites and laminates. These materials are increasingly utilized in high-performance, structurally demanding applications, largely because they are a more sustainable choice than many other engineering materials. Today, as the first glass-fiber wind turbine blades are ready to retire, wind developers are presented with an enormous challenge in disposing of these difficult-to-recycle blades. Through bio-based materials, the potential exists for these composite structures to be carbon neutral, renewable, and recyclable.
In comparison to glass and carbon composites, bio-based composites offer numerous advantages. In addition to the environmental benefits, these materials have excellent specific strength and stiffness properties, meaning that they are very strong and very stiff but also lightweight. This has made plant-based fibers especially attractive for use in large wind turbine blades because of how critical a blade’s mass is for turbine design. However, there are several unique challenges to the commercial use of bio-based composites compared to glass and carbon composites. These challenges include: limited availability of experimental data; a limited understanding of how bio-based materials behave under complex loading conditions; and the lack of a standard framework for computational modeling of these materials.

This dissertation expands the current bodies of knowledge on wood laminates, flax composites, and wind turbine blade design by addressing these potential limitations. First, the treatment of shear properties of laminated wood is addressed by comparing several existing methods for determining shear strength and stiffness and proposing a new method based on tension and compression test data of multiaxial laminates. Second, a yield criteria analysis explains how wood laminates under multiaxial stress may be integrated into commercial finite element software for structural design. Third, a similar methodology is used to make failure criteria recommendations for multiaxial flax-fiber laminates. Finally, these results are used in combination with an aero-structural optimization routine to produce examples of large bio-based and hybrid wind turbine blade designs. The techniques developed herein have broad implications for the design of bio-based composite structures worldwide.
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CHAPTER 1
INTRODUCTION

1.1 Motivation

Wood, once the material of choice for wind turbine blades, was phased out in the late 20th century as the growing size of blades imposed stricter material requirements and glass- and carbon-fiber composites gained industry popularity. However, the last several years have seen great advances in bio-based composite materials technology, including wood-based and other natural fiber reinforced materials. These materials are being utilized increasingly in high-performance, structurally demanding applications, in part because of their excellent material properties and in part because they are a more sustainable choice than many other engineering materials. Today, as the first glass-fiber wind turbine blades are ready to retire, developers are presented with an enormous challenge in disposing of these non-recyclable blades. Through bio-based materials, the potential exists for blades to be carbon neutral, renewable, and recyclable.

In comparison to traditional composite materials like fiberglass and carbon fiber, bio-based composites offer numerous advantages. These materials have excellent specific strength and stiffness properties, meaning that they are very strong and very stiff, but also lightweight. This has made plant-based fibers especially attractive for the large wind turbine blade because of how critical a blade’s mass is for blade and turbine design. Moreover, bio-based materials are renewable, biodegradable, and are generally considered to be low-cost compared to traditional composites. With
the recent growth in the wind energy industry, an enormous opportunity exists for bio-based composites to be used in wind turbine blades.

**The Promising Mechanical Properties of Bio-based Fibers**

Many research groups are working on characterizing the mechanical properties of plant fibers and their composites. Shah (2014) [128] wrote an important and current review of this work, which discusses the different types of natural materials and their properties. Using Ashby-type materials selection charts, comparisons may be drawn between natural fiber composites and other common engineering materials. What Shah has overviewed (and many researchers have shown) is that plant fibers have extremely competitive material properties in comparison to other engineering materials, and especially to other composite materials. In Figure 1.1, specific strength and specific stiffness are plotted for Plant-Fiber Reinforced Polymers (PFRPs) and some common engineering materials. PFRPs are shown in shaded shapes, while non-plant-based materials are unshaded. The ideal material for a wind turbine blade would have high stiffness and strength relative to density—corresponding to the upper right area of the graph. It is clear that the PFRPs do exceptionally well in this regard in comparison to many common engineering materials. One of the main disadvantages of bio-based composites is that they have only moderate *absolute* strength and stiffness properties, so they are best suited for applications in which the product’s self-weight influences the material requirements. The wind turbine blade is an excellent example of such a structure.

**The Problem of Turbine Blade Disposal**

Fiberglass is currently the most used structural material in turbine blades. Fiberglass manufacturing has increased worldwide from 5.9 million metric tons in 1999 to 8.7 million tons in 2011 [43]. At that time, the market share for wind energy was projected to double from 6% to 12% from 2010 to 2015, and expected to continue
Figure 1.1: Ashby-type materials selection chart for specific tensile modulus and tensile strength of Plant-Fiber Reinforced Polymer (shaded) materials and common engineering materials (unshaded).
to grow thereafter. This continuing increase in both worldwide fiberglass usage and market share attributed to wind energy makes the issue of disposing fiberglass ever more urgent. The blade is the only part of the turbine structure which is not a commodity at the end of turbine life, so it is typically just put in a landfill. However, this practice is illegal in many European countries and is expected to be prohibited in the E.U. altogether in the coming years.

Due to these strict environmental regulations, research groups from the Technical University of Denmark, Cambridge University and elsewhere have been working on technologies for recycling and reusing fiberglass from blades. Some architects are finding innovative applications for the reuse of turbine blades, like one group of Dutch architects that used them to build a children’s playground [78]. This is an effective use of what was otherwise landfill-bound material, but is not viable on the scale with which turbine blades must be disposed. Many methods of recycling fiberglass blades are being investigated in a partnership between a range of academic institutions and industry partners across Europe, under a project called GenVind [19]. The methods for decomposing the turbine blade include cutting, shredding, oven-baking, and supercritical fluid reacting. All of these methods have benefits, drawbacks, and different process outputs intended for different applications. The project demonstrates that the only process that lowers the embodied energy of the blade, or that is worth recycling from a life-cycle-analysis perspective, is to shred the fiberglass and use it as a filler material in concrete. There was a company founded in Germany to perform this process [154], but the company failed when the industry was not yet retiring enough turbine blades to supply it.

While many groups are looking at the issue of fiberglass recycling, the legislation regulating the use and disposal of fiberglass (e.g. the EU Directive on Landfill of Waste [54] and the EU End-of-life Vehicle Directive [55]) are seen as barriers to the increased, and even continued, use of fiberglass in many industries. Another
solution is to use a material that would be more easily recycled: bio-based fibers are much more readily recycled than fiberglass or carbon fiber. When coupled with bio-based adhesives, they have potential to be biodegradable entirely, making them very attractive from a life-cycle analysis, or sustainability, perspective.

The issue of landfill restrictions is not yet pressing in the United States, but it is expected to become so in the future. In the mean time, the Department of Energy commissioned a study titled *A Vision to Enhance U. S. Economic Security Through Renewable Plant/Crop-Based Resource Use* [22] to discuss the research and development needs for production, processing, and manufacturing of plant-based materials. There is interest in developing plant-based materials because of the landfill issue on a global scale, but the U. S. is also in a unique position in that there are more natural resources to begin with, and this is true in particular for farming land and timber resources. This positions the U. S. to be a leader in the development of bio-based composite materials.

**Bio-based Materials have Cost-Reduction Potential**

Simultaneously to the increased international interest in bio-based materials, the U. S. National Renewable Energy Laboratory (NREL) has issued a call for “incremental innovations” in wind turbine technology which will drive the cost of wind power down in the years and decades to come [89]. While wind energy is becoming increasingly cost-competitive with other sources of electricity, further technological innovation will drive it to become a leading source of power in the United States. There is substantial evidence to show that bio-based composite materials could offer cost reductions to wind turbine blade design because of the ease with which they are converted from their raw material state into a reinforcing fiber. [5] [110].

This cost reduction also holds for environmental cost. By far, the most costly part of the turbine from the life-cycle-analysis (LCA) perspective is its manufacturing [71],
and the rotor accounts for up to 33% of this cost because of the energy-expensive processing that is required to make the blades and their inability to be recycled. The current energy payback time (time for the turbine to produce as much energy as was used to make it) for blades is around 2 months for commercial wind turbines today, but increases as turbines become larger [95]. 39% of this energy embodiment may be attributed to the fibers alone, so fibers which are easier to process could have an important impact on the environmental cost of the blade, on top of the end-of-life benefit of being easier to recycle or waste.

The Role of Offshore Wind

The wind energy industry is trending towards offshore wind for several reasons, including limited land resource in some areas, the opportunity to build turbines closer to where the power demand is greatest (e.g. large cities), higher wind speeds, and logistical challenges with installing terrestrial wind turbines. For this and other reasons, industry is also trending towards larger turbines, as illustrated in Figure 1.2. This trend is because the wind resource improves with distance from the earth’s surface, and power available from the wind scales with wind velocity cubed in addition to rotor swept area. The size of today’s offshore turbines makes them nearly impossible to install on land. It is also these turbines, then, that are using the most composite materials. Consider especially that the mass of an individual wind turbine blade scales with length to a power of 1.7 to 2.7 [27]. Then the problems of cost and composite recyclability and disposability apply especially to offshore wind energy development. Intuitively, for as hard as fiberglass is to recycle in the first place, this difficulty is exacerbated when the part that requires disposal is on the order of 100 metric tonnes [67].
Figure 1.2: Modern turbines are trending towards taller hub heights and longer blade lengths. From [59].
Challenges with Bio-based Materials

While there is substantial motivation towards the use of bio-based materials, there are also various challenges to the commercial use of these materials. These are summarized as follows:

1. Limited experimental data for bio-based composites in general;
2. A limited understanding of complex loading conditions specifically, such as shear, off-axis, multiaxial, and fatigue loading;
3. Lack of a standard framework for finite element modeling of material failure in bio-based materials;
4. Perceived and actual variability in mechanical properties;
5. High sensitivity to moisture;

1.2 Objectives

It is the objective of this thesis to address and mitigate some of the challenges to designing multi-megawatt wind turbine blades from bio-based materials. To this end, specific objectives are:

1. Generate experimental data for novel, bio-based materials under complex loading conditions which are common to wind turbine blades.
2. Determine the shear strength and stiffness of laminated wood and a flax composite laminate.
3. Recommend failure criteria and subsequent sets of parameters for use in the finite element modeling of (a) multiaxial wood laminate and (b) flax laminate composite structures.

1.3 Contributions

The new pieces of knowledge that come out of meeting the objectives of this research are:

1. A method for measuring the shear strength and stiffness of laminates based on axial testing of multidirectional layups;

2. Shear strength and stiffness measurements for laminated wood veneer and a laminated flax composite;

3. A framework for evaluating the accuracy of failure criteria in comparison to experimental data with many different material stress states;

4. Integration of composite failure theories with bio-based wood and flax laminates, and a measurement of how accurately the theories predict material behavior;

5. Stress-strain data for wood and flax composite laminates in tension and compression across five unidirectional and multidirectional layups;

6. A framework for the baseline structural comparison of different material choices in multi-megawatt wind turbine blades;

7. A baseline structural comparison between several 5-megawatt wind turbine blade designs using conventional and bio-based materials.

1.4 Overview of Dissertation

This dissertation begins in Chapter 2 with a background discussion of engineering approaches to bio-based materials design and large turbine blade design. This background chapter reviews the literature relating to the present study.
The focus of Chapter 3 is on shear properties of multiaxial wood laminates. Experimental methods for the characterization of shear strength and stiffness of both wood-based and glass- or carbon-based composite materials are highly contested because shear properties are difficult to isolate experimentally. In this study, the researchers present a novel method for calculating shear strength, stiffness, and interaction parameters of laminated wood veneer panels by coupling experimental data from tension and compression tests of multiaxial laminates with an optimization routine for Tsai-Wu and Hashin failure criteria. Optimal shear stiffness and strength are reported for both theories. They align well with else is available in the literature, suggesting that this experimentally-straightforward method is a viable way to evaluate shear properties of wood laminates.

Chapters 4 and 5 examine failure criteria for use in wood laminates and flax laminates, respectively. These two studies use experimental mechanics to inform computational models of bio-based composite materials. In finite element modeling, combined loading conditions are modeled using failure criteria, which consider all stress tensor components in order to predict material yielding or failure. In order to understand which criteria should be used for modeling multiaxial wood and flax laminates, analyses of material behavior under different stress states are presented. Tension and compression test data of multiaxial laminates are used to fit several failure theories and parametric optimization is performed on each theory. The relative benefits and drawbacks of different theories are discussed and recommendations for best practices are given.

In Chapter 6, several designs for bio-based and hybrid bio-based 5-megawatt turbine blade designs are generated using a structural blade optimization framework. Blades are also given an environmental sustainability rating, and design advantages to bio-based materials are discussed and explored.
1.5 Terminology

1.5.1 Abbreviations

a baseline assessment of the environmental goodness of a turbine blade design. These designs allow for the discussion of design trade-offs in using wood and flax laminates for different components of a standard turbine blade.

AP - angle-ply
CLT- Classical Lamination Theory
DoE or USDoE- United States Department of Energy
FE or FEA or FEM- finite element, finite element analysis, or finite element model
FRP- fiber-reinforced polymer
LCA- life cycle analysis
LVL- laminated veneer lumber
MD- multidirectional
MoR- modulus of rupture
NREL- National Renewable Energy Laboratory
PFRP- plant-fiber reinforced polymer
PSL - parallel strand lumber
SC - spar cap
SCL- structural composite lumber
SNL or Sandia - Sandia National Laboratories
SW - shear web
TE - trailing edge reinforcement
UD - unidirectional

1.5.2 Mathematical Symbols

$a$ - larger cross section dimension of a rectangular beam
$b$ - smaller cross section dimension of a rectangular beam
\( G_{12} \) - in-plane shear modulus
\[ \mu = \sqrt{\frac{G_{xx}}{G_{yz}}} \]
\( \mu_1 \) - constant term which depends on the width to depth ratio of a rectangular cross section for isotropic shear stress

\( S_1T \) - parallel-to-grain/fiber tensile strength
\( S_1C \) - parallel-to-grain/fiber compressive strength
\( S_2T \) - perpendicular-to-grain/fiber tensile strength
\( S_2C \) - perpendicular-to-grain/fiber compressive strength
\( S_{12} \) - in-plane shear strength, parallel-to-grain
\( S_{21} \) - in-plane shear strength, perpendicular-to-grain
\( \sigma_1 \) - parallel-to-grain/fiber stress
\( \sigma_2 \) - perpendicular-to-grain/fiber stress
\( \sigma_{12} \) - shear stress
\( \tau \) - shear stress
\( \tau_{yz} \) - in-plane shear stress
\( \tau_{xz} \) - through-thickness shear stress
\( V_f \) - volume fraction fibers
\( V_m \) - volume fraction matrix
\( V_p \) - volume fraction porosity
CHAPTER 2
BACKGROUND

The objective of this thesis is to evaluate the potential for using bio-based materials in large wind turbine blades, and to make steps towards closing the knowledge gap between bio-based and traditional composite materials. This chapter is a summary of the knowledge body which applies first to design with bio-based materials including wood laminates and bast-fiber composites, then to the design of large wind turbine blades. Each section provides background knowledge that frames and sets the foundation for this research.

2.1 Bio-based Materials

Bio-based composite materials have gained market popularity in many industries in response to demands for “green materials”, materials which have less adverse impact upon the environment [110]. The environmental impact of a material may be evaluated by considering factors including the acquisition, processing, lifetime, maintenance, and disposal of that material. Bio-based materials tend to require less processing energy and far less nonrenewable resources than traditional composite materials, and they are made either mostly or entirely from biodegradable materials. Natural fibers such as wood and hemp may be used in place of glass or carbon in many applications [149], and the field of biopolymers for bonding is an active area of academic research [141] [110]. When comparing natural fibers to carbon and glass, the main advantages are renewability, biodegradability, good specific properties, and low-cost raw materials [100]. The disadvantages are that plant fibers have moderate
mechanical properties, relatively high sensitivity to moisture, and lack of developed manufacturing techniques.

In considering what types of bio-based materials would be most suitable to large wind turbine blades, this thesis considers both wood and bast-fiber derivatives, which have different characteristics, advantages and disadvantages, even compared to one another. The main limiting factor to our material search is that the size of the structure is so great. With blade lengths around 60 meters and root diameters of 3 to 4 meters for a 5-megawatt turbine, it wouldn’t be possible, for example, to carve an entire blade from solid wood. The size and the weight make a laminated shell a much more practical approach. For this reason, this thesis focuses on laminated wood and flax, which will be straightforward to incorporate into current manufacturing processes for large turbine blades.

This thesis proposal will focus first on wood-based composites, for which there exists a substantive body of literature because of wood’s relatively long history in the construction industry. Bast-fiber (the stiff, strong fibers inside the bark of a plant stem, sometimes called the “inner bark”) reinforced composites such as flax and hemp will be introduced in Section 2.1.2, and bamboo is discussed briefly in Section 2.1.3, though it is not the focus of this thesis. Later, computational design tools will help make design decisions around which of these materials to use. This can involve incorporating different types of bio-based materials in different sections of the blade, depending on the material requirements in each component of the blade as discussed in Section 2.2.

2.1.1 Wood-based Composites

Wood composites are a subsection of bio-based composites which use wood as the fibrous, reinforcing component in a composite material. The most common implementation of wood composites is in the building and construction industry, where a
line of wood composite products known as Structural Composite Lumber (SCL) has been under development since the turn of the 20th century. Sharp (1996) reviews the history, current state, and potential future developments of SCL [130]. SCL first arose in the early- to mid-1900s as a method for utilizing a higher percentage of a harvested tree. This was driven in part by a concern for the environment in a time where people were very concerned with deforestation and diminishing the wood resource, and in part by the need to use smaller logs when large logs, from which many pieces of lumber could be cut, were not in abundance.

The process of chopping or veneering lumber makes any defects, such as knots, much smaller. When these pieces are then glued back together, these defects are spread out, producing much smaller defects over a large volume. This distribution of defects led to strength and stiffness properties which were considerably more predictable than for traditional sawn lumber [74]. This concept is represented graphically in Figure 2.1. In mechanical tests for lumber in structural sizes, failure was often driven by the type, size, and location of defects in the lumber. This is highly variable across wood species, individual trees, and cuts within the tree. In engineered wood composites, failure characteristics tend to be more predictable because those defects are spread over a large volume. This is significant because in construction applications it is typical to design to the lowest fifth percentile [65], so this design strength increases substantially with the decrease in variability.

The most common types of SCL are Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), and Laminated Strand Lumber (LSL). Each have differences in material properties and use, but they are fundamentally comprised of the same materials: wood and adhesive. The differences are outlined in the following section on Manufacturing Processes.
Figure 2.1: An arbitrary strength (tensile, compressive, bending, or shear) property of a wood laminate as compared to timber of the same type.
2.1.1.1 Manufacturing Processes

Laminated veneer lumber (LVL) is produced in a similar fashion to plywood. Veneer is rotary peeled, dried, spread with adhesive, assembled in the desired configuration, and pressed either in conventional hot presses or on a continuous or step basis, then trimmed to the desired size [153], as shown in Figure 2.2. The primary distinguishing factors between plywood and LVL are (1) that plywood alternates plies at a 90-degree angle from one another, whereas LVL is a unidirectional material, (2) LVL is typically of higher quality because of more rigorous inspection and grading requirements which coincide with the more rigorous applications of the material, and (3) LVL is usually manufactured into beams, while plywood is usually manufactured in sheets.

Other concepts for wood composites include Parallel Strand Lumber (PSL), where veneers are chopped into long strands then pressed and laminated into beams, and Laminated Strand Lumber (LSL), where shorter flaked strands are oriented and laminated into beams. These manufacturing concepts and the resulting products can be visualized in Figure 2.2. Table 2.1 shows some of the physical differences in the resulting products.

Table 2.1: Comparison of material properties and utilization of three Structural Composite Lumber types. Modulus of Rupture is estimated from [65] and available datasheets. Modulus of Elasticity refers to the parallel-to-grain stiffness and is taken from [130]. Material utilization refers to the percentage of the tree which is utilized to make that product and comes from [130]. †small specimens, not in structural sizes.

<table>
<thead>
<tr>
<th>product</th>
<th>Modulus of Rupture MPa</th>
<th>Modulus of Elasticity GPa</th>
<th>Material Utilization %</th>
</tr>
</thead>
<tbody>
<tr>
<td>clear wood†</td>
<td>40-110</td>
<td>6-13</td>
<td>40</td>
</tr>
<tr>
<td>LVL</td>
<td>34-86</td>
<td>10-17</td>
<td>52</td>
</tr>
<tr>
<td>PSL</td>
<td>37</td>
<td>12-16</td>
<td>64</td>
</tr>
<tr>
<td>LSL</td>
<td>22-35</td>
<td>8-12</td>
<td>76</td>
</tr>
</tbody>
</table>
Figure 2.2: Manufacturing processes for three types of Structural Composite Lumber: Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), and Laminated Strand Lumber (LSL). Adapted from [130].
The processing of a material has great influence over that material’s characteristics and there is a great deal of literature dedicated to the effects of processing parameters on wood-based structural materials. In this thesis, the need for high performance composite materials encourages us to consider processing parameters as ways to advance and maximize the potential of these materials for our specific application.

Oregon State University and especially D. B. DeVallance [48] [49] has done extensive work on quantifying the influence of veneer roughness, lathe checks, and annual ring characteristics on the glue bond quality in Douglas Fir LVL. The researchers found that “When present, lathe checks create more surface area, thus resulting in over-penetration and adhesive dry-out at the glue line.” These lathe checks are formed on the side of the veneer in contact with the lathes knife during wood veneering. The failure load of wood was especially influenced by lathe check frequency. As lathe check frequency and average lathe check depth increased, the elasticity of the glue bond was found to decrease. In summary, lathe checks decrease both strength and elasticity, but aren’t easily avoided.

Finn (2014) [60] describes a manufacturing process for small wood veneers whereby veneers are flat cut and thickness sanded before adhesive is applied. She demonstrated in 3-point bend tests of LVL made from clear Red Spruce that this method produced significantly stiffer and stronger LVL on a small scale.

2.1.1.2 Strength and Stiffness Properties

Material properties for timber and laminated wood are given in Table 2.1, and again in comparison to other wind turbine blade materials in Table 2.6 (section 2.2.4). These values, while broad, provide a context in which to think about the strength and stiffness of wood and wood-based composites. Importantly, wood tends to have lower strength and stiffness when compared to glass and carbon, but also lower den-
sity. Therefore, the specific properties are very competitive in applications like the turbine blade, where weight is an important consideration. These specific strength and stiffness of many bio-based and traditional engineering materials were presented in Figure 1.1.

In this dissertation, the focus is on tensile strength and the experiments are performed with small, clear test specimens. To make adequate comparisons with what else exists in the literature, it is important to note that Modulus of Rupture (MoR) is more conservative than tensile strength.

Anisotropy is the property of being directionally dependent, and anisotropic materials exhibit different mechanical properties when tested in different directions. In orthotropic materials, these properties are defined in three principal, orthogonal directions. In transversely isotropic materials, these properties may be defined in two principal directions. Wood is often considered an orthotropic material, with the principal directions being longitudinal, radial, and tangential with respect to wood grain direction. However, with the properties in the radial and tangential directions being relatively close to one another as compared to the longitudinal direction, it is often close enough to see it as a transversely isotropic material, with the directions being parallel-to-grain and perpendicular-to-grain. Engineered wood products are similarly distinguished. Properties of wood laminates are defined in parallel to the glue line and perpendicular to the glue line directions. When a material property in any other direction is needed, it is found using grain-angle relationships such as Hankinson’s formula, which is presented in Section 2.1.1.6.

Especially of interest in this thesis are longitudinal and shear elastic moduli of wood laminates, since wind turbine blade designs are often governed by maximum tip deflection. Janowiak, et al., (2001) [82] present orthotropic elasticity properties of 9 different structural composite lumber products, using five point bend tests and torsional stiffness measurement tests. Orthotropic properties evaluated in this study
include flatwise longitudinal and transverse elastic moduli; in-plane and through-thickness shear moduli; poisson’s ratio; and tensile and compressive, longitudinal and transverse elastic moduli. A relevant subset of these results is presented in Table 2.2. Their experimental test data strongly indicate that structural composite lumber products have much different elastic properties than solid wood, and that the elastic moduli often exceed those of solid wood of the same species.

The Janowiak study also suggests a difference between elastic properties which have been determined using different test methods. That is, the same property of the same material evaluated using a different test method will elicit a different result. The discrepancy between shear moduli between the five-point bending test and the torsional test was found to be especially large. As seen in Table 2.2, the torsional test consistently measures a higher value for $G_{12}$ and a lower value for $G_{13}$ than does the five-point bending test.

### 2.1.1.3 Experimental Methods in Wood Laminate Mechanics

Many mechanical properties of wood may be examined by testing small wood coupons; this testing is outlined in ASTM Standard D143 [7]. However, there are issues with applying small-scale test results to full-scale structures. The size effect is the largest issue, addressed in Section 2.1.1.7. Other drawbacks to doing experimental testing on small test specimens include that in compression, delamination of the outer strands becomes a dominant failure mode when the number of strands is very small.

ASTM-D198 [8] outlines test methods for lumber in structural sizes. There are not standards which specifically address laminated wood or other structural composite lumber products, but this standard was expanded upon in 1999 (from the original version from 1927) to be adaptable to a wide variety of wood structural members, including laminates. The standard includes test methods for flexure, compression, tension, torsion, and shear modulus.
Table 2.2: Select results from Janowiak, et al., investigation of orthotropic behavior of lumber composite materials [82]. All materials are of the 2.0E grade.

<table>
<thead>
<tr>
<th>SCL Material</th>
<th>Test Method</th>
<th>Elastic Property</th>
<th>Average (MPa)</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP LVL</td>
<td>FPBT</td>
<td>$E_1$</td>
<td>16,500</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_2$</td>
<td>580</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{12}$</td>
<td>476</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>354</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{23}$</td>
<td>64</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td>TSMT</td>
<td>$G_{12}$</td>
<td>636</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>282</td>
<td>47.2</td>
</tr>
<tr>
<td>DF1 LVL</td>
<td>FPBT</td>
<td>$E_1$</td>
<td>18,300</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_2$</td>
<td>500</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{12}$</td>
<td>405</td>
<td>21.3</td>
</tr>
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<td></td>
<td></td>
<td>$G_{13}$</td>
<td>331</td>
<td>17.3</td>
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<td></td>
<td></td>
<td>$G_{23}$</td>
<td>46</td>
<td>36.5</td>
</tr>
<tr>
<td></td>
<td>TSMT</td>
<td>$G_{12}$</td>
<td>642</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>440</td>
<td>27.5</td>
</tr>
<tr>
<td>DF2 LVL</td>
<td>FPBT</td>
<td>$E_1$</td>
<td>14,400</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_2$</td>
<td>440</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{12}$</td>
<td>691</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>435</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{23}$</td>
<td>48</td>
<td>39.6</td>
</tr>
<tr>
<td></td>
<td>TSMT</td>
<td>$G_{12}$</td>
<td>805</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>86</td>
<td>14.3</td>
</tr>
<tr>
<td>YP LVL</td>
<td>FPBT</td>
<td>$E_1$</td>
<td>15,200</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_2$</td>
<td>450</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{12}$</td>
<td>247</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>314</td>
<td>33.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{23}$</td>
<td>96</td>
<td>37.9</td>
</tr>
<tr>
<td></td>
<td>TSMT</td>
<td>$G_{12}$</td>
<td>416</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>779</td>
<td>58.2</td>
</tr>
<tr>
<td>SP PSL</td>
<td>FPBT</td>
<td>$E_1$</td>
<td>17,500</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_2$</td>
<td>620</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{12}$</td>
<td>501</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>405</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{23}$</td>
<td>85</td>
<td>32.7</td>
</tr>
<tr>
<td></td>
<td>TSMT</td>
<td>$G_{23}$</td>
<td>26</td>
<td>31.7</td>
</tr>
<tr>
<td>YP PSL</td>
<td>FPBT</td>
<td>$E_1$</td>
<td>16,300</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_2$</td>
<td>550</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{12}$</td>
<td>252</td>
<td>21.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{13}$</td>
<td>372</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{23}$</td>
<td>99</td>
<td>39.4</td>
</tr>
<tr>
<td></td>
<td>TSMT</td>
<td>$G_{23}$</td>
<td>116</td>
<td>21.7</td>
</tr>
</tbody>
</table>
While there is a clear consensus for test methods to determine tensile and compressive properties of wood and its composites, there is no such consensus when it comes to shear properties. Shear strength and stiffness are essential properties to the design of wind turbine blades, and are explored in much more depth in Chapter 3. For this reason, test methods for these properties in particular are given their own section in 2.3.

2.1.1.4 Numerical Methods in Wood Mechanics

Clouston and others have done extensive work on the numerical modeling of mechanical properties of structural composite lumber [37]. The first major thrust of Clouston’s work was to demonstrate the Tsai-Wu strength theory for LVL made of Douglas Fir [41]. Clouston considered many failure theories and demonstrated that the Tsai-Wu theory was most appropriate for predicting off-axis tensile test data. The remaining results of this work are summarized in subsequent publications.

Equation 2.1 shows the general form of the Tsai-Wu failure criterion in 3D space. Equation 2.2 shows the plane stress formulation of this equation, which applies to wood laminate materials. In both Equations 2.1 and 2.2, $\sigma_i$ denotes stress components. The strength parameters $f_i$ are defined in Equation 2.3, where $X_{t,c}$ denotes the longitudinal strength in tension and compression, respectively, $Y_{t,c}$ denotes the transverse strength in tension and compression, and $S$ denotes in-plane shear strength.

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>Southern Pine</td>
</tr>
<tr>
<td>DF</td>
<td>Douglass Fir</td>
</tr>
<tr>
<td>YP</td>
<td>Yellow Poplar</td>
</tr>
<tr>
<td>PSL</td>
<td>Parallel Strand Lumber</td>
</tr>
<tr>
<td>LVL</td>
<td>Laminated Veneer Lumber</td>
</tr>
<tr>
<td>FPBT</td>
<td>Five Point Bending Test</td>
</tr>
<tr>
<td>TSMT</td>
<td>Torsional Stiffness Measurement Test</td>
</tr>
</tbody>
</table>
The only strength parameter which is undefined in Equation 2.3 is $f_{12}$, which is often defined experimentally as discussed further in this section. When Clouston, et al., compared the 2-dimensional (plane stress assumption) with the 3-dimensional Tsai-Wu criterion, they found that the plane stress assumption was valid for the specific cases they examined. In their test configurations, they showed that their analyses produced negligible out-of-plane stresses. However, they suggest that for large-scale wood composite structures, this may not be the case. The authors also present a method for incorporating size effect into the Tsai-Wu strength theory; this method is addressed in Section 2.1.1.7.

In 1998, Clouston, et al., published an investigation of the strength parameter $f_{12}$, the interaction term of the Tsai-Wu theory, for laminated veneer [40]. This parameter is valid under plane stress conditions and for Douglas Fir laminated veneer. The estimations for $f_{12}$ were made using nonlinear least-squares fit to cumulative probability distributions of off-axis tensile data. It was found that parameter $f_{12}$ has strong dependence on grain angle, and sensitivity analyses showed that data from smaller grain angles were more stable in establishing $f_{12}$ than larger grain angles.

\begin{equation}
 f_i \sigma_i + f_{ij} \sigma_i \sigma_j = 1 \quad \text{for } i,j = 1,2,3,4,5,6
	ag{2.1}
\end{equation}

\begin{equation}
 f_1 \sigma_1 + f_2 \sigma_2 + f_{11} \sigma_1^2 + f_{22} \sigma_2^2 + f_{66} \sigma_6^2 + 2 f_{12} \sigma_1 \sigma_2 = 1
	ag{2.2}
\end{equation}

\begin{equation}
 f_1 = \frac{1}{X_t} - \frac{1}{X_c}; \quad f_2 = \frac{1}{Y_t} - \frac{1}{Y_c}; \quad f_{11} = \frac{1}{X_c X_t}; \quad f_{22} = \frac{1}{Y_c Y_t}; \quad f_{66} = \frac{1}{S^2}
	ag{2.3}
\end{equation}

In 2001, Clouston, et al., [42] proposed a constitutive model that is comprised of four behavioral domains: elastic, elastoplastic, post-failure brittle, and post-failure ductile. The differences in post-failure behavior address the well-known phenomenon of wood having brittle failure in tension but ductile failure in compression. In one
study [37], the model is used to predict the behavior of $[+/- 15]$ and $[+/- 30]$ angle-ply laminates in tension and compression. The authors use the Tsai-Wu criterion in combination with an orthotropic plasticity yielding criterion developed by Hill [76]. The authors conclude that their plasticity-based stochastic finite element model is a promising method for modeling nonlinearities in stress-strain behavior of wood strand composites. For future work, they suggest additional validation for other failure modes and layup configurations. In a subsequent paper [38], the same authors also validated the model for 3-point bending.

In 2007, Clouston [36] expanded on the previous model to predict the mechanical behavior of PSL in tension, compression, and bending. In addition to the prior modeling considerations, simulations were included to predict the void content and the grain angle variation in PSL, which had not been needed in laminated veneer models. Comparison of the model to experimental results demonstrates the validity of this modeling technique for PSL.

Arwade, et al., (2009) [4] present a computational model for the spacially-variant elastic properties of parallel strand lumber. The correlation length for elastic properties is found to be on the order of several meters and is independent of cross section size but dependent upon number of strands in a cross section. As the number of strands in a cross section increases, variability in elastic properties decreases.

Xue, et al., (2012) [148] used ANSYS to produce numerical analyses on 5-point bending tests of LVL of various assembly patterns which combined poplar and birch woods. The researchers demonstrated that using a higher quality veneer for the outer plies with a lower quality veneer for the inner plies is a good practice for optimizing a strength-to-price ratio and improving the utility value of wood. They used experimental results to validate the numerical and theoretical predictions, and concluded that the ANSYS simulations were appropriate for LVL mechanical property analysis due to strong agreement between numerical and experimental results. In their ANSYS
model, they used the Plane82 element type, which is an 8-noded element with two degrees of freedom at each node, which is recommended for mixed quadrilateral-triangle meshes of irregular shapes. It should be noted that ANSYS no longer recommends the use of this element, as it has released an updated version of an element with the same basic characteristics, called Plane183.

Winans (2008) [147] developed a finite element model to examine the mechanical properties of PSL using ADINA. The author chose to use the Tsai-Hill failure criterion and 27-node 3D block elements. Strand length, elastic constants, plastic constants, and grain angle were all treated as random variables, which were determined using probability mass functions from existing data. The model was verified experimentally and determined to be very accurate. When compared to simplified models which did not include finite element analysis, the FEA results were more accurate and more computationally expensive.

Yang (2013) [150] implemented finite element analyses using ADINA for evaluating the shear strength of LVL using torsion tests. The author used 8-node brick elements. She held one end in a fixed boundary condition, while applying a force couple to the other end using opposing transverse loads. She found that results were consistent with both experimental findings and prior work within the mid-span of the beam, 2d (twice the depth) from the edges of the beam. However, the model was inaccurate close to the edges of the beam because of a discrepancy in the boundary conditions of the model and the boundaries in the actual experiment.

Gupta, et al., (2002) [69] present finite element analyses showing the stress distribution in a torsion test of full size structural lumber. The authors present a finite element model in ANSYS which they use to further their understanding of stress distribution and failure modes in torsion. Their models show that within the shear span (twice the specimen depth away from the grips), a uniform shear stress distribution occurs across the span. This distribution shows a maximum stress at center-depth.
(in the y-direction), which dissipates towards the corners of the beam. This result aligns with the theory presented by Lekhnitskii [92] and was verified experimentally in a subsequent study [70].

J. K. Cha developed a Fortran program called LAMINA as part of his Ph.D. work in off-axis cracks in wood laminates under tensile stress. This program numbers nodal points and calculates their coordinates. In later work, Cha [32] used the program in conjunction with NASTRAN to perform finite element analyses. This work is discussed in Section 2.1.1.6.

2.1.1.5 Variability in Material Properties of Engineered Wood Products

In order to consider wood laminate materials in potential markets, any variability in material properties between and within wood species must be addressed. All engineering materials have variable properties for many different reasons, and quantifying this variability is important to safe engineering design. Wood materials are often seen as highly variable properties as compared with other engineering materials, so proponents of wood design have long strived to quantify and reduce this variability.

As previously discussed, structural composite lumber products tend to have lower variability as compared to timber of the same species. Winans (2008) [147] demonstrated that the variation in bending test results from PSL were approximately 50% lower than those of dimension lumber due to the averaging of material properties for nominally sized members.

Tichy, et al., (1978) [136] experimentally quantified the stiffness, tensile strength, and MOR for glued-laminated pine beams with varying ply numbers. The ply number varied from 5-40 plies as the volume of the beam stayed the same, so the ply thickness was decreased. There were no significant effects on the magnitude of properties during this variation, but variability of properties generally decreased. The failure mode changed from tension to shear as ply number increased, with shear failure occurring.
mostly at glue lines. The authors hypothesize that if shear failures were excluded, they would see increases in strength and stiffness. An additional study with greater sample size and greater variation in laminate thickness would confirm or reject this.

2.1.1.6 Grain Direction and Ply Organization

Hankinson’s formula [73], presented in Eqn. 2.4, is used for computing the off-axis dowel bearing strength of wood in the building code. The formula was developed empirically by crushing spruce specimens and subsequently validated for other wood species. It applies both to the elastic limit in compression and the ultimate strength in compression. Hankinson suggests that \( n = 2 \) according to his experimental evidence, which has been subsequently verified by other researchers for other wood species. However, \( n \) may be different for different materials. In Equation 2.4, \( \sigma_{\parallel} \) represents parallel-to-grain strength while \( \sigma_{\perp} \) represents perpendicular-to-grain strength, and \( \theta \) is the grain angle of the specimen.

\[
\sigma = \frac{\sigma_{\parallel} \ast \sigma_{\perp}}{\sigma_{\parallel} \ast \sin^n(\theta) + \sigma_{\perp} \ast \cos^n(\theta)}
\]  

(2.4)

Bodig and Jayne (1982) [23] present the effect of grain angle rotations on the effective modulus of Sitka spruce. While some researchers have fit off-axis moduli calculations to Hankinson’s formula with success, this study suggests that straightforward transformation equations are better suited to this purpose.

Burdulu, et al., (2007) [30] examined the effects of ply organization and loading direction on the bending strength and stiffness of laminated veneer beams. In this case, all plies were aligned along the longitudinal axis, with ply organization referring to the stacking of poplar and birch plies in layups which vary by material stackup. While the study examined loading both perpendicular to the glue line and parallel to the glue line, the authors did not explicitly compare the two loading directions.
It does not appear that loading direction had a significant impact on strength or modulus.

Cha (1994) [32] developed a mathematical model to predict elastic properties in tension of 3-layer LVL which has outer layers aligned along the longitudinal axis and an inner layer which aligned off-axis and cracked. The purpose of the model is to predict the tensile behavior of material containing cracks which are not aligned longitudinally with the stress or principal material direction. The mathematical model was verified experimentally. It was demonstrated that a center layer with perpendicular grain orientation had almost no contribution to tensile strength and stiffness of the specimen. The strength and stiffness of that specimen were about two-thirds of the values for specimens with all three straight-grained layers, so the properties observed were those of the two outer layers. The authors concluded that (1) the presence of an off-axis center ply in 3-layer LVL under longitudinal tensile stress causes a complex stress state which includes high shear and transverse tensile stresses; (2) transverse stress in the center ply changed from tension to compression when the slope of the grain was near 90 degrees, while transverse stress in the outer plies was compression for grain angles up to 40 degrees, then changed to tension; (3) Hankinson’s formula with n=2.5 provided the best fit to the FEM values of longitudinal tensile stresses in all layers, while the typical value of n=2 underpredicted strength at intermediate grain angles.

2.1.1.7 Size Effect

The strength of wood and wood-based composites in brittle failure modes depends heavily on the volume of the stressed material. These effects are attributed to strength-limiting defects which are present in the material. A larger volume of material is more likely to contain a larger flaw and thus will exhibit lower strength and stiffness under the same loading conditions as a smaller volume of the same material.
Weibull (1939) developed a weakest-link theory to predict the probability of failure in perfectly brittle, homogeneous, isotropic materials. This is widely used today to predict failure in wood and wood composites [23]. Weibull postulates that variation in properties of uniformly stressed, homogeneous materials is due to the statistical probability of a critical flaw occurring within a given volume.

The Forest Products Laboratory, under the researcher B. Bohannan in 1966 [24], applied Weibull’s theory to wood members in bending. They compared experimental results evaluating the size effect on MOR of wood beams in bending to theoretical predictions and found reasonably good agreement between the two.

Madsen [99] modified Weibull’s weakest link theory to account for the material anisotropy of timber. While the weakest link theory assumes that the failure-initiating flaws are distributed uniformly within the material volume, Madsen suggest that the distribution of flaws in wood differ in the different directions of the wood. Bending tests verified this approach, and found that length effects are more important than depth effects in beams in bending.

Clouston, et al., (1998) used a similar approach to incorporate size effect into the Tsai-Wu strength criterion for Douglas-fir laminated veneer using the Weibull theory [39]. The researchers implemented the theory in two distinct ways to account for the perpendicular-to-grain and parallel-to-grain loading directions, and found that results were in reasonable agreement with experimental findings in the literature.

Arwade, et al., (2011) [3] evaluated the length effect in tensile strength for LVL and PSL in longitudinal, transverse, and through-thickness (PSL only) directions. The results indicated the existence of length effect in LVL and PSL for the longitudinal and transverse directions. Length effect adjustment factors are presented.
2.1.1.8 Fatigue

In many structural engineering applications, fatigue is not a limiting design factor, particularly for wood. For example, building elements are usually designed considering the effects of creep and load duration only. However, wind turbine blades undergo significant fatigue loading. The popularity of wood in small wind turbine blades which undergo significant fatigue loading has necessitated the investigation of fatigue properties of wood.

The static and fatigue properties of a Douglas-fir/epoxy laminated wood material were investigated by NASA in 1985 [83] for use in the NASA/DOE MOD 5A wind turbine. While the turbine was never built, this study was among the first to attempt to quantify fatigue properties of wood or wood-based materials. The researchers iteratively evaluated 14 different test configurations for the fatigue test, and finally arrived at a specimen which was dog-bone shaped, had longitudinal stiffness tapering by way of fiberglass layers built up near the grips, and included a u-shaped crushing limiter to protect the specimen from crushing under the grips of the test fixture. Fatigue tests were carried out both at room temperature and under high-temperature, high-humidity conditions. The results from this test are difficult to interpret because of the scarcity and scatter of points on the S-N plots, and the researchers recommend further testing in order to produce statistically significant results.

Tsai and Ansell (1990) [137] investigated the fatigue in flexure of laminated Khaya ivorensis (an inexpensive medium-density mahogany) manufactured using two veneering methods, solid Sitka spruce, and laminated beech in two grain orientations. These materials represent both hardwoods and softwoods which are commercially available in areas considering using wood in wind turbine blades. The specimens were tested across five $R$ ratios and three moisture contents. The study found that for the species tested, fatigue life was species-independent when normalized by static strength. Increased moisture content reduced both static and fatigue strength, and constant-life
diagrams depict the effect of \( R \) on fatigue life. Fatigue life is lowest in reversed loading \((R < 1)\) with fatigue life decreasing with decreasing \( R \). The researchers use optical microscopy to demonstrate that fatigue damage is a progressive process which begins on the compression face of flexural specimens.

Bonfield and Ansell (1991) [25] investigated fatigue properties of Khaya ivorensis and Douglas-fir in tension, compression and shear. The researchers used necked specimens to avoid end effects and aluminum tabs to avoid crushing at the grips. They also employed scanning electron microscopy (SEM) upon specimen failure to examine the fracture topography. The authors were able to attain enough data to present both S-N diagrams and constant life diagrams for Khaya in axial and shear loading. They presented Douglas-fir results in comparison with Khaya at \( R=-1 \) (meaning that the tensile and compressive stresses were equal in magnitude) and show that Douglas-fir tends to have higher static compressive strength, its strength decreases more rapidly in fatigue. The data are too scattered to determine the presence of an endurance limit. In order to evaluate the presence of a size effect, the authors tested 17 large samples at \( R=-1 \). The results suggest that the size effect is not present in axial tension-compression fatigue, but the authors suggest that this may not be the case in flexure.

### 2.1.2 Plant Fiber Reinforced Composites

In comparison to wood, there is a much smaller body of research surrounding plant-fiber composite materials, as the treatment of these materials as modern composites is relatively new, and their manufacturing processes are still under development. Though wood is also a plant-based fiber, it is common to distinguish between “wood” and “plant” based composite materials, where plant-fiber composites usually refers to non-wood fibers, mostly grasses, which have been processed into yarns, chopped mats, and other common composite products. In comparison to wood, the
processing of plant-fiber composites more closely mimics that of glass and carbon fiber composites. Madsen and Gamstedt (2013) [100] outline the manufacturing, mechanical properties, and microstructures of wood and plant fiber composites in order to draw comparisons between them and discuss the advantages and disadvantages of each in composite applications. The main advantages of plant fibers over wood fibers were their mechanical properties and high agricultural yield, while the disadvantages include lack of existing infrastructure and more difficult processability. Shah (2013) [127] argues that bast fibers have superior structural properties as compared with leaf and seed fibers. Bast fibers include hemp, flax, and jute. Shah asserts that this makes sense when one considers the role of the fiber in the living plant: bast fibers provide rigidity and strength, while leaf fibers provide flexibility (thus, could be used for toughening) and seeds have no structural role. A comparison of different bast fibers with other composite materials may be seen in Table 2.6.

There are many key aspects that need consideration in the further development of plant fiber composites for structural applications. Shah suggests (i) fiber type, fiber extraction process and fiber surface modification techniques, (ii) fiber volume fraction, (iii) fiber reinforcement geometry and interfacial properties, (iv) reinforcement packing arrangement and orientation, and (v) matrix type and composite manufacturing technique. These considerations are addressed in the coming section on Processing and Manufacturing.

2.1.2.1 Processing and Manufacturing

Nearly 90% of plant fiber reinforced polymers (PFRPs) are manufactured using compression molding, though injection molding, extrusion molding, and vacuum infusion are also choices [127]. While pre-preg technology produces higher quality structural products, this method is not widely used because of its higher cost. Material properties may also vary widely depending upon other processing parameters.
Shah highlights some examples: (i) plant growth conditions such as plant species, geographic location, climate and soil characteristics; (ii) fiber extraction and preparation including age of plant and fiber location within plant; (iii) fiber processing, such as spinning to produce rovings and yarns, production of mats and textile preforms.

Matrix material is an important aspect of any composite material. Of existing PFRPs, approximately 25% are made with thermoset matrices and 75% with thermoplastic matrices. Even so, Shah argues that thermoset materials are more suitable to structural applications because of their capacity in high-performance applications (demonstrated by higher tensile strength composites, on average, in the literature), lower processing temperatures which will not degrade the plant fibers during manufacturing, and lower viscosity which leads to better fiber wetting, lower void density, and the possibility of vacuum infusion manufacturing.

Compaction and porosity have profound impacts on the mechanical properties of composites. Madsen and Lilholt (2002) [101] compare the compaction behavior of glass, hemp, flax, and jute fibers. They find that in comparison to glass fibers, natural fibers have lower compactibility overall, but this property varies between the type of fiber and product type (mat vs. yarn). They suggest that differences in structural fiber arrangement, which they call fiber dispersion, contribute to compactibility. They demonstrate that using successive compaction cycles, rather than a single cycle, helps compactibility. Using a hemp composite, the researchers show that beyond a limiting fiber volume fraction of 0.54, the composite porosity starts to increase dramatically. Madsen, et al., (2009) then used numerical models to examine the effects of porosity on stiffness of plant fiber reinforced composites. Their model suggests an optimal trade-off point between fiber volume fraction and low porosity which leads to the maximum composite stiffness.
2.1.2.2 Mechanical Properties

A few review articles have now compiled databases on the mechanical properties of bio-based fibers and their composites. Faruk, *et al.*, [57] reviews the progress in bio-based composite materials from 2000-2010 including fiber and composite properties. Select properties from this reference and Madsen and Gamstedt (2013) [100] are presented in table 2.4

Table 2.4: Select mechanical properties of plant fibers and their composites. From references [57], [128], and [100]. All composites reported are uniaxial. PLA, PP, PET, and HDPE are resin types.

<table>
<thead>
<tr>
<th>Material</th>
<th>Fiber Volume Content (% v/v)</th>
<th>Stiffness (GPa)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flax</td>
<td>-</td>
<td>27.6</td>
<td>345-1035</td>
</tr>
<tr>
<td>Hemp</td>
<td>-</td>
<td>70</td>
<td>690</td>
</tr>
<tr>
<td>Jute</td>
<td>-</td>
<td>26.5</td>
<td>393-773</td>
</tr>
<tr>
<td>Bamboo</td>
<td>-</td>
<td>11-17</td>
<td>140-230</td>
</tr>
<tr>
<td>Flax/PLA</td>
<td>39</td>
<td>19.5</td>
<td>150</td>
</tr>
<tr>
<td>non-crimp fabric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flax/epoxy</td>
<td>35</td>
<td>19.8</td>
<td>133</td>
</tr>
<tr>
<td>non-crimp fabric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flax/epoxy</td>
<td>40</td>
<td>28.0</td>
<td>234</td>
</tr>
<tr>
<td>filament-wound yarn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flax/PET</td>
<td>48</td>
<td>32.0</td>
<td>344</td>
</tr>
<tr>
<td>filament-wound yarn</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Shah, *et al.*, (2012) examined the tensile behavior of off-axis loaded plant fiber composites. This article (i) characterizes the stress-strain response, (ii) investigates the tensile properties, and (iii) analyzes the fracture modes of unidirectional flax-polyester composites subject to off-axis loading. A key finding of this study is that the apparent laminate stiffness decreases by approximately 30\% in the strain range of 0.05 to 0.25\%, with the elastic strain limit being equal to 0.15\%. The researchers also note that biaxial composites with a \[+/-45\] layup have better mechanical properties than unidirectional layups when loaded at off-axis angles of over 30 degrees.
Shah, et al., (2013) [129] created a database of fatigue data on vacuum-infused, aligned plant fiber composites. They examined the effects of plant fiber type, fiber content, textile architecture, and stress ratio on cyclic loading behavior. Ultimately, the researchers found that while the parameters investigated all had impacts on static strength of the material, they did not significantly affect the fatigue strength coefficient $b$ from the power-law regression, which dictates the slope of the S-N curve. This is consistent with findings of Liang (2012) [93]. While fracture mechanisms were found to be the same across different fiber types, they varied for different fiber volume fractions, textile architectures and stress ratios. Unsurprisingly, increasing the stress ratio led to improved fatigue performance. Furthermore, the researchers compare fatigue performance of PFCs with GFRPs and find that though the absolute fatigue performance is superior in GFRPs, the strength degradation rates are lower in PFCs. Liang similarly found that flax shows better specific fatigue resistance within the range of their study. Liang also looked at stacking sequence, demonstrating that for the [0/90] stacking sequence, the flax composite shows a lower endurance limit, but for the [+/-45] stacking sequence it is comparable to glass at stress levels below 64 MPa.

2.1.2.3 Microstructure

The fibers typically used in structural reinforcement are bast fibers, from the stalk or stem of annual plants, as opposed to the leaves or seeds of the plant. The strength and stiffness of these fibers is attributed mostly to the cell wall [100]. The main chemical constituent of the cell wall is cellulose, a non-branched polysaccharide which forms chains that arrange in parallel to form bundles, called microfibrils, as depicted in Figure 2.3 (a). The two other important components of the cell wall are hemicellulose, or short connective polysaccharide branches, and lignin, a highly-branched polymer with a complex, three-dimensional structure. Microfibrils can be
used as a filament for particle-reinforced composites, or wound into yarns, which are used to form continuous-fiber reinforced composites, depicted in Figures 2.3 (b) and (c). It is the continuous-fiber reinforced composites that are the focus of the present thesis. There are many processing techniques used to alter the mechanical properties and chemical composition of fibers, and they are reviewed in [100], [103] and [104].

![Microstructure of reinforcing plant fiber. (a) shows a cellulose microfibril of aligned cellulose chains, from [100]. (b) is a photograph of a unidirectional (UD) flax laminate with 8 plies. (c) shows a biaxial, or multidirectional (MD), flax laminate with 8 plies.](image)

Figure 2.3: Microstructure of reinforcing plant fiber. (a) shows a cellulose microfibril of aligned cellulose chains, from [100]. (b) is a photograph of a unidirectional (UD) flax laminate with 8 plies. (c) shows a biaxial, or multidirectional (MD), flax laminate with 8 plies.

### 2.1.3 Bamboo

Bamboo is also a promising material for wind turbine blades, especially in regions where it grows plentifully. To date, it has only been used in what are now considered small turbines. Researchers at the University of Vermont have developed a small, vertical-axis bamboo wind turbine for home use in developing countries [28]. There is ongoing research into bamboo turbine blades at Cambridge University [118]. In China, there were at one time at least five companies using bamboo in their turbine blades up to 40m in length [98], though many of them appear to now be out of business.
Nugroho and Ando (2000) [114] have developed a structural composite product made from bamboo strands, called Bamboo Zephyr Board or BZB. Their results indicate that BZB exhibits superior strength properties than other commercially available SCL products. They demonstrated that smaller strand diameters and higher final densities corresponded with better strength properties.

Ahmad and Kamke (2005) [1] analyzed the mechanical properties of Calcutta bamboo for structural applications. They find that the bamboo has similar properties to timber species which have been reported in North America. In further literature on the subject, the authors also examine surface characteristics and chemical characteristics such as pH. They postulate that the high density of this particular bamboo may prohibit its use in composites. Mahdavi, et al., (2012) [106] developed a low-technology approach for the fabrication of Laminated Bamboo Lumber (LBL) and verified that the resulting product was suitable for structural applications. Lee, et al., (2012) [90] investigated five different layups of moso bamboo for structural applications and has commented on preferable layups and manufacturing practices.

2.1.4 Weatherization of Bio-Based Building Materials

For natural materials to be considered for offshore wind turbines, they must be able to be protected from the oceanic atmosphere. This topic is not widely addressed in the literature and would be a good topic for further study. Bio-based polymers are an area of active research which could address this issue, and existing coatings which are used currently for fiberglass wind turbine blades could be explored in bio-based composite applications.

2.2 Design of Wind Turbine Blades

This thesis will focus on the three-bladed, lift propelled, horizontal axis wind turbine. This design is dominant in the wind energy industry for various reasons. It has
a high theoretical efficiency on a per swept-area basis as compared with vertical axis or drag-propelled turbines. The blade number is a balance which considers material usage, manufacturing cost, tip speed ratio, structural balance and environmental effects [107]. Generally, higher tip speed ratios (fewer blades) translate to higher efficiency [126], but this comes at a cost of increased stresses in the blade, structural imbalance, and noise. Typically, on-shore turbines must be designed such that the maximum absolute tip speed does not exceed 200 meters per second because higher speeds generate noise which is disruptive to the surroundings [113], even when higher tip-speed limit would reduce cost of energy [122].

Wind turbines are currently increasing rapidly in size because turbine power scales up with both hub height and swept area. The power output of the turbine scales with wind speed cubed, and wind speeds increase with distance from the surface of the earth due to an effect called wind shear. This means that much more power may be extracted from a turbine with a hub height at 100m than one with a hub height of 50m. Power also scales with swept area, or equivalently blade length squared, so it is similarly advantageous to make blades as long as possible within loading capability, manufacturability, and physical size constraints such as transportation. Figure 2.4 shows the increase in turbine size and subsequent increase in turbine power since the mid-1980s. This drive toward larger turbines is especially the case for the offshore wind industry, which is less subject to human impact constraints and transportation challenges than terrestrial wind turbines.

2.2.1 Loads on Wind Turbine Blades

Turbine blades are exposed to loads due to gravity, wind, weather events, angular acceleration, and turbulence. The coordinate system used to qualify these loads consists of flapwise, edgewise, and spanwise directions with respect to the rotor blade. These directions are illustrated in Figure 2.5. The greatest spanwise load imposed
Figure 2.4: The increase in turbine sizes and subsequent increase in rated power since the mid-1980s. From [59]

upon the blade is its own weight. When the blade is at the top of its rotation, it is in compression due to gravitational acceleration acting on the mass of the blade. Accordingly, it is in tension at the bottom of its rotation about the hub. It follows that this gravitational force is greatest at the root of the blade where it connects to the hub, and the least at the blade tip. The blades are also under spanwise-tensile and flapwise- and edgewise-bending loads because they must compensate for the rotational inertia of the blade, which increases as a square of rotational velocity. These loads translate to strength and stiffness requirements for the turbine blade materials. As blades increase in size, the blade root bending moment becomes very high because of blade weight, so this bending moment becomes a key design driver for large blades.

In addition to gravitational loads, turbine blades experiences loads from the wind. Although the wind approaches the turbine from the direction perpendicular to the plane of the rotor, the aerodynamic lift force causes the tips of the blades to rotate much faster than the speed of the approaching wind. The blade, therefore, must be
stiff enough to resist bending moments in the edgewise direction. The subsequent
drag force on the airfoil causes the blade in a typical upwind configuration to bow
out of the rotor plane and towards the tower. The limiting case of this stiffness
requirement is that the blades must not bend so much as to hit the tower. [126] [31]

After all regular operational loading conditions have been considered, extreme and
fatigue load cases must be considered. Schubel and Crossley [126] present the most
important extreme cases as follows:

• Emergency Stop Scenario
• Extreme Loading During Operation
• Parked 50 Year Storm Conditions

However, it is important to note that extreme load cases depend greatly on factors
which change with each design and environment, so care must be taken to address
these extreme cases for each design and site. In these and other scenarios, the aero-
dynamic, gravitational, and centrifugal loads are amplified.
The design of wind turbine blades must also take fatigue loading into account, as blade failure is often governed by fatigue, rather than extreme, loading. Fatigue loading occurs in wind turbine blades due to cyclic gravitational loads and stochastic variations in wind speed. Blades must undergo rigorous fatigue testing before certification [77]. This process is time intensive, since a single test could take months or longer because of the extremely high number of fatigue cycles a blade must undergo. It is especially difficult to address fatigue for wind turbine blades because some of the primary materials used in blades—glass and carbon fiber reinforced polymers—are not thoroughly characterized in fatigue. Fatigue properties of wind turbine blade materials and laminates are discussed in Section 2.2.4.4.

2.2.2 Airfoil of a Turbine Blade

A typical blade geometry for a megawatt-plus-scale turbine blade is shown in Figure 2.6. This current geometry is the result of many decades of trial and error, and many more decades’ prior work in the aerospace industry.

Aerodynamic lift is the force responsible for moving the turbine blade about the rotor hub, and thus generating power. Often, the first consideration when looking at wind turbine blades is that they must generate lift. The magnitude of this lifting force and of the resulting drag force, which is parallel to the wind direction, depend on the angle of attack, which is shown in Figure 2.7. Optimal angle of attack depends on the airfoil shape, the relative wind speed and its direction at each point along the blade. For design wind speeds of 10-15 meters per second this angle tends to be around 10 degrees. When the angle is less than the optimal, the lift force is smaller because the distance for the wind to move over the top of the airfoil is closer to the distance for the wind to move beneath it. However, when the angle of attack is more than the optimal, the blade stalls, inducing turbulent flow, and the lift force drops off rapidly. Blades are also pitch-controlled to respond to real-time wind conditions,
Figure 2.6: Prevailing wind turbine blade design concept. Reproduced with permission from [45]
which allows the smoothing of output power and reduction of speed in above-rated wind conditions.

Structural requirements dictate a thicker airfoil towards the root of the blade, but the most efficient foils are thin, so thinner airfoils are used towards the tip of the blade in order to maximize lift where less structural strength and stiffness are required. The tip of the blade is moving at a higher velocity than a section of the blade close to the root, so the relative wind speed is at a different angle. This tip-speed ratio, combined with the need for using thicker airfoils at the root, causes the optimal angle of attack (maximal ratio of lift to drag) to vary along the length of the blade. In order to solve these discrepancies in optimum angle of attack, blades are twisted about the spanwise axis from root to tip so that optimal angles of attack may be utilized along the length of the entire blade. In total, a current utility-scale blade will twist 10 to 20 degrees from root to tip [31].

Figure 2.7: Wind turbine airfoil terminology.
2.2.3 Internal Support Structure

The internal structure of the wind turbine blade acts like a long, cantilevered beam. It is connected to the rotor hub on one end, and the other end is free. It must support the airfoil and resist the loads and moments discussed in Section 2.2.1. Historically, small wind turbine blades have been made out of a solid material, such as wood. However, with increasing size comes the need to drive weight down, so blades are now made of an aerodynamic shell and an internal support structure inspired by the I-beam, called the spar. In a bending I-beam or turbine blade, the top or low-pressure spar cap must resist tension loading and the bottom or high-pressure spar cap must resist loading in compression. This is shown in Figure 2.8.

![Figure 2.8: Internal support structure of a wind turbine blade.](image)

The beams that resist these tension and compression loads are known as spar caps. They are typically made from unidirectional fibrous materials, with fibers aligned along the length of the blade to take the tension and compression loads. They are then connected by one or multiple shear web(s) which keeps the tension and compression flanges from moving relative to one another.
As blades increase in size, additional shear web thickness is required to accommodate increasing loads. However, it is more structurally efficient to use multiple shear webs rather than adding thickness indefinitely, so larger blades often have two, or even three shear webs. A variation on the two-spar design is the box spar, where the spar caps and two shear webs form a box, which is fabricated separately and inserted into the shell. The Sandia 100-meter blades all incorporate three spars because the two-spar design does not meet the buckling criterion [67]. Figure 2.9 shows two examples of spar concepts in turbine blades.

![Figure 2.9: Two concepts for the internal structural design of a wind turbine blade. On the left, a single spar design concept from [31]. On the right, a dual-spar design from [67]](image)

### 2.2.4 Blade Materials

#### 2.2.4.1 Material Requirements

Turbine blade materials have evolved over time due to technological advances in materials science and increasing blade sizes, which have translated into more rigorous material requirements. The loading conditions presented in Section 2.2.1 lead us to the following material requirements, adapted from Bronsted, et al., [27].

- High material stiffness is needed to maintain optimal aerodynamic performance and meet deflection criteria.
- Low density is needed to minimize gravitational forces.
• Long fatigue life is needed to minimize material degradation.

Historically, small turbine blades have been made from wood, sometimes covered in cloth. Steel was used in the 20th century until the 1950s [107]. However, fiberglass and carbon fiber composite materials have gained popularity across many industries since the mid-20th century. The need for highly directional strength and stiffness properties, low density, and long fatigue life make fiber-reinforced plastic (FRP) composites a clear choice for wind turbine blades. This choice is demonstrated in Figures 2.10 and 2.11.

Figures 2.10 and 2.11 show guidelines for minimum mass design. These guidelines are developed by a process Ashby presents for what he calls Material Indices. The process for devising these guidelines consists of identifying an objective function to be minimized, applying constraints to that function from physics of the application (tension, bending, torsion, etc.), and isolating the material properties from the resulting performance function. The material index for a light, stiff beam in bending with no cross-sectional area constraints is \( \frac{E^{1/2}}{\rho} \). The material index for a light, strong beam in the same application and of the same geometry is \( \frac{\sigma^{2/3}}{\rho} \).

2.2.4.2 Glass and Carbon

With turbine sizing trends, glass and carbon fiber composites are typically the only materials considered for wind turbine blades. They are among the only materials which meet the strength and stiffness requirements, which are highly directional for most of the blade. The portions of the blade that are often made of various forms of fiberglass include the spar cap, reinforcements, skin, and shear web. An example bill of materials is given in Table 2.5 for the Sandia 100m baseline fiberglass turbine blade. This table also demonstrates the importance of directionality in the strength and stiffness requirements for turbine blades. FRP composites are excellent choices for these highly directional applications.
Figure 2.10: Ashby Charts are frequently used in engineering material decision-making. They compare two or more material properties on a scatter plot. This allows engineers to choose materials which are optimal across multiple properties. In the case of wind turbine blades, an ideal material has high strength and stiffness, but low density. This plot indicates that composites are a good choice in terms of elastic modulus and density. The material index for a light, stiff beam in bending is \( \frac{E^{1/2}}{\rho} \). From [5].
Figure 2.11: This Ashby chart demonstrates why composites are a good material choice when high strength and low density are important material properties. The material index for a light, strong beam in bending is \( \frac{\sigma^{2/3}}{\rho} \). From [5].
Table 2.5: Bill of Materials and Usage for the Sandia 100m fiberglass blade. Information from [67]

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Usage</th>
<th>Mass (kg)</th>
<th>Percent Blade Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-LT-5500</td>
<td>uniaxial fiberglass</td>
<td>spar caps, trailing edge reinforcement</td>
<td>25,522</td>
<td>22.0%</td>
</tr>
<tr>
<td>SNL Triax</td>
<td>triaxial fiberglass</td>
<td>root build-up, internal and external</td>
<td>20,050</td>
<td>17.3%</td>
</tr>
<tr>
<td>Saertex</td>
<td>double-bias fiberglass</td>
<td>shear webs</td>
<td>2,119</td>
<td>1.8%</td>
</tr>
<tr>
<td>EP-3</td>
<td>resin</td>
<td>all fiberglass parts</td>
<td>51,718</td>
<td>44.7%</td>
</tr>
<tr>
<td>Foam</td>
<td>foam</td>
<td>core panels, shear webs</td>
<td>15,333</td>
<td>13.3%</td>
</tr>
<tr>
<td>Gelcoat</td>
<td>coating</td>
<td>coating</td>
<td>920</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

2.2.4.3 Can plant-based materials compete?

Table 2.6 demonstrates the differences between wood-based and other materials which have historically been considered for wind turbine blades. There are several things to note in this simple comparison. Steel was used in some early turbine blade designs, but was phased out early on because of its weight, demonstrating the need to keep the weight of blades down. It can be seen that carbon fiber has the most promising strength, stiffness, and specific gravity. Because of these material properties, some blade designers do use some carbon fiber in their designs. However, it is so expensive and difficult to process that it has yet to take a significant share of the market.

There has been much debate among blade designers between using carbon or glass fibers, but in spite of some mechanical advantages of using carbon-fiber composites, the industry remains vastly dominated by glass-fiber composites because of the higher cost associated with carbon and the difficulties in its manufacturing. The traditional hand lay-up processes are typically not used for carbon fiber because they are so brittle that they are much less resilient to small defects that may result from that
Table 2.6: Select Specific Gravity-Normalized Properties of Wind Turbine Blade Material Candidates. Properties given only for the longitudinal fiber direction. References for material properties include [67], [125], [65], [127], [110], [82].

<table>
<thead>
<tr>
<th>Material</th>
<th>Normalized Tensile Strength (MPa)</th>
<th>Normalized Tensile Stiffness (GPa)</th>
<th>Specific Gravity (g/cc)</th>
<th>Raw Fiber Cost (USD/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber Composite</td>
<td>870-2900</td>
<td>100-230</td>
<td>1.5-2.2</td>
<td>10-40+</td>
</tr>
<tr>
<td>Glass Fiber Composite</td>
<td>440-1400</td>
<td>30-39</td>
<td>1.8-2.7</td>
<td>2.0-31</td>
</tr>
<tr>
<td>Eastern Species LVL</td>
<td>100-150</td>
<td>18-27</td>
<td>0.5-0.6</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Eastern Species Timber</td>
<td>80-220</td>
<td>12-26</td>
<td>0.5</td>
<td>0.6-1.8</td>
</tr>
<tr>
<td>Natural Fiber Composite</td>
<td>300-970</td>
<td>22-52</td>
<td>1.35-1.55</td>
<td>0.8-2.4</td>
</tr>
</tbody>
</table>

process (such as kinks) as compared to fiberglass. If carbon fiber is used in blades, it is in the form of a pre-preg.

Considering that much of the blade’s stress is a result of its own mass, and that mass scales with the cube of length, the bio-based composite materials shown in Table 2.6 look competitive. While carbon fiber is stronger and stiffer even after being normalized by specific gravity, the plant fiber composites are competitive with fiberglass. Furthermore, bio-based fibers are much less expensive than the alternatives, as shown in Figures 2.12 and 2.13, so there would be considerable incentive from blade manufacturers to utilize wood components if it is found that they can meet performance requirements.

2.2.4.4 Fatigue Properties

There are ongoing experimental efforts to address the fatigue properties of wind turbine blade composites at Sandia National Laboratories and Montana State Uni-
Figure 2.12: This Ashby chart, showing elastic modulus and volumetric cost, demonstrates an argument for looking at wood, as opposed to carbon or glass reinforced polymers, from an economic standpoint [5]. The material index for a low-cost structure constrained by bending stiffness is \( \frac{E}{C_{RP}} \).
Figure 2.13: This Ashby chart, showing strength and volumetric cost, demonstrates an argument for looking at wood from an economic standpoint [5]. The material index for a low-cost structure constrained by bending strength is \( \frac{\sigma_{2/3}}{C_{RP}} \).
versity [117], [112], [125]. The group has created an extensive database of fatigue data for glass and carbon fiber composites. Generally, carbon fiber composites are considered to have favorable fatigue and static properties.

Nair, et al., [111] reviewed the fatigue and creep-fatigue degradation of materials used in wind turbines. In composite laminates, Talreja [133] proposes a progressive damage model which consists of five stages: (i) matrix cracking, (ii) crack coupling and interfacial debonding, (iii) delamination, (iv) fiber breaking and (v) fracture. At high strain amplitudes, fractures are dominated by fiber fractures because the strain to failure of the fibers are much less than that of the matrix. In low strain amplitudes, the matrix material governs the fatigue behavior. In intermediate strain amplitudes, progressive damage such as the model proposed by Talreja occurs.

2.2.4.5 Hybrid Composite Materials

It must also be noted that blade manufacturers are also looking into hybrid composites, which contain multiple fiber types. To date, this discussion has revolved around blades which are made primarily of fiberglass, but where carbon fibers are inserted in locations of high stress [66] [111]. It is possible that the most optimal solution to integrating bio-based fibers into wind turbine design will consist of a hybrid which contains either varying types of bio-based fibers, or bio-based and traditional fibers. This possibility will be explored as a part of this thesis.

NEG Micon built 40m (2001) and 49m (2005) wood-carbon hybrid blades, which continued to be produced when the company was acquired by Vestas in 2004 [72]. These blades are discussed further in Section 2.2.8. Though the design did well in production, the company is no longer manufacturing machines less than 1.8 MW (this was a 1.5 MW machine). They also cite slimming airfoils and strict tower clearance requirements as limiting design factors that drove them away from their wood-carbon hybrid design.
2.2.5 Computational Methods

The design process for large composite structures relies heavily on numerical tools like Finite Element Analysis. These tools aid in making informed design choices without needing to expend vast amounts of resources building and testing preliminary designs of composite structures. Instead, companies and research labs use modeling to make incremental improvements to existing blades and to test new designs and concepts. For example, blade designers may perform a computational study to investigate the effect of spar cap thickness on blade stiffness. To optimize the design, the engineer might initiate an optimization routine which minimizes the mass of the blade, given a requirement for blade stiffness.

These design tools rely on accurate models of material behavior. While there is a breadth of literature which addresses mechanical behavior of traditional, glass- and carbon-based composites, the mechanical behavior of bio-based materials has been relatively poorly characterized to date.

Sandia National Laboratories has spent several years developing a series of 100-meter turbine blades of glass and carbon fiber [67] [134], which correspond to a 13.2-megawatt turbine. They start by using scaling laws to extrapolate smaller blade designs to their larger one, then they use modeling to optimize these designs to meet requirements. Scaling laws can highlight useful information about what the most important challenges are as the industry trends towards larger blades. Table 2.7 shows some of the scaling laws which are most important for large blades. The scale factor \( \alpha \) is defined as follows in Equation 2.5, where \( L \) stands for blade length:

$$\alpha = \frac{L_{\text{new}}}{L_{\text{old}}}$$  \hfill (2.5)

Once new geometries are created, composite layups must be applied. These are more difficult to discuss because this information is proprietary to most blade manufacturers, but there are some databases which keep what publicly available infor-
Table 2.7: Scaling Laws for Wind Turbine Blades. *While perfect geometric scaling in 3 dimensions would increase mass by a factor of $\alpha^3$, practical designs result in mass-to-length scaling exponents of 1.7-2.7 [27].

<table>
<thead>
<tr>
<th>Property</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>$\alpha^2$</td>
</tr>
<tr>
<td>Mass*</td>
<td>$\alpha^3$</td>
</tr>
<tr>
<td>Bending Moments due to Aerodynamic Loads</td>
<td>$\alpha^3$</td>
</tr>
<tr>
<td>Bending Moments due to Gravitational Loads</td>
<td>$\alpha^4$</td>
</tr>
</tbody>
</table>

Information exists available through the National Laboratories [50] [134]. The National Renewable Energy Laboratory (henceforth NREL) has a baseline 5-megawatt turbine which is often used as a reference, and is defined by Jonkman, et al., [85]. The NREL 5MW reference blade is based on specifications for the LM Glasfiber blades used on the REpower 5MW machine and is 61.5 meters in length.

These fully defined blades must then undergo computational testing using finite element analyses and other computational methods to test whether they meet structural and aerodynamic requirements. NREL and Sandia National Laboratories (henceforth Sandia) have a library of design codes that are used for these purposes [88]. Companies and research laboratories which design turbine blades also model and test blades rigorously using finite element analyses in commercially available software packages. Sandia has developed a code called NuMAD [21] which defines high-fidelity finite element geometries which may be imported into commercial software packages for analysis.

Extreme and fatigue cases will influence the success or failure of the blades under various requirements, so a wide variety of cases must be tested. Where blades fail to meet requirements, redesign efforts must be taken. Conversely, redesign may also occur for areas in which the blade far exceeds requirements in order to cut down on material usage and blade mass. Engineering optimization techniques are
often employed in order to balance these effects [29]. A current effort at SNL is the development of a more comprehensive blade optimization process which evaluates aerodynamic performance, structural performance, and cost of turbine blades. [122].

2.2.6 Manufacturing

The first blades to be manufactured were made using the wet hand-lay-up technique, which had been used for at least half a century prior in boat building [27]. In wet hand-lay-up, fibrous mats are laid in a mold, resin is applied, and the process is repeated until the desired thickness is achieved [47]. This process is easily scaled and has been used for blades up to about 50 meters. [142] The application of resin has been automated, as in Figure 2.14, and this method is referred to now as an open-mold process. However, with thicker and larger layups comes the potential for larger air gaps in the resin, so measures must be taken to minimize these air gaps. A straightforward upgrade to the open mold lay-up process is to use a vacuum bag to increase the pressure at which the composite cures, thereby reducing air gaps.

Figure 2.14: An automation concept for resin application to an open mold manufactured wind turbine blade. This technology was developed by the MAG-IAS corporation of Hebron, KY. From [105]

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Another concept for reducing air gaps is to use “prepreg” or pre-impregnated technology. This is a widely used technology today and has been adapted from the aerospace industry [27]. It also reduces air gaps, and has additional advantages including increased fiber alignment precision, increased volume fraction of fibers, and fewer toxic chemical emissions inside factories. Fabrics come pre-impregnated with resin which is not yet cured, and the composite is tacky at room temperature. Once the desired lay-up is produced, the resin is cured in a vacuum bag using increased temperature and pressure.

Resin infusion technology is the most widely used composite manufacturing technology in the wind industry, having gained popularity in the 1990s [27]. Fibers are first laid dry into a mold, then sealed off into a vacuum bag, as shown in Figure 2.15. Wet resin is injected into the bag and the composite cures. The main issue with this technology is that it is very difficult to inject the resin such that all fibers are thoroughly and evenly wetted. This issue has gained a great deal of attention and there have been many research efforts devoted to this in the last two decades, many having to do with the optimization of fluid flow. Even with this substantial drawback, resin infusion has most of the same advantages as prepreg technology.

2.2.7 Cost

The materials and manufacturing cost of blades typically represents 10 to 15 percent of total manufacturing cost for wind farms [107]. According to the National Renewable Energy Laboratory, “Incremental innovations in a variety of aspects of wind turbine design as well as in turbine erection, [operation and maintenance] strategies, and manufacturing are expected to contribute to reduced wind energy costs in the future”. Onshore, this applies especially to components like blades whose costs make up such a significant portion of the capital cost. However, the blades under investigation are better suited to offshore wind applications because of their large size. The
move to offshore wind changes the current view of the cost of wind energy. Because of the additional costs associated with installation infrastructure and support structures, the cost of the turbine, and its components, comprise less of the total wind farm cost.

In the interest of quantifying the effect of “incremental innovations” that may lead to reduced costs of wind energy in the future, a simple sensitivity study was performed. The cost of a wind turbine blade was reduced by up to 20% as shown in Table 2.8 and the subsequent reduction cost of entire wind farms was calculated based on reference [109]. Table 2.8 shows that a 10% reduction in the manufacturing cost of a turbine blade translates to a reduction in offshore wind farm capital cost of 0.94-2.44%. This range of percentages was based on an annual cost study performed at NREL by Tegen, et al., [135]. These results are summarized in Figure 2.16.

In 2003, Ashwill and Veers [6] did an extensive cost study for large wind turbine blades. The researchers propose manufacturing costs for 30, 50, and 70-meter blades, based on structures, materials, and fabrication processes for all three blades.
Table 2.8: Capital cost reduction of wind farm projects as a result of incremental reductions in blade manufacturing cost.

<table>
<thead>
<tr>
<th>Blade Manufacturing Cost Reduction</th>
<th>Onshore Wind Farm Capital Cost Reduction</th>
<th>Offshore Wind Farm Capital Cost Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>0.09-0.18%</td>
<td>0.05-0.12%</td>
</tr>
<tr>
<td>5%</td>
<td>0.44-0.88%</td>
<td>0.23-0.61%</td>
</tr>
<tr>
<td>10%</td>
<td>0.88-1.76%</td>
<td>0.47-1.22%</td>
</tr>
<tr>
<td>15%</td>
<td>1.33-2.65%</td>
<td>0.70-1.83%</td>
</tr>
<tr>
<td>20%</td>
<td>1.77-3.53%</td>
<td>0.94-2.44%</td>
</tr>
</tbody>
</table>

Figure 2.16: Cost of offshore wind energy in 2011. From [135]
They present several cost breakdowns, including bill of materials, labor tasks, tooling, transportation, and overall cost including profit.

The manufacturing costs for a 50-meter turbine blade follow the distribution shown in Figure 2.17. Ashwill and Veers found that as the size of a wind turbine increases, the materials costs increase as a percentage of the total cost, and the labor and transportation costs decrease. Therefore, blade cost reduction efforts for increasingly large blades should focus on materials cost. They also show that as the turbine size increases, the blade makes up a larger portion of the capital cost of the wind turbine as a whole. This further motivates looking at the turbine blade as a place to cut the cost of wind energy.

![Pie chart showing cost breakdowns](Image)

Figure 2.17: Manufacturing costs for a 50-meter wind turbine blade. From [6].

The cost of a wind turbine is also related to the environmental cost of manufacturing that turbine. Wind turbines are known to have low energy payback periods. The payback period is the time it requires for the system to produce as much energy as was put into the system, which for wind turbines is almost entirely materials processing and manufacturing energy. Owens [116] developed a process for comparing the environmental impacts of different common blade manufacturing processes and ma-
terials. This study illuminates the differences that processing parameters may have on environmental impact. Haapala, et al. [71], found that the typical energy payback period for a 2MW turbine was 6 months. This statistic indicates that wind turbines are quite good at making much more energy than they require to produce. However, there is concern among blade designers and manufacturers about the lifetime environmental cost of turbine blades because traditional composite materials are not only difficult to produce and process, but also to dispose of.

2.2.8 Bio-based Materials in Wind Energy

Wood composites have been considered for wind turbine blade materials in a few select instances, most of which apply to small wind turbines. Faddoul (1981) showed that wood composites are strong enough to withstand loading conditions for small wind turbine blades at the blade root [56]. Ansell, et al., (1991) showed that the fatigue properties of wood composites make them the ideal material candidate for wind turbine blades in comparison with fiberglass [2]. Lieblein, et al., (1982) demonstrated that a wood composite blade design would be cost competitive for a 200-kW turbine [94].

The case for small turbine blades which include wood-based materials is often made using the financial benefits of wood. Moreover, Ashwill and Veers (2003) showed that as turbine size increases, materials costs increase as a proportion of total cost of blades [6]. This result has since been reproduced using higher fidelity modeling by Griffith, et al. [68]. This suggests that any materials cost savings from using wood laminates would magnify with increasingly large turbine blades.

According to environmental statements from Vestas, the company is producing 40m wood-glass-carbon hybrid turbine blades for their 1.5MW machines. In 2008, these blades were fabricated using approximately 43% by weight of balsa and birch-wood [143]. Whether the company is using multidirectional laminates is unknown,
but it is suspected based on photos of their manufacturing process that they are only using unidirectional wood laminates. In a 2007 magazine article, an affiliated R&D manager discussed the technology: “The combination of aerodynamic design, use of carbon fiber and dry layup of materials means a weight reduction of around 30 percent, compared with the traditional wind blade made from fiberglass-reinforced polyester. Another advantage over the traditional fiberglass blade is that carbon achieves a slimmer and lighter blade design, reduced load on the main components and lower costs.” The article also notes that according to an independent financial analysts report, Vestas has built a 59m wood-epoxy composite blade that has a total weight of 12.6 metric tonnes, a significant reduction in weight compared to others of the same length. However, there is no public documentation of this technology.

The work herein seeks to expand the use of bio-based materials in large wind turbine blades. Novel contributions will include investigating the viability of multidirectional wood laminates, developing accurate numerical tools with which to design these blades, and proposing designs of larger bio-based blades than exist today.

2.3 Composite Mechanics

2.3.1 Experimental Methods for the Determination of In-Plane Shear Stress

There is considerable research about the test methods for determining in-plane shear strength of both wood products and fiber reinforced composites, with no clear consensus among researchers as to the best method, especially for thin wood laminates in plate or shell structures. This review summarizes the most popular and promising test methods.

+/- 45-degree Tension Test

This methodology is developed for polymer-matrix composites and presented in ASTM D3518 (2013) [13]. Small test coupons of continuous-fiber, +/- 45-degree
angle-ply laminates are tested in tension. Rosen (1972) [124] developed expressions which allow the in-plane, 0-degree, shear stress-strain curve to be generated from the longitudinal and transverse stress-strain curves from uniaxial tension tests of 45-degree, angle-ply laminates. Rosen also suggested the presence of an edge effect and highlighted the importance of specimen size and fabrication. The benefits of this test include that the coupon is small, easy to fabricate, and the results are easily reproducible. The main drawback is a complex, coupled stress state which makes it difficult to isolate the shear stress property. Based on a comparison between six methods for evaluating shear properties for an aramid-epoxy composite, Chiao, et al., (1977) [35] recommended the +/- 45 degree tension test because it gives closest stress-strain response to the torsion tube test (which is hailed for its accuracy but difficult to perform) while remaining simple, inexpensive, and reliable.

Off-Axis Test

The 10-degree off-axis tension test was first proposed by Chamis and Sinclair (1976) [34]. The researchers found through theoretical and experimental investigations that this test is promising for unidirectional laminates and single plies; it has advantages of small test coupons, simple testing, no laminate residual stresses from multiaxial laminates, and uniform shear through the test section. The main drawback is that the method is very sensitive to small misorientation errors. Chiao, et al., (1977) [35] found that in comparison to the +/- 45-degree tension test, the 10-degree off axis test gave consistently higher shear modulus, lower failure stress and lower failure strain. Clouston, et al., (1998) [40] used off-axis tension testing to determine the interaction term of the Tsai-Wu failure theory for Douglas Fir laminated veneer. The study compared 15, 30, 45, and 60 degree off-axis test data and found that the 15 degree data was most reliable since it was less sensitive to experimental variations. Clouston and Lam (2001) [37] went on to propose a minimization approach to esti-
mate simultaneously three parameters (shear strength, modulus of rigidity, and the interaction parameter) based on the compression properties of 15 angle-ply laminates.

**Rail Shear Test**

The rail shear test method is outlined in ASTM D4255 (2007) [14] and covers both two-rail and three-rail shear. In two-rail shear testing, laminates are clamped between two pairs of rails and when loaded in tension the rails introduce shear forces in the specimen. In three-rail testing, laminates are clamped on opposite edges while a third rail in the center applies a tensile or compressive force. Whitney and Stansbarger (1971) [146] did an extensive theoretical stress analysis, concluding that the method is valid for finding shear modulus when the length to width ratio is at least 10. For shear strength, there is an additional criterion that the effective laminate Poisson’s ratio must be less than 1, which is not the case for 45-degree angle ply specimens. Garcia, et al., (1980) [62] showed that the aspect ratio of the specimen can have a major effect on the stress distribution, depending on the laminate. Subsequently, an ASTM round-robin review in 1981 (Lockwood, 1981 [97]) concluded that the variation in averages across different studies was great enough to cast doubt on the validity of the data from these tests.

**Iosipescu Shear Block Test**

Iosipescu is the most common test methodology for isotropic materials, also called the V-notched beam method and adapted for composite materials as described in ASTM-D5379 (2012) [16]. In this method, a small specimen with symmetrical, center-span v-notches is tested in a special fixture that translates compressive forces from a Universal Testing Machine to act on opposite ends of the specimen, shearing the specimen in the notched center section. Walrath and Adams (1983) [144] extended the test to fibrous composites with some success. However, finite element analyses have since shown that because of the highly nonuniform stress distribution through the cross section, it is very hard to accurately determine stress and strain which
cause failure (Wang, 1994 [145]). Another major limitation is that shear strength is affected by geometry of the notches and gripping systems. The main advantages to this method are that the test is easy to conduct and uses small test specimens.

**Torsion of Thin-walled Tubes**

Many researchers agree that torsion tests of thin-walled tubes are both precise and accurate in determining shear strength of composite laminates, with many citing this as the most accurate method for determining in-plane shear strength. The methodology is presented in ASTM D5448 (2011) [17]. Thin, hoop-wound (90 degree) cylinders are bonded to two end fixtures and tested in pure torsion. The main drawback of this methodology is that specimens are difficult to fabricate, especially for natural materials like wood. The tests both require more labor-intensive fabrication processes, and are sensitive to defects which may result from those processes. Still, Lee and Munro (1986) [91] argue that it is the test to which other, simpler tests should be compared.

**Torsion Tests of Full Size Beams**

The testing protocol for determining the shear properties of full size lumber is given in ASTM D198 (1999). Full-size structural beams are tested in pure torsion using a torsion test machine or adapting a Universal Testing Machine [8]. Riyanto and Gupta (1998) [123] compared full-beam torsion tests to 3-point, 4-point, and 5-point bending tests on solid wood in structural sizes. The researchers found that the torsion test gave the highest shear strength of all methods, and concluded that the torsion test is a good method to determine shear stress in structural lumber because of its ability to isolate pure shear. Gupta and Siller (2005) [70] went on to compare the shear strength of Structural Composite Lumber (SCL) using torsion and shear block tests, and found that torsion tests gave a lower shear strength compared to shear block tests. The researchers recommended the torsion test as the best practical method for determining pure shear strength of SCL as well as full size structural

Other Methods

Duggan, et al., (1978) [53] proposed a cross-beam sandwich method, where a cross-shaped specimen is loaded in bending on two opposite arms and supported on the remaining two arms. This method was found to produce significantly different strength values as compared to the +/- 45-degree tension test, so is not widely used. Later, an author from the same group [52] proposed a biaxial slotted-tension shear test, where the specimen is under biaxial tension-compression loading with slots used to control loading. The slots were causing stress concentrations, and failures in this test were in tension, so it is not a good measure of shear strength. Wang and Socie (1994) [145] expanded on the biaxial tension-compression test method by creating flexible end reinforcements of aluminum which don’t transfer transverse loads. The concept was that this configuration would eliminate stress concentrations caused by tensile grips and prevent laminate edges from being crushed in compression. Shear failures as predicted by failure criteria were not observed in this test method, with maximum stress/strain failures observed instead. The short beam method is promising and is reviewed in ASTM D2344 (2013) [9]. The method allows the calculation of the apparent interlaminar shear strength of fiber-reinforced plastic composites. The failure mode in this test will depend upon layup, size parameters, and manufacturing. Thus, the method is not recommended for strength determination, but is a simple method which can be used for screening. Finally, the plate twist test, outlined in ISO-15310 (1999) [79], is often used to determine shear modulus of composite laminates. The procedure was modified by Yoshihara (2012) [152] to calculate apparent shear strength, but the results varied with plate thickness and the researchers suggest future work in order to evaluate the accuracy of this method.
2.3.2 Failure Theories

In Chapters 4 and 5, this dissertation will evaluate how well several existing failure theories fit experimental data from wood and flax laminates. This section presents an introduction to these theories.

2.3.2.1 Tsai-Hill Criterion

Equation 2.6 represents the in-plane formulation of the Tsai-Hill failure criterion. The Tsai-Hill theory is used widely in composite laminate analysis. While its clear disadvantage is its failure to consider tensile and compressive behavior separately, it is a good basis for comparison because of its widespread and historical use in the analysis of composite materials.

\[
\left( \frac{\sigma_1}{S_1} \right)^2 + \left( \frac{\sigma_2}{S_2} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 - \left( \frac{\sigma_1 \sigma_2}{S_1^2} \right) = 1 \tag{2.6}
\]

2.3.2.2 Tsai-Wu Criterion

Equations 2.7a and 2.7b represent the in-plane formulation of the Tsai-Wu failure criterion (Tsai and Wu, 1971 [138]). The Tsai-Wu theory is also used widely, especially in finite element modelling (FEM). It is similarly easy to implement compared to the Tsai-Hill criterion, but offers the advantage of considering tensile and compressive strengths separately.

\[
f_1 \sigma_1 + f_2 \sigma_2 + f_{11} \sigma_1^2 + f_{22} \sigma_2^2 + f_{66} \sigma_{12}^2 + 2f_{12} \sigma_1 \sigma_2 = 1 \tag{2.7a}
\]

\[
f_1 = \frac{1}{S_{1T}} - \frac{1}{S_{1C}}; \quad f_2 = \frac{1}{S_{2T}} - \frac{1}{S_{2C}}; \quad f_{11} = \frac{1}{S_{1T}S_{1C}}; \quad f_{22} = \frac{1}{S_{2T}S_{2C}}; \quad f_{66} = \frac{1}{S_{12}} \tag{2.7b}
\]
2.3.2.3 Chamis Criterion

The Chamis Criterion [33] (Equation 2.8a) was developed by C. Chamis of NASA in 1969 for filamentary composite materials. Chamis introduced the interaction factors $K_{12}$ and $K'_{12}$ where $K_{12}$ (Equation 2.8b) is based on material properties. $K'_{12}$ has been introduced in order to compensate for the disparity between material behaviors in different quadrants of the biaxial loading regime. This parameter is allowed to vary between quadrants of the biaxial stress distribution, with quadrants I (tension-tension) and III (compression-compression) being especially sensitive to the parameter. $K'_{12}$ has the default value of 1 for all quadrants. The strength parameters also vary by quadrant, such that $S_1$ should be substituted with $S_{1T}$ when $\sigma_1 > 0$ and with $S_{1C}$ when $\sigma_1 < 0$.

\[
\left(\frac{\sigma_1}{S_1}\right)^2 + \left(\frac{\sigma_2}{S_2}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 - K'_{12}K_{12} \left(\frac{\sigma_1\sigma_2}{||S_1||S_2||}\right) = 1 \quad (2.8a)
\]

\[
K_{12} = \frac{(1 + 4\nu_{12} - 4\nu_{13})E_2 + (1 - \nu_{23})E_1}{E_1E_2(2 + \nu_{12} + \nu_{13})(2 + \nu_{21} + \nu_{23})}^{1/2} \quad (2.8b)
\]

2.3.2.4 Hashin Criterion

Hashin (1980) [75] (Equation 4) presents a semi-empirical approach, to address the problem that the different phases of a composite material (typically fiber and matrix) cause them to fail in different modes. Prior criteria had only allowed these modes to be represented by variation in the interaction parameters. Hashin defines four modes by which the composite could fail and considers the stress state under which each would occur, resulting in a piecewise failure surface. Several updates have been proposed to the original yield theory to account for phenomenological differences in the behavior of different materials (e.g. the Sun criterion for matrix compression [132]). Herein, the original theory is used.

1. Tensile Fiber Mode
\[
\left( \frac{\sigma_1}{S_{1T}} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 = 1; \quad \sigma_1 > 0 \quad (2.9a)
\]

2. Fiber Compressive Mode

\[
\sigma_1 = -S_{1C}; \quad \sigma_1 < 0 \quad (2.9b)
\]

3. Tensile Matrix Mode

\[
\left( \frac{\sigma_2}{S_{2T}} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 = 1; \quad \sigma_2 > 0 \quad (2.9c)
\]

4. Compressive Matrix Mode

\[
\left( \frac{\sigma_2}{S_{21}} \right)^2 + \left[ \left( \frac{S_{2C}}{2S_{21}} \right)^2 - 1 \right] \frac{\sigma_2}{S_{2C}} + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 = 1; \quad \sigma_2 < 0 \quad (2.9d)
\]

2.3.2.5 Puck Criterion

Puck’s approach was chosen because of its success in the World-Wide Failure Exercise, which assessed 13 different failure theories in 125 different cases (Soden 2002 [81]). Puck’s theory did particularly well in the category of cases which assessed final strengths of multidirectional laminates, which is the category of cases presented herein. Puck’s approach (Puck 1998 [119]) distinguishes between two main failure types: Fiber Failure (FF) and Inter-Fiber Fracture (IFF). The FF category is subcategorized into tension and compression modes, while IFFs are subcategorized into Modes A, B, and C, which depend upon the ratio of transverse to shear stress. Furthermore, Puck’s theory is the only one considered here which includes a degradation model, describing laminate behavior after crack initiation.

1. FF Tension
\[ \frac{1}{\epsilon_{1T}} \left( \epsilon_1 + \frac{\nu f_{12}}{E_{f1}} m_{sf} \sigma_2 \right) = 1 \]  

(2.10a)

2. FF Compression

\[ \frac{1}{\epsilon_{1C}^1} \left| \left( \epsilon_1 + \frac{\nu f_{12}}{E_{f1}} m_{sf} \sigma_2 \right) \right| = 1 - (10 \gamma_{21})^2 \]  

(2.10b)

3. IFF Mode A

\[ \sqrt{\left( \frac{\tau_{12}}{S_{21}} \right)^2 + \left( 1 - p_{\perp\parallel}^{(+)} \frac{S_{2T}}{S_{21}} \right)^2 \left( \frac{\sigma_2}{S_{2T}} \right)^2 + p_{\perp\parallel}^{(+)} \frac{\sigma_2}{S_{21}} = 1 - \left| \frac{\sigma_1}{\sigma_{1D}} \right|} \]  

(2.10c)

4. IFF Mode B

\[ \frac{1}{S_{21}} \left( \sqrt{\tau_{21}^2 + \left( p_{\perp\parallel}^{(-)} \sigma_2 \right)^2 + p_{\perp\parallel}^{(-)} \sigma_2} \right) = 1 - \left| \frac{\sigma_1}{\sigma_{1D}} \right| \]  

(2.10d)

5. IFF Mode C

\[ \left[ \left( \frac{\tau_{21}}{2(1 + p_{\perp\perp}^{(-)}) S_{21}} \right)^2 + \left( \frac{\sigma_2}{S_{2C}} \right)^2 \right] \frac{S_{2C}}{-\sigma_2} = 1 - \left| \frac{\sigma_1}{\sigma_{1D}} \right| \]  

(2.10e)
CHAPTER 3

IN-PLANE SHEAR PROPERTIES OF LAMINATED WOOD FROM TENSION AND COMPRESSION TESTS OF ANGLE-PLY LAMINATES

3.1 Introduction

Experimental methods for the characterization of shear strength and stiffness of both wood-based and glass- or carbon-based composite materials are highly contested because shear properties are difficult to isolate experimentally. Meanwhile, in-plane shear properties of laminated wood are needed in applications such as diaphragms, shear webs, and plates and shells under combined loading. In this thesis, the author is interested in using laminated wood veneer panels in large wind turbine blades. Like many advanced composite structures, the wind turbine blade utilizes multiaxial laminates in order to optimize for complex, combined loading conditions. In large wind turbine blades, the shell (or skin) and shear webs are often made of multidirectional materials, while the spar caps are unidirectional. The shear web of a wind turbine especially experiences a great amount of shear stress, and the skin sees shear stress components in combined, multiaxial loading. Shear failures are common under such conditions, so the accurate measure of shear properties is essential.

In this chapter, a novel method for calculating the in-plane shear strength and stiffness based on uni-axial tension and compression tests of symmetric, angle-ply wood laminates is presented. The test data are compared to predictions from the Tsai-Wu and Hashin failure criteria, and shear parameters are determined using genetic optimization.
3.2 Methods

3.2.1 Experimental Methods

The source material used in this study was rotary peeled, 1.22 x 2.44m (4 x 8 ft.) Spruce-Pine-Fir (SPF) veneer sheets in 3.175mm (1/8 in.) thickness donated to the study by Louisiana Pacific. They are high quality veneers used in the production of Laminated Veneer Lumber. These veneers were laminated and machined as detailed in Figure 3.1. T-88 Structural Epoxy was used as the adhesive because of its ability to cure in ambient room temperatures. The veneers were glued in ambient room conditions leading to a moisture content of 7-10%. Specimens were laminated in a hydraulic press with uniform pressure of approximately 690-970 kPa (100-140 psi). The specimen geometry and the testing procedure were determined according to ASTM D3500 (2009) (tension) and ASTM D3501 (2011) (compression). The gage sections for the unidirectional and transverse tension specimens were 6.35 x 12.7mm (1/4 x 1/2 in.), the gage sections for the multiaxial tension specimens were 12.7 x 12.7mm (1/2 x 1/2 in.), and the gage sections for all compression specimens were 25.4 x 12.7mm (1 x 1/2 in.). Specimens were fabricated at 0, 30, 45, 60, and 90-degrees in symmetric, 4-ply layups. Ten specimens were tested for each tension and compression, in each of 5 layups, for a total of 100 experiments.

The specific gravity measurement was taken in accordance with ASTM D2395 (2014) and moisture content measurement was taken using the oven-dry method, specified by ASTM D4442 (1997). The specific gravity of the laminated specimens was 0.73 +/- 0.045 g/cm³ with no significant variation between treatments. The moisture content was 7.1 +/- 0.35% with no significant variation between treatments. The strength is defined as the maximum stress recorded during testing and the stiffness is taken from the linear portion of the stress-strain curve.

Tension and compression tests were performed at room temperature on a MTS universal testing system, pictured in Figure 3.2. Tensile strain was measured using
Figure 3.1: Manufacturing process for angle-ply laminates: (A) Veneer is cut into panels corresponding to the desired grain angles. The solid black rectangle is a sketch of a UD panel, whereas the dashed rectangle is a sketch of a panel at approximately 30°. (B) Adhesive is applied manually to both sides of each lamina. (C) Laminate is pressed at room temperature using a hydraulic press and Cross-Laminated Timber panels to distribute the load from the press. (D) Dog-bone shaped tension specimens and rectangular compression specimens (not pictured) are cut using a CNC router.
a single extensometer centered on the side of the test specimen. The strength is defined as the maximum stress recorded during testing and the stiffness is taken from the low-strain, linear portion of the stress-strain curve. Elastic moduli $E_1$ and $E_2$ were measured from the unidirectional, 0 and 90 degree specimens. The reported values reflect the mean across the 10 specimens.

Figure 3.2: Tension tests (left) and compression tests (right) were performed on a MTS Universal Test System.

3.2.2 Numerical Methods

From experimental data, global stresses and strains were transformed into those in the local material coordinates of the ply following the assumptions of Classical Lamination Theory (CLT), as in Figure 3.3. It is these lamina-level stresses and strains that are employed in failure criteria. The global coordinate system is defined by $(\sigma_x, \epsilon_x)$ where $x$ is the testing direction. The lamina coordinate system is defined by $(\sigma_1, \epsilon_1)$ representing the parallel-to-grain direction and $(\sigma_2, \epsilon_2)$ representing the perpendicular-to-grain direction. For a symmetric, balanced laminate using only
one angle (e.g. $[+30/ -30]_s$), the lamina-level stresses and strains are of the same magnitude for each lamina in the stackup.

Figure 3.3: Global stresses and strains are transformed into lamina stresses and strains.

3.2.2.1 Shear Modulus, $G_{12}$

Shear modulus was determined through least squares minimization of error between the experimentally obtained laminate stiffness and analytically obtained laminate stiffness. The latter uses Classical Laminate Theory with shear modulus as the inherent unknown to be optimized. Stiffness was calculated for each of the 60 multiaxial specimens (at 30, 45, and 60 degrees) and the optimization routine was performed using MATLAB® as depicted in Figure 3.4. The optimization boundaries (presented in Table 1) were estimated from Janowiak (2001) who determined $G_{12}$ for several structural composite lumber products using the torsion test.

It is well known that a dependency exists between the Poisson’s Ratio $\nu_{12}$, the Elastic Moduli $E_1$ and $E_2$, and Shear Modulus $G_{12}$. Therefore, to arrive at an accurate characterization of $G_{12}$, the remaining parameters must be defined. $E_1$ and $E_2$ were determined by testing uniaxial wood laminates in the 0- and 90-degree orientations. $\nu_{12}$ for several similar materials (e.g. clear Eastern Species and several types of LVL) are reported by Ross (2010) and Janowiak (2001), but the variation in reported values
Figure 3.4: The optimization routine for shear stiffness minimizes the least squares error between Classical Laminate Theory and test data from 30, 45, and 60 degree symmetric laminates in tension and compression.

from these sources is substantial. In this study, the value reported by Janowiak for 2.0E Southern Pine LVL was used, but a range of values was tested to illustrate that the dependency of $G_{12}$ on $\nu_{12}$ is quite small.

### 3.2.2.2 Shear Strength, $S_{12}$ and $S_{21}$

Lamina-level stresses are used to inform a parametric optimization of two failure theories: the Tsai-Wu failure criterion and the Hashin criterion. The Tsai-Wu theory [138] is chosen because of its prevalence in the industry, its use by other researchers for wood composites (Clouston and Lam 2002; Oh 2011; Mascia and Nicolas 2012), and its ability to consider tensile and compressive strengths separately. The theory is summarized in Equations 2.1 - 2.3. Equation 2.1 shows the general 3D formulation and equation 2.2 is the plane stress formulation. Equation 2.3 defines the combined strength parameters used in the in-plane formulation. The Hashin criterion (Hashin 1980) is a semi-empirical theory which considers specific failure modes, and has been shown by the authors [86] to better fit experimental data for multiaxial wood laminates. The piecewise theory, shown in Equations 2.9a - 2.9d, was originally
formulated for fiber reinforced composites. It considers four distinct modes of failure and the combined stress states that contribute to each.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{12}$ (MPa)</td>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>$S_{12}$ (MPa)</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>$S_{21}$ (MPa)</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>$f_{12}$ (MPa)</td>
<td>-.0021</td>
<td>.0021</td>
</tr>
</tbody>
</table>

Table 3.1: Optimization Boundaries

The Tsai-Wu theory contains an interaction parameter $f_{12}$ which characterizes the interaction between parallel-to-grain and perpendicular-to-grain stresses, as in Equation 2.2. Theoretically, this parameter can vary for each quadrant of the loading regime ($\sigma_1 - \sigma_2$ in tension-tension, tension-compression, compression-tension, and compression-compression). However, it is common practice to use a single interaction parameter and that practice has been adopted in this study. While there was at least one treatment in each regime, there were not sufficient treatments in each regime to create four separate optimized surfaces. The interaction parameter was optimized concurrently with shear strength $S_{12}$ in the Tsai-Wu case. The boundaries of $f_{12}$, presented in Table 3.1, are calculated by a stability criterion [138] which forces the failure surface to converge.

### 3.2.2.3 Strength Optimization Routine

A MATLAB® genetic algorithm solver was used to optimize the shear strength and interaction parameters concurrently. A schematic for the parametric optimization for strength is depicted in Figure 3.5. CLT and the failure criterion are coupled to solve for a single failure point in 3D space ($\sigma_1, \sigma_2, \sigma_{12}$), the predicted strength. The fitness function minimizes the least squares error between the predicted and the actual (experimental) strength for each treatment (orientation angle and test direction). Stress tensor components $\sigma_1, \sigma_2$, and $\sigma_{12}$ were normalized before calculating mean

78
square error to account for the difference in material strengths in parallel, perpendicular, and shear. In the Tsai-Wu case, the fitness function optimizes parallel-to-grain shear strength $S_{12}$ and interaction parameter $f_{12}$. In the Hashin case, the fitness function optimizes parallel-to-grain shear strength $S_{12}$ and perpendicular-to-grain shear strength $S_{21}$.

![Figure 3.5: The optimization routine for shear strength minimizes the least squares error between predicted and test data from 30, 45, and 60 degree symmetric laminates in tension and compression.]

3.3 Results

Axial tension and compression tests were performed on 0, 30, 45, 60, and 90 degree symmetric, angle-ply wood laminates. The results of these tests are reported in Figure 3.6, with error bars showing one standard deviation ($n = 10$ tests for each treatment). It is normal for 0-degree specimens to display a larger variation because they are especially subject to small misalignments and variations in grain orientation. This is also the case with traditional fiber-reinforced polymer composites.
Figure 3.6: Strength of angle-ply wood laminates in tension (top) and compression (bottom).
3.3.1 Shear Modulus, $G_{12}$

The optimal shear stiffness from tension and compression tests of multiaxial laminates was found to be 566 MPa. This is in good agreement with Janowiak (2001) [82] who used torsion tests to determine $G_{12}$ for Southern Pine, Douglas Fir, and Yellow Poplar Laminated Veneer Lumber. All elastic parameters are presented in Table 3.2. $E_1$ and $E_2$ were determined by preliminary experiments and Poisson’s Ratio $\nu_{12}$ is the value reported by Janowiak (2001) for a similar material, Southern Pine LVL. Because of the known interaction between $\nu_{12}$ and $G_{12}$, the variation of $G_{12}$ in response to a range of possible $\nu_{12}$ values was also examined. The result is shown in Figure 3.7. In comparison to the variation of $G_{12}$ between different studies on similar materials, the variation resulting from Poisson’s Ratio is relatively small.

The value of Poisson’s Ratio reported by [82] seems high because $\nu_{12}$ is limited to 0.5 for isotropic materials by the physical argument for Young’s modulus, the shear modulus, and the bulk modulus to be positive [140]. In composite materials, it is common to have $\nu_{12} > 0.5$, and the limits of $\nu_{12}$ for an orthotropic material are given by $\nu_{12} < \left( \frac{E_1}{E_2} \right)^{0.5}$ [84], which is derived by applying the same physical argument for Young’s modulus, shear modulus, and bulk modulus as positive to the 6x6 stiffness matrix for an orthotropic material.

<table>
<thead>
<tr>
<th>$E_1$ (GPa)</th>
<th>$E_2$ (GPa)</th>
<th>$\nu_{12}$</th>
<th>$G_{12}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.8</td>
<td>1.15</td>
<td>0.743</td>
<td>567</td>
</tr>
</tbody>
</table>

Table 3.2: In-plane Elastic Properties

3.3.2 Shear Strength, $S_{12}$ and $S_{21}$

Strength parameters $S_{1T}$, $S_{1C}$, $S_{2T}$, and $S_{2C}$ were determined by tests of 0 and 90 degree specimens and are reported in Table 3.3. The optimal shear strength values for the Tsai-Wu and Hashin criteria are reported in Table 3.3, along with interaction
Figure 3.7: Relationship between Shear Modulus $G_{12}$ and Poisson’s Ratio $\nu_{12}$. * Indicates the value selected in this study.
parameter \( f_{12} \) for the Tsai-Wu theory. For \( S_{12} \), shear parallel-to-grain, there is quite good agreement between the two criteria and reasonable agreement with what little is available in the literature. While the present study reports \( S_{12} \) values of 7.10 MPa (Tsai-Wu) and 7.33 MPa (Hashin), Gupta and Siller (2005) reported a value of 4.90 MPa from the shear block test and 6.99 MPa from the torsion test for a similar material. For clear wood, an expected range for \( S_{21} \) is 5-10 MPa [65]. This study reports \( S_{21} \), perpendicular-to-grain shear, to be 18.4 MPa per the Hashin criterion. This parameter is not commonly reported in the literature (and has not been verified experimentally) because it tends not to be a limiting factor when designing with wood, but is known to be higher than parallel-to-grain shear.

\[
\begin{array}{cccccc}
S_1 T & S_1 C & S_2 T & S_2 C & \text{Tsai-Wu} & \text{Hashin} \\
\text{(MPa)} & \text{(MPa)} & \text{(MPa)} & \text{(MPa)} & \text{(MPa)} & \text{(MPa)} & \text{(MPa)} & \text{(MPa)} \\
69.8 & 59.1 & 4.55 & 19.2 & -0.0010 & 7.10 & 7.31 & 18.4 \\
\end{array}
\]

Table 3.3: In-plane Strength Properties of Wood Laminate

### 3.3.3 Tsai-Wu Interaction Parameter, \( f_{12} \)

The optimal interaction parameter \( f_{12} \) for the Tsai-Wu theory is -0.0010 MPa\(^{-2}\). Clouston et al. (1998) showed that this parameter varies by orientation angle, reporting values from -0.00053 to 0.0409 MPa\(^{-2}\) in laminates tested from 15 to 60 degrees off-axis in tension and ultimately recommending the value of +0.00003 MPa\(^{-2}\) for Douglas-fir LVL based on a probabilistic minimization using 15-degree test data. By comparison, the present study uses balanced, symmetric laminates in both tension and compression and the optimization results account for all angles. The value of -0.0010 MPa\(^{-2}\) is comparable with the range of values reported by Clouston (1998) and falls within the boundaries of the stability criterion.
3.4 Conclusions

In this study, a novel method for determining shear properties of laminated wood by coupling tension and compression tests of angle-ply laminates with a failure criterion optimization routine is presented. Shear strength, stiffness, and Tsai-Wu interaction parameter $f_{12}$ are presented for 4-ply wood laminates. The results are in relatively good agreement with what is found by other test methods in the literature for similar materials. They are especially close to torsion test results from Gupta and Siller (2005), which is promising because the torsion test is widely considered to be among the best methods to determine shear strength. Importantly, rather than trying to isolate pure shear strength which is uncommon in plate and shell structures, this study examines the shear properties using a testing program which more closely mimics real-life applications and failure modes.
CHAPTER 4
FAILURE CRITERIA ASSESSMENT FOR MULTIAXIAL WOOD LAMINATES

4.1 Introduction

The goal of this research is to address some of the challenging aspects of designing high-performance composites with bio-based materials. The wind turbine blade exemplifies many important challenges in designing with composite materials, including complex, combined and time-variant stress states in the material. As such, it provides an ideal case for which to apply modeling techniques being developed and experimentally verified herein for the design of high-performance bio-based composite materials.

The present chapter uses experimental mechanics to inform computational models for the behavior of wood laminate composites exposed to off-axis and multiaxial loading conditions. In finite element modeling, combined loading conditions are modeled using failure criteria which consider all stress tensor components in order to predict material yielding. There are numerous criteria which have been proposed for use in composite materials [18], and others which have been recommended for wood [40] [151]. Even in the FRP industry, there is disagreement on the best practice for the treatment of ply failure. In Figure 4.1, a 1996 survey by AIAA shows the variance in failure criteria used in the fiber-reinforced-polymer (FRP) industry. In order to understand which criteria should be used for modeling multiaxial wood laminate composites, an analysis of material behavior under different stress states is performed. Experimental data is used to fit several failure theories, first using parameters from
the literature, then by performing parametric optimization on each model. The chapter concludes with remarks on which failure theories are best suited for computational modeling of multiaxial wood laminate structures and give recommendations for best practices.

![Figure 4.1: Popularity of different failure criteria in the Fiber-Reinforced Polymer (FRP) industry, based on a 1996 survey from AIAA. From [131].](image)

**Figure 4.1**: Popularity of different failure criteria in the Fiber-Reinforced Polymer (FRP) industry, based on a 1996 survey from AIAA. From [131].

### 4.2 Methods

#### 4.2.1 Materials

The experimental data used in this chapter are the same data presented in Chapter 3. For experimental methods, including materials, fabrication, and testing, refer to Section 3.2. Preliminary experiments were used to measure axial and transverse,
tension and compression properties of unidirectional laminates. These preliminary experimental treatments are outlined in Figure 4.2. Experimental treatments were chosen for a range of grain orientations that would (1) represent common layups that might be used in turbine blades, and (2) represent all four quadrants of the biaxial loading regime ($\sigma_1 - \sigma_2$ in tension-tension, tension-compression, compression-tension, compression-compression). Experimental treatments are outlined in Figure 4.3.

<table>
<thead>
<tr>
<th>treatment#</th>
<th>loading type</th>
<th>grain orientation and loading diagram</th>
<th>layup</th>
<th>quadrant of biaxial failure criteria</th>
</tr>
</thead>
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<tr>
<td>prelim 1</td>
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<tr>
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</tr>
<tr>
<td>prelim 3</td>
<td>tension</td>
<td><img src="image3.png" alt="Diagram" /></td>
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<td>1, 2</td>
</tr>
<tr>
<td>prelim 4</td>
<td>tension</td>
<td><img src="image4.png" alt="Diagram" /></td>
<td>[90]_4</td>
<td>1, 4</td>
</tr>
</tbody>
</table>

Figure 4.2: Preliminary test treatments for multiaxial wood laminate study. Tests were performed in order to measure baseline, axial and transverse, tension and compression properties.
<table>
<thead>
<tr>
<th>treatment#</th>
<th>loading type</th>
<th>grain orientation and loading diagram</th>
<th>layup</th>
<th>quadrant of biaxial failure criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>compression</td>
<td>[30/-30]s</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>compression</td>
<td>[45/-45]s</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>compression</td>
<td>[60/-60]s</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>tension</td>
<td>[30/-30]s</td>
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</tr>
<tr>
<td>5</td>
<td>tension</td>
<td>[45/-45]s</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>tension</td>
<td>[60/-60]s</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.3: Test treatments for multiaxial wood laminate study.
4.2.2 Failure Criteria

Failure criteria are used in computational modeling of composite structures to describe when a material will yield under multiple simultaneous types of stress (e.g. axial, transverse, and shear). There are numerous criteria which have been proposed for use in composite materials and others which have been used in wood. The similarity between all of these theories is that they each allow for orthotropic material behavior, meaning that the material may behave differently according to three principal material directions. This in itself was a great improvement upon the most basic yield theories because of the substantial difference in material behavior parallel to the grain, perpendicular to the grain, and between plies. The failure theories presented herein are all simplified into plane stress formulations, because the wind turbine blade is a shell structure which is relatively thin compared to its width and height. Thus, it is commonly assumed that stresses in the through-thickness or $z$ direction are zero.

There are several different ways to think about failure depending on the material and application. For the practical application of a laminate structure, material yielding is of greatest concern. Tensile specimens exhibited little to no plastic zone (brittle failure modes), so the ultimate strength and the yield strength are the same. Therefore, tensile failures are defined using the ultimate strength. However, wood is phenomenologically plastic in compression (the failure modes observed were crushing/micro-buckling, shear, and a combination thereof) so defining a yield stress before ultimate failure is more appropriate. Good consistency was found using the 0.2% offset yield strain method [63].

The failure criteria evaluated in this study are the Tsai-Hill, Tsai-Wu, Chamis, and Hashin theories, which are reviewed in Chapter 2.3.2. The Tsai-Hill criterion is chosen for its widespread and historical prevalence, making it a good basis for comparison with other theories. The Tsai-Wu criterion is chosen because it is widely used in both wood and FRP industries, and offers an improvement upon the Tsai-
Hill criterion because it considers tensile and compressive properties separately. The Chamis criterion is selected because of its use in aerospace FRP composites, especially at NASA. Finally, the Hashin criterion is selected because of its success in predicting failure in FRP composites, which is attributed especially to its piecewise formulation.

4.2.3 Numerical Methods

4.2.3.1 Deterministic Model

In the deterministic model, several parameters were taken from the literature and some were found using preliminary experiments. The parameters were used to define the failure criteria, and then criteria predictions were compared to experimental results. $S_{1T}$, $S_{1C}$, $S_{2T}$, and $S_{2C}$ were determined experimentally using axial tension and compression tests on a unidirectional laminate parallel to the grain (0 degree angle) and perpendicular to the grain (90 degree angle). The shear stiffness $G_{12}$ has a significant impact on the results from the Classical Lamination Theory, whose use is explained in the forthcoming section. In this study, the value of 476 MPa was selected, as reported by Janowiak, et al. [82] for Southern Pine LVL, because this value should be close to our Spruce-Pine-Fir veneer from Louisiana Pacific. Clouston [40] reported the $F_{12}$ interaction parameter for the Tsai-Wu criterion for the same material. Chamis [33] suggests using the default value of $K_{12} = 1$ when the actual value, which can only be determined experimentally, is unknown. All model parameters are presented in Table 4.1.

4.2.3.2 Optimal Model Using the Genetic Algorithm

The MATLAB® genetic algorithm solver was used to optimize the input parameters because even well characterized wood products have some variation and many parameters are difficult to determine experimentally. Additionally, the characterization of multiaxial yield strength involves parameters like shear strength and shear stiffness whose methods for determining are highly contested, with significant varia-
Table 4.1: Failure criteria parameters used in the deterministic model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel-to-grain Tensile Strength</td>
<td>$S_{1T}$</td>
<td>69.8 MPa</td>
</tr>
<tr>
<td>Parallel-to-grain Compressive Strength</td>
<td>$S_{1C}$</td>
<td>53.3 MPa</td>
</tr>
<tr>
<td>Perpendicular-to-grain Tensile Strength</td>
<td>$S_{2T}$</td>
<td>4.55 MPa</td>
</tr>
<tr>
<td>Perpendicular-to-grain Compressive Strength</td>
<td>$S_{2C}$</td>
<td>13.3 MPa</td>
</tr>
<tr>
<td>In-plane Shear Strength</td>
<td>$S_{12}$</td>
<td>8.79 MPa</td>
</tr>
<tr>
<td>In-plane Shear Stiffness</td>
<td>$G_{12}$</td>
<td>476 MPa</td>
</tr>
<tr>
<td>Tsai-Wu Interaction Parameter</td>
<td>$F_{12}$</td>
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</tr>
<tr>
<td>Chamis Interaction Parameter I</td>
<td>$K_{12}$</td>
<td>0.9494</td>
</tr>
<tr>
<td>Chamis Interaction Parameter II</td>
<td>$K_{12}'$</td>
<td>1</td>
</tr>
</tbody>
</table>

...tion between test methods. Treating these parameters as unknowns in the parametric optimization allows the algorithm to search for material models which better fit the experimental data.

A schematic for the parametric optimization is depicted in Figure 4.4. The first step in the fitness function is to calculate the stress tensors from the experimental data using Classical Lamination Theory (CLT). Though the experimental data does not change, the CLT calculation for stress tensors depends upon elastic constants, which are treated as random variables. Then, the algorithm-determined input parameters are substituted into the failure theory. The failure theory can be coupled with CLT to form a system of equations, which is solved for the predicted stress tensor. The fitness function minimizes the least squares error between the predicted failure and the actual (experimental) failure for each treatment.

The bounds for the parametric optimization are presented in Table 4.2. Strength parameters were taken to be within a reasonable range reported in the Wood Handbook [65]. Shear modulus was taken to be within a reasonable range given by [82]. The interaction parameter $f_{12}$ for the Tsai-Wu criterion must comply with a stability condition which was calculated using deterministic strength parameters and the equation in [40]. The interaction parameters $K_{12}$ and $K_{12}'$ in the Chamis criterion...
have no theoretical limits but many common materials have K values between 0 and 2.

Figure 4.4: Schematic for the fitness function used in the parametric optimization of the failure criteria. Data are shown in rectangles, while equations or processes are shown in circles. The function minimizes the least squares error between the experimental and theoretical yield stress tensors.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{1T}$ (MPa)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>$S_{1C}$ (MPa)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>$S_{2T}$ (MPa)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>$S_{2C}$ (MPa)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>$S_{12}$ (MPa)</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>$S_{21}$ (MPa)</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>$G_{12}$ (MPa)</td>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>$f_{12}$</td>
<td>-.0021</td>
<td>.0021</td>
</tr>
<tr>
<td>$K'<em>{12} \ast K</em>{12}$</td>
<td>$-\text{Inf}$</td>
<td>$\text{Inf}$</td>
</tr>
</tbody>
</table>

4.3 Results

4.3.1 Tension and Compression Tests

Axial tension and compression tests were performed on 0, 30, 45, 60, and 90 degree symmetric, angle-ply wood laminates. The yield strength from these tests is reported previously in Chapter 3, Figure 3.6.

4.3.2 Failure Criteria Analysis

Failure criteria have been used to create yield surfaces, which represent all possible combinations of $\sigma_1$, $\sigma_2$, and $\sigma_{12}$ that will result in material yielding. 3-dimensional yield surfaces for the Tsai-Wu and Hashin criteria with experimental data are depicted in Figure 4.5. Theoretically these surfaces are full ellipsoids (or in the Hashin case a surface with symmetry across the $\sigma_{12}$ plane), but positive and negative shear stresses produce the same mechanical behavior, thus only the positive-shear half is shown.

These plots can be difficult to interpret, so yield surfaces are often represented as 2-dimensional envelopes where shear stress is set to a constant value and an envelope is drawn in the $\sigma_1 - \sigma_2$ plane. Figure 4.6 shows all yield surfaces plotted together in 2 dimensions in the $\sigma_{12} = 0$ plane, using deterministic parameter values from Table
4.1. Finally, Figure 4.7 shows the difference between yield envelopes created with parameters from the literature and optimized parameters.

Optimal model parameters are presented in Table 4.3. In most cases, the strength parameters came close to values reported for the deterministic model. The main exception to this is $S_{Xt}$ for the Tsai-Wu criterion. The optimal values for shear stiffness $G_{12}$ vary considerably, which is also true for reported values in the literature for wood laminates. Because shear stiffness plays an important role in the calculation of fiber stresses using Classical Lamination Theory, further exploration of this parameter would be a good topic for future study. The values for the interaction parameters for both the Tsai-Wu and Chamis criteria agree reasonably well with what is in the literature, but the literature represents quite a large range in both cases.

Table 4.3: Optimal failure criteria strength, stiffness, and interaction parameters.

<table>
<thead>
<tr>
<th>Strength and Stiffness</th>
<th>Tsai-Hill</th>
<th>Tsai-Wu</th>
<th>Chamis</th>
<th>Hashin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{1T}$ (MPa)</td>
<td>69.1</td>
<td>34.4</td>
<td>50.0</td>
<td>63.7</td>
</tr>
<tr>
<td>$S_{1C}$ (MPa)</td>
<td>-</td>
<td>60.3</td>
<td>56.9</td>
<td>53.3</td>
</tr>
<tr>
<td>$S_{2T}$ (MPa)</td>
<td>5.4</td>
<td>5.5</td>
<td>4.9</td>
<td>5.4</td>
</tr>
<tr>
<td>$S_{2C}$ (MPa)</td>
<td>-</td>
<td>13.6</td>
<td>14.9</td>
<td>13.4</td>
</tr>
<tr>
<td>$S_{12}$ (MPa)</td>
<td>9.6</td>
<td>9.0</td>
<td>8.7</td>
<td>7.3</td>
</tr>
<tr>
<td>$S_{21}$ (MPa)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.4</td>
</tr>
<tr>
<td>$G_{12}$ (MPa)</td>
<td>686</td>
<td>507</td>
<td>571</td>
<td>520</td>
</tr>
</tbody>
</table>

Interaction Parameters

<table>
<thead>
<tr>
<th>Tsai-Wu ($f_{12}$)</th>
<th>.00079</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamis ($K'<em>{12} * K</em>{12}$)</td>
<td>-0.946</td>
</tr>
</tbody>
</table>

Fitness scores for deterministic and optimized models are presented in Table 4.4. Scores are represented as the average percent error between the yield theory prediction and the experimental mean for all ten treatments (0, 30, 45, 60, 90 degrees in tension and compression). In both cases, the Hashin criterion does the best job of predicting yielding of wood laminates. Furthermore, the Hashin criterion has been expanded
Figure 4.5: Yield envelopes for Tsai-Wu and Hashin criteria in $\sigma_1, \sigma_2, \sigma_{12}$ space. Strength parameters, which determine the envelope shape, were optimized to fit the experimental data. Averages for the 30, 60, and 90-degree experimental treatments are shown by *.
Figure 4.6: Optimal yield envelopes from the Tsai-Hill, Tsai-Wu, Chamis, and Hashin yield criteria were determined by performing parametric optimization to best fit the criteria to experimental data. Experimental data is shown in points, with ° indicating fiber failure and * indicating inter-fiber failure.
Figure 4.7: There is a considerable difference between yield envelopes created with parameters from the literature and optimized parameters for the Tsai-Wu and Hashin criteria. Average experimental data for each sample group (e.g. 30 degrees, tension) is indicated by points with o corresponding to wood fiber failure and * corresponding to inter-fiber failure. Top: Yield criteria are represented in $\sigma_1 - \sigma_2$ space, where $\sigma_{12} = 0$. Bottom: Yield criteria are represented in $\sigma_2 - \sigma_{12}$ space, where $\sigma_1 = 0$. For both criteria, the optimal model provides an improvement compared to the deterministic model.
upon by several authors since its original formulation. One of these improvements was
evaluated in this study (the Sun criterion for matrix compression [132]) but did not
provide an improvement upon the original criterion (avg. error of 5.32%). Still, given
that the criterion was formulated from empirical observations of traditional fiber-
reinforced composites, it is possible that an improved version of the Hashin criterion
which accounts specifically for the failure mechanisms in wood could provide an even
better fit than is reported herein. This would be a good opportunity for further
development of this study.

The Tsai-Wu and Chamis models have similar fitness scores and fit the data rea-
sonably well. With parameters from the literature, the Chamis criterion gives less
error than the Tsai-Wu criterion by nearly 2.5%. The main disadvantage to using the
Chamis criterion is that even in its deterministic form, it relies on the knowledge of
many elastic parameters which can be tedious to determine experimentally and diffi-
cult to find in the literature. As expected, the Tsai-Hill criterion does not perform as
well as the others because of its neglect to consider tensile and compressive properties
separately. However, given its continued prevalence in the industry it provides a good
baseline from which to compare the other theories.

Table 4.4: Fitness scores for deterministic and optimized models. Scores are rep-
resented as the average percent error between the yield theory prediction and the
experimental mean for all ten treatments (0, 30, 45, 60, 90 degrees in tension and
compression).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Deterministic Model Fitness (avg. % error)</th>
<th>Optimized Model Fitness (avg. % error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsai-Hill</td>
<td>18.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Tsai-Wu</td>
<td>12.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Chamis</td>
<td>9.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Hashin</td>
<td>8.4</td>
<td>5.3</td>
</tr>
</tbody>
</table>
4.4 Conclusions

A framework for evaluating the accuracy of failure criteria in comparison to experimental data, using axial testing of multiaxial laminates, is presented. Four failure theories are compared to experimental data from tension and compression tests of laminated wood veneer at 0, 30, 45, 60, and 90 degree angles. The theories are first evaluated using parameters from preliminary experiments and the literature in a deterministic model. They are then integrated with a genetic optimization routine and best-fit parameters are determined for each theory.

The Hashin criterion demonstrates the best fit to the experimental data in both deterministic and optimized model cases, with an average error of 8.35% using parameters from the literature and an average error of 5.30% using optimized parameters. The Hashin criterion was formulated semi-empirically based on observations of failures in traditional fiber-reinforced polymer composites. Wood laminates demonstrate similar failure mechanisms in general, but it is possible that a thorough analysis of the differences in failure mechanics between FRP and wood laminate composites could illuminate further improvements to the Hashin criterion in its application to laminated wood. The main disadvantage to the Hashin criterion is that it can be more complex to implement into a finite-element model because there are two distinct possible failure modes for each stress tensor under combined loading.

The Tsai-Wu and Chamis criteria had reasonably good agreement (< 10% average error) with the experimental data once parameters were optimized. These criteria represent continuous surfaces (unlike the piecewise Hashin surface) so they can be more easily implemented computationally. All theories were improved through parametric optimization, but this was especially the case for the Tsai-Wu theory where the average error decreased by over 5% through parametric optimization. This speaks both to the importance of using correct parameters, and to the difficulty of doing so when parameters vary widely in the literature and can be difficult to isolate experimentally.
CHAPTER 5
FAILURE CRITERIA ASSESSMENT FOR MULTIAXIAL FLAX-FIBER REINFORCED POLYMER COMPOSITES

5.1 Introduction

In a similar fashion to Chapter 4, the present chapter uses experimental mechanics to inform computational models for the behavior of flax laminate composites exposed to off-axis and multiaxial loading conditions. In order to understand which criteria should be used for modeling multiaxial flax laminate composites, an analysis of material behavior under different stress states is presented. Experimental data is used to fit several failure theories, using parametric optimization to determine model parameters. The chapter concludes with remarks on which failure theories are best suited for computational modeling of multiaxial flax laminate structures and gives recommendations for best practices.

5.2 Methods
5.2.1 Materials

Unidirectional (UD) and multidirectional (MD) composite laminates were manufactured using vacuum infusion. The fiber component is a 2-ply, non-crimp, biaxial flax yarn fabric from Bcomp Ltd., Switzerland, called Amplitex 5008, with an area weight of 350 g/m². Its yarn orientation is nominally +/- 45° in the machine direction of the fabric, but was measured in the present study to be +51/-52°. The polyester stitches that hold the two plies in the fabric together were carefully removed with tweezers so that the plies could be re-oriented for making a UD laminate. In the
case of the MD laminates, the stitches were also removed for consistency. The matrix component is Huntsmans Araldite 1568 / Aradur 3489 epoxy resin, using a mix ratio of 100:28 parts by weight. The cure cycle is 19 hours at 40 C followed by 5 hours at 75 C. The resulting 8-ply (i.e. layup of 4 fabric sheets) laminates have planar dimensions of 400 x 400 mm (UD) and 470 x 670 mm (MD), and with thickness of 2.4 mm (UD) and 2.8 mm (MD).

Composite density was measured using Archimedes’ principle, where 3 specimens measuring 25 x 25 mm were cut from each plate and weighed submerged in water. Volumetric composition of the composites ($V_f$, $V_m$, and $V_p$) was calculated using measured values of density and weight fraction ($W_f$), as demonstrated in Equations 5.1a - 5.1b. Density of the raw fibers ($\rho_f$) was taken to be 1.540 g/cm$^3$ from a previous study by Madsen, *et al.*, [103] and density of the cured matrix was measured to be 1.14 g/cm$^3$.

\[
V_f = \left( \frac{\rho_c}{\rho_f} \right) \times W_f \tag{5.1a}
\]

\[
V_m = \left( \frac{\rho_c}{\rho_m} \right) \times (1 - W_f) \tag{5.1b}
\]

\[
V_p = 1 - V_f - V_m \tag{5.1c}
\]

In order to get a representation of different fiber orientations, mechanical test specimens were cut from the laminates at different angles. UD specimens were cut at two angles, 0° and 90° from the UD laminate. MD specimens were cut at three angles, 0°, 15°, and 90° from the MD laminate. See Figure 5.1 for a schematic drawing of the cut test specimens. The tensile test specimens had rectangular dimensions (width x length) of 15 x 250 mm (UD) and 25 x 250 mm (MD), gauge section lengths of 50 mm (UD and MD), and grip lengths of 50 mm (UD and MD), as per the tension testing standard ISO527-4 [80] (similar to ASTM D3039). Dogbone-shaped specimens
were cut for compression tests with total dimensions of 19 x 136 mm (UD and MD), grip lengths of 51 mm with tapered tabs, and gauge sections of 15 x 14 mm.

Figure 5.1: Schematic drawing of the mechanical test specimens cut from the UD laminate (left) and MD laminate (right), giving specimens with five different fiber orientations.

5.2.2 Experimental Methods

Static tensile tests were performed on an Instron test machine with a crosshead speed of 1 mm/min, grip capacity of 100 kN and loadcell capacity of 20 kN. Tests were done at room temperature. Strain was measured with two extensometers, centered on either side of the test specimen. Ultimate strength was determined as the recorded maximum stress, and stiffness was determined in the strain range of 0.05% to 0.25%. Static compression tests were performed using a combined mechanical loading fixture [20], which applies a fixed ratio of compression to grip loading with a novel mechanical fixture. This fixture has proven to yield repeatable results and acceptable failure modes in tests with glass and carbon fiber composites [20]. The fixture was mounted on an Instron test machine. Strain gauges were used on either side of the
test specimen. Specimens were strained to failure at a crosshead speed of 1 mm/min. Ultimate strength was determined as the recorded maximum stress, and stiffness was determined in the strain range of 0.05% to 0.25%.

The fiber angles of the test specimens were measured using a Fast Fourier Transform (FFT) image analysis procedure, as shown in Figure 5.2. The use of FFT for the purpose of determining fiber angles in composites has previously been reported by Ueki, et al., (2017) [139]. In the present study, the term fiber angle is used to refer to the angle of the yarn in the specimen relative to the testing direction, and as such it does not account for the twist direction of the fibers in the yarn [103]. First, photographs of specimens were taken on a light table using a Sony A7R II digital camera (Figure 5.2, left). It was possible to capture all 8 plies at once by using front-light from the light table, with individual plies being indistinguishable from one another. Then, MATLABs FFT algorithm (fft2) was used to transform the photograph into a frequency domain image (Figure 5.2, middle). The reference direction of the specimen is defined by the lengthwise specimen edge. 2-dimensional FFT interprets an image as a superposition of spatial patterns with frequencies and directions. For example, an image of exactly vertical stripes would be recognized as a composition with angle of 0° and frequency corresponding to the distance in pixels between the stripes. In this application, the direction is of most concern. In addition to the detected main fiber direction frequencies, smaller contributions from other frequencies were also detected in each image (Figure 5.2, right). These frequencies were filtered out using a high-pass filter. Finally, the mean fiber angles were taken by averaging the two clusters that passed through the filter.

5.2.3 Composite Laminate Analysis

From experimental data, global stresses and strains were transformed into lamina stresses and strains following the assumptions of Classical Lamination Theory (CLT),
Figure 5.2: Image analysis procedure to measure fiber angles in test specimens by using Fast Fourier Transform (FFT). Left: Example of specimen photograph of a MD specimen with fiber angles of +51/-52. Center: Scaled and centered FFT frequency domain image. Horizontal and vertical axes represent spatial frequency, with lowest frequency (DC value) at the center and higher frequency at the edges. The frequency amplitude is represented by the heat map, such that the fiber orientation is represented by the dark red coloring. Right: Histogram showing the fiber angle distribution detected by FFT.

as shown previously in Figure 3.3. It is these lamina-level stresses and strains that are employed in failure criteria. The global coordinate system is defined by \((\sigma_x, \epsilon_x)\) where \(x\) is the testing direction. The lamina coordinate system is defined by \((\sigma_1, \epsilon_1)\) representing the parallel-to-fiber direction and \((\sigma_2, \epsilon_2)\) representing the perpendicular-to-fiber direction.

5.2.4 Failure Criteria

Failure criteria are used in computational modelling of composite structures to describe when a material will fail under multiple and simultaneous types of stresses (e.g. axial, transverse, and shear). There are numerous criteria which have been proposed for use in composite materials. The criteria evaluated in this study are the Tsai-Hill, Tsai-Wu, Hashin, and Puck criteria, which are detailed in Section 2.3.2. There is considerable disagreement in the literature about what the correct definition
of failure is for composite laminates. Herein, ultimate strength is used to define failure because it is the only point on the stress-strain curves that is easily defined for all fiber orientations tested. Different definitions of failure could, however, straightforwardly be implemented in the presented optimization methodology.

5.2.5 Optimization

The Genetic Algorithm solver in MATLAB was used to optimize the various strength, strain and interaction parameters of the failure criteria equations with respect to the experimental data. A schematic for the parametric optimization procedure is the same as used in the previous chapter, depicted in Figure 4.4. First, the stress tensors are calculated from the experimental data using CLT. During this step, the strength properties of UD laminates were corrected using the rule of mixtures to account for the difference in fiber volume fractions between UD and MD laminates. Next, the strength and other parameters are substituted into the failure criterion which is solved for the predicted stress tensor. The fitness function minimizes the least squares error between the predicted failure and the experimental failure for each of the analyzed fiber orientations. The average was weighted so that all sample groups contribute equally to the mean error, to adjust for having different sample sizes across treatments.

5.3 Results

5.3.1 Composite Properties

As shown in Table 5.1, the UD and MD composite laminates were fabricated with fiber volume contents of 37% and 31%, respectively. The higher fiber content in the UD laminate is expected due to the better packing ability of the fiber yarns when the two plies of the fabrics are aligned with each other. The porosity content for both composites is below 1% indicating good quality of the laminates. Table
5.1 presents also the measured fiber angles of the test specimens. For the two UD test specimens, U1 and U2, the fiber angles are measured to be 0 and 87 degrees, respectively, which demonstrates that the approach of re-orienting the two plies in the fabric was successful. For the three MD test specimens, M1, M2 and M3, the fiber angles are measured to be $+51/-52$, $+36/-66$ and $+38/-38$ degrees, respectively. These angles are almost identical to the expected values based on the cutting angles of the specimens (see Figure 5.1), i.e. for M2: $51-15=36$ degrees, $-52-15=-67$ degrees, and for M3: $90-52=38$ degrees, $51-90=-39$ degrees.

Tension and compression tests were performed on the test specimens from the UD and MD composite laminates. The resulting stiffnesses and strengths are reported in Table 5.2. The variation in number of specimens per fiber orientation is a result of optimizing the cut plan of the laminates, and prioritizing fiber orientations in which fiber failure is expected. Composite failure modes governed by fiber failure are known to have more variation compared to composite failure modes governed by matrix failure [64]. Additionally, a smaller number of specimens were tested in compression because of the greater complexity in performing these tests. The results presented in Table 5.2 for tensile properties are consistent with Madsen and Lilholt (2013) [100] who reviewed the subject, presenting results from several studies of plant fiber composites. For the UD laminate, the U1 tensile specimen has a stiffness of 20 GPa. By using a simple rule-of-mixtures relationship, the effective stiffness of the flax fibers can be back-calculated to be 48 GPa, which is a typical stiffness value for flax fibers in composites ([104]). Compression properties are less studied and there is limited availability of data for which to compare with the results in the present paper. However, previous research has shown that compressive strength tends to be similar but somewhat less than tensile strength ([26]). This trend is consistent with the findings for the U1 and M3 test specimens, where fiber failures were observed. In cases where matrix failure was observed (U2 and M1), compression strength is higher.
Table 5.1: Flax composite physical properties from manufacturing.

<table>
<thead>
<tr>
<th>Composite laminate</th>
<th>Density (g/cm(^3))</th>
<th>(V_f) (%)</th>
<th>(V_p) (%)</th>
<th>Test specimen</th>
<th>Fiber angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional (UD)</td>
<td>1.28</td>
<td>37</td>
<td>0.7</td>
<td>U1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U2</td>
<td>87</td>
</tr>
<tr>
<td>Multidirectional (MD)</td>
<td>1.26</td>
<td>31</td>
<td>0.7</td>
<td>M1</td>
<td>+51/-52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M2</td>
<td>+36/-66</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M3</td>
<td>+38/-38</td>
</tr>
</tbody>
</table>

than tensile strength. Compressive stiffness is similar to tensile stiffness across all specimens.

For the UD laminate, the tensile strength in the 0\(^o\) direction (U1 specimens) was corrected to be 235 MPa (from the measured value of 269 MPa) using the rule of mixtures, to account for the lower fiber content in the MD laminate on 31 % (instead of 37 %). The tensile strength in the 90\(^o\) direction (U2 specimens) was not corrected, due to the known low sensitivity of the fiber content on strength in this direction [102]. Due to the lack of widely accepted analytical models for compression properties of composites, it was decided not to correct the compression strength values of the UD laminate.

5.3.2 Failure Criteria

As detailed in Table 5.3, the parameters of the four failure criteria were optimized by using a genetic algorithm to fit the equations of the criteria to the experimental data of the UD and MD specimens. The generated optimal parameter values, along with the mean error (fitness), are reported in Table 5.3.

Figure 5.3 depicts plots of each failure theory in \(\sigma_1 - \sigma_2\) space. This is a common representation of failure criteria. However, since the \(\sigma_1 - \sigma_2\) space does not depict shear stress, it does not capture how well the theories predict failure of MD composites. It is therefore most useful to notice how well the theories fit failure of UD composites. It
Table 5.2: Results of axial testing unidirectional and multidirectional composites.

<table>
<thead>
<tr>
<th>Tensile specimen</th>
<th>Fiber angle (degrees)</th>
<th>Tensile Properties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of specimens</td>
<td>Stiffness (GPa)</td>
<td>Strength (MPa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>U1</td>
<td>0</td>
<td>10</td>
<td>20.3</td>
<td>1.5</td>
</tr>
<tr>
<td>U2</td>
<td>87</td>
<td>3</td>
<td>3.6</td>
<td>0.2</td>
</tr>
<tr>
<td>M1</td>
<td>+51/-52</td>
<td>8</td>
<td>4.5</td>
<td>0.1</td>
</tr>
<tr>
<td>M2</td>
<td>+36/-66</td>
<td>10</td>
<td>5.0</td>
<td>0.1</td>
</tr>
<tr>
<td>M3</td>
<td>+38/-38</td>
<td>6</td>
<td>7.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compression specimen</th>
<th>Fiber angle (degrees)</th>
<th>Compression Properties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of specimens</td>
<td>Stiffness (GPa)</td>
<td>Strength (MPa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>U1</td>
<td>0</td>
<td>3</td>
<td>16.2</td>
<td>0.4</td>
</tr>
<tr>
<td>U2</td>
<td>87</td>
<td>2</td>
<td>4.5</td>
<td>0.6</td>
</tr>
<tr>
<td>M1</td>
<td>+51/-52</td>
<td>3</td>
<td>4.1</td>
<td>0.2</td>
</tr>
<tr>
<td>M2</td>
<td>+36/-66</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M3</td>
<td>+38/-38</td>
<td>3</td>
<td>5.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 5.3: Mean error (fitness) and optimal model parameters for Tsai Hill, Tsai Wu, Hashin, and Puck Failure Theories.

(a) Tension, compression, and shear strength parameters.

<table>
<thead>
<tr>
<th>Failure Criterion</th>
<th>Parameter</th>
<th>$S_{1T}$ (MPa)</th>
<th>$S_{1C}$ (MPa)</th>
<th>$S_{2T}$ (MPa)</th>
<th>$S_{2C}$ (MPa)</th>
<th>$S_{12}$ (MPa)</th>
<th>Mean Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsai-Hill</td>
<td></td>
<td>110</td>
<td>-110</td>
<td>23</td>
<td>-23</td>
<td>58</td>
<td>19</td>
</tr>
<tr>
<td>Tsai-Wu</td>
<td></td>
<td>112</td>
<td>-42</td>
<td>21</td>
<td>-79</td>
<td>37</td>
<td>15</td>
</tr>
<tr>
<td>Hashin</td>
<td></td>
<td>240</td>
<td>-112</td>
<td>20</td>
<td>-97</td>
<td>37</td>
<td>7</td>
</tr>
<tr>
<td>Puck</td>
<td></td>
<td>-</td>
<td>-</td>
<td>21</td>
<td>-77</td>
<td>43</td>
<td>6</td>
</tr>
</tbody>
</table>

(b) Additional strength, strain, and interaction parameters.

<table>
<thead>
<tr>
<th>Failure Criterion</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsai Wu</td>
<td>$F_{12,T}$ (MPa$^{-2}$)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$F_{12,C}$ (MPa$^{-2}$)</td>
<td>0</td>
</tr>
<tr>
<td>Hashin</td>
<td>$S_{21}$ (MPa)</td>
<td>-87</td>
</tr>
<tr>
<td>Puck</td>
<td>$\epsilon_{XT}$</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>$\epsilon_{XC}$</td>
<td>-3.2</td>
</tr>
<tr>
<td></td>
<td>$p^{(+)}$</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>$p^{(-)}$</td>
<td>-1.57</td>
</tr>
</tbody>
</table>
is clear from the plots that the Hashin and Puck theories fit the UD specimens best, while the Tsai-Hill and Tsai-Wu theories are quite far off. Figure 5.4 depicts plots of the theories in $\sigma_2 - \sigma_{12}$ space. It is often useful to look at failure criteria in this plane because it constitutes matrix (or inter-fiber) failures. This view better depicts the fit of each theory to the failure of the three MD specimens, together with the U2 specimens. The Tsai-Wu, Hashin, and Puck theories all perform well in this space.

Figure 5.3: Tsai-Hill, Tsai-Wu, Hashin, and Puck Criteria in $\sigma_1 - \sigma_2$ space, with $\sigma_{12} = 0$. All 9 treatments of experimental data are shown, with UD specimens marked by open circles and MD specimens marked by filled circles. In this view, it is important to focus on the open symbols because the closed symbols represent specimens for which there was a nonzero shear component.
Figure 5.4: Tsai-Hill, Tsai-Wu, Hashin, and Puck Criteria plotted with experimental data in $\sigma_2 - \sigma_{12}$ space. It is often useful to look at failure criteria in this plane because $\sigma_2 - \sigma_{12}$ constitute matrix (or inter-fiber) failures. Experimental data represents only samples which failed in this mode (8 of 9 treatments), including all MD specimens and the UD specimens in the 90-degree treatment.
The Tsai-Hill theory gives the highest error at 19.9% and is clearly not a good fit to experimental data because of its neglect to consider tensile and compressive properties separately. It was chosen for study because of its use historically and in the industry, and as a baseline from which to compare other theories. As seen in Figure 5.3, much the error of the Tsai-Hill failure criterion comes from parallel-to-fiber tension and perpendicular-to-fiber compression. Matrix failure is more closely predicted, as seen in Figure 5.4, but strength is overestimated for all cases where $\sigma_2 > 0$, and underestimated in all cases where $\sigma_2 < 0$, highlighting the major drawback of the Tsai-Hill theory, which is that it fails to consider tensile and compressive strength separately.

The Tsai-Wu theory is an improvement on Tsai-Hill because of its consideration for tensile and compressive properties separately, but the Tsai-Wu theory is limited by its ellipsoidal formulation, and thus gives very conservative strength values in tension and compression parallel-to-fibers. While with the optimal parameters, it predicts matrix failure well (Figure 5.4), it far under-predicts the fiber failures (Figure 5.3), leading to a high mean error of 15%. It should also be noted that the optimal strength parameters found for this theory (see Table 5.3) are far less than strengths reported in the literature for typical plant fiber composites. Thus, importantly, if this theory was implemented using parameters from the literature ($S_{1T}$, $S_{1C}$ etc.), the Tsai-Wu criterion would far overestimate composite strength in cases of matrix failure. Finally, it can be noted that the Tsai-Wu theory uses interaction parameters, $f_{12,T}$ and $f_{12,C}$, which are difficult to determine experimentally. Within the optimization bounds (determined by the stability criterion previously mentioned), $f_{12,T}$ and $f_{12,C}$ were found to have negligible effect on the fit of the surface; therefore it is recommended to use $f_{12,T} = f_{12,C} = 0$.

The Hashin theory demonstrates a relatively low mean error of 7%, and it also demonstrates optimal strength parameters which align closely with what exists in the
literature for typical plant fiber composites. The main disadvantage to the Hashin theory, as compared to Tsai-Hill or Tsai-Wu, is that it is of moderate complexity, requiring four piecewise equations which depend upon the fracture mode. Considering the use of four equations, though, it does not use interaction or other parameters, which are often difficult to determine experimentally; in this way it is still relative simple to implement.

The Puck theory shares several of the advantages of the Hashin theory, and it has the lowest mean error of 6% among the presented four theories. The main disadvantage to the Puck theory is that it is of high complexity with five modes of failure and two parameters, \( p^+) \) and \( p^-(+) \), in addition to the strength and strain parameters. The parameters \( p^+) \) and \( p^(-) \) define the slopes of the \((\sigma_2, \sigma_{12})\) failure curve for \( \sigma_2 > 0 \) and \( \sigma_2 < 0 \), respectively, and are determined empirically in practice. The Puck theory is the best fit for matrix failures because it allows for three different modes of matrix failure, as opposed to the Hashin criterion which allows for two modes of matrix failure. Furthermore, the Puck theory includes a degradation model. While this model is not used herein, it is a good subject for further study and one of the reasons the Puck criterion is recommended by Soden et al., (2002) [81].

In general, for strengths (and ultimate strains in the case of the Puck theory) of plant fiber composites, it is recommended to use the values associated with the Hashin and Puck failure theories because of their lower mean errors. The Tsai-Hill and Tsai-Wu theories substantially under-predict \( S_{1T} \) and \( S_{1C} \). Conversely, the piecewise formulation of the Hashin and Puck theories allow for a more accurate assessment of strength and ultimate strain.

A further conclusion from the present study is the demonstrated advantage of using a genetic algorithm in combination with failure theories to report shear strength and interaction parameters, which are difficult to determine experimentally and not widely reported in the literature. There is a lack of reported shear strength data for
plant fiber composites in the literature today, but it is well known that the matrix component drives the composite shear strength more than the fiber component, so it is expected that the shear properties of the flax composite will be similar to those of glass composites with similar matrix components. The values reported for shear strength of the flax fiber composites, in the range of 36 to 49 MPa for the four failure theories, are consistent with the design values for glass fiber composites with similar matrix types, as recommended by the AIMS Fiberglass Structural Design Manual ([96]). With these model parameters, structural designs with plant fiber composites are now possible.

5.4 Conclusions

The Tsai-Hill, Tsai-Wu, Hashin, and Puck failure theories are compared to experimental data from tension and compression tests of flax laminates in 5 layups with varying fiber orientations. Each failure theory is coupled with a parametric optimization routine, and best-fit parameters are presented for each theory.

The Hashin and Puck theories have the lowest error compared to experimental data. Hashin’s theory offers the advantage of being more simple to implement, while Puck’s theory has the advantage of a degradation component, which allows for a plastic failure regime after yielding. The Tsai-Hill and Tsai-Wu theories, when fit to test data of multiaxial specimens, substantially under-predict uniaxial strengths $S_{1T}$ and $S_{1C}$. This also means that if these theories are used with common parameters reported in the literature, they would dangerously overestimate strength in multiaxial cases.

Finally, the parametric optimization results lead to a measurement of parallel-to-fibre shear strength of flax laminate composites, a property which is difficult to determine experimentally and not widely reported in the literature. As a measurement for shear stress and strength, the tension and compression testing of multiaxial
composites more closely mimic real-life applications of shell and plate structures, rather than isolating pure shear stress.
6.1 Introduction

The final stage of this thesis work is to incorporate experimental findings of material properties into computational models and assess the feasibility and design trade-offs for full and hybrid bio-based wind turbine blades. In this chapter, material properties from Chapters 3 to 5 are used in a blade structural optimization model to create five bio-based and hybrid blade cases, and explore design trade-offs in comparison to a baseline, 5-megawatt turbine blade. In addition to structural trade-offs, environmental considerations are also explored.

6.2 Methods
6.2.1 Materials

This study begins with a baseline blade defined by Sandia National Laboratories in [121], using glass and carbon fiber composite materials as defined in the Sandia blade and repeated in Table 6.1. This baseline blade is 61.5m long and weighs 17 metric tons. It is typical of blades used in 5MW turbines. The bio-based material candidates for this study were selected from wood and flax laminates tested previously in this thesis, whose properties are reported in Chapters 3 to 5, with important parameters reiterated in Table 6.1. In addition to the composite materials presented in Table 6.1, the blades also contain foam panels in the leading and trailing edges, which act as the core material in the composite sandwich structure.
Table 6.1: Material candidates used in blade optimization. For blade components, represented in the second column, TE is an abbreviation for Trailing Edge Reinforcement, LE for Leading Edge, SC for Spar Caps, and SW for Shear Webs. DB stands for Double Bias, or Biaxial. Properties of carbon, glass, and foam are taken from [121]. Properties of wood and flax are from the present study.

<table>
<thead>
<tr>
<th>Material</th>
<th>Location</th>
<th>$E_1$ (GPa)</th>
<th>$E_2$ (GPa)</th>
<th>$G_{12}$ (GPa)</th>
<th>Density (g/cm$^3$)</th>
<th>Cost (USD/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD Glass</td>
<td>Skin, TE</td>
<td>41.8</td>
<td>14.0</td>
<td>2.6</td>
<td>1.9</td>
<td>2.59</td>
</tr>
<tr>
<td>UD Wood</td>
<td>Skin, TE</td>
<td>14.8</td>
<td>1.2</td>
<td>0.6</td>
<td>0.7</td>
<td>0.80</td>
</tr>
<tr>
<td>UD Flax</td>
<td>Skin, TE, SC</td>
<td>20.3</td>
<td>3.6</td>
<td>1.7</td>
<td>1.3</td>
<td>1.53</td>
</tr>
<tr>
<td>UD Carbon</td>
<td>SC</td>
<td>114.5</td>
<td>8.4</td>
<td>6.0</td>
<td>1.2</td>
<td>8.19</td>
</tr>
<tr>
<td>DB Glass</td>
<td>Skin, SW</td>
<td>13.6</td>
<td>13.3</td>
<td>11.8</td>
<td>1.8</td>
<td>2.54</td>
</tr>
<tr>
<td>DB Wood</td>
<td>Skin, SW</td>
<td>2.1</td>
<td>2.1</td>
<td>2.6</td>
<td>0.7</td>
<td>0.80</td>
</tr>
<tr>
<td>DB Flax</td>
<td>Skin, SW</td>
<td>6.0</td>
<td>6.0</td>
<td>7.8</td>
<td>1.3</td>
<td>1.53</td>
</tr>
<tr>
<td>Foam</td>
<td>SW, LE, TE</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
<td>5.94</td>
</tr>
</tbody>
</table>

6.2.2 Structural Design Optimization

In order to evaluate engineering design trade-offs between bio-based and traditional engineering materials in a wind turbine blade, a blade structural optimization routine is employed. The optimization tool used herein is developed by (Gaertner, 2017) [61] and overviewed in Figure 6.1. Because the purpose of this study is to do basic structural comparisons between different material layups, the FAST simulations are excluded herein and replaced by a static blade element momentum calculation from CCBlade. This means that the blades have been optimized for operational conditions, but to assess their full performance including hydrodynamics for offshore structures, higher-level aerodynamics including wake effects, controls, and structural dynamics, a more robust analysis would be needed.

Blade candidates are generated by modifying a reference model using several design variables. These variables are defined in Table 6.2. As the focus of this study is to make a comparison between bio-based and traditional composite materials, the design variables of interest in this study control the thickness of composite layups in the blade. Optimization bounds are presented in Table 6.2, but these boundaries are
Figure 6.1: Blade optimization flowchart. From [61].
non-binding. For example, the practical limit for root thickness is the root radius, or approximately 1.7m. Bounds were chosen based on available models in the literature [121] [67] and allowed to expand when the optimization reached a limit and an increase was physically possible. Using these design variables as inputs, PreComp is used to generate the blade’s distributed structural properties. These distributed structural properties are then used in BModes to calculate the blade’s mode shapes and natural frequencies, and in RotorSE which determines structural constraints.

Table 6.2: Definitions and boundaries of design variables used in structural optimization.

<table>
<thead>
<tr>
<th>Optimization Variable</th>
<th>Lower Bound (mm)</th>
<th>Upper Bound (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin thickness</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Root thickness</td>
<td>30</td>
<td>500</td>
</tr>
<tr>
<td>Spar cap thickness</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>Trailing edge composite thickness</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Trailing edge foam thickness</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Leading edge foam thickness</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Shear web composite thickness</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Shear web foam thickness</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fixed Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>61.5 m</td>
</tr>
<tr>
<td>Maximum chord width</td>
<td>4.65 m</td>
</tr>
<tr>
<td>Root diameter</td>
<td>3.39 m</td>
</tr>
<tr>
<td>Initial twist angle</td>
<td>13.3°</td>
</tr>
</tbody>
</table>

The objective function (Equation 6.1) seeks to minimize blade cost / annual energy production (AEP), and is constrained by tip deflection, resonance avoidance, and spar cap and trailing edge buckling. Blade cost is calculated by summing the material layers and multiplying by material cost per kilogram (Table 6.1). In reality, the material cost is only a portion of the total manufacturing cost of the blade, which has the other major cost components of labor and capital expenditures. For the 61.5m baseline blade used in this study, material costs amount to 74% of the total...
cost of the blade [87]. It is assumed in this study that the labor and capital costs are similar across different material choices, so they are not important to include in the optimization. However, it is important to note that costs reported herein only reflect materials costs. AEP is a function of the turbine’s power curve and wind speed distribution. The constraints are applied by applying penalties to blades that violate tip deflection (as limited by tower clearance), resonance, and buckling criteria.

\[
\text{fitness} = \frac{\text{blade cost}}{AEP} * P_{\text{tipDef}} * P_{\text{buckle}} * P_{\text{res}}
\]  \tag{6.1}

### 6.2.3 Blade Cases

Five total blade cases are evaluated with one being a baseline blade of carbon and fiberglass, two hybrid bio-based designs and two full bio-based designs. The major blade components are outlined in Table 6.3. Component materials were chosen strategically to put the stiffest materials in the spar cap where they are most needed, then placing less stiff materials in other blade locations.

<table>
<thead>
<tr>
<th>Blade case</th>
<th>Component</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Skin</td>
<td>Spar Cap</td>
<td>Shear Web</td>
<td>Trailing Edge</td>
<td>Reinforcement</td>
</tr>
<tr>
<td>Baseline</td>
<td>Glass</td>
<td>Carbon</td>
<td>Glass</td>
<td>Glass</td>
<td></td>
</tr>
<tr>
<td>Wood Carbon</td>
<td>Wood</td>
<td>Carbon</td>
<td>Wood</td>
<td>Wood</td>
<td></td>
</tr>
<tr>
<td>Flax Carbon</td>
<td>Flax</td>
<td>Carbon</td>
<td>Flax</td>
<td>Flax</td>
<td></td>
</tr>
<tr>
<td>All Flax</td>
<td>Flax</td>
<td>Flax</td>
<td>Flax</td>
<td>Flax</td>
<td></td>
</tr>
<tr>
<td>Wood Flax</td>
<td>Wood</td>
<td>Flax</td>
<td>Wood</td>
<td>Flax</td>
<td></td>
</tr>
<tr>
<td>All Wood</td>
<td>Wood</td>
<td>Wood</td>
<td>Wood</td>
<td>Wood</td>
<td></td>
</tr>
</tbody>
</table>

### 6.2.4 Environmental Cost Framework

The environmental cost of the turbine blades is determined by correlating component masses with scores of the environmental goodness of each material. These scores
are taken from life-cycle analysis (LCA) style assessments in the literature. LCA is a technique for systematically analyzing the environmental impact of a product from “cradle-to-grave”, or from resource extraction to disposal of the product.

Corona, et al., (2015) [44] performed a comparative environmental sustainability assessment between flax, carbon, and glass turbine blades. The assessment used GaBi 4.4 software, combined with the ReCiPe Life Cycle Impacts Assessment methodology. The ReCiPe score incorporates ecosystem damage, resource depletion, and human health. From their blade-level analysis, a per-kilogram estimate was backed out and normalized, with the material environmental scores reported in Table 6.4. As is typical in environmental assessment, these parameters are unitless. They have been normalized so that one kilogram of glass has a score of 1.

Because [44] did not consider laminated wood in their analysis, additional references were needed to account for this parameter. Feliciano (2015) [58] performed a comparative environmental sustainability assessment between glass and wood laminate turbine blades, also using GaBi (version 6). This analysis has been verified by comparing to life-cycle impact analyses for fiberglass ([51]) and LVL ([120]) which gave agreeable results. Fiberglass and laminated wood were compared using Global Warming Potential (measured in kg of CO₂ equivalent per kg of material), which is less all-encompassing than the ReCiPe score used for the other materials, but similarly accounts for ecosystem damage, resource depletion, and human health. Glass was again normalized to the score of 1, and the score of wood was adjusted accordingly.

One of the reasons for looking at flax as a replacement for glass in composites is because of a presumed environmental benefit. However, as Table 6.4 shows, flax has an environmental score that is only marginally better than glass. This difference is because of the lower volume fraction attainable with flax composites as compared to glass [44]. While the flax fibers are more environmentally friendly than glass fibers, the resin component is worse than both. Therefore, most of the environmental benefit
associated with the use of natural fibers in this study is cancelled out by the use of more resin.

In addition to structural composites, the blades also contain foam as a composite sandwich core material. Due to the relatively small contribution of foam to the blades (3% to 5% by mass) and the scope of this study, foam was neglected from the environmental analysis of the blades.

Table 6.4: Environmental scores used to evaluate environmental impact of blade designs.

<table>
<thead>
<tr>
<th>Material</th>
<th>Environmental Score (per kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Composite</td>
<td>1</td>
</tr>
<tr>
<td>Carbon Composite</td>
<td>3.20</td>
</tr>
<tr>
<td>Flax Composite</td>
<td>0.98</td>
</tr>
<tr>
<td>Wood Laminate</td>
<td>0.15</td>
</tr>
</tbody>
</table>

6.3 Results

Results of the blade structural optimization are shown in Table 6.5. The main contributions to a stiff, low-cost, aerodynamically efficient blade are the blade root, spar cap, and trailing edge reinforcement thicknesses. Of these, the root and the trailing edge reinforcement are defined by a single composite thickness, while the spar cap is a spline controlled by two control points and interpolated in between, as depicted in [121]. Skin and shear web thickness were minimized in all cases, indicating that they were not significant contributors to the structural stiffness, buckling or resonance avoidance. Trailing edge and shear web foam were also minimized in all cases. Leading edge foam varied over the range of 22 to 43 mm, indicating that an increase in leading edge foam correlates to an increase in stiffness. This foam thickness was especially high (38 to 43 mm) in blades with flax spar caps, while it was lower in blades with carbon spar caps (22 to 28 mm).
Table 6.5: Blade structural optimization results.

<table>
<thead>
<tr>
<th>Blade Case</th>
<th>Mass (MT$^1$)</th>
<th>Cost (*1000 USD)</th>
<th>Component Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Root (mm)</td>
</tr>
<tr>
<td>Baseline</td>
<td>17.0</td>
<td>76.6</td>
<td>51</td>
</tr>
<tr>
<td>Wood-Carbon</td>
<td>13.9</td>
<td>60.4</td>
<td>117</td>
</tr>
<tr>
<td>Flax-Carbon</td>
<td>15.1</td>
<td>67.1</td>
<td>64</td>
</tr>
<tr>
<td>All-Flax$^2$</td>
<td>29.4</td>
<td>48.8</td>
<td>77</td>
</tr>
<tr>
<td>All-Flax, high $V_f$ $^3$</td>
<td>95.2</td>
<td>147.8</td>
<td>55</td>
</tr>
<tr>
<td>Wood-Flax$^2$</td>
<td>24.0</td>
<td>35.6</td>
<td>90</td>
</tr>
<tr>
<td>All-Wood</td>
<td>64.1</td>
<td>54.3</td>
<td>92</td>
</tr>
</tbody>
</table>

$^1$MT = metric ton  
$^2$The All-Flax and Wood-Flax blades did not meet the minimum stiffness requirement for tip clearance.  
$^3$The high volume fraction flax blade has a flax $V_f = 0.54$, while the other flax and flax hybrid blades have a flax $V_f = 0.31$.

6.3.1 Wood-Carbon Case

The Wood-Carbon blade has wood skin, root, shear webs, and trailing edge reinforcement with a carbon spar cap. Compared to the baseline case, it provides significant reductions in mass and material cost. There is a modest increase in the use of carbon fiber, from 5,700 kg to 6,200 kg compared to the baseline blade. The overall weight reduction comes from the low density of the wood and is especially apparent in the skin and root, which together decreased from 10,300 kg to 6,600 kg compared to the baseline blade where they were composed of fiberglass. The density of laminated wood is so much less than fiberglass that this weight reduction occurs even as the root thickness has more than doubled. The trailing edge reinforcement thickness has also increased from 0 to 12 mm. Overall, the blade’s reduction in mass of over 18% provides a significant design advantage compared to the baseline case because lighter blades lead to reduced loading on the rest of the turbine. The materials
cost reduction of 21% is also compelling, and indicates a great benefit to using wood strategically in structural components which require less absolute stiffness.

6.3.2 Flax-Carbon Case

The Flax-Carbon case has flax skin, root, shear webs, and trailing edge reinforcement with a carbon spar cap. Compared to the baseline case, it has substantially reduced weight and cost. However, compared to the Wood-Carbon case it has a higher weight and cost; this pattern correlates to the density of wood, flax, and glass, indicating that lower-density materials have a structural design advantage in turbine blades even when their stiffness is also lower. In a similar manner to the Wood-Carbon case, the Flax-Carbon case sees an increase in the use of carbon fiber associated with the increased spar cap thickness. While the root thickness has increased by 13 mm compared to the baseline case, it is not such a drastic increase as in the Wood Carbon case. This should be expected because the mechanical behavior of a laminated flax composite is known to be closer to a laminated glass composite than it is to wood.

6.3.3 All-Flax Cases

Although flax fibers are known for being lightweight and having excellent specific properties, the resulting composites have very low fiber volume fractions ($V_f$). The flax composite properties for this study were defined using composites with $V_f$ ranging from 31 to 37% as opposed to the glass, with $V_f$ of 60 to 70%. When the composite is mostly matrix material, the weight and stiffness advantages of the flax fibers are compromised by the more dense, less stiff matrix. The All-Flax blade design was not successful for this reason, with a blade mass increasing 73% from the baseline blade. The blade could not fulfill the tip clearance requirement even in its most optimal layup. The result indicates a need to increase $V_f$ through improvements in processing the flax composite. Several researchers are now investigating how to increase the fiber
volume fraction through different coatings and processing techniques that could help increase the fiber volume fraction in plant-fiber reinforced composites [101] [102] [46].

Properties for a hypothetical flax composite with \( V_f = 54\% \) (the limit after which composite porosity starts to increase dramatically, per [101]) were calculated using the Rule of Mixtures, and a high volume-fraction all-flax case was run. The blade was able to meet the minimum stiffness requirement, but at great mass and cost. This result suggests that flax is best used in hybrid blades with lighter or stiffer materials.

6.3.4 Wood-Flax Case

It was suspected that a Wood-Flax case would be a competitive design, combining the higher-stiffness but higher-density flax in the spar cap with lower-stiffness but lower-density wood in the other major blade components. For these reasons, it is more competitive than the other bio-based blade cases with a lower mass and cost compared to the All-Flax and All-Wood cases. However, the blade could not fulfill the tip clearance requirement. As more composite layers are added to stiffen the blade, the stiffness increase is not enough to overcome the associated mass increase because the materials specific stiffness is not high enough. It is significantly heavier than the baseline blade, increasing by 41%. The improvements to manufacturing suggested in Sections 6.3.5 and 6.3.3, which would increase specific stiffness of both materials and decrease the density of flax, could make the blade far more competitive. The Wood-Flax blade has the lowest materials cost of all cases, with a materials cost of 54% of the baseline case, demonstrating the well-known cost advantage to bio-based materials.

6.3.5 All-Wood Case

In spite of the low density of wood, the All-Wood blade is the heaviest of all cases because of the great number of layers in the spar cap needed to make the blade stiff enough to meet the tip clearance requirement. With a mass of 277% of the baseline
case, and a laminate over 50cm thick, a wood spar cap is unrealistic with currently available manufacturing technologies. The wood laminate material used in this study is meant to closely mimic Laminated Veneer Lumber, using veneers from an LVL plant and a similar manufacturing process as discussed in Chapter 3. However, as discussed in Chapter 2, it is possible to improve the stiffness of wood laminates with manufacturing innovations like thickness sanding of lathe checks, or flat-cutting and edge-joining of smaller veneer pieces. Scaling and devising connections for some of these manufacturing techniques to large-scale structures would be a good area of further research.

6.3.6 Sustainability Assessment

The environmental scores of the blades are presented in Table 6.6. Unsurprisingly, the models incorporating wood have lower environmental impact scores compared to the models which do not. What is somewhat unexpected is that flax does not seem to provide a great environmental improvement over glass, demonstrated by the marginal difference in environmental scores between the baseline and flax-carbon blades. This can be explained because the volume fraction of fibers, $V_f$, in the flax composite (30 to 40%) is much lower than than in the glass composite (60 to 70%). Although flax fibers have environmental benefits compared to glass fibers, the resin component is more harmful than both. In the flax composite, most of the benefit gained by using natural fiber are lost by using more resin. As discussed in Section 6.3.3, there are efforts underway to increase the volume fraction of flax composites.

6.4 Conclusions

A framework is presented for the baseline structural comparison of different materials in a 5MW, 61.5m wind turbine blade. Material properties from Chapters 3 to 5 are used in a blade structural optimization model to create five bio-based and hy-
Table 6.6: Blade environmental assessment results.

<table>
<thead>
<tr>
<th>Blade Case</th>
<th>Environmental Score ($10^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>29</td>
</tr>
<tr>
<td>Wood-Carbon</td>
<td>21</td>
</tr>
<tr>
<td>Flax-Carbon</td>
<td>28</td>
</tr>
<tr>
<td>All-Flax</td>
<td>28</td>
</tr>
<tr>
<td>Wood-Flax</td>
<td>17</td>
</tr>
<tr>
<td>All-Wood</td>
<td>9</td>
</tr>
</tbody>
</table>

brid bio-based blade cases, and explore design trade-offs in comparison to a baseline, 5-megawatt turbine blade.

6.4.1 Hybrid Bio-based Blades

Part of the work of structural design optimization is to highlight areas in the blade where bio-based materials have the best design advantages. The hybrid bio-based blade designs presented herein demonstrate that when used in combination with traditional composite materials, bio-based materials offer benefits to the mass and cost of the blade while keeping the same structural and aerodynamic performance as current blade designs.

As discussed in Chapter 2, NEG Micon was making 40m, wood-skin, carbon-spar blades for their 1.5MW machines. Shortly after being bought out by Vestas, the company retired this turbine design altogether, and with its retirement stopped the fabrication of wood skin blades. The existence of this technology indicates that on a smaller scale, this hybrid technology has already been proof tested. More information might indicate why the company’s 59m, 12.6MT wood-carbon blade was never mass produced. This thesis has focused on multidirectional wood laminates, and it is unclear if Vestas was using MD laminates, or only UD. While the present chapter has assessed baseline structural viability, there are numerous other factors that contribute to materials selection. This analysis has assumed, for cost and environmental
purposes, that wood is being sourced from the U. S. southeast. Wood is not as inex-
pensive or available in Western Europe where a great deal of Vestas’ manufacturing
plants are located.

6.4.2 Full Bio-based Blades

On their own, the bio-based materials evaluated in this thesis do not have the
specific stiffness to make competitive turbine blades. The Wood-Flax hybrid blade is
most competitive of the full bio-based designs (compared to All-Flax and All-Wood)
because it combines the higher-stiffness but higher-density flax in the spar cap with
lower-stiffness but lower-density wood in the other major blade components. Still, the
blade is unable to meet the minimum stiffness requirement and it is heavier than the
baseline case and much heavier than the Wood-Carbon design. Additional refinement
of manufacturing processes for both wood and flax, which would increase the stiffness
of both materials and decrease the density of the flax composite, would make it far
more competitive. With these improvements, a full bio-based design would be far
more competitive with current wind turbine blade designs.
The objectives of this thesis were:

1. Generate novel experimental data for bio-based materials under complex loading conditions which are common to wind turbine blades.

2. Determine the shear strength and stiffness of laminated wood and a flax composite laminate.

3. Recommend failure criteria and subsequent sets of parameters for use in the finite element modeling of (a) multiaxial wood laminate and (b) flax laminate composite structures.


These objectives have been addressed in the following ways:

7.1 Generation of Experimental Data for Bio-based Laminates Under Complex Loading Conditions

One of the gaps in knowledge limiting the use of bio-based laminates in structural composites today is a lack of experimental data for bio-based materials in complex or combined loading conditions. As discussed in detail in Chapter 4, axial testing of multiaxial laminates in different layups allows the simulation of complex loading conditions that are seen by composite materials in wind turbine blades. 100 tests of wood laminate specimens were performed in tension and compression on symmetric
layups ranging from 0 to 90 degrees. The results of these tests are reported in Chapter 3, and also inform the work in Chapters 4 and 6. 48 tests of flax laminate specimens were performed in tension and compression in five multiaxial layups. The results of these tests are reported in Chapter 5 and are also used in Chapter 6.

7.2 Shear Properties of Laminated Wood and Flax

Shear properties are essential to the design of wind turbine blades. The shear web of a wind turbine is designed to resist shear loads, and the skin sees shear stress components in combined, multiaxial loading. Shear failures are common under such conditions, so the accurate measure of shear properties is essential. In Chapter 2, current methods of determining the shear properties of laminated wood and fiber-reinforced composites are reviewed. In Chapter 3, a novel method is presented for determining the in-plane shear strength and stiffness based on uniaxial tension and compression tests of symmetric, angle-ply laminates. The test data are compared to predictions from the Tsai-Wu and Hashin failure criteria, and shear properties are determined using genetic optimization. The results are found to be in good agreement with the torsion test, which is a much more difficult test to perform but is hailed for its accuracy. Finally, in Chapter 5, the parametric optimization of failure criteria lead to a measurement of parallel-to-fibre shear strength of a flax laminate composite, a property which is difficult to determine experimentally and not widely reported in the literature.

7.3 Using Failure Criteria to Model Mechanical Performance of Bio-Based Materials

The goal of this research is to address some of the challenging aspects of designing high-performance composites with bio-based materials. One challenge to the widespread adaptation of bio-based laminates is that they are not often perceived as
legitimate, trustworthy engineering materials. Computational modeling techniques are applied in an effort to close the knowledge gap between bio-based and glass or carbon composite materials. The use of failure criteria in modeling the strength of glass and carbon composites is widespread and accepted in industry and academy. However, prior to this thesis there was very little work at the intersection of bio-based laminates and composite failure criteria. In Chapters 4 and 5, a framework for evaluating the accuracy of failure criteria in comparison to experimental data is presented.

In Chapter 4, four failure criteria were compared to experimental data from tension and compression tests of laminated wood veneer in five different layups. The theories were first evaluated using parameters from preliminary experiments and the literature in a deterministic model. They were then integrated with a genetic optimization routine and best-fit parameters are determined for each criterion. The Hashin criterion was found to demonstrate the best fit to the experimental data in both deterministic and optimized model cases. While its formulation is more complex than other theories tested, it has the advantage of not using interaction parameters, which are difficult to determine experimentally and often unknown. All theories were improved through parametric optimization, but this was especially the case for the Tsai-Wu theory where the average strength prediction error decreased by over 5% through parametric optimization. This speaks both to the importance of using correct parameters, and to the difficulty of doing so when parameters vary widely in the literature and can be difficult to isolate experimentally.

In Chapter 5, a similar procedure is followed to determine best fit criteria and their parameters for flax laminates. This chapter also introduced a novel image analysis technique, which applies the Fourier Transform to images of composite laminates to determine the fiber orientation angle. The Tsai-Hill, Tsai-Wu, Hashin, and Puck failure criteria are compared to experimental data from tension and compression tests.
of flax laminates in five layups with varying fiber orientations. Each failure theory is coupled with a parametric optimization routine, and best-fit parameters are presented for each theory. The Hashin and Puck theories best predict composite strength when compared to experimental data. Hashin’s theory offers the advantage of being more simple to implement, while Puck’s theory has the advantage of a degradation component, which allows for a plastic failure regime after yielding. The Tsai-Hill and Tsai-Wu theories, when fit to test data of multiaxial specimens, substantially under-predict uniaxial strengths $S_{1T}$ and $S_{1C}$. This also means that if these theories are used with common parameters reported in the literature, they would dangerously overestimate strength in multiaxial cases.

### 7.4 Structural Design Optimization of Bio-based Wind Turbine Blades

A framework is presented for the baseline structural comparison of different materials in a 5MW, 61.5m wind turbine blade. Material properties from Chapters 3 to 5 are used in a blade structural optimization model to create five bio-based and hybrid bio-based blade cases, and explore design trade-offs in comparison to a baseline, 5-megawatt turbine blade. Part of the work of structural design optimization is to highlight areas in the blade where bio-based materials have the best design advantages. The hybrid bio-based blade designs presented herein demonstrate that when used in combination with traditional composite materials, bio-based materials offer benefits to the mass and cost of the blade while keeping the same structural and aerodynamic performance as current blade designs. On their own, the bio-based materials evaluated in this thesis do not have the specific stiffness to make competitive turbine blades. The Wood-Flax hybrid blade is the most competitive of the full bio-based designs (compared to All-Flax and All-Wood) because it combines the higher-stiffness but higher-density flax in the spar cap with lower-stiffness but lower-density wood in
the other major blade components. Still, this blade is heavier than the baseline case and much heavier than the Wood-Carbon design. Because the blade does not meet the minimum stiffness requirement, additional refinement of manufacturing processes for both wood and flax would make it far more competitive.

7.5 Limitations

This thesis makes several steps towards realizing multi-megawatt bio-based wind turbine designs, but there is still a substantial amount of work to be done. Some limitations of the present study are presented as follows, with recommendations for future work in the next section.

1. **Size effect.** Discussed in Chapter 2, size effect has not been well studied on a scale this large for bio-based laminates, and is especially a concern in wood. Laminates tend to have less of a size effect as compared to solid wood, but researchers should still be concerned with how material properties scale from the test coupons to full-size laminates.

2. **Dimensional Stability.** Bio-based materials are subject to dimensional instability; their material properties including dimensions change based on atmospheric conditions like temperature and moisture. This is a concern in wind turbine blades because they need to perform in all weather conditions, and especially for the hybrid blade designs, because of the bonding together of different types of materials. There are many existing solutions, including designing in large tolerances, or using products like coatings and adhesives, that should be explored for bio-based blades to be viable.

3. **Finite Element Modeling.** This study makes several recommendations for how to use failure criteria to inform finite element modeling, but there are still additional considerations that would aid the finite element modeling of bio-
based materials. In particular, researchers would need to validate models for
hybrid, curved shell shapes, and develop methods for scaling them up.

4. **Load Duration.** Fatigue and creep loading are known design drivers for multi-
megawatt turbine blades, as discussed in Chapter 2, but fatigue and creep
performance for bio-based materials has not been characterized nearly to the
extent that it has been for carbon and fiberglass.

## 7.6 Recommendations for Further work

While the objectives of the current thesis have been met, several areas of future
study will continue to elevate the use of bio-based materials in composite structures.
A select few of these areas are addressed:

### 7.6.1 Manufacturing

Although flax fibers have excellent specific properties, they absorb so much resin
in the manufacturing process that their composites are less competitive. With further
research into processing techniques for these fibers, they could be very competitive in
the future. The same is true for wood; if manufacturing techniques which have been
demonstrated on small scales (discussed in more detail in Chapter 6) can be scaled to
large structures, a full bio-based design would be far more competitive with current
wind turbine blade designs.

### 7.6.2 Fatigue

Chapter 6 provides a baseline comparison between blades of different materials
under structural constraints of wind turbine blades in maximum static loading con-
ditions. The next steps in evaluating these blades would include full aerodynamic
models and, importantly, fatigue loading of these materials. There is currently a lack
of experimental fatigue data for both wood and flax laminates, and bio-based materi-
als in general. Further experimental work should address fatigue properties of wood and flax laminates, as this analysis would allow higher fidelity modeling and a more full understanding of bio-based turbine blade performance.

7.6.3 Variability

One of the challenges to the widespread adoption of bio-based materials is that they are seen as less reliable, or more variable, than synthetic materials. What is shown in this research was that the variance in our wood and flax laminates was no more than what would have been observed in the testing of glass or carbon laminates. This suggests that within one batch, wood and flax are not any more variable than traditional composites. However, between batches from different forests or farms, or different growing seasons, the variance may be greater or less controllable than what is able to be achieved with glass or carbon fibers. The wood industry uses a grading system to address some of this discrepancy, but it is unclear if that system is refined enough to meet the needs of high-performance composite materials. Plant fibers such as flax also have grading systems, but most do not address structural properties. A framework for standardizing the quality of plant fibers for composite reinforcement would help engineers be able to design plant-fiber reinforced composite structures with more confidence.
Figure A.1: Veneer cutting at a 45° angle using a table saw. Veneers were cut into 7" strips from 4’x 8’ sheets.
Figure A.2: Adhesive spreading (left) and specimen clamping (right).

Figure A.3: Edge effects during clamping (left) and finished test specimens (right).
B.1 Vacuum Infusion Process

Process steps correspond to Figure B.1, numbered from top left to bottom right.

1. The raw material used in this study is Amplitex 5008 from BComp, a biaxial (+/-45 degrees) non-crimp (non-woven) flax fabric. The fabric contains polyester stitches to keep the flax aligned and glass rovings, which are presumably to stiffen the fabric though they are not reported by the manufacturer.

2. The fabric is cut into rectangles, 50cm x 70cm, using a utility knife and shears.

3. A stack of 4, 2-ply fabric sheets is placed between some distribution media. Distribution media is disposable material which helps to distribute the resin (also known as matrix or adhesive) evenly over the entire composite, since it will enter the stack at only one spot. This stackup used peel-ply (white with red stripes) on either side of the stack, release foil on the bottom of the stack and perforated release film on the top of the stack.

4. Additional distribution media is added to the top of the stack, including felt/plastic channels for the inlet and outlet tubes where resin will flow.

5. A vacuum bag (which is not actually a bag but a thick sheet of plastic) is taped over the top of the whole stack using yellow tack. It is important to get rid of any air gaps, but the yellow tack used to adhere it to the aluminum table is very forgiving.
Figure B.1: Vacuum Infusion Process for Flax Laminates. See text for full image description.
6. A vacuum pump is connected to the laminate via an aluminum canister so that when excess resin gets drawn into the line, it drips into the aluminum canister and won’t get drawn into the vacuum pump.

7. The vacuum pump is hooked up to the outlet side of the bag with the inlet plugged, and we do a vacuum test to make sure there are no gaps where air may enter from the atmosphere. Having a break in the seal is common and leaks can be plugged using tack.

8. After the vacuum test, the inlet is unplugged and resin is allowed to flow into the system by the pressure differential created by the vacuum pump.

9. When the resin has saturated the entire sheet the inlet is clamped. About half an hour later, the outlet will be clamped and the vacuum stopped. Then, it cures for about 24 hours at elevated temperatures. These temperatures may be reached either by using a heated surface (like the aluminum surface above) with a heating blanket on top, or by using a glass surface which can be placed in an oven.

10. After 24 hours of curing (and a few extra for the laminate to cool off), the vacuum bag and distribution media are removed and thrown away. Though flax fibers can be considered much more sustainable than glass fibers, vacuum infusion (used commonly for both glass/carbon and natural fibers) is not a sustainable manufacturing process. Many disposable plastics are used once and then have to be thrown away.

11. The final plate has some warping and this is normal. The blackened color is cured resin. The ruler in this photograph is 40cm in length.

12. Zoomed in, the laminate does not look so black. It looks like the fibers we started with but it is shiny because its coated in resin.
B.2 Cutting and Tabbing Process

The process of cutting test specimens from plates and gluing tabs on is enumerated as follows:

1. **Square plate edges.** All cuts are made on a table saw. The initial cut is made by approximating the optimal grain orientation, then following cuts may be made from that edge. Use a square edge to check squareness of plate. Height (y-direction), width (x-direction), and mass measurements need to be taken at this stage to calculate the area weight of the plate, which informs the volume fraction calculations.

2. **Cut plate into sections by specimen treatment.** In this case, there were 2 to 3 different experimental treatments for each plate. We were testing grain orientation effects, so these treatments were in the form of different angles. Each section should be cut to exact specimen length (y-direction), and width is determined by the sum of specimen widths, plus 4mm per specimen, plus 1-2cm. The extra width allows for material which is cut away by the saw blade. An example cut plan is shown in Figure B.2. If the specimens are angled, they must be cut to width at this stage but can be over length.

3. **Prepare for tabs.** Slats of tab material (a pre-fabricated glass fiber composite) are cut to gauge length (or total length minus tab length) and placed on the specimen ends as spacers to help with tab placement. These slats may be seen in Figure B.3.
Figure B.2: Example cut plan for composite laminate.
Figure B.3: The cutting and tabbing process for test samples. From top left to bottom right: (1) Plate is cut into sections; (2) Spacing tabs are adhered to the ends of plate sections to help with sand blasting and tab placement; (3) All cuts are made using a table saw; (4) Tabs are glued to plate sections using epoxy. In this photo, you can also see the line at the bottom of the plate section where sand-blasting has occurred.


[47] Dennehy. (wet) hand lay-up: Combining of reinforcing fiber and resin at the time of part fabrication.


[78] Inhabitat. Wikado playground is built from recycled wind turbine blades in the netherlands, March 2012.


