The Structure and Mechanical Behavior of Bamboo and Bamboo Products

by

Patrick G. Dixon

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Signature of Author: ____________________________________________
Department of Materials Science and Engineering
May 23, 2017

Certified by: _______________________________________________________
Lorna J. Gibson
Matoula S. Salapatas Professor of Materials Science and Engineering
Thesis Supervisor

Accepted by: _______________________________________________________
Donald R. Sadoway
Chair, Departmental Committee on Graduate Studies
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ABSTRACT

Bamboo is a unique lignocellulosic material with considerable potential in sustainable construction. Structural bamboo products are analogous to wood products, such as oriented strand board (OSB), but composed primarily of bamboo elements, as opposed to wood elements. Such products could extend the use of bamboo. The mechanical behavior of structural bamboo products in large part depends on that of bamboo tissue. In this thesis, the structure and mechanical properties of dry bamboo tissue are related. Cellular level models are developed and explored, with a focus on density. Density is a practical parameter: it corresponds to weight, and places bamboo in the broader context of cellular solids.

Bamboo tissue is made up of parenchyma and vascular bundles, consisting of sclerenchyma fibers and vessels; the structure can be thought of as a fiber reinforced composite. There is a radial gradient in the volume fraction of vascular bundles as well as the fraction of quite solid sclerenchyma fibers within the vascular bundles, increasing from the inside to the outside of the culm wall. Longitudinal flexural properties (modulus of elasticity \( MOE \) and modulus of rupture \( MOR \)) and compressive strength increase with increasing sclerenchyma fiber volume fraction, indicating the mechanical importance of these fibers. The density also increases with increasing fiber volume fraction. Thus, these longitudinal mechanical properties increase with density. This suggests that in bamboo tissue density reflects the underlying sclerenchyma fiber volume fraction. For moso bamboo (\( Phyllostachys pubescens \)), the extrapolated cell wall longitudinal Young’s modulus estimate from tests on small flexural specimens, 39.8 GPa, agrees well with the value of 36.6 GPa obtained from a simple cell wall model for the fibers. From mechanical tests of 3D printed models of bamboo parenchyma, an open-cell foam model seems appropriate for bamboo parenchyma. The densification of bamboo increases the longitudinal flexural properties, but natural bamboo at the same density of densified bamboo has higher properties. A multiscale model for wood OSB is adapted for bamboo OSB based on the natural tissue’s structure and properties; this model gives a good description of the modulus of elasticity of bamboo OSB made with internode strands.

Thesis Supervisor: Lorna J. Gibson
Matoula S. Salapatas Professor of Materials Science and Engineering
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Patrick G. Dixon
1 Introduction
1.1 Overview of Bamboo

Bamboo is a compelling material for sustainable construction (Vogtländer et al. 2010; Liese and Köhl 2015; Sharma et al. 2015a). It is inherently renewable and abundant: roughly 30 million hectares of land are covered by bamboo (FAO 2010). It is native to all continents, except Europe and Antarctica (Clark et al. 2015). Much of the resource is concentrated in countries with emerging and rapidly expanding economies, like India, China, and Brazil (Nayyar 2008; FAO 2010; Kuehl 2015). Bamboo’s annual yield per area is competitive with timber (Alig et al. 2000; Vogtländer et al. 2010; Kuehl 2015). **Fig. 1.1** shows countries particularly rich in bamboo resources based on the forest resource assessment of the Food and Agriculture Organization of the United Nations (FAO) (2010).

![Fig. 1.1 World Map showing Bamboo-rich Countries](http://www.freeworldmaps.net/download/maps/outline-world-map.jpg) Countries highlighted have at least 500,000 hectares of bamboo, (FAO 2010). The world map template is from [http://www.freeworldmaps.net/download/maps/outline-world-map.jpg](http://www.freeworldmaps.net/download/maps/outline-world-map.jpg) (Feher 2005).
There are nearly 1500 species of bamboo, all of which are members of the grass family *Poaceae* (Clark et al. 2015). Being grasses, bamboos can be more broadly categorized as monocotyledons (Lucas 2013), which makes their taxonomy relatively distinct from the major types of woody plants. Most hardwoods, or deciduous trees are eudicotyledons, and softwoods, or conifers are gymnosperms (Bodig and Jayne 1982; Alexander et al. 2010; Forest Products Laboratory 2010). However, not all bamboo species are what would be commonly considered when imagining bamboo (tall woody plants), as one of three tribes, in which bamboos are divided, is composed of herbaceous (non-woody) bamboo (Clark et al. 2015).

Bamboo has been used for building and other purposes for thousands of years (Jiang 2007; Lucas 2013; Liese and Köhl 2015). Traditional use of bamboo in construction often makes use of large sections of the bamboo stems, which are termed culms (Jiang 2007; Harries et al. 2012; Liese et al. 2015). While this use is described as traditional, a number of contemporary architects use this traditional culm method to build modern and beautiful structures (Lucas 2013). Simón Vélez and Elora Hardy are notable examples (Lucas 2013; Hardy 2015; Liese et al. 2015). Research for this type of construction is ongoing (Correal and Arbeláez 2010; Harries et al. 2012; Taylor et al. 2015; Liese et al. 2015).

Recently, there has been increasing interest in engineered structural bamboo products, analogous to engineered wood products such as plywood, oriented strand board and glue-laminated timber. These products allow more flexibility in the geometry, size, and design of components than that permitted by “full” culm elements. This thesis describes the structure and mechanical properties of bamboo as well as its use in structural bamboo products.
1.2 The Structure of Bamboo

1.2.1 The Macrostructure and Growth of Bamboo

A single plant of bamboo consists of several culms which emanate from an extensive subterranean rhizome system (Liese 1987; Whittaker 2005; Banik 2015a). The rhizomes can be classified into two broad groups, pachymorph (sympodial) or leptomorph (monopodial). Pachymorph rhizomes give rise to closely spaced or clumped culms. Leptomorph rhizomes give rise to more widely spaced culms, which cause these plants to be called running bamboos (Liese 1987; Whittaker 2005; Banik 2015a). The culms grow from these rhizomes quite quickly, generally reaching full height in less than a year (Banik 2015a). After reaching full height, the tissue in a culm then matures over approximately the next four years (Vogtländer et al. 2010; Banik 2015a). This process includes thickening of the cell wall, decreases in moisture content, and chemical changes in the tissue (Liese and Weiner 1996; Banik 2015a). Individual culms die after roughly 6-10 years (Banik 2015a); the entire plant generally lives much longer, several decades (Liese 1987; Banik 2015b).

The culms are generally tubular in structure. Bamboo culms consist of longitudinal sections called internodes which are separated by nodes which run transversely through the culm section (Liese 1985; Wegst 2011; Chaowana 2013; Liese and Tang 2015). Fig. 1.2 shows photographs of a culm section of bamboo, showing these important elements of the culms’ macrostructure. The culms are generally tapered in diameter with increasing height (Chaowana 2013; Banik 2015a; Liese and Tang 2015).
1.2.2 The Cellular Level Structure of Bamboo

Fig. 1.2 also shows a mesostructural image of bamboo culm wall tissue in the internode sections. The structure of this tissue resembles a fiber reinforced composite, with the vascular bundles (darker structures) and the parenchyma (the lighter colored tissue) analogous to the fibers and matrix, respectively. This analogy has been made by many researchers of bamboo (Nogata and Takahashi 1995; Amada et al. 1997; Shao et al. 2010a; Liu et al. 2014; Habibi et al. 2015). This vascular bundle – parenchyma composite-like structure is typical of woody monocotyledons (Masselter et al. 2016). The culm wall edges have somewhat distinct tissue, which is clear on Fig. 1.2. The innermost layer of the culm wall, or the terminal layer, consists of parenchyma, with thick-walled cells elongated in the tangential direction of the culm and shortened in the
other directions relative to the parenchyma of the majority of the tissue; the layer is also covered by a thin layer of pith cells (Grosser and Liese 1971; Liese and Schmitt 2006). The outer layer also differs from the majority of the cull wall tissue (Grosser and Liese 1971), consisting of various cell types and a waxy surface (Jiang 2007). In the internodes, in the majority of the culm wall tissue, the vascular bundles and parenchyma are aligned longitudinally (Grosser and Liese 1971; Liese 1985; Huang et al. 2015). Node tissue is considerably more complex with winding vascular bundles orientated along transverse directions as well the longitudinal direction (Grosser and Liese 1971; Peng et al. 2014; Huang et al. 2015). The two major constituents of bamboo tissue, the vascular bundles and the parenchyma, will next be described.

The vascular bundles are arrangements of sclerenchyma fibers, which give bamboo its mechanical integrity (Nogata and Takahashi 1995; Amada et al. 1997; Shao et al. 2010a; Tan et al. 2011; Liu et al. 2014), and other cells, associated with the conduction of water and nutrients (Grosser and Liese 1971). A vascular bundle is shown in Fig. 1.3; the exact arrangement varies among species and with position in the culm (Grosser and Liese 1971), but has the same general organization. Vascular bundles consist of sclerenchyma fibers in distinct regions, two large metaxylem vessels, phloem sieve tubes, and a few other cells (Grosser and Liese 1971). In this work, for simplicity the term “vessels” is generally used to refer to both the metaxylem vessels and phloem sieve tubes, as both cell types are large low density cells (Grosser and Liese 1971), serving the same role, essentially that of void, in dead and dry tissue. In bamboo, many of the sclerenchyma fibers of these vascular bundles seem to be generally quite thick-walled and dense (appearing almost fully dense) in many species’ mature tissue (Parameswaran and Liese 1976; Liese and Weiner 1996; Gritsch et al. 2004; Yu et al. 2014). The length of these fibers varies
from roughly 0.5 to 3.5 mm (Li 2004; Yu et al. 2014; Liese and Tang 2015), with aspect ratios (longitudinal dimension to transverse dimension) in the hundreds (Liese 1985; Yu et al. 2014). The cell size and shape is not unlike that of the fiber cells in wood (although generally much denser) (Bodig and Jayne 1982; Sjöström 1993).

![Fig. 1.3 Bamboo Vascular Bundle](image)

Cross-sectional SEM image of a bamboo vascular bundle

The parenchyma serves as the storage tissue in bamboo (storing starch) (Liese 1987; He et al. 2002). Micrographs of the parenchyma are shown in Fig. 1.4. The parenchyma consists of lower density cells, permitting storage (Grosser and Liese 1971). While many of these cells are elongated along the longitudinal direction; the aspect ratio of these cells is considerably smaller than that of the fibers (Grosser and Liese 1971; Liese 1985). Bamboo parenchyma generally consists of two types of cell. One type (forming the majority) is elongated on the longitudinal direction, and the other is very short and cube-like (Grosser and Liese 1971; He et al. 2002).
An important mesostructural aspect of bamboo not yet discussed is the presence of gradients in the culm. The volume fractions of the vascular bundles and their associated fibers increase radially going from the inside to the outside of the culm wall (Grosser and Liese 1971; Amada et al. 1997; Ghavami et al. 2003; Li 2004; Shao et al. 2010a; Liu et al. 2014). This gradient, visible in Fig. 1.2, increases the flexural rigidity of bamboo culms (compared with that for a uniform density across the culm wall thickness) and suggests the structure is tailored for bending due to wind loads in-vivo (Wegst 2011). These gradients are generally found to be nonlinear with position across the culm wall; the fiber volume fraction ranges from roughly 10% on the inside of the culm wall to 60% on the outside (Nogata and Takahashi 1995; Amada et al. 1997; Ghavami et al. 2003; Liu et al. 2014). A similar but more gradual and less well studied gradient of increasing vascular bundle and fiber volume fraction is noted along the length of the culm (Grosser and Liese 1971; Nogata and Takahashi 1995; Amada et al. 1997; Li 2004). Density increases with the fiber volume fraction, increasing from the inside to the outside of the culm wall and up the height of the culm (Liese 1987). Note the fiber volume fraction and related
density variations over the height of the culm are gradual, especially compared to the radial variation; they occur over multiple internodes and large length scales. Within internodes, the density is fairly consistent along the longitudinal direction. Huang et al. (2015) observed substantial radial variation in density from 336 kg/m³ (inside of the culm wall) to 1283 kg/m³ (outside of the culm wall) by X-ray computed tomography (XCT) in bamboo, *Phyllostachys pubescens* (which also known by many other names (ITIS 2017)) or moso bamboo, as it is commonly referred (and will be in this thesis). They found the density to be remarkably consistent within internodes along the longitudinal direction, and they attributed this to the high longitudinal alignment of the vascular bundles (Huang et al. 2015).

1.2.3 Aside: Cellular level Structure of Wood

This work is not about wood. It is about bamboo, but in describing bamboo, it is often helpful and logical to compare or relate its characteristics to wood. This is likely evident from the previous section regarding the cellular level structure of bamboo, and it will also be from the following discussion and this entire work. Bamboo is not wood, and while this could be stated for taxonomic reasons, in many ways the distinction is more relevant because of the cellular level differences. Softwoods and hardwoods are very different plants (Sjöström 1993; Hoadley 2000), but much of their tissue is still classified as wood. Wood refers to tissue from a number species with varying microstructures (Hoadley 2000; Forest Products Laboratory 2010), but in general these structures resemble honeycombs of fiber (or the fiber-like tracheid) cells (Gibson and Ashby 1997). There are other cell types present in wood, but the structure is not quite as heterogeneous as that of bamboo with its quite distinct and isolated vascular units (Liese 1987; Sjöström 1993). In wood, there is an alternating radial variation of earlywood (low density cells)
and latewood (higher density cells), which can be marked (Sjöström 1993; Hoadley 2000). However, the overall radial gradient in wood is considerably less intense than that of bamboo (Wegst 2011). Note this is not meant to mean the cellular level structure of tissue from bamboo species is more variable than that of wood (as the opposite is noted (Liese and Tang 2015)), but rather bamboo tissue is generally more heterogeneous. These cellular-level differences, in the author’s opinion, are the defining differences between wood and bamboo.

1.2.4 Ultrastructure and Chemical Composition of Bamboo

The cell wall of both the fibers and the parenchyma consist of multiple layers with different structural arrangements (Gritsch and Murphy 2005; Liese and Tang 2015). In the case of the fibers, the layers can be categorized as primary, secondary, and tertiary layers, with a middle lamella between separate fibers (Parameswaran and Liese 1976; Liese and Tang 2015). This cell wall layering is not unlike that of wood (Fengel and Wegener 2003), but unlike that in wood, the secondary layer in bamboo can have several more sublayers with varying microfibril angle (MFA) (Parameswaran and Liese 1976). The MFA, which describes the arrangement of cellulose fibrils in the cell wall of plants, is an important and widely studied ultrastructural parameter of wood (Donaldson 2008). The MFA has considerable influence on the stiffness and strength of wood (Cave 1968; Sahlberg et al. 1997; Gherardi Hein and Tarcisio Lima 2012). The MFA has been studied considerably in bamboo (Crow and Murphy 2000; Yu et al. 2007; Wang et al. 2010, 2012b, 2014a, b; Yan-hui et al. 2012). With X-ray scattering measurements, average MFAs (generally thought to be reflective of the fibers) in bamboo are found to be near $10^\circ$ (Yu et al. 2007; Wang et al. 2010, 2012b, 2014a, b; Yan-hui et al. 2012). Bamboo’s unique structure can lead to difficulties in interpretation of these measurements.
The primary chemical components of bamboo are the same as those for wood: cellulose, hemicellulose, and lignin (Janssen 1981; Sjöström 1993; Jiang 2007). Minor chemical components of bamboo are ash, the inorganic material, and extractives, which are smaller organic substances soluble in unaggressive solvents (Bodig and Jayne 1982; Jiang 2007). The values noted by Jiang (2007) suggest that in bamboo, cellulose constitutes 40% to 60% of the bamboo cell wall material, hemicellulose and lignin roughly 20% and 30%, respectively. Chemical component analysis performed by Fu et al. (2012) on samples of Moso bamboo, gave 39.4% cellulose, 26.5% hemicellulose, and 23.2% lignin, and roughly 5-6% extractives (ash is not reported). All of these percentages likely reflect weight-based percentages as this is typical of chemical analysis on biomass (Sluiter et al. 2008). It also noted here that the densities of the major chemical constituents noted in literature are similar (Qing and Mishnaevsky 2009; Gibson 2012), thus volume fractions and weight fractions would not be remarkably different. Cellulose in wood and bamboo contains crystalline and amorphous regions (Ahvenainen et al. 2016). Lignin and hemicellulose are amorphous polymers (Bodig and Jayne 1982; Sjöström 1993).

The exact arrangement of these compounds in the cell wall of wood and, logically, bamboo, still remains one of the great questions of wood science. However, aspects of the ultrastructure are known. Cellulose is observed in elementary (micro)fibrils, with cross sectional dimension of roughly 2 nm to 4 nm, which generally form microfibril aggregates 20 nm to 25 nm in diameter in wood (Jakob et al. 1995; Fahlén and Salmén 2003; Donaldson 2007; Borrega et al. 2015). In bamboo fibers cellulose microfibril aggregates were found to be similarly sized (Chen et al.
Hemicellulose, lignin, and disordered cellulose are thought to make up the rest of the cell wall (Sjöström 1993).

### 1.3 Mechanical Properties of Bamboo

Considerable research has been performed on the mechanical properties of bamboo tissue. Much of the work is devoted to basic mechanical properties (longitudinal elastic moduli, longitudinal strengths). A number of studies have investigated the effect of position within the culm and the related vascular bundle and fiber volume fraction gradients on the mechanical properties. Several researchers studied longitudinal tensile properties with respect to the radial density gradient, with tensile tests of specimens from slices at different locations in the bamboo culm (Nogata and Takahashi 1995; Amada et al. 1997; Amada and Untao 2001; Yu et al. 2008; Shao et al. 2010a; Liu et al. 2014; Richard and Harries 2015). Most of these studies, which are on moso bamboo, consistently find that the longitudinal Young's modulus ranges from around 5 GPa (inside) to 30 GPa (outside); the longitudinal tensile strengths from these studies are less consistent, but the majority of data fall in the 50 MPa to 400 MPa range (Nogata and Takahashi 1995; Amada et al. 1997; Amada and Untao 2001; Yu et al. 2008; Shao et al. 2010a; Liu et al. 2014). Similar studies on the longitudinal flexural properties of moso bamboo found a similar range in properties (Li 2004). Lo et al. (2004, 2008) studied longitudinal compressive strength using full cylindrical sections of bamboo internodes with varying longitudinal position and fiber volume fraction; they obtained longitudinal compressive strengths in the range of 35 to 65 MPa. Lee et al. (1994) found the strength properties in bamboo increase up the height of a culm. Tan et al. (2011) studied the radial gradient in mechanical properties of moso bamboo using nanoindentation. The
indentation elastic moduli measured over the tissue were found to vary from approximately 7 GPa to 14 GPa from the inside to the outside of the culm wall (Tan et al. 2011). Yu et al. (2007) investigated the properties of the fiber and parenchyma tissue separately with nanoindentation; they found little variation in the elastic moduli of the fibers from indentation with position in the culm wall and only a slight increase in the hardness of the fibers from the inside to the outside of the culm wall (Yu et al. 2007). In similar work, Wang et al. (2014a) investigated the properties of single fibers in bamboo (*Dendrocalamus latiflorus*) with microtensile experiments and found little variation in the strength and Young’s modulus with position in the culm. The results of Yu et al. (2007) and Wang et al. (2014a) suggest (as Wang et al. conclude) that the variation is the macroscopic mechanical properties of bamboo is primarily due to changes in the amount of fiber, rather than changes in the fiber properties.

As noted, the density of bamboo clearly is affected by the gradient in the vascular bundle volume fraction. Several researchers, aware of the underlying gradient in vascular bundle (and associated fiber) volume fraction and in the mechanical properties of bamboo tissue, reported density parameters for their materials (Lee et al. 1994; Li 2004; Yu et al. 2008; Malanit 2009; Armandei et al. 2015). A few studies clearly viewed the properties with respect to a density parameter and found an increase in the longitudinal properties with increasing density (Li 2004; Malanit 2009). In early work, Janssen (1981) developed empirical strength-density relationships for bamboo.

While the graded nature of bamboo is one of its defining aspects, several studies looked at the effect of other variables, such as moisture content (MC), on mechanical properties. MC in wood is defined as the weight of water in the wood over the weight of the completely (oven) dry wood,
and it is usually expressed as a percentage (Wangaard 1950; Hoadley 2000; Forest Products Laboratory 2010). MC is an important factor governing the mechanical properties of wood (Wangaard 1950; Bodig and Jayne 1982; Gerhards 1982). As MC increases, properties generally decrease in wood. At MC above the fiber saturation point, generally a MC of 25-30%, properties stabilize (Wangaard 1950; Bodig and Jayne 1982). Bamboo, consisting of the same chemical constituents as wood, exhibits the same trend. Lee et al. (1994) found the longitudinal flexural strength varies from 70 MPa in the green state (MC ~ 150%) to 103 MPa in air-dried state for bamboo. They also found a similar variation in the longitudinal flexural modulus from 7.2 GPa (green) to 10.7 GPa (air dry) (Lee et al. 1994). A more focused study on the effect of MC in moso bamboo, performed by Jiang et al. (2012), found rates of changes in mechanical properties per 1% change in MC; a value of 1.49% is found for the longitudinal flexural modulus, similar to, but lower than, the 2% noted for wood (Wangaard 1950; Bodig and Jayne 1982).

Because bamboo grows to its full height in a few months and then matures over several years, the mechanical properties depend on the age of the culm. Fiber cell walls thicken with age (Liese and Weiner 1996; Gritsch et al. 2004), affecting density and mechanical performance. Studies of the effect of age on mechanical properties are often focused on the fibers. Yu et al. (2011b) studied Moso bamboo fibers from different age culms with nanoindentation and microtensile tests. Little variation with age in the fiber cell wall properties was found, and it was concluded that macroscopic improvements in bamboo properties with increasing age are due to fiber cell wall thickening rather than changes in fiber cell wall itself (Yu et al. 2011b). Similarly, Yan-hui et al. (2012) observed very little difference in the longitudinal Young’s modulus of Moso bamboo fibers but some differences in the strength with age. Wang et al. (2014a) found larger differences
in the Young’s moduli of fibers with age in microtensile tests from the bamboo species, *Dendrocalamus latiflorus*, but from a practical point of view the differences (39.5 GPa average in 1-year-old case to 45.8 GPa average in 4-year-old case) are not very large. These results suggest differences in macroscopic properties of bamboo tissue due to age (over the range 0.5 to 5 years) stem from thicker, denser fibers, and thus should be captured by the fiber density (solidness of the fibers here, not to be confused with fiber volume fraction) and to an extent the overall tissue density. When viewing the flexural properties and specific gravities of moso bamboo at different ages of Li (2004), this seems a plausible consideration.

The impact of nodes on the mechanical properties of bamboo has also been researched. Longitudinal tensile properties of bamboo are generally found to decrease substantially with the presence of a node (Lee et al. 1994; Shao et al. 2010b; Taylor et al. 2015; Srivaro and Jakranod 2016). The effect of nodes on the longitudinal flexural properties of bamboo is not yet clearly understood; the literature is mixed on their effect. Some authors found reductions only in the flexural strength (Lee et al. 1994; Semple et al. 2013; Srivaro and Jakranod 2016), while others found reductions in both the flexural strength and modulus (Hamdan et al. 2009), some found no or negligible reductions for both properties (Shao et al. 2010b), and one found differences in the presence of a property reduction in two different species (de Vos 2010).

The literature on more complex mechanical properties of bamboo is sparser. The relatively thin-walled tubular structure of bamboo presents difficulties in the measurement of such properties. Shao et al. (2009) investigated the mode I fracture properties of moso bamboo tissue along the fiber direction, and Wang et al. (2013) investigated the mode II fracture properties of the
material along the same direction. For mode I (opening) a critical strain energy release rate of 358 J/m² was measured (Shao et al. 2009), and for mode II (sliding) a critical strain energy release rate of roughly 1200 J/m² (Wang et al. 2013). Similarly, only a few studies have investigated the viscoelastic characteristics of bamboo (Amada and Lakes 1997; Gottron et al. 2014; Habibi et al. 2016). Gottron et al. (Gottron et al. 2014) found significant plastic deformation under creep in small clear specimens of Tre Gai bamboo (*Bambusa stenostachya*), but also found that the material in general passed creep standard requirements for wood.

### 1.4 Structural Bamboo Products

#### 1.4.1 Overview of Structural Bamboo Products

The term, structural bamboo products, can refer to a wide variety of bamboo products; in this work the term is essentially synonymous with engineered bamboo or engineered bamboo products such as bamboo plywood, oriented strand board or laminates (Liese et al. 2015; Sharma et al. 2015a; Liu et al. 2016). All products under this umbrella label consist of pieces of bamboo broken down from the culm and processed into straight-edged components to be used in construction (Liese et al. 2015; Liu et al. 2016). Exploration of structural bamboo products began in earnest only recently, over the last two decades or so (Liese et al. 2015; Liu et al. 2016). Ply bamboo consists of bamboo strips arranged cross-wise and laminated in layers (Liese et al. 2015). It generally is not made up of peeled veneers (thin sheets), as is the case with plywood (Liu et al. 2016). For a survey of structural bamboo products, see the work of Liu et al. (2016) and Liese et al. (2015).
The three structural bamboo products considered in this thesis are: bamboo glulam (laminated bamboo), bamboo scrimber, and bamboo Oriented Strand Board (OSB). Each one of these products falls into a separate category of the three major types of engineered bamboo classified by Liu et al. (2016). Bamboo glulam falls into the category of laminated bamboo (which is also an alternate name for the actual product). Bamboo scrimber falls into the category of densified bamboo products, and bamboo OSB falls into the category of bamboo boards (Liu et al. 2016). Fig. 1.5 shows small pieces of bamboo glulam and OSB.

**Fig. 1.5 Bamboo Products**
Small pieces of bamboo glulam sitting on top of small pieces of bamboo OSB (roughly 150 mm on each long edge).

### 1.4.2 Bamboo Glulam

Bamboo glulam is a close analog to conventional wood glulam (Lam 2001; Forest Products Laboratory 2010; Liu et al. 2016). With both wood and bamboo, glulam is made by gluing together long strips of the respective material to make up large members with sizable cross sections (Lam 2001; Forest Products Laboratory 2010; Sharma et al. 2015a; Liu et al. 2016). While cross-laminated products are technically glue-laminated, laminated bamboo and bamboo
glulam generally refer to uni-directional products preserving the longitudinal direction of the
plant tissue along the loading axis of the product (Sharma et al. 2015b; Liu et al. 2016). In this
work bamboo glulam refers to such products. Glulam appears to be an ideal application for
bamboo and much research has been devoted to the mechanical properties of this product
(Correal et al. 2014; Sharma et al. 2015b, c, 2017). However, bamboo glulam has a low
efficiency of material use, with only roughly 30% of the culm inputs being used in the product
(van der Lugt 2008).

1.4.3 Bamboo Scrimer

Bamboo scrimber, also known as strand woven bamboo (Sharma et al. 2015a; Liu et al. 2016),
is a highly dense product consisting of crushed sections of bamboo culms, covered with resin,
compressed and heated; it has a material use efficiency of about 80%, higher than that of bamboo
glulam (van der Lugt 2008; Yu et al. 2015; Sharma et al. 2016). Bamboo scrimber, like bamboo
glulam, generally refers to products preserving the longitudinal direction of the bamboo fibers
(Sharma et al. 2015b). Wood scrimber is a similar analog (Coleman 2002; Li et al. 2016).
Densities of bamboo scrimber are generally in the range of 900 kg/m³ to 1300 kg/m³ (Yu et al.
2015; Sharma et al. 2015b). Bamboo scrimber’s material efficiency, despite its high weight,
causes it to be a considerable area of research (Yu et al. 2015; Sharma et al. 2015b; Kumar et al.
2016).

1.4.4 Bamboo Oriented Strand Board (OSB)

Bamboo OSB, like bamboo glulam and scrimber, has an analog in wood OSB. Wood OSB is
widely used in sheathing and other applications (Chapman 2006). In both bamboo and wood
OSB, strands of the respective material, which serve as the structural elements of the board, are consolidated into a board with resin and hot-pressing (Chapman 2006; Semple et al. 2015b, e). In OSB, the strands are generally oriented to a specific purpose (as the name suggests). Often strands are aligned preferentially along the major loading direction of the board in the faces and either randomly or perpendicularly in the middle core of the board (Forest Products Laboratory 2010). This alignment is not as high as that in glulam or scrimber products (which is nearly perfect), as typically there is some distribution of orientation of the strands (Barnes 2000; Painter et al. 2006a). To an extent, bamboo OSB balances retention of the structure of natural bamboo tissue (as in bamboo glulam) with high material use efficiency (as in bamboo scrimber) (Semple et al. 2015c, d, b, e). In particular, bamboo OSB can be used in paneling and sheathing applications, with reduced material waste compared to laminated boards and with reduced weight compared to scrimber or scrimber-like products. Additionally, bamboo OSB has great potential for industrial production, for example, in terms of consistent quality and efficiency of mass production (Semple et al. 2015b, e). While there have been several studies regarding bamboo OSB fabrication and properties (Lee et al. 1996; Sumardi et al. 2007, 2015; Sumardi and Suzuki 2013; Semple et al. 2015c, d, b, e), bamboo OSB has yet to be fully commercialized (Semple et al. 2015c, d, b, e).

1.5 Overview of Thesis

The purpose of this work is to understand the structure and the mechanical properties bamboo and structural bamboo products. This work logically divides into two parts. The first part focuses on developing structure-property relationships for bamboo tissue. Much of the work in this
portion of the thesis relates the cellular level structure of bamboo to its mechanical properties. Structure-property models are developed, similar to the treatment of wood in Gibson and Ashby (1997). Cell wall level length scales are considered with the intention of improving the cellular level understanding. The second part of the thesis applies this knowledge to the mechanical properties of structural bamboo products, specifically bamboo glulam, bamboo scrimber, and bamboo OSB. These two parts of the thesis are further subdivided into chapters. The overall organization of this thesis is shown below:

1. Introduction

Part I

2. Structure and Mechanics of Moso Bamboo

3. Simple Model of the Sclerenchyma Fiber and Parenchyma Cell Walls of Moso Bamboo

4. 3D Printed Structures for Modeling the Young's Modulus of Moso Bamboo Parenchyma

5. Comparison of the Structure and Flexural Properties of Moso, Guadua and Tre Gai bamboo

Part II

6. Comparison of Densified and Natural Moso Bamboo and Relation to Bamboo Glulam and Scrimber

7. Application of a Model for Wood OSB to Moso Bamboo OSB

8. Conclusion

The remaining chapters are summarized below.
**Chapter 2** – In this chapter, the properties of natural moso bamboo are investigated to further enable the processing and design of structural bamboo products. The radial and longitudinal density gradients in bamboo give rise to variations in the mechanical properties. The flexural properties of moso bamboo in the longitudinal direction, along with the compressive strengths in the longitudinal and transverse directions are measured. Based on the microstructural variations (observed with scanning electron microscopy) and extrapolated solid cell wall properties of bamboo, simple models are developed, which describe the experimental results well.

**Chapter 3** – In this brief chapter, the solid cell wall properties of moso bamboo fibers and parenchyma are explored. Results presented in other chapters and from highly related work, are used to construct simple cell wall models of the fibers and parenchyma for the longitudinal cell wall Young’s moduli. The model results are compared to the experimental results of Chapter 2.

**Chapter 4** – An advanced micromechanical model for bamboo will depend on the mechanical behavior of both the parenchyma and the vascular bundles. This chapter aims to increase understanding of the deformation of the parenchyma’s cellular geometry. Isolating the parenchyma for the fabrication of micro-test specimens is difficult. Here, an alternative approach to understanding the parenchyma’s deformation is described, in which larger scale models of plant tissues are fabricated using 3D printing based on micro X-ray computed tomography (XCT) images of moso bamboo parenchyma tissue. The printed models are then tested mechanically. The normalized longitudinal Young’s moduli of the fabricated structures depend on relative density raised to a power between 2 and 3, suggesting that elastic deformation of the parenchyma cellular structure involves considerable cell wall bending. The general
method developed has considerable potential for understanding the mechanical behavior of many biological tissues; this potential is also considered in this chapter. The results are used with those of Chapter 3 to modify the model of Chapter 2.

**Chapter 5** – Here, the ultrastructure, microstructure, fiber properties and flexural properties of three species of bamboo (moso, guadua and Tre Gai) are compared. At a given density, the longitudinal modulus of elasticity of guadua is higher than that of moso or Tre Gai, which are similar; ultrastructural results suggest that guadua has a higher solid cell wall stiffness. At a given density, the moduli of rupture of all three species are similar.

**Chapter 6** – The flexural properties in the longitudinal direction for natural and thermo-hydro-mechanically densified moso culm wall material are measured. The modulus of elasticity (MOE) and modulus of rupture (MOR) increase with densification, but at the same density, the natural material is stiffer and stronger than the densified material. This observation is primarily attributed to bamboo’s heterogeneous structure and the role of the parenchyma in densification. The MOE and MOR of both the natural and densified bamboo appear linearly related to density. Simple models are developed to predict the flexural properties of natural bamboo. The structure of the densified bamboo is modeled, assuming no densification of bamboo fibers, and the flexural properties of densified bamboo are then predicted using this structure and the same cell wall properties of that of the natural material modeling. The results are then compared with those for two analogous structural bamboo products: moso bamboo glulam and scrimber.
Chapter 7 – The MOE of three-layer moso bamboo Oriented Strand Board (OSB) was modeled using a multiscale approach proposed for wood OSB. The modeling approach for wood OSB was adapted to bamboo OSB by accounting for the different structures of wood and bamboo tissue. The MOE of moso bamboo OSB was measured previously in bending; the strands in the surface layer had a preferred orientation and were either from the internode region of the culm or contained node tissue. The model for loading parallel to the preferred orientation of the surface strands gives a good description of the measured values of MOE for boards with internode surface strands (8.6 GPa modeled compared to 8.1 GPa previously measured), but overpredicts that for boards with surface strands containing nodes (8.8 GPa modeled compared to 6.7 GPa previously measured). The model for loading perpendicular to the preferred orientation of the surface strands gives a good description of the MOE data if the core layer moduli are estimated using compliance averaging, for specimens with and without nodes (1.5 GPa modeled compared to 1.5 GPa previously measured).

Chapter 8 – The main results of this thesis are summarized. Recommendations for future work in bamboo research are proposed.
2 Structure and Mechanics of Moso Bamboo
2.1 Author Contribution

The work described in this chapter appeared in the publication:


The author of thesis (PG Dixon) carried out all experiments and modeled the materials with the help of LJ Gibson.

2.2 Background

The use of structural bamboo products is currently limited by the lack of material property data and appropriate building codes. In structural bamboo products, bamboo elements (strands, strips, or otherwise) make up the load-carrying constituents of the product (Liu et al. 2016), thus the structural performance of the structural bamboo product depends, in large part, on the mechanical behavior of bamboo. This chapter is aimed at increasing the understanding of the structure-property relationships for natural (relatively unprocessed) moso bamboo (*Phyllostachys pubescens*) material.

Moso bamboo, the particular species of interest in this chapter, and many subsequent chapters, is the most commercially important species in China and globally (Fu 2000, 2001; Ding et al. 2007; Liese and Köhl 2015). As evident in the previous chapter, much of the research on bamboo is devoted to moso. Many authors studied longitudinal tensile properties of the tissue material as function of the vascular bundle and associated fiber volume fraction gradients, and they found
that the axial Young's modulus ranges from around 5 to 30 GPa; the axial tensile strengths from these studies are less consistent, but the majority of data fall in the 50 MPa to 400 MPa range (Nogata and Takahashi 1995; Amada et al. 1997; Amada and Untao 2001; Yu et al. 2008; Shao et al. 2010a; Liu et al. 2014). In this chapter, similar work is described with consideration of other properties and a focus on developing initial cellular level models of the mechanical properties of bamboo, similar to those developed by Gibson and Ashby for wood (1997), in order to better contextualize bamboo in the broader category of cellular solids.

In this chapter the mesostructure and microstructure (cellular level structure) of moso bamboo is characterized, and the longitudinal modulus of elasticity, \( \text{MOE}^* \), longitudinal modulus of rupture (in bending) \( \text{MOR}^* \), longitudinal compressive strength \( \sigma_L^* \), and radial \( \sigma_R^* \), and tangential \( \sigma_T^* \), compressive strengths are measured to assess the effect of the radial density gradient on the mechanical properties of moso bamboo. In addition, nanoindentation experiments were performed to determine if there is a gradient in modulus or hardness with position in the culm at the cell wall level. Finally, cellular level models relating the structure and mechanical properties were developed and compared with the experimental data.

### 2.3 Materials

A fifteen internode section of dried Moso bamboo from the lower section of the total culm was obtained from Bamboo Craftsman Company (Portland, OR). Exact age of the culm is uncertain, but the importer notes the sections are harvested from culms three to five years old. The culm section underwent a borate treatment prior to importation (to meet requirements for importation).
Internodes were labeled from zero at the lowest internode and increasing up the height of the culm. The outer diameter of these internodes ranged from 16.8 cm (bottom) to 12.4 cm (top), suitable for structural elements. The diameter at breast height (DBH) was 13.7 cm, with an average culm wall thickness of 12.0 mm at this height.

Specimens were air-dry (moisture content, MC ~ 4 - 7%). MC was determined by measuring the mass of three blocks of entire culm wall thickness of the internodes 3, 5, 7, 11 and 14, before and after drying in an oven at 103°C for 24 hours. These specimens gave an average MC ~ 7%. The MC of six flexural test specimens from internodes 5, 11, and 14 were measured in the same way after mechanical testing. These specimens gave an average MC ~ 4%. The density of each specimen used for mechanical testing was determined by recording its mass and measuring the specimen dimensions with calipers. The density is plotted against radial position, $r$, in the culm measured from the inside of the culm wall ($r = 0$ at the inner edge of the culm wall), normalized by the culm wall thickness, $a$, for internodes 5, 11 and 14 in Fig. 2.1. The density of the innermost specimens ($r/a < 0.15$) varies between about 500 to 650 kg/m$^3$. The variation stems from the dense inner terminal layer which constitutes more of the specimen volume in the higher internodes, since the culm wall is thinner, making the specimens denser.
Fig. 2.1 Density Variation across the Bamboo Culm Wall
Flexural test specimens’ densities plotted against their normalized radial position. The calculated contribution of the parenchyma to the density for internode 11 is also shown. IN = internode.

2.4 Microstructure

Uncoated bamboo specimens were imaged using a JEOL JSM-6610LV scanning electron microscope (Peabody, MA), in low vacuum mode, at a pressure of 30 Pascal. Specimens were imaged in both backscatter and secondary modes. Surfaces were prepared by grinding on a Struers Rotopol-1 model polishing wheel (Cleveland, OH) with progressively finer silicon carbide papers: 800-grit, 1200-grit, 2400-grit, and 4000-grit silicon carbide. Image analysis was performed manually using Image J, an open-source image analysis software package developed at the National Institutes of Health (https://imagej.nih.gov/ij/).
The volume fractions of vascular bundles, $V_{vb}$, with respect to radial position, were measured from individual cross sections of the full culm wall thickness of internodes 3, 5, 7, 11, and 14, using sections of roughly 2 mm in length along the culm wall thickness and the middle of the sections for the radial position. The solid fractions of the vascular bundles, $S_v$, were measured with higher magnification images of individual vascular bundles along the culm wall thicknesses. The fibers and intercellular space were approximated as fully solid, namely vessels (metaxylem vessels and phloem sieve tubes) were considered the only voids of vascular bundles. Parenchyma solid fraction was determined from a total of 13 images of about 30 cells each, from different radial and longitudinal positions in the culm. Areal measurements were used in all cases.

The microstructure of the culm wall, at internode 7, is shown in the scanning electron micrograph of Fig. 2.2. The volume fraction of vascular bundles ($V_{vb}$) increases radially, from the inner to the outer wall. SEM micrographs of individual vascular bundles are shown in Fig. 2.3(a, b); similar images were used to measure the solid fraction of the vascular bundles ($S_v$). These micrographs illustrate the increase in the volume fraction of solid within the vascular bundle, towards the outside of the culm. A SEM micrograph of a cross-section of sclerenchyma fibers within a vascular bundle are shown in Fig. 2.3(c): the fibers are rather solid, with insignificant lumens. A longitudinal section of the sclerenchyma fibers and parenchyma cells is shown in Fig. 2.3(d).
Fig. 2.2 SEM Image of Moso Bamboo Culm Wall
Internode 7.

The volume fractions of vascular bundles for four internodes (3, 7, 11 and 14) are plotted as a function of radial position measured starting from the inner edge of the culm wall thickness, normalized by total culm wall thickness $r/a$ in Fig. 2.4(a). Best fit curves, using a constant y-intercept, given below, are also shown:

Internode 3:
\[
V_{vb} = 0.09 \exp \left( 1.654 \frac{r}{a} \right) \quad r^2 = 0.95 \tag{2.1}
\]

Internode 5:
\[
V_{vb} = 0.09 \exp \left( 1.640 \frac{r}{a} \right) \quad r^2 = 0.89 \tag{2.2}
\]

Internode 7:
\[
V_{vb} = 0.09 \exp \left( 1.834 \frac{r}{a} \right) \quad r^2 = 0.92 \tag{2.3}
\]

Internode 11:
\[
V_{vb} = 0.09 \exp \left( 1.938 \frac{r}{a} \right) \quad r^2 = 0.96 \tag{2.4}
\]

Internode 14:
\[
V_{vb} = 0.09 \exp \left( 2.110 \frac{r}{a} \right) \quad r^2 = 0.98 \tag{2.5}
\]

These results are consistent with the nonlinear increase of fiber volume fraction with radial position and the values of fiber fraction found by Nogata and Amada and their co-workers (note: vascular bundle fraction and fiber volume fraction are not the same quantity, but in the plant
studied the values are quite similar due to the high solid fraction of the vascular bundles) (Nogata and Takahashi 1995; Amada et al. 1997).

**Fig. 2.3 Moso Bamboo Microstructural Characteristics**
Cross sectional SEM images of (a) inner ($r/a = 0.074$) and (b) outer ($r/a = 0.869$) vascular bundles, (c) sclerenchyma fibers ($r/a \sim 0.5$), and (d) a longitudinal image with sclerenchyma fibers (center) and surrounding parenchyma ($r/a \sim 0.5$).
Fig. 2.4 Vascular Bundle Volume and Solid Fractions with Normalized Radial Position
(a) Vascular bundle volume fraction plotted against normalized radial position with best fit equations (2.1, 2.3-2.5) (Internode 5 data and fit not shown very similar to IN 3).
(b) Vascular bundle solid fraction plotted against with best fit equation (2.6).

The general increase in the volume fraction of vascular bundles with radial position gets more pronounced with increasing height on the culm, consistent with the general trend of increasing fiber fraction with height found by Grosser and Liese (1971). Differences between the various
internodes appear slight for the inner portion of the culm. The radial variation is considerably
greater than the longitudinal (internode to internode) variation among the internodes studied.

The volume fraction of solid within the vascular bundles is plotted as a function of radial
position in Fig. 2.4(b); the data is well described by a linear fit:

\[ S_j = 0.226 \left( \frac{r}{a} \right) + 0.710 \quad r^2 = 0.84 \]  

The vascular bundles' solid fraction increases with radial position, but not with height in the
culm over the section studied. The vessels clearly shrink from the inside to the periphery of the
culm wall (Fig. 2.2, 2.3(a, b)). The vascular bundles also show a change in shape with radial
position. The inner and middle bundles show four distinct sclerenchyma fiber areas surrounding
the vessels and appear clover shaped. The outer vascular bundles show two surrounding
sclerenchyma regions, and appear skull shaped. These changes are not considered in subsequent
analysis.

The average of relative density (or solid fraction) of the parenchyma was found to be 0.22 ±
0.03, and while the parenchyma lumen size does tend to be smaller in the outermost regions of
the culm, a constant value of solid fraction of the parenchyma was used for simplicity. For
internode 3, the relative density of the parenchyma tissue ranged from 0.23 to 0.26, from the
inner to the outer region, while for internode 7, it ranged from 0.18 to 0.21. Assuming that the
density of the solid cell wall material is similar to that for wood (1500 kg/m³ (Kellogg and
Wangaard 1969; Gibson and Ashby 1997; Gibson 2012)) the average density of the parenchyma
is 330 kg/m³. The contribution of the parenchyma to the overall density, as a function of radial
position, can then obtained by multiplying this value times the volume fraction of parenchyma $V_p = 1 - V_{vb}$; this is shown on Fig. 2.1, for internode 11. The aspect ratio of the elongated brick-like parenchyma cells was $1.9 \pm 0.4$, measured from longitudinal-tangential cross sections of internodes 3, 7 and 11, similar to Fig. 2.3(d). Ahvenainen et al. (2017) obtained a similar parenchyma aspect ratio of 1.6 with a 3D measurement using X-ray tomography data in moso bamboo.

2.5 Mechanical Test Methods

Fig. 2.5 shows a schematic depicting the geometry and location within the culm wall of the internodes of all mechanical test specimens.

![Fig. 2.5 Geometry and Position of Mechanical Test Specimens](image)

2.5.1 Flexural Tests

Small longitudinal bending specimens were cut at different radial positions within the culm wall thickness from internodes 5, 11, and 14 to determine the radial variation of flexural properties.
The waxy epidermal layer was removed and four strips were cut by splitting. Beams were then manually cut and sanded from these strips. The beams had the following nominal dimensions: length, 100-130 mm (along the longitudinal direction); width, 6-12 mm (along the tangential direction); and thickness, 1-4 mm (along the radial direction). The span to depth ratio was no less than 20 for each specimen (Fig. 2.5). Specimen density was measured. Three sets of specimens were taken from each internode, giving a total of 36 specimens tested in flexure. Beams were tested in an Instron model 4201 (Norwood, MA), with outer surfaces face up, at a crosshead speed of 1 mm/min, in three-point bending. The deflection in the center of the beam was measured with a linear variable differential transducer, and the load was measured with a 500 N load cell.

2.5.2 Compression Tests

Compression tests were performed in the longitudinal, radial and tangential directions on rectangular prismatic specimens that were cut from the bulk and minimally planed and sanded to achieve a rectangular cross section. For testing in the longitudinal direction, rectangular prisms were fabricated from internodes 3, 7, and 11. Rectangular blocks from the entire culm thickness were split in the middle to create an inner and outer piece giving a nominal thickness: width: height ratio of 1:2:2, and in the neighboring regions, specimens were cut from the middle of the blocks with the same geometry. The aspect ratio was chosen to avoid failure by macro-buckling, and obtain crushing strength values. Specimen dimensions were from 5 mm to 7 mm (along the radial direction): 10 mm to 14 mm (along the tangential direction): 10 mm to 14 mm (along the longitudinal direction) (Fig. 2.5). At least three tests were performed using specimens at each of the various radial positions and heights. Specimens were tested in an Instron model 1321. The
crosshead speed was 0.5 mm/min. Displacement was measured either using a linear variable differential transducer measuring the displacement between the compression plates or the crosshead displacement directly from the Instron; a comparison of the two methods on individual specimens gave similar results. Load was measured with a 45 kN load cell. Thirty-six longitudinal compression tests were performed in total.

Specimens for testing in compression in the radial direction were prepared from internodes 3, 7, and 14. Rectangular pieces were cut from the entire culm wall thickness. These specimens were then split longitudinally in the middle. Specimens had a nominal thickness: width: height ratio of 1:1:2. Specimen dimensions were from 2.5 mm to 4 mm (along the longitudinal direction): 2.5 to 4 mm (along the tangential direction): 5 mm to 8 mm (along the radial direction) (Fig. 2.5). A set of at least three tests was done using each of these types of specimens. The specimens were tested in an Instron model 4201. Displacement between the compression plates was measured with a linear variable differential transducer the crosshead speed was 0.3 mm/min. Load was measured with a 500 N load cell. Twenty-one radial compression tests were performed in total.

Tangential compressive strength specimens were prepared from internodes 3 and 7. The entire wall thickness was split into four blocks with the dimension parallel to tangential being the largest. In the case of internode 3 the inner terminal layer and the cortex were removed, while in internode 7 these regions were left on the innermost and outermost specimens. Specimen dimensions were from 3 mm to 4 mm (along the radial direction): 3 mm to 4 mm (along the longitudinal direction): 6 mm to 8 mm (along the tangential direction) (Fig. 2.5). The load was measured with a 5 kN load cell, and the displacement was measured with the crosshead
displacement or a linear variable differential transducer, while testing with an Instron model 4201.

Radial compression tests were also performed in a deformation stage within the SEM (Deßen Microtest 200 N Tensile Tester). Specimens of similar geometry to those used in the Instron tests were used. Uncoated and gold coated specimens were tested. The load was measured with a 200 N load cell and the displacement was measured using the stepper motor that drove the crosshead. The test speed was 0.1 mm/min. The crosshead was stopped at several points during the loading, to obtain images of the deformation. It was not possible to do longitudinal compression tests in the deformation stage, as the specimen dimensions would have to be unreasonably small to fail using the 200 N load cell.

2.5.3 Nanoindentation

Nanoindentation was performed on the sclerenchyma fiber bundles using a Hysitron TriboIndenter with a diamond Berkovich tip, and a dynamic mechanical analysis transducer. A trapezoidal loading profile with a peak load of 500 µN, 5 second hold, and 10 second ramps was used. Five by five grid patterns with 25 µm separation were used, for a total of 25 indents on each fiber bundle indented. Nanoindentation was performed on internodes 3, 7, and 14. For each internode 25 indents were made on fibers at three different radial positions: inner, middle, and outer (approximately, \( r/a = 0.25, 0.50, \text{ and } 0.75 \) respectively). Oliver-Pharr analysis of the unloading curve was used for the determination of reduced moduli (Oliver and Pharr 1992). The raw data suggested that the reduced modulus and hardness showed little positional effects, in either the radial or longitudinal direction. Indents were filtered for outliers using the interquartile
range (IQR) of the effective depth computed from all the indents. The effective depths outside
the 1.5 x IQR of the median were removed, leaving 191 indents out of a total of 225.

2.6 Mechanical Test Results

A typical load-deflection curve for a bending test is shown in Fig. 2.6. Ultimate failure always
occurred on the tensile side of the beams.

![Typical Load – Deflection Curve For a Bending Test](image)

**Fig. 2.6 Typical Load – Deflection Curve For a Bending Test**
Specimen: Internode 14, $r/a = 0.817$, $\rho^* = 888 \, \text{kg/m}^3$, width = 6.85 mm, thickness = 1.90 mm, span length = 85.73 mm.

The longitudinal modulus of elasticity, $MOE^*$, and modulus of rupture, $MOR^*$, are plotted against
density in Fig. 2.7. For the specimens at $r/a > 0.15$, both the modulus of elasticity and modulus
of rupture increase linearly with density. The best linear fit to the modulus of elasticity data for
these specimens is:

$$MOE^* = 1.27 MOE_s \left( \frac{\rho^*}{\rho_s} \right) - 10.59 \quad r^2 = 0.97 \quad n = 27 \quad (2.7)$$
with $MOE^*$ in GPa. The best linear fit to the modulus of rupture data for these specimens is:

$$MOR^* = 1.25MOR\left(\frac{\rho^*}{\rho_s}\right) - 117.5 \quad r^2 = 0.93 \quad n = 27 \quad (2.8)$$

with $MOR^*$ in MPa.

Fig. 2.7 Longitudinal (a) MOE* and (b) MOR* Against Density
Lines represent the models.
Extrapolation of $\rho^*$ to the fully dense value for the cell wall, $\rho_s = 1500$ kg/m$^3$, gives estimates for the modulus of elasticity, $MOE_s$, and modulus of rupture, $MOR_s$, of the solid cell wall material on the longitudinal direction: $MOE_s = 39.8$ GPa and $MOR_s = 472$ MPa. For the innermost specimens, at $r/a = 0.08$ to 0.15, the modulus of elasticity and modulus of rupture are nearly constant. The modulus of elasticity and modulus of rupture data are replotted against...
radial position within the culm, $r/a$, in Fig. 2.8. The lines in Fig. 2.7 and the curves in Fig. 2.8, representing models for the flexural Young’s modulus and modulus of rupture, are described in the following section.

Typical compressive stress-strain curves are shown in Fig. 2.9.

![Fig. 2.9 Typical Compression Stress Strain Curves](image)

Axial specimen: internode 11, $r/a = 0.444$, $\rho^* = 541$ kg/m$^3$. Radial specimen: internode 7, $r/a = 0.259$, $\rho^* = 585$ kg/m$^3$. Tangential specimen: internode 7, $r/a = 0.357$, $\rho^* = 556$ kg/m$^3$.

Compressive strengths for loading in the longitudinal, radial and tangential directions are plotted against density in Fig. 2.10. The longitudinal compressive strength, $\sigma_A$, increases linearly with density, $\rho^*$; the best linear fit to the data is:

$$\sigma_A^* = 1.20\sigma_s \left( \frac{\rho^*}{\rho_s} \right) - 49.69$$

$$r^2 = 0.95 \quad n = 36$$

(2.9)
with $\sigma^*_L$ in MPa. Extrapolation to the fully dense value for the cell wall, at $\rho_s = 1500$ kg/m$^3$, gives an estimate for the compressive strength of the solid cell wall material, $\sigma_s = 248$ MPa.

**Fig. 2.10 Compressive Strengths Plotted Against Density**
Upper line represents the model for longitudinal compressive strength, and the lower line is the radial compressive strength average.

In contrast, the radial strength is roughly constant at about 20 MPa, independent of density. The compressive strength in the tangential direction is similar to that in the radial direction, with the exception of the outermost and innermost specimens of internode 7, which included, respectively, the hard outer cortex and the inner terminal layer, with thick walled parenchyma cells elongated on the tangential direction. The dense epidermal layer and terminal layer bear higher stresses when loaded in the tangential direction than in the radial direction. The lines on **Fig. 2.10** represent the longitudinal model, described in the following section, and the radial average.
The longitudinal compressive data, plotted against normalized radial position, \( r/a \), within the culm, for each internode (3, 7 and 11), are shown in Fig. 2.11; the curves, representing models for the compressive strengths, are described in the following section.

![Fig. 2.11 Longitudinal Compressive Strength Plotted Against Radial Position](image)

Curves represent the models.

Deformation stage tests in the SEM indicate that in radial compression, the bamboo fails by collapse of the vessels in the vascular bundles (Fig. 2.12, 2.13). Note that the images in Fig. 2.13 clearly show the vascular bundles collapsing, with little deformation visible in the parenchyma tissue.
Fig. 2.12 Stress Strain Curves From Deformation Stage Test
Micrographs of the specimen also shown on the curve with arrows indicating the stress

Fig. 2.13 Micrographs from the Deformation Stage Test
Gold-coated internode 7 specimen under radial compression. (a) Vascular bundles (b) parenchyma.

The average reduced modulus and hardness, from nanoindentation of the solid cell wall in the sclerenchyma fibers, are 14.9 ± 2.3 GPa and 289 ± 64 MPa (Table 2.1), respectively, similar to literature values of 16.0 ± 3.15 GPa and 360 ± 104 MPa for moso bamboo (values given as average ± standard deviation) (Yu et al. 2007). While there are slightly different values with
varying radial and longitudinal positions, all values of both reduced modulus and hardness were within one standard deviation of the mean, suggesting that the sclerenchyma fiber properties are roughly constant within the culm, similar to the results of Yu et al. (2007) and those of Yang et al. (2014) for the bamboo species *Dendrocalamus farinosus*. The mean reduced modulus value, 14.9 GPa, is substantially lower than the longitudinal modulus of elasticity of the solid cell wall, 39.8 GPa, extrapolated from flexural tests at the density of the solid cell wall ($\rho_s = 1500 \text{ kg/m}^3$). The reduced modulus obtained from nanoindentation is also considerably lower than the longitudinal modulus of elasticity of the densest specimens (20 GPa). This underestimation is due to anisotropy in the cell wall; contact experiments, by their design, measure a combination of the transverse and longitudinal properties. The reduced modulus of wood cell wall has been found to depend on the anisotropic elastic constants (Eder et al. 2013; Gamstedt et al. 2013). The transverse fiber Young’s modulus of bamboo is likely substantially less than the longitudinal value, as is the case in wood, where, for example, the transverse and longitudinal moduli for the solid cell wall are estimated as 10 GPa and 35 GPa, respectively (Cave 1968). Gindl and Schöberl (2004) tabulated a range of roughly 13 GPa to 21 GPa for indentation elastic moduli of spruce wood, and Wu et al. (2009), who investigated several hardwoods, found a higher range from roughly 17 GPa to 25 GPa. Note these ranges include values of sample elastic moduli with corrections for the sample Poisson’s ratio and probe elastic behavior opposed to the direct reduced moduli; the difference in these quantities is likely near 1 GPa. The obtained result for moso bamboo fibers is similar but lower than (or on the lower end of) these ranges.
### Table 2.1 Reduced Modulus and Hardness from Nanoindentation Tests

<table>
<thead>
<tr>
<th>radial position</th>
<th>internode number</th>
<th>reduced modulus (GPa)</th>
<th>hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>r/a ~ 0.25</td>
<td>13.9 ± 2.49 (14)</td>
<td>16.08 ± 1.89 (23)</td>
<td>13.52 ± 1.79 (23)</td>
</tr>
<tr>
<td>r/a ~ 0.50</td>
<td>12.93 ± 2.27 (14)</td>
<td>16.04 ± 2.29 (25)</td>
<td>14.04 ± 1.65 (21)</td>
</tr>
<tr>
<td>r/a ~ 0.75</td>
<td>15.2 ± 1.29 (24)</td>
<td>16.72 ± 2.30 (24)</td>
<td>14.11 ± 1.38 (23)</td>
</tr>
<tr>
<td>internode average</td>
<td>14.24 ± 2.14 (52)</td>
<td>16.28 ± 2.17 (72)</td>
<td>13.88 ± 1.61 (67)</td>
</tr>
<tr>
<td>combined average</td>
<td></td>
<td>14.88 ± 2.26</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>radial position</th>
<th>internode number</th>
<th>reduced modulus (GPa)</th>
<th>hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>r/a ~ 0.25</td>
<td>266.2 ± 87.5 (14)</td>
<td>296.5 ± 54.5 (23)</td>
<td>249.4 ± 48.8 (23)</td>
</tr>
<tr>
<td>r/a ~ 0.50</td>
<td>255.1 ± 75.6 (14)</td>
<td>310.3 ± 59.5 (25)</td>
<td>258.0 ± 47.3 (21)</td>
</tr>
<tr>
<td>r/a ~ 0.75</td>
<td>301.6 ± 42.5 (24)</td>
<td>346.0 ± 69.7 (24)</td>
<td>284.8 ± 34.4 (23)</td>
</tr>
<tr>
<td>internode average</td>
<td>279.6 ± 68.3 (52)</td>
<td>317.8 ± 64.2 (72)</td>
<td>264.2 ± 45.9 (67)</td>
</tr>
<tr>
<td>combined average</td>
<td></td>
<td>288.6 ± 63.9</td>
<td></td>
</tr>
</tbody>
</table>

Note: mean ± standard deviation, (n) is the number of indentations

### 2.7 Modeling

The structure of moso bamboo can be modeled as a fiber composite, with the vascular bundles acting as the fiber and the parenchyma as the matrix. In this model, it is assumed that the properties of the solid in both the vascular bundles and the parenchyma are the same; this assumption is investigated further in the next chapter. Also, the longitudinal modulus of
elasticity obtained from the flexural tests is simply treated as the longitudinal Young’s modulus in the modeling. Given the large span to depth ratios, the longitudinal modulus of elasticity should approximate the true longitudinal Young’s modulus quite well (Bodig and Jayne 1982). Note also, for modeling, the average normalized radial position of the specimens is used to estimate properties; integration over specimen thickness for modified fractions of tissues is not done. It is noted that the observed variation in tissue and specimen thicknesses along the radial direction would make integration-based values quite similar to those at the average radial position.

2.7.1 Young’s modulus

The Young’s modulus of the bamboo, $E_L^*$, in the longitudinal direction is then:

$$E_L^* = E_p V_p + E_{vb} V_{vb}$$  \hspace{1cm} (2.10)

where $E_p$ and $E_{vb}$ are the Young's moduli of the parenchyma and vascular bundles, respectively, and $V_p$ and $V_{vb}$ are their respective volume fractions.

The parenchyma cells are roughly aligned, but have substantial curvature in many of the cell walls and are relatively equiaxed compared with fibers: they resemble a closed-cell foam with curved cell walls (Fig. 2.3(d)). Previous studies on closed-cell aluminum foams with curved cell walls have found that they behave mechanically like open-cell foams: the modulus varies with relative density squared and the compressive strength varies with relative density raised to the $3/2$ power; these relationships describe the modulus and strength up to relative densities of 0.3 (Andrews et al. 1999). The estimate of the Young's modulus of the parenchyma is:
\[ E_p = \left(\frac{\rho^*}{\rho_s}\right)_p^2 E_s \]  

(2.11)

where \( E_s \) is the Young's modulus of the solid cell wall material. The relative density of the parenchyma \( \left(\frac{\rho^*}{\rho_s}\right)_p \) is roughly constant, at 0.22, throughout the moso bamboo culm section. It is assumed that the solid cell wall moduli of the parenchyma and the fibers are the same. Taking \( E_s = 39.8 \text{ GPa} \), extrapolated from our bending tests, \( E_p \) is 1.93 GPa. The Young’s modulus of the vascular bundles can be estimated from the solid fraction of the bundles, \( S_f \) (Fig. 2.4(b)), and the solid cell wall modulus, \( E_s = 39.8 \text{ GPa} \), so that:

\[ E^*_L = E_p (1 - V_{vb}) + S_f E_s V_{vb} \]  

(2.12)

The dependence of the longitudinal modulus with density can then be found given the dependence of the vascular bundle volume fraction, \( V_{vb} \), and solid fraction, \( S_f \), on radial and internode number (longitudinal position) (Fig. 2.4) and the radial position and density of each of the flexural specimens. For each of the flexural test specimens, for \( r/a > 0.15 \), the vascular bundle volume fraction and solid fraction were calculated based on each specimen's radial position and internode number using the best fit curves to the data in Fig. 2.4 (Eq. (2.1-2.6)).

The calculated values of \( V_{vb} \) and \( V_{vb}S_f \) are plotted against specimen density, \( \rho^* \) in Fig. 2.14. It is noted the product, \( V_{vb}S_f \), is essentially the fiber volume fraction and fiber cell wall volume fraction. At zero volume fraction of vascular bundles, the tissue is entirely parenchyma, with an average density equal to the relative density of the parenchyma times the solid cell wall density; using \( \left(\frac{\rho^*}{\rho_s}\right)_p = 0.22 \) and \( \rho_s = 1500 \text{ kg/m}^3 \) the parenchyma density is 330 kg/m^3. Linear equations were then fit to the calculated values for the \( V_{vb} \) and \( V_{vb}S_f \) as functions of density, with
zero volume fraction of vascular bundles (i.e. all parenchyma) fixed to a density of 330 kg/m$^3$ (Eq. (2.13-2.14))

\[
V_{vb}S_f = 0.000825 \rho^* - 0.27228 \quad r^2 = 0.86 \quad (2.13)
\]

\[
V_{vb} = 0.000945 \rho^* - 0.31172 \quad r^2 = 0.80 \quad (2.14)
\]

The linear fits are also shown in Fig. 2.14. Substituting Eq. (2.13) and (2.14) into Eq. (2.12) then gives the dependence of the longitudinal Young's modulus on density.

![Fig. 2.14 Calculated fractions of $V_{vb}$ and $V_{vbS_f}$ Plotted Against Density](image)

Fig. 2.14 Calculated fractions of $V_{vb}$ and $V_{vbS_f}$ Plotted Against Density
Calculation done using the normalized radial position of the outer flexural test specimens ($r/a > 0.15$); calculated values for the specimens are plotted against their measured density.

The model is plotted along with the $MOE^*$ data for the specimens with $r/a > 0.15$ in Fig. 2.7(a); it overpredicts the modulus slightly at lower densities, and gives a good description of the data at higher densities. The model is valid for densities above 330 kg/m$^3$, which corresponds to all parenchyma tissue. The lowest measured density of the flexural specimens was roughly 460 kg/m$^3$, which occurred at $r/a \sim 0.30$ in internode 5. The lowest density occurs in the second
innermost position due to the terminal layer on the innermost specimens. At this density, the tissue is estimated to have roughly 88% parenchyma and 12% vascular bundles.

The modulus of elasticity of the "innermost" tissue represented in Fig. 2.7(a), at $r/a < 0.15$, is roughly constant at 5.13 GPa. The density of these specimens varies between about 500 and 650 kg/m$^3$. For $r/a = 0.10$, the volume fraction of vascular bundles, $V_{vb} = 0.11$ and the solid fraction within the bundles is about 0.73; the corresponding theoretical density is 450 kg/m$^3$; the somewhat higher density of the innermost specimens and their variation in density is due to the dense terminal layer. Substituting $V_{vb} = 0.11$ and $S_f = 0.73$ values in Eq. (2.12) gives $E^* = 4.91$ GPa, similar to the measured values. The terminal layer region constitutes more of the specimen volume in the higher internodes, since the culm wall is thinner. The cells in the dense terminal layer are oriented with their prism axis in the tangential direction (Liese and Schmitt 2006), so that in the bending tests, they are relatively compliant.

This model can also be applied to the variation in the Young’s modulus with radial and internode position (Fig. 2.8(a)), using the best-fit curves for the volume fraction of vascular bundles, $V_{vb}$, and the solid fraction within the vascular bundles, $S_f$, as a function of the radial position, $r/a$ (Fig. 2.4, Eq. (2.1-2.6)). The model gives a good description of the results for internodes 11 and 14, but overpredicts the data for internode 5. On Fig. 2.15(a), the longitudinal modulus of elasticity results for the outer specimens ($r/a > 0.15$) and model are again plotted but now with respect to $V_{vb}S_f$ (calculated based on the specimens’ radial position).
**Fig. 2.15** Longitudinal Properties Against Calculated Fiber Volume Fraction
(a) Longitudinal $MOE^*$, (b) Longitudinal $MOR^*$, (c) Longitudinal compressive strength. Lines represent models.
The linear nature of the model and data can be understood directly from the similarity between the bamboo tissue and a unidirectional fiber reinforce composite. The density, $\rho^*$ (kg/m³), of such a structure is given by the rule of mixtures (treating all non-fiber tissue as parenchyma matrix, $V_p = 1 - V_f$),

$$\rho^* = \rho_f V_f + \rho_p V_p$$  \hspace{1cm} (2.15)

where, $\rho$ and $V$ denote densities (kg/m³) and volume fractions, respectively, and the subscripts $f$ and $p$ refer to the fibers and parenchyma, respectively. The longitudinal Young’s modulus, $E^*$ (GPa) follows the same rule of mixtures,

$$E^* = E_f V_f + E_p V_p$$  \hspace{1cm} (2.16)

in which $E$ refers to Young’s modulus (GPa). Combining Eq. (2.15) and Eq. (2.16) results in a linear density-Young’s modulus relationship,

$$E^* = \frac{E_f - E_p}{\rho_f - \rho_p} \rho^* + \frac{E_p \rho_f - E_f \rho_p}{\rho_f - \rho_p}$$  \hspace{1cm} (2.17)

This formulation provides justification for the earlier linear fit of the experimental data and is consistent with the cellular formulation.

### 2.7.2 Modulus of Rupture

The modulus of rupture of bamboo, for loading in the longitudinal direction, can be estimated using the rule of mixtures:

$$MOR^* = 0.3\left(\frac{\rho^*}{\rho_s}\right)^{3/2} MOR_s \left(1-V_{vb}\right) + S_f V_{vb} MOR_s$$  \hspace{1cm} (2.18)
where $MOR_s$ is the modulus of rupture of the solid cell wall material, estimated by extrapolating the bending strength results to a relative density of 1 ($MOR_s = 472$ MPa). The rule of mixtures for the strength is a simplification of composites failure, but often predicts experimental results well (Hull and Clyne 1996; Jones 1999). The first term models the parenchyma contribution as that of an open-cell foam (Gibson and Ashby 1997), similar to previous results on closed-cell aluminum foams with curved cell walls (Andrews et al. 1999); for the constant relative density of 0.22 of the parenchyma, its modulus of rupture is 14.6 MPa. The second term gives the vascular bundle contribution. The dependence of the modulus of rupture of bamboo on density can then be obtained using Eq. (2.13) and (2.14). The model is shown in Fig. 2.7(b); it gives a good description of the modulus of rupture of the bamboo for the specimens with $r/a > 0.15$. As for Young's modulus, the model is valid for densities greater than 330 kg/m$^3$.

The modulus of rupture of the "innermost" tissue represented in Fig. 2.7(b), at $r/a < 0.15$, is roughly constant at 45.0 MPa. For normalized radial position, $r/a = 0.10$, the volume fraction of vascular bundles, $V_{vb} = 0.11$ and the solid fraction within the bundles is about 0.73; the corresponding theoretical density is 450 kg/m$^3$. Substituting $V_{vb} = 0.11$ and $S_f = 0.73$ values in Eq. (2.18) gives $MOR^* = 50.9$ MPa, similar to the measured values. The contribution of the terminal layer to the modulus of rupture is small, for the same reasons as for the Young’s modulus.

The model can also be applied to the variation in the modulus of rupture with radial position (Fig. 2.8(b)), using the best-fit curves for the volume fraction of vascular bundles, $V_{vb}$, and the solid fraction within the vascular bundles, $S_f$, as a function of the radial position, $r/a$ (Fig. 2.4,
The model gives a good description of the data. On Fig. 2.15(b), the longitudinal modulus of rupture results for the outer specimens \((r/a > 0.15)\) and model are again plotted but now with respect to \(V_{vb}S_f\).

### 2.7.3 Longitudinal compressive strength

The compressive strength in the longitudinal direction is modeled in a similar way:

\[
\sigma_L^* = 0.3 \left( \rho^*/\rho_s \right)^{3/2} \text{MOR}_s (1 - V_{vb}) + S_f V_{vb} \sigma_s
\]  
(2.19)

where \(\sigma_s\) is the compressive strength, in the longitudinal direction, of the solid cell wall material, extrapolated from the compression test results at a relative density of 1 \((\sigma_s = 248 \text{ MPa})\). In Eq. (2.19), the strength of the parenchyma, is modeled assuming cell wall bending and failure by plastic hinges (Gibson and Ashby 1997). Thus the solid cell wall modulus of rupture \((\text{MOR}_s = 472 \text{ MPa})\) is used. Substituting Eq. (2.13) and (2.14) into Eq. (2.19) gives the model for the longitudinal compressive strength in terms of density. The solid black line on Fig. 2.10 corresponds to the model; it predicts the compressive strength over the range of densities of bamboo tested fairly well. The model is valid for densities over 330 kg/m\(^3\); the density 330 kg/m\(^3\) corresponds to all parenchyma.

This model can also be applied to the variation in the compressive strength in the longitudinal direction with radial and internode position (Fig. 2.11), using the best-fit curves for the volume fraction of vascular bundles, \(V_{vb}\), and the solid fraction within the vascular bundles, \(S_f\), as a function of the radial position, \(r/a\) (Fig. 2.4, Eq. (2.1-2.6)). The model follows the same trend as the data, but somewhat underpredicts it. On Fig. 2.15(c), the longitudinal compressive strength
results and model are again plotted but now with respect to $V_{vb}S_f$ (in the case of the experimental results these values are based on the specimens radial position).

### 2.7.4 Transverse compressive strength

The transverse compressive strength showed little density dependence, except at the highest densities, for which the terminal layer or epidermal layer increased the strength. The overall lack of density dependence is not surprising, considering that the transverse compressive strength of fiber-reinforced composites is thought to be relatively independent of fiber volume fraction (Collings 1974). Deformation stage results (Fig. 2.12, 2.13) suggest transverse compressive failure occurs by crushing of the vessels in the vascular bundles. We note that the volume fraction of vessels, $V_{vb}(1-S_f)$, is roughly constant with radial position, $r/a$ and with density, consistent with the roughly constant transverse compressive strength.

### 2.8 Discussion

Moso bamboo has both a radial and longitudinal density gradient as a result of the variation in the volume fraction and solid fraction of the vascular bundles (Fig. 2.2, 2.4). Measurements of the vascular bundle volume fraction and solid fraction and the overall density were used to develop models for the mechanical properties of bamboo based on both density and radial position.

The flexural modulus and strength in the longitudinal direction, of all but the innermost specimens at $r/a < 0.15$, increase linearly with density, demonstrating the same general trend as
wood (Gibson and Ashby 1997). The longitudinal modulus of elasticity varies from about 5 to 20 GPa (Fig. 2.7(a), 2.8(a)), in general agreement with data for tensile Young’s moduli from the literature; the modulus of rupture has a range from 50 MPa to 250 MPa, slightly lower than the range of the majority of literature for tensile strength (50 MPa to 400 MPa) (Nogata and Takahashi 1995; Amada et al. 1997; Amada and Untao 2001; Yu et al. 2008; Shao et al. 2010a; Liu et al. 2014). The variation of these flexural properties with density is similar to that found by Li (2004).

The extrapolated modulus of elasticity of the solid cell wall, $MOE_s = 39.8$ GPa is similar to values extrapolated from tensile tests by Shao et al. (40 GPa) and lower than that found by Amada et al. (46 GPa) and Nogata et al. (55 GPa) (Nogata and Takahashi 1995; Amada et al. 1997; Shao et al. 2010a). This extrapolated modulus of elasticity is similar to the longitudinal Young’s moduli of other researchers obtained from microtensile measurements on moso bamboo fibers, which are generally found in the 30 GPa to 35 GPa range (Yu et al. 2011b, a; Yan-hui et al. 2012), and higher than the ~28 GPa modulus measured by Wang et al. (2014b). It is also noted that the extrapolated solid cell wall longitudinal modulus of elasticity for moso bamboo here is higher but similar to the solid cell wall longitudinal Young’s modulus of wood of 35 GPa, given by Gibson and Ashby (1997).

The extrapolated modulus of rupture of the cell wall, $MOR_s = 472$ MPa, is lower than extrapolated tensile strengths (580 to 810 MPa) (Nogata and Takahashi 1995; Amada et al. 1997; Shao et al. 2010a). These results suggest that the modulus of rupture is a conservative estimate of tensile strength, much like modulus of rupture for clear wood (Forest Products Laboratory
Single fiber tensile strengths in moso bamboo are found in the 1 GPa to 2 GPa range (Yu et al. 2011b, a; Yan-hui et al. 2012; Wang et al. 2014b). This difference with the extrapolated modulus of rupture is primarily attributed to the small volume of single fibers and restriction of failure modes in a single fiber compared to the tissue, indicating that the extrapolated value is reflective of bamboo tissue. In the case of strengths, the bamboo extrapolated value is higher than that of wood (Gibson and Ashby 1997).

The model for the Young’s modulus in the longitudinal direction somewhat over predicts the data at low densities and radial positions (Fig. 2.7(a), 2.8(a), 2.15(a)). It is assumed that the Young's modulus of the solid cell wall is the same for the parenchyma and sclerenchyma (Eq. (2.11, 2.12)); this likely causes an overestimation of the parenchyma's role in longitudinal elasticity, which manifests at higher fractions of parenchyma, corresponding to lower densities and radial positions. Despite the over prediction, the modeled Young’s modulus captures the general range and variation of the experimental values. The model for the modulus of rupture in the longitudinal direction predicts the experimental values well (Fig. 2.7(b), 2.8(b), 2.15(b)).

The innermost specimens, at $r/a < 0.15$, show relatively constant Young's modulus and modulus of rupture with density. For $r/a < 0.15$, the volume fraction of vascular bundles and their solid fraction are about constant; the variation in density, between about 500 and 650 kg/m³, largely arises from the dense terminal layer. The model, using the value for the vascular bundle volume fraction and solid fraction at $r/a = 0.10$, gives a good estimate of the Young's modulus of the innermost specimens. The innermost specimens also have a roughly constant value of modulus of rupture, for the same reason.
The compressive strength of moso bamboo in the longitudinal direction increases linearly with density, from 40 MPa to 110 MPa (Fig. 2.10), similar to the trend of flexural properties of bamboo, and to that of wood (Gibson and Ashby 1997). Literature values, from 45-65 MPa, have been obtained on tests on short longitudinal specimens of the entire culm (Lo et al. 2004), which include both low and high density regions of the culm. Additional factors, such as moisture content, specimen size, aspect ratio may also contribute to the difference in the data. The moisture content for the specimens in this study is ~ 5%, while that for previous study is about 12% (Lo et al. 2004). Moso bamboo shows a decrease in its compressive strength with increasing moisture content (Jiang et al. 2012), similar to wood (Wangaard 1950; Bodig and Jayne 1982). The model for the compressive strength predicts the experimental values well (Fig. 2.10, 2.11, 2.15(c)). The radial and tangential compressive strengths of moso bamboo are roughly constant with density (Fig. 2.10). Deformation stage results suggest that transverse compressive failure occurs by crushing of the vessels of vascular bundles (Fig. 2.12, 2.13), consistent with the roughly constant volume fraction of vessels. It was somewhat surprising that the parenchyma did not fail in transverse loading, but there was little indication of this.

Flexure was investigated due to its importance for structures. Unfortunately, the modulus of rupture is not a fundamental materials strength property, as flexural strength is governed by both tensile and compressive behavior, and is calculated assuming linear elasticity (Wangaard 1950). This fact complicates the extrapolation of the solid cell wall modulus of rupture, \(MOR_s\) and subsequent modeling. The extrapolation and modeling of modulus of rupture tacitly assumes the property behaves like tensile strength. For wood the modulus of rupture is a conservative
estimate of tensile strength, and considered a quality material property for beams of different sizes and species (Wangaard 1950; Forest Products Laboratory 2010). Based on the tensile results of others (Nogata and Takahashi 1995; Amada et al. 1997; Shao et al. 2010a) this appears to be the case for moso bamboo justifying the model to an extent. The model’s good agreement with the experimental data provides some verification of this assumption.

The longitudinal properties of moso bamboo scale linearly with density, similar to wood as previously mentioned. However, in the case of bamboo, relationships between the longitudinal properties (modulus of elasticity, modulus of rupture, and compressive strength) and density are not proportional (or nearly so) as is the case with wood (Gibson and Ashby 1997). This deviation from proportionality arises from the composite like structure of bamboo, consisting mainly of sclerenchyma fibers and parenchyma each of different relative densities and properties (here the differences are modeled as cellular level differences, opposed to cell wall differences). The wood structure resembles a honeycomb, in which the density variation is due to differences in the fiber cell wall thickness relative to the fiber cell size (Gibson and Ashby 1997; Mishnaevsky and Qing 2008). In bamboo, the density variation is due to different proportions of the constituents. The model accounts for the variation in the fractions of parenchyma and vascular bundles, and applies simple cellular material models to these constituents. In the model, cell wall properties of both the fibers and the parenchyma are assumed to be the same, and are obtained from fits of the data (Eq. (2.7-2.9)) extrapolated to the density of the solid cell wall ($\rho_s = 1500$ kg/m$^3$).

To further highlight the difference in density relationships of the longitudinal moduli of elasticity and moduli of rupture of wood and bamboo, the results of this study and wood data from the
literature (Kukachka 1969; Winandy 1994) are plotted with fits on Fig. 2.16. The wood specific gravity was multiplied by 1000 kg/m$^3$ and a factor of 1.12 to obtain the approximate densities of the wood at the MC at which the mechanical properties are measured.

**Fig. 2.16 Longitudinal $MOE^*$ and $MOR^*$ of Moso Bamboo and Wood**

At lower densities the parenchyma (lower property constituent) causes bamboo’s $MOE^*$ and $MOR^*$ (to a lesser extent) to be less than those of the more homogeneous wood, forcing these properties of bamboo to exhibit much less proportional behavior with density than those of
wood. It should be noted the wood properties were determined with larger specimens of higher moisture content; any corrections made to adjust for this would have the effect of relative raising the wood properties to the bamboo properties, making the observed differences more pronounced. These differences should also be considered in comparison of the extrapolated solid cell wall properties. It is also worth noting the transverse compressive strength – density relationship in wood and bamboo are very different as a result of the different structures. In wood, with its more honeycomb-like structure, transverse compressive strength increases with density squared, suggesting wood cell wall failure in plastic bending as expected for many honeycomb structures (Gibson and Ashby 1997; Borrega and Gibson 2015). Bamboo’s transverse compressive strength appears relatively independent of its density (Fig. 2.10), distinctly different from that of wood and also logical given its fiber-reinforced composite-like structure.

2.9 Conclusions

The moso bamboo structure is clearly graded, and the volume fraction of vascular bundles is significantly higher in the outer regions of the culm wall. In addition to bamboo’s vascular bundle volume fraction increasing radially, their solid fraction increases radially as well. Nanoindentation results suggest the fibers properties do not vary greatly with position in the culm.

The mechanical properties show variation with radial position, increasing from the inside to the outside of the culm wall. This variation is a result of the graded structure, which manifests in the
engineering property of density. Longitudinal properties increase linearly with density, while the
transverse compressive strength shows little variation. Given moso bamboo’s high density,
stiffness-weight requirements would seem to be a possible limiting factor in the design and use
of moso bamboo. Additionally the density and strength would likely present difficulties in the
processing of moso bamboo; traditional wood processing techniques would likely need to be
modified to account for this as well as bamboo’s tubular geometry.

Moso bamboo can be modeled as a fiber-reinforced composite, with a parenchyma matrix and
vascular bundle fibers as a first approximation. The experimental Young’s modulus and models
created from images suggest that the sclerenchyma fibers dominate longitudinal elasticity. The
longitudinal properties are well predicted by simple rule of mixtures models (an extension and
simplification in the strength cases), modeling parenchyma contributions as that of an open-cell
foam with the same extrapolated properties as those used for the fiber. The next two chapters are
devoted to exploring these assumptions for the parenchyma in this model.
3 Simple Model of the Sclerenchyma Fiber and Parenchyma Cell Walls of Moso Bamboo
3.1 Background

Much research has been devoted to modeling the elastic properties of the cell wall of wood (Harrington et al. 1998; Bergander and Salmén 2002; Salmén 2004; Hofstetter et al. 2005; Qing and Mishnaevsky 2009; Malek and Gibson 2017). Often cell wall modeling is performed in the broader context of the multiscale modeling of wood (Astley et al. 1998; Harrington et al. 1998; Hofstetter et al. 2005; Qing and Mishnaevsky 2009; Malek and Gibson 2017). There are a number of parameters to consider in the modeling of the wood cell wall: the structural arrangement of cell wall layers, including the chemical composition and the cellulose microfibril angle in each layer, the elastic properties of each constituent and the moisture content of the cell wall. Bergander and Salmén (2002) model the double cell wall of wood using lamination theory, lamina theories (e.g. Halpin-Tsai) applied to the estimated ultrastructural arrangements of the different layers and the elastic properties of the chemical constituents. Hofstetter et al. (2005) created a model for wood using a four-step homogenization scheme, with a matrix of lignin, hemicellulose and water at the smallest length scale (~ 10 nanometers) and pores on the order of hundreds of microns (to approximate hardwood vessels) at the largest length scale of a few millimeters.

For bamboo, existing models for the cell wall are much more limited. A detailed elasticity model to determine stresses in the cell wall of sclerenchyma fibers in bamboo was proposed by Janssen (1981). Janssen created a layered model of the fiber cell wall based on the multilayer wall structure for bamboo sclerenchyma fibers observed by Parameswaran and Liese (1976). Janssen (1981) calculated layer properties with an assumed chemical composition of 50% cellulose
fibrils and 50% matrix and elastic properties for cellulose microfibrils and surrounding matrix from the literature. Janssen (1981) calculated a stress of 42.1 MPa in the majority of the cell wall (~84% based on his assumptions) under uniaxial strain of $10^{-3}$ along the longitudinal direction. A simpler 2D model is presented here. This model is not meant to be a rigorous model for bamboo cell wall properties, but instead a simple model, based on the experimental results in this thesis and highly related work. The results of this model can be compared with experimental results, and they can be used to adjust the cellular level modeling of the previous chapter.

### 3.2 Simple Approximation of the Cell Wall Structure

The longitudinal Young’s modulus of the cell wall of moso bamboo is estimated using a simplified, approximate 2D model of the cell wall, shown in Fig. 3.1. It consists of only the major constituents of the bamboo cell wall, cellulose, hemicellulose, and lignin.

![Fig. 3.1 Moso Bamboo Cell Wall Schematic](image)

Showing the main constituents and the cellulose microfibril angle (MFA)
These constituents are considered as distinct regions laminated in parallel in a single layer, oriented at an angle of the average microfibril angle, $<MFA>$, from the longitudinal direction on the cell and plant. Note the actual bamboo cell wall is much more complicated! The cell walls in bamboo consist of multiple layers (Parameswaran and Liese 1976; Gritsch and Murphy 2005; Liese and Tang 2015). There are also other minor chemical constituents, ash and extractives, in the cell wall (Jiang 2007). The arrangement of the cell wall likely involves a matrix of intermixed hemicellulose and lignin with possible gradients in composition in relation to the cellulose microfibrils. Rather than making more involved assumptions about the cell wall structure, this simplified approximation is taken.

### 3.3 Chemical Constituents: Properties and Fractions

The elastic properties of cellulose, hemicellulose, and lignin were taken from the literature (Table 3.1). The densities of constituents used were those noted by Qing and Mishnaevsky (2009). Calculated volume fractions, described at the end of this section, are also shown on this table. Hemicellulose and lignin properties were estimated from work of Cousins (1977, 1978), who measured the properties of hemicellulose and lignin isolated from radiata pine ($Pinus radiata$) as function of moisture content (MC) with an indentation method. The Young’s moduli were estimated at 5% MC, reflecting the MC of the previous experimental work of this thesis. The Poisson’s ratio assumed by Cousins to calculate these moduli was used (rounded to 0.35) (1977, 1978). For lignin, the periodate lignin was used (Cousins 1977). Both materials were taken as isotropic, so the two elastic constants for each give a complete description of their elastic behavior. Both of these components are amorphous, though hemicellulose is known to
have some orientation along the cellulose microfibril direction (Sjöström 1993). Thus, often in mechanical models of the wood cell wall, hemicellulose is modeled as an orthotropic material, while lignin is modeled as isotropic (Bergander and Salmén 2002; Qing and Mishnaevsky 2009; Malek and Gibson 2017). Here, isotropic models are used for both hemicellulose and lignin, in light of their characterization as amorphous and the nature of experimental measurements used to arrive at their values.

Table 3.1 Chemical Constituent Properties from Literature (Cousins 1977, 1978; Qing and Mishnaevsky 2009) and Calculated Volume Fractions

<table>
<thead>
<tr>
<th>Cellulose</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_L$ (GPa)</td>
<td>$E_T$ (GPa)</td>
<td>$G_{LT}$ (GPa)</td>
<td>$v_{LT}$</td>
<td>$v_{TT}$</td>
<td>$\rho$ (kg/m$^3$)</td>
<td>$V_{rel}$</td>
</tr>
<tr>
<td>138.0</td>
<td>27.2</td>
<td>4.4</td>
<td>0.235</td>
<td>0.48</td>
<td>1600</td>
<td>0.397</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hemicellulose</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (GPa)</td>
<td>$v$</td>
<td>$\rho$ (kg/m$^3$)</td>
<td>$V_{hem}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td>0.35</td>
<td>1500</td>
<td>0.233</td>
<td></td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Lignin</th>
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</thead>
<tbody>
<tr>
<td>$E$ (GPa)</td>
<td>$v$</td>
<td>$\rho$ (kg/m$^3$)</td>
<td>$V_{lig}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>0.35</td>
<td>1400</td>
<td>0.371</td>
<td></td>
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</tr>
</tbody>
</table>

For cellulose a transversely isotropic model is used; elastic properties were taken as those listed by Qing and Mishnaevsky (2009), who developed their values from various works. The “longitudinal” Young’s modulus value (“that along the chain direction”) of 138 GPa is consistent with experimental and theoretical studies for cellulose I (Sakurada et al. 1964; Tashiro and Kobayashi 1991; Nishino et al. 1995 (source)), which is the crystalline polymorph in plants (O’Sullivan 1997). The values of Qing and Mishnaevsky (2009) are noted for 12% MC. These values are assumed accurate at 5% MC, as Sakurada et al. (1964) found no change in this value in dry and wet states for cellulose I. An important note about the use of these values for cellulose in bamboo (or wood cell walls) is that crystalline cellulose’s properties are assumed to reflect the
total cellulose properties, even though there are amorphous regions in the cellulose (Andersson et al. 2004; Fernandes et al. 2011; Ahvenainen et al. 2016). In wood cell wall models, this assumption gives surprisingly accurate results (Bergander and Salmén 2002). Furthermore, Fernandes et al. (2011) found that, in general, the disordered cellulose in Sitka spruce (*Picea sitchensis*) was oriented and retained the bonding required for rigidity. This suggests the elastic properties of the amorphous cellulose are similar to those of crystalline cellulose.

Next, the relative amounts of each chemical constituent in the cell wall are needed. Weight fractions relating to the cellulose, hemicellulose and lignin of the cell wall are measured for moso bamboo in Chapter 5 (*Table 5.2*). The sum of those values is somewhat less than 100%; the weight fractions are adjusted based on the sum of these constituents making up 100% of the cell wall and used here. They are then converted to volume fractions based on their densities, which are shown in *Table 3.1*.

### 3.4 Average Microfibril Angle (MFA)

The other required input for this model is the average MFA. Ahvenainen et al. used a coupled micro X-ray computed tomography (XCT) and localized X-ray scattering approach to measure MFA distributions of the moso bamboo vascular bundles (which are dominated by the fibers) and parenchyma separately (2017). A combination micro XCT–X-ray scattering set-up was used that allowed small matchstick moso bamboo specimens’ alignment and tissue regions to be determined and selectively studied with X-ray scattering using a pencil beam. The fibers gave peaked and fairly narrow MFA distributions while the parenchyma had broad MFA distributions.
Ahvenainen et al. (2017). Fig. 3.2 depicts one of these measurements, with scattering beam paths and the associated azimuthal X-ray scattering patterns shown (Ahvenainen et al. 2017) (Fig 3.2 is courtesy and used with the kind permission of Patrik Ahvenainen).

![Diagram of scattering beam paths and azimuthal X-ray scattering patterns](image)

**Fig. 3.2 Azimuthal X-ray Scattering Patterns from Specific Regions of Moso Bamboo**
(a) Scattering beam paths and (b) azimuthal X-ray scattering patterns. Path 1 is nearly entirely through sclerenchyma, paths 2 is mostly through sclerenchyma and path 4 is entirely through parenchyma. From (Ahvenainen et al. 2017) and with courtesy and kind permission of Patrik Ahvenainen.

Ahvenainen et al. (2017) found average MFAs of 11° and 46° for the fibers and parenchyma respectively (directly from the measurements). The cellulose in the sclerenchyma fibers is highly aligned while that in the parenchyma is more randomly oriented.

### 3.5 Calculation and Results

In order to calculate the longitudinal Young’s modulus of the bamboo cell wall, the elastic properties of a cell wall with perfectly aligned cellulose microfibrils were calculated. They were
calculated using composite bound equations from a simple mechanics of materials approach: the longitudinal Young’s modulus and Poisson’s ratio were calculated with the rule of mixtures, and the transverse Young’s modulus and shear modulus were calculated with the inverse rule of mixtures (Jones 1999).

These properties were then transformed to obtain the properties along the longitudinal (loading) direction for the cell wall oriented at the average MFA by Eq. (3.1) (Mallick 2008).

\[
(E_{ls})_{\text{avg MFA}} = \left[ \frac{\cos^2(<\text{MFA}>)}{(E_{ls})_0} + \frac{\sin^2(<\text{MFA}>)}{(E_{ts})_0} + \frac{1}{4} \left( \frac{1}{(G_{lt})_0} - \frac{2(v_{ls})_0}{(E_{ls})_0} \right) \right]^{-\frac{1}{2}} (3.1)
\]

Where \((E_{ls})_{\text{avg MFA}}\) is the longitudinal Young’s modulus of the moso bamboo solid cell wall as a function of the average MFA, \(<\text{MFA}>>\); \((E_{ls})_0\) is the longitudinal Young’s modulus of the perfectly aligned cell wall \(<\text{MFA}>=0^\circ\); \((E_{ts})_0\) is the transverse Young’s modulus of the perfectly aligned cell wall; \((G_{lt})_0\) is the shear modulus of the perfectly aligned cell wall, and \((v_{lt})_0\) is the Poisson’s ratio of the perfectly aligned cell wall \((v_{lt} = -\varepsilon_T / \varepsilon_L\). The average MFA was first used as a parameter ranging from 0° to 90°. The longitudinal Young’s modulus is plotted as a function of the average MFA in Fig 3.3.
Fig. 3.3 Longitudinal Solid Cell Wall Young’s Modulus as a Function of the Average MFA
The red dots are the MFA corresponding to the measured average MFA for the sclerenchyma fibers (11°) and the parenchyma cell wall (46°).

3.6 Discussion

The longitudinal Young’s modulus values at the average MFAs of both the parenchyma and fibers are highlighted by red dots on Fig 3.3. To estimate the longitudinal Young’s modulus of the sclerenchyma fiber cell wall, the value is taken at the measured average MFA of 11° (Ahvenainen et al. 2017). The estimated solid cell wall modulus from the model is 36.6 GPa, similar to the value of the longitudinal cell wall Young's modulus of moso bamboo estimated from extrapolation of the macroscopic flexural data, 39.8 GPa, given in Chapter 2. The model estimate (like the extrapolated one) is also similar to other researchers’ results from microtensile measurements on moso bamboo fibers, which are generally found to be in the range of 30 GPa to 35 GPa (Yu et al. 2011b, a; Yan-hui et al. 2012). The model estimate is higher than the ~28 GPa
modulus measured by Wang et. al (2014b). The model estimate of 36.6 GPa also seems to be consistent with the calculations of Janssen (1981). The Young's modulus of the parenchyma cell wall is estimated using the value at an average MFA of 46° (Ahvenainen et al. 2017), giving a longitudinal parenchyma cell wall modulus of 8.8 GPa. It is concluded that the cell walls of the two tissues have two very different longitudinal Young’s moduli.

The reduced modulus of the moso bamboo cell wall measured in nanoindentation tests using a Berkovitch tip was 14.9 GPa (Chapter 2). For a Berkovich tip, the angle between the direction that the faces of the tip load the cell wall and the longitudinal axis is nearly 25° (Gindl and Schöberl 2004). An additional interesting finding from the model is that at an average MFA of 25° the longitudinal Young’s modulus of the cell wall is 16.0 GPa (Fig. 3.3), slightly higher than 14.9 GPa, the value of the average reduced modulus of moso bamboo fibers measured in Chapter 2. Clearly, the nonzero MFA of the bamboo cell wall makes any formal comparison of these values difficult, but the general similarity is expected and worth noting. Gindl and Schöberl (2004) noted this in wood.

In using this relationship to estimate the longitudinal Young’s moduli of the fiber and parenchyma cell walls in moso bamboo, there is an assumption that the chemical composition of the two tissues is the same. Li (2004) found clear variations in the chemical composition with radial and longitudinal position in the culm wall, with cellulose content increasing with the directions of increasing fiber volume fractions, but cellulose weight fractions roughly remained within 40-50% range. Thus the assumption is a simplification, but not an entirely unrealistic one.
given the large variability in the tissue and relatively slight one in chemistry. The impact of average MFA difference is likely much larger than that of the probable chemical differences.

3.7 Conclusions

A simple single layer model for the cell wall of bamboo, with cellulose oriented at the average MFA, was presented in this chapter. The longitudinal cell wall Young’s moduli for the sclerenchyma fibers and parenchyma, estimated by this model, are 36.6 GPa and 8.8 GPa respectively. The fiber cell wall prediction is similar to the extrapolated estimate in Chapter 2 and experimental measurements of others (Yu et al. 2011b, a; Yan-hui et al. 2012). The estimate for parenchyma is one fourth of that of the fibers, implying the elastic solid cell wall properties of these two constituents are very different, even with the same assumed chemistry. These results, combined with those of the next chapter, Chapter 4, are used to create an updated contribution of the parenchyma to the overall bamboo elastic moduli.
4 3D Printed Structures for Modeling the Young's Modulus of Moso Bamboo Parenchyma
4.1 Author Contribution

The author of this thesis (PG Dixon) performed: the X-ray tomography with help of X Xiao (the Advanced Photon Source), the printing with the help of MA Skylar-Scott (Harvard University), the mechanical testing and related analysis with the help of JT Muth (Harvard University). JA Lewis (Harvard University) facilitated the printing and mechanical testing.

4.2 Background

From the previous chapters, it is clear that there are two main cell types that form bamboo’s structure: sclerenchyma fibers and parenchyma cells. The sclerenchyma fibers often have several layers, alternating between thick layers with low microfibril angle and thin layers with high microfibril angle in the secondary wall (Parameswaran and Liese 1976); the cellulose microfibrils are arranged such that the Young’s modulus of the sclerenchyma fibers is much greater along the length of the fibers than in the transverse directions (Yu et al. 2007).

The parenchyma cells are more thinly walled and lower density than the fibers (Grosser and Liese 1971; Liese 1987). In Chapter 2, a relative density 0.22 for moso bamboo parenchyma from SEM images was measured; Palombini et al. (2016) measured a relative density of 0.274 for parenchyma in Bambusa tuldoides with micro X-ray computed tomography (XCT). Note that relative density is the density of the cellular material, $\rho^*$, in this case the parenchyma, divided by that of the solid cell wall material, $\rho_s$. Ahvenainen et al. (2017) measured an average aspect
ratio of the parenchyma cells of 1.6 with micro XCT. Additionally, the cellulose microfibrils in
the parenchyma cell wall show much a lower degree of orientation than those of the
sclerenchyma fibers (Ahvenainen et al. 2017), suggesting that the parenchyma cell wall is
roughly isotropic.

The sclerenchyma fibers of the vascular bundles have been the focus of a number of mechanics
investigations, including a numerical investigation of the molecular bonding of their microfibils
(Youssefian and Rahbar 2015), nanoindentation (Yu et al. 2007, 2011b; Yang et al. 2014) and
studies of single fiber tensile properties (Yu et al. 2011b, 2014; Yan-hui et al. 2012; Wang et al.
2014b). Bamboo parenchyma mechanics, however, is less well studied; investigations of the
parenchyma properties are generally limited to nanoindentation measurements (Yu et al. 2007;
Habibi et al. 2015, 2016).

Models for the mechanical behavior of bamboo require an understanding of how the parenchyma
properties depend on density. Bamboo parenchyma tissue is a cellular solid, with elongated cells
that stack in roughly vertical columns (Fig. 1.4). Cellular solids are generally thought of as
either honeycomb-like (with two-dimensional prismatic cells) or foam-like (with three-
dimensional polyhedral cells). Bamboo parenchyma appears to be intermediate to these two
cellular geometries. When loaded along the prism axis, honeycombs deform by uniaxial
compression or stretching, and their longitudinal Young’s moduli are linearly related to their
relative density. When loaded across the prism axis, they deform by bending, and their in-plane
Young’s moduli depend on the cube of their relative density (Gibson and Ashby 1997). Open-
cell foams deform by bending; their Young's moduli depend on the square of their relative
density. In closed-cell foams, the edges of the cells deform by bending while the faces stretch, so that their Young's moduli depend on relative density raised to a power between one and two (Gibson and Ashby 1997). From images of the structure of bamboo parenchyma, it is not exactly clear which of these models is most appropriate. In Chapter 2, an open-cell foam model was chosen for moso bamboo parenchyma. This chapter will investigate the mechanical behavior of the parenchyma cellular structure more deeply, and in doing so, develop a novel method.

In this chapter, 3D printing is used to fabricate larger scale models of bamboo parenchyma, based on micro X-ray computed tomography (XCT) imaging. This method allows the fabrication of parenchyma models with the same cellular geometry but different relative densities. Mechanical testing of the models then gives insight into the mechanism of deformation of the cell walls and the appropriate cellular solid model to use for bamboo parenchyma. The method is broadly applicable to understanding the mechanics of plant tissues.

Micro XCT is a powerful tool for the visualization of plant structure (Dhondt et al. 2010; Brodersen and Roddy 2016). The technique has been employed to understand the structure of wood (Steppe et al. 2004; Trtik et al. 2007), adhesive behavior in wood (Kamke et al. 2014; Paris et al. 2014; McKinley et al. 2016), and mechanical deformation of wood (Forsberg et al. 2008; Zauner et al. 2012). Even the structure of bamboo has been investigated with micro XCT (Peng et al. 2014; Huang et al. 2015; Palombini et al. 2016; Krause et al. 2016; Ahvenainen et al. 2017). Synchrotron radiation was used in this study to image moso bamboo as it provides for higher quality micro XCT with better contrast and resolution than those of conventional XCT set-ups (Mannes et al. 2010).
3D printing and other additive manufacturing techniques similarly have great potential in the study of biological systems (Studart 2016). Studart (2016) noted the potential use of additive manufacturing techniques to create models to aid in understanding structure-property relationships in bioinspired and biological materials. Here, 3D printing is used to generate models of bamboo parenchyma and measure their Young's moduli. Much like Studart’s review (2016), this work is not an application or investigation in bioprinting (that is the printing of actual biologics (Datta et al. 2017)), but rather describes the printing of a biological cellular geometry with a synthetic material.

Previous 3D printing work has captured aspects of plant structure. Muth et al. (2017) were inspired by the level of hierarchies present in plants to print ceramic honeycombs with foam walls. Inspired by low density of balsa wood, Compton and Lewis (2014) printed honeycombs with composite cell walls consisting of silicon carbide and carbon fibers in epoxy; Malek et al. (2017) developed finite element models of these types of structures. Gladman et al. (2016) printed flower-like structures, with a composite hydrogel ink, that change shape with water uptake. Denes 3D (2015a, b) printed and mechanically tested highly-simplified cellular structures based on the structure of spruce for preliminary assessments of sandwich panel core material fabrication and suitability. Despite this exciting botanically inspired work, the true cellular structure of plant tissue has not yet been captured using 3D printing.

Many plant tissues and structures are small in length scale and soft, making extraction and fabrication of test specimens difficult, limiting mechanical testing. In addition, separating the
contributions of the cell wall and the cellular geometry of the tissue to its mechanical behavior may be of interest in some cases. Micro XCT can comprehensively determine the 3D cellular geometry of plant tissue. Subsequent 3D printing of models developed from the XCT data allows for the plant tissue geometry to be printed at a larger scale suitable for conventional mechanical testing. The 3D printing of models developed from 3D image data is well established in medical research (Rengier et al. 2010), but seems relatively unexplored in plants. Bamboo parenchyma is an excellent tissue to use in exploring this method due to the small regions between sclerenchyma fibers and its low stiffness, but there are many other complex plant tissues that could also be investigated with this methodology.

For this chapter, image slices corresponding to the 3D structure of moso bamboo parenchyma were obtained with micro XCT using synchrotron radiation. These images were then processed to allow 3D printing of models of the structures of different cellular geometry and the same cellular geometry but different relative densities. The printed parenchyma structures were then mechanically tested in effort to understand the mechanical behavior of the tissue’s cellular geometry. The mechanical test results provided evidence that the parenchyma cellular structure deforms by considerable cell wall bending. Lastly, this general approach for modeling biological materials is discussed.

### 4.3 Materials

All materials came from a single internode of moso bamboo, obtained from the importer, Bamboo Craftsman Company (Portland, OR). This internode was not from the same culm
section as that of the material in Chapters 2, 5, and 6. Approximately 30 small matchstick specimens (long axis – longitudinal, approximate dimensions were 1.5 mm x 1.5 mm x 20 mm) were cut from the moso bamboo internode. Specimens were air-dry.

4.4 Methods

4.4.1 Micro X-ray Computed Tomography (XCT)

Micro XCT scans were performed on the specimens, using synchrotron radiation at the 2-BM-A beamline of the Advanced Photon Source (APS) at Argonne National Laboratory (Argonne, IL). An X-ray beam energy of 20.2 keV, a voxel size of 0.87³ µm³, a sample to detector distance of 90 mm, 1500 projections over 0° to 180°, and an exposure time of 100 ms were used. X-ray phase contrast was used to enhance the image contrast. Reconstructions were performed with Tomopy, an open-source software package developed at the APS (Gürsoy et al. 2014). The gridrec algorithm was used for reconstruction (Dowd et al. 1999), and the reconstructed slices were saved as floating-point greyscale images.

4.4.2 Image Processing

Three individual reconstructed image stacks (from separate specimens and scans) were selected for printing based on their longitudinal alignment with the stack direction and the availability of relatively large regions parenchyma tissue. The reconstructed slices had to be processed so that the 3D printer software could read the files for printing. Stereolithography-based (SLA) 3D printers were used to fabricate the models, as this method of printing permits spanning members in intricate structures without internal support. Two printers (Printer 1 and Printer 2) were used
as the first one malfunctioned before all the specimens were fabricated; the printers are described in more detail in the next section. Printer 1 was used to print three models based on parenchyma tissue in three different specimens of bamboo; these models had different cellular geometries but roughly constant relative densities. Printer 2 was used to fabricate models that all had the same cellular geometry, but were of different relative densities (Table 4.1). Two slightly different image processing methods were used for the two printers to arrive at correct file formats and correctly scaled structures. In both cases reconstructed slices were opened and processed as an image stack in ImageJ, an open-source image analysis program developed by the National Institutes of Health (https://imagej.nih.gov/ij/).

For Printer 1, image stacks from scans of the three specimens with different cellular geometries were used; these are referred to as cellular geometries 1, 2 and 3 (Table 4.1). The relative densities of the specimens were similar (0.309-0.326). 684 pixel x 513 pixel (595.08 µm x 446.31 µm) regions consisting of nearly all parenchyma (and only parenchyma in the central region) were selected and cropped from the stacks. These were then resized to 1024 pixel x 768 pixel with a bilinear interpolation, changing the pixel size in the two dimensions of an image slice from 0.87 µm to 0.58 µm. However, the spacing between the stacks remained 0.87 µm. These stacks were then made binary (white/black, with the “Make Binary” operation in ImageJ, using the default settings). Even with synchrotron radiation, segmenting the parenchyma cell walls from the air in lumens proved difficult, so that the binary method left some noise in the lumens. This was removed using the Particle Remover plugin with a size setting of 0 to 1000 pixel². The 730 pixel x 730 pixel central region was then selected. For printing the cell walls were made white with a value of 255 and the voids were black with a value of 0. The stacks were
saved as PNG image sequences. To match scales for Printer 1, each image was repeated three times in the print stack as each image slice prints with 50 µm thickness (in the z direction) while each pixel prints with a dimension of 97.58 µm in the x-y plane (0.58 µm $\rightarrow$ 97.58 µm in x-y and 0.87 µm $\rightarrow$ 150 µm in z). Note for the scales to exactly match 2.92 slices would have to be used for every individual image, as opposed to three; three and 2.92 are different by less than 3%. The relative densities of the cellular geometries, used for printing, were measured with the voxel counter plugin of ImageJ.

For Printer 2, the overall method was similar. One cellular geometry (cellular geometry no. 3 of those used with Printer 1) was used and the relative density of the printed models was varied by thickening or thinning the cell walls using image processing to give relative densities of 0.326 (corresponding to the original scan), 0.362, 0.430 and 0.494. The cropped images from the reconstructed slices were used. The images were not resized. The images were made binary and particles were removed with the same methods (particle size for removal scaled down, 0 to 446 pixel$^2$). Similarly, the 488 pixel x 488 pixel center was then selected. These files were saved as a PNG image sequence, and then used to adjust the densities by dilating and then eroding the cell wall thickness. Images were first dilated by adding four pixels to each side of the wall, thickening the cell walls and closing small holes that were observed at the nodes of the cell walls. These images were then eroded by two pixels on each side of the cell wall and saved as a PNG sequence giving a relative density of 0.494. The image stack was eroded once more to give a relative density of 0.430 and yet again to give a relative density of 0.362. To create the STL files, required for Printer 2, these stacks (the original, 0.326 relative density model, which preserved the holes at the nodes of the cell walls, and the density adjusted models) were opened
and cropped to remove the boundary, and then the plugin BoneJ (Doube et al. 2010) was used with the isosurface command (resampling of 6 and threshold of 128) to create surfaces and save binary STL files. Lower density models of the cellular geometries, requiring further erosion of the cell walls, could not be created because of extensive connectivity issues. The relative densities of the adjusted density image sequences of the cellular geometry were measured with the voxel counter plugin of ImageJ.

4.4.3 Printing

Three models, with three different cellular geometries, were printed directly from the prepared image stacks (described above) using Printer 1, an EnvisionTEC Perfactory MicroXL-Printer, and HTM 140 V2 resin (Dearborn, MI, US). Sixteen 1024 pixel x 768 pixel fully filled (255 valued) PNG files were added to the beginning of the stack to support the print. Print resolution and scaling was noted above, but to clarify the 1024 pixel x 768 pixel images map to 99.93 mm x 74.97 mm in real space. The maximum height permitted by this printer is 100 mm, allowing for 2000 images. This and the scale allowed for 662 individual slices to be fed into the printer, with the first parenchyma slice image printed only once and the remainder printed three times. The model volume of 99 mm x 71 mm x 71 mm corresponds to an actual parenchyma volume of 575 µm x 424 µm x 424 µm, giving a printed magnification of ~170x. Note the magnification in the z is slightly higher (~ 3%) due to the slightly mismatched scales.

Build instructions were created in a text file by inspecting the build instructions of other simple print jobs created from STL files. The build instructions were adjusted so that the first 34 images (including the support images) were printed with support settings to allow for removal from the
printer platen. Each build was then loaded into the EnvisionTEC Perfactory MicroXL printer’s software. The print direction was through the stack, i.e. along the longitudinal direction of the structure. These large prints require considerable resin; the print jobs were paused when refills of the reservoir were required. When the jobs were finished, the part was removed and cleaned thoroughly with isopropanol, and the printed models were milled to remove the supporting base.

Duplicate prints of one bamboo specimen, cellular geometry no. 3, with adjustments for different densities, were fabricated on another SLA printer, Printer 2, a Formlabs Form 2 Printer (Somerville, MA). The STL files were loaded into Formlabs software, Preform. Then they were resized to 96 mm x 71 mm x 71 mm, to use a similar magnification of ~170x in the prints. Support was generated without internal support. These specimens were printed with Formlabs Grey Resin V3 (GPGR03) at a layer thickness of 100 µm. When printing was complete, they were removed from the platen and cleaned with isopropanol, and the supporting material was removed by hand and subsequent sanding of the remaining bumps on the faces to be loaded in compression.

Additionally, 50 mm x 13 mm x 13 mm solid blocks of the two resins were printed (using the printer corresponding to each) to assess their Young's moduli. With all prints, no post cure procedure was performed, in order to avoid possible curing of liquid resin enclosed in the cells and differential curing on such large parts.
4.4.4 Density and Mechanical Testing

The density of all specimens was calculated from measurements of their dimensions and mass. All printed specimens were tested non-destructively in uniaxial compression, along the structure’s longitudinal direction. Testing was done using an Instron 5566 test frame (Instron, Norwood, MA), equipped with a 10 kN load cell. The parenchyma structures do not lend themselves well to the placement of extensometers, so the strain was measured by imaging. Six dot pairs were placed over the middle (approximately middle 60-70 mm) of one face of the printed parenchyma models, serving as a visual extensometer. The three dot pairs were used on the solid blocks (middle 20-30 mm). The imaging was done with either a Canon EOS 5D Mark III camera or a Canon EOS Rebel T2i camera with a Canon Macro Lens EF 100 mm 1:2.8 L (Melville, NY). Each parenchyma structure and solid block was tested three times at crosshead speed of 0.0015 mm/s. For the parenchyma models and solid blocks made with Printer 1, maximum nominal stresses of 0.6 MPa and 8.6 MPa were used, respectively. The parenchyma models made with Printer 2 were loaded to different maximum stresses based on their relative density, from 0.7 MPa (for the two lowest relative density structures, that generated from the original binary stack with a relative density of 0.326 and the 0.362 relative density structure) to 1.1 MPa (for the highest relative density structure). The solid blocks made with Printer 2 were loaded to a maximum nominal stress of 10.7 MPa. The load and optical deformation data were processed using Matlab (Mathworks, Natick, MA) to give stress-strain curves. The first and last five images extracted from the videos were removed from the analysis, as the first few images may have contained noise from vibrations as result of starting to record and the last images may have been from video after the test was stopped. For each specimen, the Young's modulus was
calculated based on the linear fit of the stress-strain curve from 25% to 85% of the maximum test stress.

4.5 Results

Fig. 4.1 is a visualization of the parenchyma tissue, with images from cellular geometry no. 3. Fig. 4.1(a) shows a slice of an image stack obtained from micro XCT and cropped to consist of parenchyma only. Note the small holes at the nodes of the cell walls. The green outline shows the region selected for printing. Fig. 4.1(b) shows this same image but now processed for printing. The processed image here was used with Printer 1, so it was printed directly. The processed slices to construct the STL files, used on Printer 2, look almost identical, but without surrounding background (and very slightly different as result of the different image size). A view of this STL file (corresponding to the original image stack, i.e. without erosion and dilation operations) is shown in Fig. 4.1(c) (this view taken in Microsoft’s 3D builder). Fig. 4.1(d) shows a longitudinal view of the processed image stack in Image J’s Volume Viewer plugin; this image is only for visualization purposes and was not used in printing; again note the small holes at the nodes of the cell walls. A photograph of a printed structure is displayed in Fig. 4.2.
Fig. 4.1 Visualization of the Parenchyma Tissue from Cellular Geometry No. 3
(a) shows a micro XCT slice of an image stack. Note the small pores in the nodes of the cell walls. (b) is the same image but now processed for printing. (c) shows a view of the STL file created from the image stacks corresponding to the unaltered processed geometry (i.e. without erosion and dilation operations). The short edges are 425 µm and 71 mm in the tissue and print, respectively. (d) shows a longitudinal view of the processed image stack.
For the models of scans of different bamboo specimens, with different cellular geometries and roughly constant relative density (those printed on Printer 1) the average relative density calculated from the processed images was $0.316 \pm 0.009$ (mean ± standard deviation) The images used for STL construction (cellular geometry 3, for Printer 2) gave a relative density of 0.326, the same as that for the images for printing directly with Printer 1, as expected. Densities measured for the two solid blocks were 1191 kg/m$^3$ and 1162 kg/m$^3$, for the HTM 140 V2 and Grey Resin V3, respectively. For the structures printed from Printer 1, the measured densities and corresponding relative densities were roughly 25% higher than the relative densities obtained from the images. The structures created with Printer 2, the measured densities and corresponding relative densities were nearly 20% higher than the relative densities obtained from the images with the exception of the 0.326 relative density models which were nearly same as those obtained in the images. This difference is attributed to some liquid resin entrapped in the closed
cells in the prints, observed when cutting open a model from each printer. An opened print from Printer 1 is shown in Fig. 4.3. This is not observed in the 0.326 relative density set of printed structures in Printer 2, as there are connectivity issues, small gaps and holes in the cell walls, which allow for the resin to flow out.

**Fig. 4.3 Liquid Resin in the Cell Lumens**
Printer 1 parenchyma print cut open; edges of pieces are roughly 71 mm.

**Fig. 4.4** shows a stress strain curve from a compression test on a parenchyma model (relative density of 0.362) prepared with Printer 2.
Fig. 4.4 The Compressive Stress Strain Curve of a Parenchyma Model
0.362 relative density model fabricated with Printer 2. The Young's modulus is obtained from the best fit line through the data between 25% and 85% of the maximum stress.

The Young's modulus for each model is shown in Table 4.1. Note the standard deviations of the parenchyma print results are for the repeated tests of the same specimen. In the case of the Young's moduli of the solid blocks, the standard deviations are for tests on multiple samples, listed in parentheses as n.
Table 4.1 Young’s Moduli and Relative Densities of Prints

<table>
<thead>
<tr>
<th>Printer</th>
<th>Print</th>
<th>Relative Density, ( (\rho^<em>/\rho_s)^</em> )</th>
<th>Young’s modulus, ( E ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printer 1</td>
<td>Cellular Geometry No. 1</td>
<td>0.314</td>
<td>280.6 ± 8.2</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.309</td>
<td>228.0 ± 7.9</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.326</td>
<td>258.9 ± 11.0</td>
</tr>
<tr>
<td></td>
<td>Solid</td>
<td>1.000</td>
<td>1855.3 ± 62.1 ((n = 3))</td>
</tr>
<tr>
<td>Printer 2</td>
<td>Cellular Geometry No. 3</td>
<td>0.326</td>
<td>118.4 ± 6.2</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.326</td>
<td>131.0 ± 9.2</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.362</td>
<td>261.6 ± 17.5</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.362</td>
<td>296.3 ± 22.1</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.430</td>
<td>423.1 ± 33.8</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.430</td>
<td>469.3 ± 27.4</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.494</td>
<td>544.6 ± 32.5</td>
</tr>
<tr>
<td></td>
<td>Cellular Geometry No. 3</td>
<td>0.494</td>
<td>656.0 ± 44.8</td>
</tr>
<tr>
<td></td>
<td>Solid</td>
<td>1.000</td>
<td>1580.9 ± 72.2 ((n = 4))</td>
</tr>
</tbody>
</table>

* Relative densities obtained from image stacks

The Young’s moduli of the parenchyma models, \( E^* \), normalized by that of the solid cell wall (the resin), \( E_s \), are plotted against the relative density, \( (\rho^*/\rho_s) \) obtained from the image stacks in Fig. 4.5. A fit, given by Eq. (4.1), is also shown on this Fig. 4.5.

\[
\left( \frac{E^*}{E_s} \right) = 1.979 \left( \frac{\rho^*}{\rho_s} \right)^{2.333} \quad r^2 = 0.956 \quad n = 9 \quad (4.1)
\]

The normalized Young’s moduli, \( (E^*/E_s) \) clearly increase with relative density, \( (\rho^*/\rho_s) \). The normalized Young’s modulus values take a range of 0.07 to 0.42 over the relative density range of 0.3 to 0.5. The power law fit shown on Fig. 4.5 and given by Eq. (4.1), is determined using all the data except for those from the two 0.326 relative density prints made using Printer 2, which were excluded due to connectivity issues (discussed below in the next section).
4.6 Discussion

4.6.1 Discussion of the Normalized Young’s Moduli

The compression tests on the models of bamboo parenchyma indicate that their relative Young's moduli vary with relative density raised to the power 2.33, suggesting that bending of the cell walls is the dominant mechanism of deformation (Gibson and Ashby 1997; Fleck et al. 2010). For an ideal open-cell foam (isotropic and with relative densities below 0.3), models indicate that the relative modulus varies with relative density squared (Gibson and Ashby 1997). It is noted that the relative densities of the models in this study were somewhat higher than the upper limit of 0.3 for modeling an ideal foam; however, a squared dependence of modulus on density has been observed in foams at higher densities (Gibson and Ashby 1997). An exponent of two is often the largest observed for closed-cell foams (Roberts and Garboczi 2001). However, it is also
noted that closed-cell metallic foams often exhibit open-cell foam mechanical behavior due to curvature in the cell walls (Gibson 2000); in this case, the exponent is slightly larger than two. Moso bamboo parenchyma cells, too, have some curvature in the cell walls (Fig. 4.1). The exponent slightly above two may also be a result of the high range of relative density of the specimens or increased connectivity at higher densities (limitations are later discussed in more detail). For ideal open-cell foams, the constant in the Young's modulus-density relationship depends on the cellular geometry; for many foams, the constant is one. The value of 1.979 found here for moso bamboo parenchyma is not surprising, given the box-like shape of the cells and the anisotropy in cell shape of 1.6 (Ahvenainen et al. 2017).

The low degree of orientation of the microfibrils in the cell walls of moso bamboo parenchyma found by (Ahvenainen et al. 2017), and noted previously in Chapter 3, suggests that the cell wall is roughly isotropic, like the resin used to print the models (Hague et al. 2004). While the solid cell wall properties of the parenchyma and resin differ, for isotropic materials, the same deformation mechanism is expected, bending, in the model materials and the moso bamboo parenchyma. The estimated longitudinal Young’s modulus of the moso bamboo parenchyma cell wall from Chapter 3 can be used with the cellular geometry’s behavior of this chapter to create an updated parenchyma contribution to the longitudinal Young’s modulus of moso bamboo. This is given in Eq. (4.2).

\[
E_p = 1.98 \left( \rho^*/\rho_s \right)_p^{2.33} (E_s)_p
\]  

(4.2)

Where \(E_p\) is the Young’s modulus of the parenchyma; \((E_s)_p\) is the solid cell wall Young’s modulus of the parenchyma estimated at 8.8 GPa from Chapter 3, and \(\rho^*/\rho_s\) is the relative density of the parenchyma. Using parenchyma relative densities of 0.22 (from Chapter 2) and
0.32 (this chapter), the estimates for the parenchyma tissue’s Young modulus are 0.51 GPa and 1.23 GPa. The average of these estimates is roughly half of the previous estimate.

The Printer 2 parenchyma structures with a relative density of 0.326 have considerably lower normalized Young’s moduli than the Printer 1 models (Fig. 4.5). This unexpected knockdown of roughly 3/5 is a result of the different printing methods. STL generation leads to some information loss. In the case of the original image stack (no erode or dilate operations applied), small gaps and holes in the cell walls, leading to connectivity issues, not seen to such a degree in the other prints, are visible. The poor connectivity of the Printer 2 0.326 model is shown in Fig. 4.6. It is hypothesized that the more prevalent connectivity issues in the 0.326 relative density models fabricated with Printer 2 led to the lower measured normalized Young’s moduli. STL generation from images likely allows for a wider variety of 3D printers to be used more easily. This approach is, however, less direct. For future work, 3D printing directly from images is recommended.
4.6.2 Limitations of this Study

As mentioned earlier, aspects of the specific method used in this study limit the interpretation of the results. These limitations pertain to the structure of printed parenchyma models. They stem from a variety of sources. Limitations associated primarily with imaging and image processing will be discussed first. The relative density range of the test specimens is limited and high. It was initially planned to test lower densities, but the images, and, to a greater degree the generated STL files, had cell wall connectivity issues. These issues required the images to be dilated to remove the holes at nodes of the cell walls. It should also be noted that the binary operation did not result in all cell walls being completely connected; there were rare instances in the cell wall where the grey value was considerably lower and thresh-held as background. These instances were not corrected. These areas of cell wall, thresh-held as background, may very well correspond to physical regions of the cell wall of much lower stiffness and poorer load transfer.
capability. It may be better to approximate these areas as background than cell wall. In higher density structures, some of these areas may become solid cell wall, resulting in some stiffness increases due to increased connectivity as well as that from the simple increase in density.

Similar limitations are associated with the tissue itself and printing. In the tissue, regions of parenchyma are interrupted by vascular bundles, limiting the number of cells in a cross section. The printer build volumes and required magnification to print high fidelity structures and to avoid filling the cells completely with entrapped resin similarly limit the number of cells along the longitudinal direction. The printed structures are roughly 8 cells x 8 cells x 6 cells (Fig. 4.1), roughly approaching the number needed to treat the cellular material as a continuum (Gibson 2000; Andrews et al. 2001). Liquid resin entrapped in the cells increases the relative density of the printed parenchyma models, compared with that measured from the images. Partially filling the lumen of the cells with liquid does not affect the mechanical response; Warner et al. (2000) demonstrated that partially filled closed-cell foams show a bending dominated response (like that of dry foams). Note that if a liquid fully fills the lumens, then the incompressibility of the liquid does contribute to the mechanical response of a closed-cell foam. Given that the measured densities are such that the liquid only partially fills the cells and the small strains (and thus volume changes) in the mechanical testing of the prints, it is highly unlikely that liquid resin considerably alters the mechanical response.

### 4.6.3 Potential and Limitations of the General Approach

Mechanical testing of models of biological tissues made by 3D printing, based on micro XCT imaging of those tissues, has potential for increasing understanding of their mechanical behavior.
The method allows the three-dimensional nature of tissues to be captured and mechanical testing of larger specimens than the available tissue. It also has key limitations, which are inherent to the approach.

The resolution of commercial SLA printers is on the order of 100 µm, and build volumes are on the order of a million mm³ (as is the case with the printers used in this study) (EnvisionTEC, Inc. not given, not given; Formlabs, Inc. 2017). This allows quite small features of tissues to be captured in printing using enlarged models. In this study with the enrollment of ~170x, the holes at the cell wall nodes, on the length scale of 5 µm, were captured in printing with Printer 1, see Fig. 4.7. Printing high fidelity models of tissue at the actual scale is not yet realizable with this method. The required scaling thus is an inherent limitation of this method. Similar to this limitation, micro XCT has a tradeoff between magnification and scanned volume (Dhondt et al. 2010). As mentioned, in this particular case, this was not limiting as the parenchyma tissue sampling was limited by the presence of vascular bundles rather than the field of view (1.9 mm x 2.2 mm x 2.2 mm, with 0.87³ µm³ voxel size), but it is expected this could be an issue for some tissues. Advancements in SLA printing and micro XCT should lessen these inherent limitations.
Fig. 4.7 Cross Sectional Photograph of Printer 1 Parenchyma Print
Edges are roughly 71 mm. Photo credit: Lori Sanders.

An additional major limitation is the print material; actual solid cell walls of tissue are likely more complex than the SLA printed polymers. Polymers produced by stereolithography are generally homogenous and isotropic (Hague et al. 2004). As explained previously, the low degree of orientation of cellulose fibrils in the parenchyma cell wall (Ahvenainen et al. 2017), substantially lessens this problem in the current study. However, the solid cell wall of actual tissues is often more complex; for instance, plant cell walls are often highly oriented fiber composites (Gibson and Ashby 1997).

With more advanced additive manufacturing techniques, this method could better capture the complex nature of biological cell walls. Multi-material techniques, which Yu et al. noted to be likely in the near future of mainstream additive manufacturing (2017), could allow for the construction of more complex models. Recently, fiber reinforced 3D printing inks for ink-writing
have been developed (Compton and Lewis 2014; Malek et al. 2017). Additionally, advanced SLA printers, similar to that described in the work of Martin et al. (2015) could be used allowing for reinforcement in the printed material. It is possible (likely even) that in the future, the fiber composite nature of plant cell walls could be captured in 3D printed models of plant tissues. Oxman et al. (2011) noted that work is being performed in the field of 3D printing with photopolymers with variable properties to work mechanical property gradients into a printed solid. As the printable solids become more advanced and allow better capture of the cell wall structure in nature, the possibility of an approach combined with micro XCT to capture the cellular structure presents interesting possibilities.

This method allows study of the behavior of the effect of a tissue’s cellular geometry on its mechanical behavior, independent of that of a complex cell wall. This may be useful in the validation of numerical models for the mechanical behavior of plant tissues. Models created and tested with this method ideally could be used to verify a numerical model of a tissue’s structure, before applying complex tissue cell wall properties in the model. Aimene and Nairn (2015) performed work along these lines in a two dimensional case, considering the transverse compression of wood. They created material point method models from SEM cross-sectional micrographs of wood and first verified the model with deformation from simplified polyoxymethylene model capturing the wood tissue anatomy (Aimene and Nairn 2015). The method of this current work could extend studies like that of Aimene and Nairn (2015) to capture tissue structure in three dimensions in model fabrication. Similarly, this method could be used with mechanical testing of both the tissue and the cell walls to aid interpretation of the results, given the difficulties and limitations of micro-mechanical test methods (Burgert 2006;
Eder et al. 2013; Gamstedt et al. 2013). This combined method of micro XCT imaging and 3D printing needs to further development for it to be truly deployed in this way.

4.7 Conclusions

A novel method was developed to aid in the understanding of plant tissue structure-property relationships. Physical models of bamboo parenchyma’s cellular geometries were created from micro XCT imaging of bamboo tissue using SLA 3D printing. The dependence of the longitudinal Young’s modulus of these printed structures on relative density is well described with an exponent somewhat above 2. This suggests that the parenchyma cell walls deform primarily by cell wall bending. Describing the parenchyma as an open-cell foam in Chapter 2 seems reasonable. The limitations of the developed method may be addressed in the future with advancements in micro XCT imaging and 3D printing and further study of this method. The potential of this method is considerable, with validation of numerical models and high fidelity bio-mimicking considered as promising applications.
5 Comparison of the Structure and Flexural Properties of Moso, Guadua and Tre Gai bamboo
5.1 Author Contribution

The work described in this chapter appeared in the publication:


The author of this thesis (PG Dixon) performed microscopy and image analysis, flexural and nanoindentation specimen preparation and tests with AN Aijazi, SH Chen, S Lin, and PK Augusciak. P Ahvenainen performed the X-ray scattering measurements and analysis with the help of KS Svedström at the University of Helsinki. M Borrega performed the chemical composition analysis at Aalto University. The overall study was managed by the author with LJ Gibson. The aspects not performed by the author at MIT are included in this chapter directly for clarity as they relate to the discussion.

5.2 Background

In Chapters 2 to 4, the structure and mechanics of moso bamboo (*Phyllostachys pubescens*) were described. In this chapter, selected properties of moso bamboo are compared with two other timber bamboos: *Guadua angustifolia* (referred to as guadua), and *Bambusa stenostachya* (referred to as Tre Gai). "Timber" refers to their large size and woody nature which make them appropriate for harvesting and processing into structural bamboo products.

Moso bamboo is a temperate bamboo species, which grows primarily in China. Currently, it is the most economically important timber bamboo globally (Fu 2000, 2001; Ding et al. 2007). In
China, moso bamboo is often used in scaffolding, in small structures and in goods such as furniture and crafts. Engineered moso bamboo products, particularly flooring, are an important export (Fu 2000, 2001; Ding et al. 2007). Guadua is a neotropical bamboo with a range from southern Mexico to northern Argentina. It is the most economically important species that grows in the western hemisphere (Young and Judd 1992). It especially flourishes in Ecuador and Colombia, where it is an important resource (Young and Judd 1992; van der Lugt 2005). Guadua is often used in traditional construction and crafts in rural areas (Young and Judd 1992; Klop et al. 2003; Kleinn and Morales-Hidalgo 2006). The structural bamboo product sector for guadua in this region currently lags behind that of moso in China, but ongoing work is expanding and improving the sector (Klop et al. 2003; van der Lugt 2005). Finally, Tre Gai is a paleotropical species, distributed primarily in Vietnam, where it is a prominent resource, utilized both in traditional small structures and in the paper industry (Le et al. 1999).

A survey of the mechanical properties of moso bamboo has already been provided in previous chapters. However, a few points from previous research are re-iterated here. A number of researchers studied longitudinal tensile properties with respect to the vascular bundle and associated fiber volume fractions, by testing tensile specimens from slices at different locations in moso culms (Nogata and Takahashi 1995; Amada et al. 1997; Amada and Untao 2001; Shao et al. 2010a; Liu et al. 2014). Lo et al. (2008) investigated longitudinal compressive strength using full cylindrical sections of Moso bamboo culms with varying longitudinal position and fiber volume fraction, finding a range of 45 to 65 MPa. Yu and colleagues (2011b) performed a study of the mechanical properties of the cell wall of moso bamboo, using nanoindentation and microtension tests on single fibers, determining an indentation elastic modulus ca. 20 GPa from
indentation and longitudinal Young’s modulus ca. 33 GPa.

There is also a significant body of work on guadua which focuses primarily on end products (Correal and Ramirez 2010; Archila-Santos et al. 2014; Correal et al. 2014). A few of the products investigated include guadua glulam (Correal and Ramirez 2010; Correal et al. 2014) and hydrothermally densified guadua materials (Archila-Santos et al. 2014). In addition, the properties of native guadua culm material have also been studied. Correal and Arbelaez (2010) explored the effects of height and age on the mechanical properties of guadua using large sections of culms; they found the average longitudinal modulus of elasticity in compression and bending is around 17 GPa (Correal and Arbeláez 2010).

There are fewer studies of Tre Gai. Richard and Harries (2015) investigated the effect of the radial density gradient on the tensile strength of Tre Gai, and they obtained a range of about 100 to 200 MPa from the inner to outer regions of the culm wall, respectively. Harries and colleagues have also investigated the fracture and creep characteristics of this species (Mitch et al. 2010; Gottron et al. 2014).

In this chapter, the flexural properties in the longitudinal direction of small clear (internode) specimens of these three timber bamboo species are studied. Specimens are taken at different locations (radial positions and, to some extent, heights) in the culm, in an effort to compare the properties at various densities. The microstructures of the species are investigated using scanning electron microscopy, and the ultrastructure of the solid cell walls is probed with chemical analysis and X-ray scattering to understand differences in mechanical properties between the
three species.

5.3 Materials

Longitudinal sections of round culms of the three species of bamboo were obtained from importers: moso bamboo from Bamboo Craftsman Company (Portland, OR), guadua bamboo from KoolBamboo (Miami, FL), and Tre Gai bamboo from amaZulu (Clermont, FL). For the Guadua and Tre Gai species, three longitudinal sections were obtained from the bottom to middle sections of the entire culm height (as noted by the importers) of three separate culms for each species. For the moso bamboo, the materials and results are those from Chapter 2, in which only a single culm were used; data from six culms (two each from 1, 3, and 5 year age groups) available in the literature, was used for comparison (Li 2004). Similarly in the case of Guadua, the micrographs (with separate image analysis) and nanoindentation results used were from the work of Aijazi (2013).

All materials were treated with boric acid/borates to increase resistance to biological attack prior to importation. The ages of these materials are uncertain, but according to the importers all culms were 3 to 6 years old when harvested, suggesting that the materials are from relatively mature culms at an age appropriate for harvesting. The average height of the guadua culm sections used in this chapter was 6 m; that of the Tre Gai was 2.4 m and the height of the single moso culm section was 3 m.

The moisture contents (MC) of the culms tested in this chapter were determined by placing six
beams of each bamboo pole in an oven at 103°C for 24 hours: the moisture content of the moso was about 4%, Guadua 6%, and Tre Gai 6%. The MC of the moso bamboo tested by Li was reported to be about 10%, somewhat higher than that of the moso flexural test specimens of this thesis (Li 2004).

5.4 Methods

5.4.1 Microscopy

Uncoated bamboo specimens from different internodes of one culm section of each species were imaged using a JEOL JSM-6610LV scanning electron microscope (Peabody, MA), in low vacuum mode. Specimens were imaged in both backscatter and secondary modes. Surfaces were prepared by grinding on a Struers Rotopol-1 model polishing wheel (Cleveland, OH) with progressively finer silicon carbide papers: 800-grit, 1200-grit, 2400-grit, and 4000-grit. Cross-sectional images of the entire culm wall were created by stitching individual images. The fiber volume fraction, opposed to the total vascular bundle volume fraction as in Chapter 2, with respect to position in the culm wall was then obtained manually with image analysis using Image J, an open-source image analysis software package developed at the National Institutes of Health (https://imagej.nih.gov/ij/).

5.4.2 Flexural Tests

Small beams were cut at various longitudinal (bottom, middle, and top of the sections) and radial (inside, middle, and outside of the culm wall) internode positions from all the culm materials. The inner terminal and outer epidermal layers were removed. The length, width, thickness and
mass of each specimen were recorded and the density calculated. Specimens dimensions fell into the following ranges: length (along the longitudinal direction) 100-160 mm, width (along the tangential direction) 5-20 mm, and thickness (along the radial direction) 1-6 mm. Span was set such that the span to depth ratio was no less than 20. A schematic of the test orientation is shown in Fig. 5.1.

![Fig. 5.1 Flexural Test Specimen Orientation](image)

Fig. 5.1 Flexural Test Specimen Orientation

The beams were tested with inner surface face down, i.e. with the lower density side in tension. Note that the thicknesses of moso specimens from Li's study were not reported, but are likely larger than the range given for the specimens in this study, as in the Li study, specimens were prepared by sanding away the inner and outer layers (Li 2004). The flexural test specimens’ small sizes and low MC must be considered when viewing the results with respect to bamboo structural members. Specimens were tested in three-point bending in an Instron model 4201 (Norwood, MA), at a speed of 1mm/min, with the central deflection measured by a linear variable differential transducer and load measured by 500 N load cell. As noted, some of the moso flexural tests were previously reported in Chapter 2 while the remainder are from the literature (Li 2004). The modulus of elasticity ($MOE^*$) was calculated from the slope of the middle 80% of the linear elastic portion of the load-deflection curve ($r^2 > 0.99$ for all fits) and
the modulus of rupture \((MOR^\ast)\) was calculated from the peak load.

5.4.3 Nanoindentation

Nanoindentation was performed on the sclerenchyma fibers with a Hysitron TriboIndenter with a diamond Berkovich tip and dynamic mechanical analysis transducer. Specimens from different internodes from one culm section of each species (the same culm as was used for microscopy) were tested. Specimens were mounted in epoxy, and cross-sectional surfaces were prepared by the same polishing method as the specimens for microscopy (indentation axis along the longitudinal axis of the material). Fibers from the inside, middle, and outside of the culm wall thickness were tested. A maximum load of 500 µN was used which gave average indent depths near 200 nm (with a range from 90 nm to 1664 nm). Indent separation was 10 to 25 µm. At least 191 indents were preformed and analyzed on each species. Oliver-Pharr analysis of the unloading curve was performed to determine reduced moduli (Oliver and Pharr 1992). For the moso bamboo, the results from Chapter 2 were used.

5.4.4 Chemical Composition

The materials used in the analyses consisted of the full culm wall material from an internode from one culm section of each species (the same culm as used for microscopy and nanoindentation). Internodes were chosen for each species, in an attempt to minimize differences in densities and fiber volume fractions. No ash analysis was performed. The extractives content was obtained by acetone extraction for 6 h in a Soxhlet apparatus. The extracted bamboo samples were then used to determine the carbohydrates and lignin composition according to the analytical method NREL/TP-510-42618 issued by the US National Renewable Energy Laboratory (Sluiter
et al. 2008). Monosaccharides were determined by high performance anion exchange chromatography with pulse amperometric detection in a Dionex ICS-3000 system. Acid-insoluble (Klason) lignin was determined gravimetrically and acid-soluble lignin (ASL) was determined in a Shimadzu UV-2550 spectrophotometer at a wavelength of 205 nm. Duplicates were run for total carbohydrates, lignin, and extractives contents.

### 5.4.5 X-Ray Scattering Measurements

The relative sample crystallinities and the cellulose microfibril angle (MFA) distributions of the samples were determined from wide-angle X-ray scattering (WAXS) measurements of radial slices (tangential thicknesses ranging from 1.4 to 1.8 mm). Three specimens from an internode of a single culm section (the same internode and culm section combination used for chemical analysis) of each bamboo species were measured with perpendicular transmission geometry for 30 min per sample.

Two-dimensional WAXS patterns were measured with the MAR345 image plate detector and analyzed in MATLAB. Copper $\text{K}_\alpha_1$ wavelength (1.541 Å) was selected with a monochromator and a totally reflecting mirror. Data were corrected for air scattering, read-out noise, polarization from the sample and the monochromator, and detector geometry (flat panel) prior to integration over azimuthal angles (crystallinity) or selected scattering angles (orientation, i.e. MFA) that was followed by the angle-dependent absorption correction.

To separate the contribution of crystalline cellulose in order to determine the MFA distribution, a background representing the scattering from the amorphous parts was determined from the
average scattering intensity in two scattering angle regions: $\theta = 12...14^\circ$ and $\theta = 24.5...26^\circ$.

To minimize the overlap of scattering peaks only two 40-degree azimuthal regions were used. These were selected to be perpendicular to the line containing the strongest of cellulose reflections in these scattering angles (200, 110 and 110). The average intensities of these regions were used to calculate a linear background for the scattering angles of 22$^\circ$ to 24$^\circ$ that were used to produce the MFA distribution corresponding to the azimuthal intensity profile of the cellulose Ib reflection 200.

The bamboo cell wall is a multilayer structure with differing microfibril orientations in the different layers (Parameswaran and Liese 1980; Crow and Murphy 2000). It is not expected to be able to identify the orientation of the microfibrils in each layer. Rather the MFA distribution was characterized by subtracting a linear background from the azimuthal profiles and fitting Gaussian peak pairs to the data, similar to the method in (Peura et al. 2008; Wang et al. 2012b) Two peak pairs were fitted within -30$^\circ$ to +30$^\circ$ of the sharp peak (corresponding to the preferred orientation) and one peak pair was fitted to +30...+90$^\circ$ (and symmetrically to -30...-90$^\circ$). These peaks were characterized by parameters called the average MFA, the standard deviation of the MFA and the T-parameter determined with the method of Cave (1966). The latter method considers only the peak at 0$^\circ$ and as such does not represent well the MFA distribution for the samples, but using the T-parameter, these results can be compared with the literature values (with $<\text{MFA}> = 0.6$ T; (Yu et al. 2007; Wang et al. 2010)).

The crystallinity was obtained by fitting the data integrated azimuthally 180$^\circ$ at scattering angles 13$^\circ$ to 48$^\circ$ with a linear superposition of 15 strongest reflections of cellulose Ib (Nishiyama et al. 2008;.(Peura et al. 2008; Wang et al. 2012b) Two peak pairs were fitted within -30$^\circ$ to +30$^\circ$ of the sharp peak (corresponding to the preferred orientation) and one peak pair was fitted to +30...+90$^\circ$ (and symmetrically to -30...-90$^\circ$). These peaks were characterized by parameters called the average MFA, the standard deviation of the MFA and the T-parameter determined with the method of Cave (1966). The latter method considers only the peak at 0$^\circ$ and as such does not represent well the MFA distribution for the samples, but using the T-parameter, these results can be compared with the literature values (with $<\text{MFA}> = 0.6$ T; (Yu et al. 2007; Wang et al. 2010)).

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and a scattering intensity curve of sulphate-lignin for modeling the amorphous parts. Due to low ambient humidity (15%), low sample MC (4 to 6%) and small MC differences between the species, no water background correction was done to the data. The crystallinity was calculated from the area of the amorphous background relative to the sample intensity as

\[
C = 1 - \frac{\int_{dq} I_{\text{amorph}} \, dq}{\int_{dq} I_{\text{sample}} \, dq} \approx 1 - \frac{\int_{d2\theta} I_{\text{amorph}} \, d2\theta}{\int_{d2\theta} I_{\text{sample}} \, d2\theta}
\]  

(5.1)

Because no single measurement geometry can produce crystallinity values that are independent of the sample texture (Paakkari et al. 1988), the obtained values should be considered to represent only relative differences between the samples. It should be noted that only those samples that have a similar kind of texture (i.e. the MFA distribution) can be compared reliably with each other.

5.5 Results and Discussion

5.5.1 Microscopy

Fig. 5.2(a-c) depicts low vacuum secondary mode micrographs of vascular bundles from the middle of the culm wall of each species. In the vascular bundles of moso and guadua bamboo, the fibers are all extremely dense while in those of Tre Gai, there are also some lower density fibers.
Fig. 5.2 Bamboo Vascular Bundles
(a) Moso. (b) Guadua. (c) Tre Gai, low density fibers visible (left in (c)); low density fibers, like these observed in the Tre Gai bamboo, were not included in the fiber volume fraction measurement.

Fig. 5.3 shows the fiber volume fraction plotted against the normalized radial position; the fiber volume fraction includes only the extremely dense fibers. The normalized radial quantity is the distance from the inner edge of the culm wall divided by the total culm wall thickness. The moso and Tre Gai have similar volume fractions of fibers, and similar variations across the culm wall, while the guadua has generally a higher fiber volume fraction but similar distribution. The average fiber volume fraction obtained for each species is: 0.20 for moso, 0.33 for guadua, and 0.16 for Tre Gai.
Fig. 5.3 Fiber Volume Fraction Plotted Against Normalized Radial Position

5.5.2 Flexural tests

Fig. 5.4 depicts a typical load deflection curve, showing initial linear elasticity, a peak stress, and subsequent failure.

Fig. 5.4 Typical Load Deflection Curve for a Flexural Test
Guadua, \( \rho^* = 909 \text{ kg/m}^3 \), width = 10.146 mm, thickness = 4.254 mm, span = 100.58 mm.
Fig. 5.5 shows the longitudinal $MOE^*$ and $MOR^*$ as a function of density. The longitudinal mechanical properties of wood tend to vary linearly with density (Wangaard 1950; Gibson and Ashby 1997). The longitudinal $MOE^*$ and $MOR^*$ of moso bamboo also vary linearly with density, as described in Chapter 2. The best fit linear equations of the flexural properties of each of the three species with respect to density, $\rho^*$ (kg/m$^3$), are:

Moso  \[ MOE^* = 0.0274 \rho^* - 6.61 \] (GPa) \[ r^2 = 0.78 \] \[ n = 104 \]  (5.2a)

Guadua  \[ MOE^* = 0.0399 \rho^* - 11.4 \] (GPa) \[ r^2 = 0.69 \] \[ n = 76 \]  (5.2b)

Tre Gai  \[ MOE^* = 0.0205 \rho^* - 2.35 \] (GPa) \[ r^2 = 0.59 \] \[ n = 70 \]  (5.2c)

Moso  \[ MOR^* = 0.362 \rho^* - 92.5 \] (MPa) \[ r^2 = 0.85 \] \[ n = 110 \]  (5.3a)

Guadua  \[ MOR^* = 0.417 \rho^* - 137 \] (MPa) \[ r^2 = 0.91 \] \[ n = 76 \]  (5.3b)

Tre Gai  \[ MOR^* = 0.264 \rho^* - 39.6 \] (MPa) \[ r^2 = 0.75 \] \[ n = 70 \]  (5.3c)

Note the Moso relationships were obtained using the two combined data sets, that of Li (2004) and Chapter 2.

The $MOE^*$ values of the moso and Tre Gai bamboos and their variations with density are similar. Most of the densities tested for these species are in the range of 400 to 850 kg/m$^3$ with associated range of $MOE^*$ from 5 to 20 GPa (Fig. 5.5(a)). This range of $MOE^*$ is consistent with that of Young’s modulus from tensile tests of moso (Nogata and Takahashi 1995; Amada and Untao 2001; Shao et al. 2010a). The range of densities of the guadua specimens, roughly 500 to 1000 kg/m$^3$, was higher than that of the moso and Tre Gai specimens. At a given density, the guadua has a higher $MOE^*$ than the moso and Tre Gai; this, combined with the higher densities of the
guadua, gives rise to a higher range of values of $MOE^*$, from 10 to 35 GPa, for most of the data (Fig. 5.5(a)).

![Fig. 5.5 Flexural Properties Plotted Against Density](image)

**Fig. 5.5 Flexural Properties Plotted Against Density**
(a) longitudinal $MOE^*$ (b) longitudinal $MOR^*$

Moso bamboo has the lowest scatter in $MOE^*$ with respect to density, in spite of the difference in moisture content between the specimens tested in this thesis and those from the literature (Li 2004). This is a surprising result given that the $MOE^*$ of bamboo increases with decreasing moisture content. Using a standard correction for moisture content, extending its lower bound
from 5% to 4% moisture content (People’s Republic of China Ministry of Construction 2007), the \( MOE^* \) for Li’s data was estimated if it was at 4% moisture content, consistent with the moso specimens in this thesis. This increases Li’s reported \( MOE^* \) by 9%. Density also must be adjusted for MC. Density of Li’s specimens was given in terms of specific gravity (Li 2004). To scale the data, the specific gravity was multiplied by 1000. The specific gravity may be the density at MC normalized by that of water, or as typical with wood (Forest Products Laboratory 2010), it may be the oven dry mass over the volume at MC. In the former case, assuming no shrinkage from 10% to 4%, the densities of Li’s specimens can be reduced based on the moisture content. These adjustments change Eq. (5.2a) to

\[
MOE^* = 0.0296 \rho^* - 6.56 \quad \text{(GPa)} \quad r^2 = 0.74 \quad n = 104 \quad (5.4)
\]

In the latter case, the densities are scaled up by 1.04 and the equation changes to

\[
MOE^* = 0.0282 \rho^* - 6.94 \quad \text{(GPa)} \quad r^2 = 0.78 \quad n = 104 \quad (5.5)
\]

which is quite similar to the Eq. (5.2a) using the unadjusted data from Li (2004). In the latter case, one also can think about a new equation for the unaltered relationship. For this, the specific gravity of Li (2004) is scaled by 1000 kg/m\(^3\) and multiplied by 1.10 (for the 10% MC noted (Li 2004)) and the unadjusted \( MOE^* \) are used. The equation becomes

\[
MOE^* = 0.0242 \rho^* - 5.73 \quad \text{(GPa)} \quad r^2 = 0.75 \quad n = 104 \quad (5.6)
\]

Given the relative similarity of the adjusted data and all these relationships (especially that of Eq. (5.2a) and Eq. (5.5)), the data used to construct Eq. (5.2a), with no adjustments to \( MOE^* \) and with specific gravity scaled to density simply by 1000 kg/m\(^3\), are considered reasonable and used for comparison. The largest scatter is observed in the Tre Gai values.
The higher density range of guadua is consistent with its higher volume fraction of fibers (Fig. 5.3, 5.5). The explanation of the higher MOE* values for guadua at given density compared with those of moso and Tre Gai, especially apparent at high densities, is not quite as clear. One would expect that the higher fiber volume fraction would be linked to a higher MOE* and higher density, by the same rule of mixtures, and thus the MOE* values at a given density would be similar. A possible explanation is that the species may have different solid cell wall properties, with guadua having a higher solid cell wall (fiber) MOE*. This is discussed further below.

Like the longitudinal MOE*, the longitudinal MOR* of each species shows a linear relationship with density (Fig. 5.5(b)). All three species show similar MOR* values at a given density. The densities of the three species overlap in the range of 400 to 900 kg/m³, with associated MOR* values of about 50 to 250 MPa. The MOR* data have less scatter than the MOE* data, both within and among individual species. The scatter among species appears no greater than that within the individual species. A single linear MOR* – density relationship describes all the results well:

\[ \text{Moso, Guadua, Tre Gai } \quad \text{MOR}^* = 0.353 \rho^* - 87.0 \ \text{(MPa)} \quad r^2 = 0.88 \quad n = 256 \quad (5.7) \]

This is a surprising result, given that the MOE* of the guadua is higher than those of the other two species. However, in a similar study comparing moso and guadua, using larger beams with approximately half of the full culm wall, de Vos (2010) obtains similar results: guadua is substantially stiffer than moso, but not stronger. Elastic modulus reflects the average deformation over the entire specimen, while failure may depend on a characteristic flaw that occurs independent of the species. The bamboo microstructure may give rise to similarly sized flaws in the beams with a characteristic failure mechanism, causing all species to fail at similar stresses at
given density, as suggested by Janssen (1981). On a finer level, the solid cell walls of the three species could have different elastic moduli, but similar strengths, as the weakest link of the cell wall, which is likely similar in all three species (same chemical constituents and similar bonding), would likely govern failure.

Assuming the solid cell wall density of bamboo to be the same as that of wood, which is commonly taken as 1500 kg/m³ (Wangaard 1950; Gibson and Ashby 1997), the solid cell wall properties of bamboo can be estimated by extrapolating the best fit equations (Eq. (5.2-5.3)) to this density. Due to the large scatter and correspondingly low $r^2$ values in the guadua and Tre Gai MOE* – density fits, there is some uncertainty in the extrapolated value; however, the extrapolations serve comparison purposes. The extrapolated solid cell wall $MOE_s$ values are 34.5 GPa for moso (37.8 GPa, 35.4 GPa, and 30.6 GPa with Eq. (5.4, 5.5, and 5.6) respectively), 48.5 GPa for guadua and 28.4 GPa for Tre Gai. The extrapolated solid cell wall $MOR_s$ values are 451 MPa for moso, 489 MPa for guadua and 356 MPa for Tre Gai. As in Chapter 2, the extrapolated $MOE_s$ value of moso is quite similar to that of wood, 35 GPa, (Gibson and Ashby 1997) and to direct measurements of the longitudinal Young’s modulus of moso bamboo fibers which gave average values generally in the 30 to 35 GPa range (Yu et al. 2011b, a; Yan-hui et al. 2012). The Tre Gai solid cell wall $MOE_s$ is lower than that of moso and wood, whereas the $MOE_s$ of guadua is higher than the $MOE_s$ of wood. The extrapolated solid cell wall $MOR_s$ values of moso and guadua are similar, while that of Tre Gai is lower.

It is worth noting that extrapolating flexural properties is slightly problematic. The $MOE^*$ is not a true Young’s modulus as shear deformation occurs (Bodig and Jayne 1982). The span to depth
ratio was kept large (>20) in the current chapter’s tests to minimize this effect. The $MOR^*$ is not a true strength value; bending is governed by both tension and compression, and $MOR^*$ is calculated assuming elastic behavior (Wangaard 1950). Longitudinal bending properties ($MOE^*$ and $MOR^*$) are often tabulated for wood, due to their importance for structures and experimental simplicity. The properties are considered meaningful and consistent measures of stiffness and strength (Wangaard 1950; Forest Products Laboratory 2010).

In addition to comparing extrapolated properties, the values can be compared directly. The $MOE^*$ and $MOR^*$ results in the 550 to 750 kg/m$^3$ density range (which overlaps for all three species) can be compared with two sample t-tests and the Bonferroni correction. In comparing the density distributions of the species in this range, the smallest p-value obtained is 0.0859, found between Tre Gai and guadua. Therefore differences in the density distributions are not statistically significant at common $\alpha$-levels of 0.05 or 0.01. Thus densities in this range are similar enough to merit some comparison. The $MOE^*$ p-values are as follows: between the moso and guadua $p=4.2 \times 10^{-9}$, between Tre Gai and guadua $p=0.0025$, and between Tre Gai and moso $p=0.076$. This analysis implies guadua may have the stiffer plant tissue at a given density than the two others, which are similar. The smallest p-value found for the $MOR^*$ is 0.81 (between moso and guadua), thus there is no statistical significance at typical $\alpha$-levels.

5.5.3 **Nanoscale: nanoindentation, chemical composition, X-ray scattering**

Average reduced modulus and hardness from nanoindentation tests for each species are shown in Table 5.1. Once again, the similarities between the moso and the Tre Gai bamboos are apparent, while the guadua has higher values of reduced modulus and hardness. The moso nanoindentation
reduced modulus values obtained are on the lower end of literature values, which range from about 14 to 20 GPa (Yu et al. 2007, 2011b; Wang et al. 2012a). This difference may be attributed to the relatively simple sample preparation method used in the current work. As in this thesis nanoindentation specimens were prepared by embedding in atmosphere followed by wet polishing and subsequent drying, rather than microtoming of specimens embedded in resin in vacuum; the less damaged surfaces from microtoming and the drying from embedding in vacuum both tend to increase reduced modulus values. All the values of indentation elastic moduli for all species are within the range obtained on wood cells: 13 to 21 GPa (Gindl and Schöberl 2004).

Table 5.1 Nanoindentation Results

<table>
<thead>
<tr>
<th>Species</th>
<th>Reduced moduli (GPa)</th>
<th>Hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moso</td>
<td>14.9 ± 2.3</td>
<td>289 ± 64</td>
</tr>
<tr>
<td>Guadua</td>
<td>19.7 ± 4.9</td>
<td>596 ± 202</td>
</tr>
<tr>
<td>Tre Gai</td>
<td>13.8 ± 2.7</td>
<td>287 ± 97</td>
</tr>
</tbody>
</table>

Note values are written as mean ± standard deviation. Moso result is taken from Ch. 2

It should be noted that since indentation produces a multiaxial stress state beneath the indenter, the reduced modulus is a measurement of a combination of the elastic constants of material. In the case of highly anisotropic materials like wood and bamboo, evaluation of the elastic constants in a particular direction is difficult by indentation (Gindl and Schöberl 2004; Eder et al. 2013; Gamstedt et al. 2013).

Table 5.2 gives the measured chemical composition of the species. Guadua has somewhat higher glucose content compared with the moso and Tre Gai species. Glucose corresponds to the cellulose (Fengel and Wegener 2003) and crystalline cellulose gives rise to the outstanding
mechanical properties of ligno-cellulosic materials (Mishnaevsky and Qing 2008; Gibson 2012). The results of the chemical analysis, coupled with those from nanoindentation, suggest that the mechanical properties of the solid cell wall of the fiber of guadua may be higher than those of the other two species. Only ca. 90% of the bamboo mass of each species was accounted for by the analysis. The ash content range for bamboo is reported to be between 0.75 and 2.87% (Jiang 2007), and the ash content is likely to be artificially inflated by the borate treatments. Other unaccounted mass corresponds to acetyl and uronic acid groups bound to xylose units in the xylan (Fengel and Wegener 2003). The remaining unaccounted mass could also be partially made up of extractives that were not removed by the acetone extraction, as the determined extractives content is low compared with the reported range of hot water extractives 5.0 to 12.5% in the literature (Jiang 2007).

**Table 5.2 Chemical Compositions**

<table>
<thead>
<tr>
<th></th>
<th>Moso</th>
<th>Guadua</th>
<th>Tre Gai</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extractives</strong></td>
<td>2.46</td>
<td>0.80</td>
<td>1.39</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>2.46</td>
<td>0.80</td>
<td>1.39</td>
</tr>
<tr>
<td><strong>Sugars</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Glucose</em></td>
<td>37.14</td>
<td>42.90</td>
<td>37.40</td>
</tr>
<tr>
<td><em>Xylose</em></td>
<td>19.12</td>
<td>15.02</td>
<td>16.98</td>
</tr>
<tr>
<td><em>Others</em></td>
<td>1.32</td>
<td>1.25</td>
<td>1.68</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>57.58</td>
<td>59.17</td>
<td>56.07</td>
</tr>
<tr>
<td><strong>Lignin</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Klason</em></td>
<td>27.60</td>
<td>27.55</td>
<td>28.86</td>
</tr>
<tr>
<td><em>ASL</em></td>
<td>2.75</td>
<td>1.61</td>
<td>1.87</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>30.35</td>
<td>29.16</td>
<td>30.73</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>90.40</strong></td>
<td><strong>89.12</strong></td>
<td><strong>88.19</strong></td>
</tr>
</tbody>
</table>

Note values are given in % weight fractions.

The MFA distributions of all the samples featured a sharp peak at 0° and a flat distribution of all
the orientation angles, as is evident from the azimuthal intensity profiles (Fig. 5.6). The peak corresponds to a preferred orientation while the flat distribution shows that not all crystallites follow this preferred orientation. The T-method of Cave (1966) shows that the preferred orientation peak is slightly wider in Tre Gai than in moso and guadua (Table 5.3). The T-method MFA values are similar to others measured for bamboo, which have a range of 8 to 11° (Yu et al. 2007; Wang et al. 2010; Yan-hui et al. 2012). The impact of preferred orientation, based on the average MFA (Table 5.3) and the azimuthal profiles in Fig. 5.6, was strongest in guadua and weakest in moso. The azimuthal intensity profiles of the 004 reflection (data not shown) suggested similar trends as those shown in Fig. 5.6. However, the magnitude of the differences between the plant species was much smaller. This implies that the differences in the profiles shown in Fig. 5.6 cannot be explained only with differences in the MFA distribution but that other factors, such as the shape of the cells, might also affect the profile shape to some smaller degree.

**Fig. 5.6 Azimuthal Intensity Profiles of the 200-Diffraction Peaks for the Species**
Three samples for each species; each curve is a sample.
### Table 5.3 X-ray Scattering Results

<table>
<thead>
<tr>
<th>Species</th>
<th>Moso</th>
<th>Guadua</th>
<th>Tre Gai</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample crystallinity (%)*</td>
<td>19.9 ± 0.4</td>
<td>24.3 ± 1.8</td>
<td>21.5 ± 1.5</td>
</tr>
<tr>
<td>Average MFA [°] *</td>
<td>31 ± 3</td>
<td>10 ± 4</td>
<td>13 ± 2</td>
</tr>
<tr>
<td>T-parameter MFA (0.6 T) [°] *</td>
<td>8.31 ± 0.08</td>
<td>8.3 ± 0.3</td>
<td>10.7 ± 1.2</td>
</tr>
<tr>
<td>Standard deviation of the MFA [°] *</td>
<td>34 ± 1</td>
<td>16 ± 3</td>
<td>19 ± 2</td>
</tr>
<tr>
<td>FWHM of the peak centered at 0° [°] *</td>
<td>15.8 ± 0.1</td>
<td>15.6 ± 0.5</td>
<td>19.2 ± 1.6</td>
</tr>
</tbody>
</table>

Note: MFA = microfibril angle, FWHM = full width at half maximum, mean ± standard deviation.

The crystallinities of the samples (Table 5.3) did not show large differences between the bamboo species although the values matched the trend of glucose content shown in Table 5.2, suggesting that the higher sample crystallinity for guadua could be due to the higher cellulose content rather than the higher crystallinity of cellulose. The relative sample crystallinity values (Table 5.3) can be compared to those of wood samples with similar MFA distributions that are measured using the same measurement geometry. Previous results on samples of oak wood from the Swedish warship Vasa (Svedström et al. 2012) showed similar crystallinity values while those of balsa (Ochroma pyramidale) (Borrega et al. 2015) were much higher. Small differences in the sample crystallinity values between the bamboo species can also be due to the differences in the orientation distribution of the cellulose microfibrils and might not be an independent result.

Guadua has the highest reduced modulus and fiber hardness, highest cellulose content, highest
crystallinity and strongest microfibril orientation of the three species, while moso and Tre Gai have generally comparable values of these parameters. Together these results suggest that guadua has the highest fiber cell wall mechanical properties along the longitudinal direction, and therefore should have the highest macroscopic mechanical properties in that direction. Macroscopic flexural tests show guadua to be stiffer at a given density and yield a higher extrapolated cell wall $MOE_s$, compared with moso and Tre Gai species. However, these nanoscale characteristics could partially be influenced by the microscale: the higher cellulose content, crystallinity, and microfibril orientation of guadua could be due to the higher volume fraction of fibers present in guadua. The microstructural differences likely partially give rise to the differences seen in the nanoscale measurements. However, all measurements provide evidence that guadua is stiffer in the longitudinal direction than moso and Tre Gai.

### 5.6 Conclusions

This chapter examines the properties of three common species of timber bamboo: moso, guadua and Tre Gai. The $MOE^*$ and $MOR^*$ values were analyzed using linear relationships with density. For all three species the $MOR^*$ values could be better described using linear relations than the $MOE^*$ values. The $MOE^*$ of guadua is higher than that of moso and Tre Gai for a given density while the $MOR^*$ of all three species are found to be similar at a given density. This observation suggests the solid cell wall of guadua is stiffer, a possibility further supported by nanoindentation, chemical analysis, and X-ray scattering measurements. From this initial investigation, guadua’s higher $MOE^*$ would suggest that of the three species studied, it is best suited in deflection-limited structural applications. However, in this chapter the $MOE^*$ of moso
has the least scatter with respect to density, possibly making it ideal for reducing variability. Interestingly, the $MOR^*$ – density relationships for all three species are essentially the same, presenting interesting possibilities for the strength prediction of structural bamboo products. However, larger scale (more culms, different species, and additional types of loading) testing programs are recommended to gain a better understanding of the mechanical differences between species of bamboo to determine the optimal material from a purely mechanical view.
6 Comparison of Densified and Natural Moso Bamboo and Relation to Bamboo Glulam and Scrimber
6.1 Author Contribution

The work described in this chapter appeared in the publication:


The author of this thesis (PG Dixon) cut strips and flexural test specimens and performed microscopy and mechanical testing. The author also modeled the materials as described in this chapter with the help of LJ Gibson. KE Semple, A Kutnar, FA Kamke, and GD Smith performed or facilitated the bamboo densification.

6.2 Background

Two important structural bamboo products are laminated bamboo (glulam) and scrimber (Jiang 2007; Sharma et al. 2015a; Liu et al. 2016). Conventional wood glulam is made by gluing together long strips of wood to make up large members (Lam 2001; Forest Products Laboratory 2010). Glulam appears to be an ideal application for bamboo; however, this product has a low material use efficiency, with only roughly 30% of the culm inputs being used in the product (van der Lugt 2008). Bamboo scrimber, also known as strand woven bamboo, is a highly dense product consisting of crushed sections of bamboo culms, covered with resin, compressed and heated; it has a material use efficiency of about 80%, higher than that of bamboo glulam (van der Lugt 2008; Yu et al. 2015; Sharma et al. 2015a). Bamboo oriented strand board (OSB) is an additional product, which to an extent combines the mechanical efficiency (specific stiffness and
specific strength) of the natural bamboo tissue with high material use efficiency (Semple et al. 2015b). Bamboo OSB is discussed in more detail in the next chapter.

For many composite wood products, an important aspect of their processing is densification, which occurs as a secondary effect during the hot-pressing operation needed for thermosetting adhesives (Kamke and Casey 1988; Wolcott et al. 1994; Winistorfer et al. 2000). Densified wood as a product in itself has potential to be a useful material. Thermo-hydro-mechanical (THM) compression processes on wood, combining steam and compression at elevated temperature, can produce material with higher mechanical properties than natural wood (Kamke 2006; Kutnar et al. 2008, 2009). One such process is known as viscoelastic thermal compression (VTC), which is a type of THM process (Kamke and Sizemore 2008). The effect of the heat in VTC is to bring the wood cell wall above its glass transition temperature, which has been reduced by plasticization from steam. The compression of the wood then buckles the softened cell walls without fracturing them, resulting in an increase in wood density with corresponding increases in stiffness and strength (Kamke 2006; Kutnar et al. 2008, 2009; Kamke and Rathi 2011).

Similarly, densification could be important for processing structural bamboo products; it is certainly involved in processing scrimber and could be in other bamboo products. Due to the more heterogeneous structure of bamboo, compared with wood, bamboo will densify differently, and the properties of bamboo may be altered in a way unlike that of wood. Initial direct investigations of the fabrication and properties of THM densified bamboo products have recently been carried out (Semple et al. 2013, 2015a; Archila-Santos et al. 2014). The longitudinal Young’s moduli of densified guadua (Guadua angustifolia) materials increase as a result of
densification, giving an increase in specific stiffness from 0.030 GPa m³/kg at a density of 540 kg/m³ to 0.038 GPa m³/kg at a density of 830 kg/m³ (Archila-Santos et al. 2014). The flexural modulus of elasticity (MOE*) and the modulus of rupture (MOR*) along the longitudinal direction of moso materials, densified using the VTC closed-chamber steam press, both increase compared with undensified material (Semple et al. 2013). However, from exploratory trials on THM densification of moso bamboo material, densified bamboo appears to have a lower MOE* than that of natural moso bamboo material of similar high density, from the outer regions of the culm wall (Semple et al. 2013).

In this chapter, the flexural properties along the longitudinal direction of natural and THM densified moso bamboo are measured. Rule of mixture models are developed to estimate the density, the MOE*, and the MOR* of natural moso bamboo. A simple model of bamboo densification is developed to abstract the structural changes in the tissue resulting from densification. The model for the densified structure is then used, along with the rule of mixtures, to estimate the MOE* and MOR* of densified bamboo. Finally, the flexural properties of moso bamboo glulam and scrimber, available in the literature, are compared with those of the natural and THM densified moso bamboo material.

### 6.3 Materials

The materials used are from a lower section of a moso culm, obtained from the importer Bamboo Craftsman Company (Portland, OR). This culm section is the same as that of Chapter 2. Prior to importation, the culm underwent a borate treatment, as is required for importation from China to
the United States. In this paper, materials cut directly from the culm section without densification are simply referred to as “natural.” Age of the imported culm materials is noted as 3 to 5 years by the importer.

6.4 Methods

6.4.1 Densification

Tangentially and radially oriented strips were cut from the moso culm section (Fig. 6.1). The strips were subsequently sanded so that each strip was of uniform thickness, between 3 mm and 5 mm. Nominal strip length and width were 90 mm and 20 mm, respectively. The tangential strips were cut from the inner regions of the culm wall, i.e. the lower density regions. Strips of clear internode material and strips with nodes near their midpoints were prepared for both orientations. Approximately half of the strips (roughly 40) were compressed to 50% of their original thickness in a VTC process, using the same densification procedure as that of Semple et al. (2013). In a previous study, Semple et al. (2013) found that compression to 50% (1080 kg/m³ average density) was optimal for void-space closure whereas compression to 33% thickness (1261 kg/m³ average density) caused excessive lateral displacement and shear damage to the tissue. The VTC process was a closed chamber procedure with platen temperatures of 170°C. Maximum steam pressure during the process was 775 kPa; exposure to pressurized steam was for about 150 s. Total processing time was roughly 800 s. Note the strips were densified along their thicknesses, meaning the radially oriented strips were densified along the tangential direction and tangentially oriented strips were densified along the radial direction. The remaining natural strips
were further sanded in their natural state to more closely match the thickness of the densified specimens.

Fig. 6.1 Strip and Flexural Test Specimen Orientation
Entire strips shown with dashed lines, beams with solid lines; “w” refers to strip width.

6.4.2 Microscopy

Cross-sections (normal to the longitudinal direction) of specimens were imaged with a JEOL JSM-6610LV scanning electron microscope (Peabody, MA). Surfaces were prepared by grinding on a Struers Rotopol-1 model polishing wheel (Cleveland, OH) with progressively finer silicon carbide papers: 800-grit, 1200-grit, 2400-grit, and 4000-grit. After air-drying, samples were imaged. Most specimens used for imaging were uncoated and imaged in low vacuum mode, at roughly 30 Pa.
6.4.3 Flexural Tests

Two flexural test specimens (termed ‘beams’) were laser cut from roughly 25 individual strips for each case (natural and densified). This procedure created inner and outer bending test specimens from each radial strip (width along the radial direction), while for tangential strips it simply created a duplicate (width along the tangential direction); beam locations are shown on the strips in Fig. 6.1. Beam dimensions were as follows: width 5 mm, depth 1 mm to 3 mm and length 70 mm. Dimensions and masses of all the beams were measured at their respective moisture contents and used to calculate specimen density. Three-point bending was performed using a span of 60 mm. The beams were tested in an Instron model 4201 (Norwood, MA) at a speed of 2 mm/min. The central deflection was measured with a linear variable differential transducer (Trans-Tek 240 Series; Ellington, CT) and the load was measured with a 500 N load cell. A total of 44 densified and 42 natural specimens were tested. Specimens were not specifically selected or grouped by density; the determined density of each beam was simply linked to its respective obtained $MOE^*$ and $MOR^*$.

6.4.4 Moisture Content

Six natural and six densified beams post-testing were used to determine the moisture content gravimetrically. The specimens were put in an oven at 103°C for 24 h and the moisture content was calculated from the air-dry and oven-dry weights.

6.4.5 Nanoindentation

Tangentially cut natural and densified sections were mounted in epoxy (one each) at atmospheric pressure. The cross-sections were perpendicular to the indentation axis. Surfaces were prepared
by the same method as noted for microscopy. Nanoindentation was performed with a Hysitron TriboIndenter (Minneapolis, MN), equipped with a diamond Berkovich tip and a dynamic mechanical analysis transducer. A maximum load of 500 µN was used. Each sample received 96 indents on the fiber areas. Atypically shaped load-depth curves were removed from analysis leaving 94 and 88 indents in the natural and densified cases, respectively. As in previous chapters, Oliver-Pharr analysis of the unloading curve was performed to determine reduced moduli (Oliver and Pharr 1992).

6.4.6 Modeling

Natural bamboo can be modeled using a simple rule of mixtures approach. The tissue can be considered composed of two constituents, fibers (referring to actual sclerenchyma fibers, opposed to vascular bundles) and parenchyma. This assumes other constituents (vessels, sieve tubes, and the additional cells of the vascular bundle, some of which are parenchymatous (Grosser and Liese 1971)) are treated the same as the basic parenchyma surrounding the vascular bundles. Vessels and sieve tubes compose roughly 10% of the culm tissue (Liese 1987) and calculations using the vascular bundle volume fraction and solid fraction in Chapter 2 suggest a combined vessel (vessels and sieve tubes) volume fraction from 3 to 6%. Krause et al. (2016) obtained a range of roughly 6 to 11% for volume fraction of conducting tubes in the bamboo species *Dendrocalamus giganteus* with X-ray tomography. The density, $\rho^*$ of such a structure is then given by the rule of mixtures:

$$\rho^* = \rho_f V_f + \rho_p^* V_p$$  

(6.1)
where $\rho$ is the density, $V$ is the volume fraction, the subscripts $f$ and $p$ refer to fibers and parenchyma, respectively, and with $V_p = 1 - V_f$. As the sclerenchyma fibers have an extremely small lumen, in the tissue studied, they are assumed to have the same density, $\rho_f$ (fiber density), as the solid cell wall in wood, $\rho_s$ (wood solid cell wall density), $\rho_f = \rho_s = 1500$ kg/m$^3$ (Gibson and Ashby 1997). The density of the parenchyma can be estimated from the measured relative density $(\rho_p^* / \rho_s)_p = 0.22$ in Chapter 2; assuming the same solid cell wall density, then the density of the parenchyma is $\rho_p^* = 330$ kg/m$^3$. As noted above, this density is that of the parenchyma surrounding the vascular bundles and is applied to the volume that is not fiber.

The $MOE^*$ underestimates the Young’s modulus by roughly 1% to 5%, given the span to depth ratios used, assuming similar ratios of elastic constants as wood (Bodig and Jayne 1982); for the remainder of the chapter they are taken to be the same. The longitudinal Young’s modulus of the bamboo, $E^*$, which the longitudinal $MOE^*$ approximates, is given by the rule of mixtures:

$$E^* = E_f V_f$$

(6.2)

where $E_f$ is the longitudinal Young's modulus of the sclerenchyma fibers, estimated to be 39.8 GPa, based on the extrapolated value from Chapter 2. Here, the parenchyma contribution to the longitudinal Young’s modulus is neglected ($E_p \sim 0$), as the fibers dominate the mechanical response even at low fiber volume fraction. In Chapter 2, the fiber contribution was found to account for roughly 90% of the measured longitudinal $MOE^*$ in moso bamboo even at low fiber volume fraction and density (excluding the innermost specimens with the terminal layer). In Chapter 3, the Young's modulus of the cell wall of the parenchyma is estimated to be 8.8 GPa.
compared with that for sclerenchyma, 36.6 GPa; this further suggests that the parenchyma play a negligible role. Rather than use the parenchyma model developed in Ch. 4, the parenchyma’s contribution is simply neglected.

This rule of mixtures can be extended to the longitudinal $MOR^*$, albeit non-rigorously:

$$MOR^* = MOR_f V_f$$  \hspace{1cm} (6.3)

using a $MOR_f$ of 472 MPa from Chapter 2. The parenchyma contribution has similarly been neglected; in the previous study, the fiber contribution was found to account for roughly 85% of measured longitudinal $MOR^*$ at low fiber volume fraction and density in Chapter 2 (excluding the innermost specimens with the terminal layer).

If the fiber volume fraction is assumed to vary from 0.05 to 0.50, a range indicative of the variation across the bamboo culm wall seen in literature (Amada et al. 1997; Shao et al. 2010a; Liu et al. 2014) and previous chapters, paired (i.e. at the same fiber volume fraction) densities, longitudinal Young’s moduli, longitudinal $MOR^*$ can be calculated.

Additionally, densification can be modeled to approximate the densified bamboo structure and properties. The following simple treatment of the densification applies only up to an initial fiber volume fraction of the natural material of approximately 0.36. The fiber volume fraction of natural specimens in this study ranged from roughly 0.10 to 0.23, calculated based on their density with Eq. (6.1), well within this limit. During densification, the thickness, $t$ of a specimen is reduced to a fraction, $C$, of the original thickness; in this study $C$ is 0.5.
If lateral expansion is ignored, the original specimen width and length, \( b \) and \( l \), are the same as the final specimen width and length. The plastic Poisson’s ratio of cellular solids is typically close to zero (Shaw and Sata 1966), and THM compression to 50% of the thickness in moso bamboo with the same VTC device is noted to cause only slight lateral expansion by Semple et al. (2013). It is noted that Eq. (6.4) could be modified to include the width, and \( C \) could be adjusted to account for lateral expansion, if a value of the plastic Poisson’s ratio was considered.

The fibers are virtually solid in the tissue studied, thus their total volume cannot change during plastic deformation. The new fiber volume fraction, after densification, then becomes

\[
V_{f,\text{dens}} = \frac{V_f}{C}
\]

(6.5)

where \( V_{f,\text{dens}} \) is the volume fraction of fibers in the densified state. In the particular case with \( C = 0.5 \), the fiber volume fraction doubles. This expression is based on the assumption of fully solid fibers and neglects natural variability in the ratio of cell wall thickness to cell diameter. In immature bamboo tissue (or any bamboo tissue otherwise with fibers that have significant lumen relative to cell wall thickness) (Liese and Weiner 1996; Gritsch et al. 2004), this assumption cannot be made. The new parenchyma volume fraction, \( V_{p,\text{dens}} \), is simply given by

\[
V_{p,\text{dens}} = 1 - V_{f,\text{dens}}
\]

(6.6)

The parenchyma tissues densifies, i.e. the relative density increases. The total volume of parenchyma solid cell wall is given as the product \( bhlV_p \left( \rho_p^* / \rho_p \right) \). The total volume of
parenchyma tissue in the densified structure is given by $C_{blt}V_{p_{dens}}$. The new relative density is then given by the quotient:

$$\left(\frac{\rho^*_p}{\rho_s}\right)_{p_{dens}} = \frac{(\rho^*_p / \rho_s)_p V_p}{CV_{p_{dens}}} \quad (6.7)$$

The properties now can be modeled using the new fiber and parenchyma volume fractions and the new parenchyma relative density. The equations are as follows

$$\rho^*_{dens} = \rho_f V_{f_{dens}} + \rho_s \left(\frac{\rho^*_p}{\rho_s}\right)_{p_{dens}} V_{p_{dens}} \quad (6.8)$$

$$E^*_{dens} = E_f V_{f_{dens}} \quad (6.9)$$

$$MOR^*_{dens} = MOR_f V_{f_{dens}} \quad (6.10)$$

with the fiber and parenchyma solid cell wall properties unchanged. The parenchyma contribution to the $MOR^*$ is neglected, as is the case with $E^*$.

### 6.5 Results and Discussion

Densification of the parenchyma and closure of the vessels are evident from the micrographs in Fig. 6.2. The parenchyma have undergone large plastic deformations without noticeable fracture of the cell walls, similar to wood processed by VTC (Kamke 2006; Kutnar et al. 2009). The highly dense fibers appear undeformed.
The longitudinal $MOE^*$ and $MOR^*$ of the natural and densified bamboo are plotted with respect to density in Fig. 6.3. The data for natural bamboo from this study match those of Chapter 2, albeit over a lower range of densities, about 450 to 600 kg/m$^3$ (average ± standard deviation, 527 ± 44 kg/m$^3$); the specimens from Chapter 2 were from tangential cuts at different radial positions, giving the larger range of densities. The moisture content of the natural specimens in this study was 7%. That of the beams in Chapter 2 was ~4%. The densified specimens’ density ranges from 800 to 1200 kg/m$^3$ (average ± standard deviation, 997 ± 124 kg/m$^3$). The moisture content of the densified specimens was 5%. There was little difference between tangential and radial cut specimens, internode specimens and specimens containing a node; graphs showing the data by these individual groups are shown Fig. 6.4. The orientations of the vascular bundles and their gradient are the only variables. The rotation of the vascular bundles would not be expected to affect the elastic response or failure mechanism in bending. The beams are small enough that any directional effects from the radial density gradient are negligible compared to the general scatter; this has been found to not be the case for larger beams (Habibi et al. 2015). On the other hand, it is somewhat surprising that the presence of a mid-span node has no noticeable effect.
However, as mentioned, the literature on this point is mixed: some studies have found that the presence of a node decreases strength properties (Lee et al. 1994; Hamdan et al. 2009) while others find no or a negligible effect in moso bamboo (de Vos 2010; Shao et al. 2010b). The observation is consistent with the latter studies, though the relatively small size of each subgroup \((n = 6 \text{ to } 16)\) should be considered.

Fig. 6.3 Longitudinal (a) \(MOE^*\) and (b) \(MOR^*\) Plotted Against Density
Overall, the natural and densified bending properties along the longitudinal direction vary linearly with density (Fig. 6.3), as would be expected given the fiber-reinforced composite-like structure of bamboo. Densification increases the bamboo’s flexural properties, but the highest density natural material from this study is stiffer and stronger than the lowest density densified materials, even though this natural material is 25% less dense.

Fig. 6.4 Longitudinal (a) $MOE^*$ and (b) $MOR^*$ Plotted Against Density
Natural = nat, densified = dens, internode = IN, node = N, radial = rad, tangential = tan.
When the flexural properties of the densified bamboo are compared to those of the natural moso material at the same density from Chapter 2, the relative reduction is even more apparent (Fig. 6.3). The densest natural material from Chapter 2 is about twice as stiff and strong as the densified material from this study, at the same density. This is an expected, though undesirable, result. The scatter in the densified material $MOR^*$, is higher than that of the natural material as might be expected due to damage in the microstructure as a result of the THM process.

The models are also plotted on Fig. 6.3, using the densities calculated from Eq. (6.1) and (6.8) at a given fiber volume fraction, paired with flexural properties calculated with Eq. (6.2, 6.3) (for the natural material) and (6.9, 6.10) (for the densified material) at the same fiber volume fraction. The models relating the $MOE^*$ to density give a good description of the experimental results for both the natural and densified materials (Fig. 6.3(a)). The models capture the range and variation of $MOE^*$ with density of the natural and densified material well, and, more importantly, capture the relative $MOE^*$ reduction of the densified material. The contribution of the parenchyma to the $MOE^*$ appears to be negligible, so that it is appropriate to neglect it.

The $MOR^*$ – density model for the natural bamboo describes the experimental data well, too (Fig. 6.3(b)). The $MOR^*$ – density model for the densified bamboo generally under predicts the experimental data (Fig. 6.3(b)), suggesting the densified parenchyma does have a meaningful contribution to the $MOR^*$, which appears to be a roughly constant 30 MPa at all densities. Note that the contributions of the constituents in the exact sense to failure is not truly meaningful, but this result implies the densification of the parenchyma, the closure of the vessels, or possibly a combination of the two positively alters the weakest link and related failure mechanism in the
bamboo structure. Despite the under-prediction, the model captures the general range of the \( MOR^* \), the \( MOR^* \)'s variation with density, and the relative \( MOR^* \) reduction of the densified material.

In general, the fibers have very small lumens and are nearly all cell wall substance in the natural moso bamboo (Fig. 6.2); densification occurs by parenchyma densifying and vessels closing. Flexural properties along the longitudinal direction are dominated by the fibers’ contribution, in the natural state of the bamboo material. Even in the case of densified parenchyma (stiffer and likely stronger than the natural parenchyma material), the fibers’ contribution still dominates, especially if damage to parenchyma as a result of densification is considered. Then, the purely geometrical increase in fiber volume fraction, from the parenchyma densification, is the most substantial change affecting mechanical properties. However, the increase in density of the bamboo tissue exceeds that of the fiber volume fraction, and the fiber volume fraction, \( MOE^* \) and \( MOR^* \) of the densified material are less than that of the equally dense natural material.

The densification model crudely simulates the densification of the parenchyma and increase in the fiber volume fraction, without fiber densification. The exclusion of the parenchyma contribution from the mechanical properties assumes the fibers’ dominance. As mentioned previously, for the natural bamboo specimens in the current study, the density range was roughly 450 to 600 kg/m\(^3\), which corresponds to a fiber volume fraction of roughly 0.10 to 0.23 (Eq. (6.1)). Given the preparation method, namely tangential beams from the inner culm wall regions and radially oriented beams, the low fiber volume fraction is expected. Using the range 0.10 to 0.23 for the natural bamboo fiber volume fraction (corresponding to the natural bamboo density
prior to densification), a density range for the densified bamboo from roughly 890 to 1200 kg/m³ is calculated with the densification model, agreeing relatively well with the observed range.

The correspondence between the natural and densified density suggests the simple model of bamboo densification is appropriate. Likewise, the satisfactory agreement of the models for $MOE^*$ with density and $MOR^*$ with density with experimental data imply appropriate modeling of the mechanical properties and structure. Thus, the densification of parenchyma, which produces a structure with lower volume fraction of fibers at a given density than the natural bamboo structure, is suggested as the primary reason for the lower stiffness and strength of the densified bamboo compared to the high density natural bamboo. The THM compression study of Semple et al. (2013) found $MOE^*$ and $MOR^*$ increased proportionally with increasing compaction level and density (219 MPa and 13.6 GPa at the maximum compression to 33%), but also noted that the $MOE^*$ of the THM densified bamboo is lower than values for the outer wall of natural bamboo. Flattening of the cross-sectional profiles of the reinforcing fiber bundles was observed during compression changing their shape from longer in the radial direction to longer in the tangential direction (in tangential strips, densified along the radial direction) (Semple et al. 2013). This was thought to be one factor contributing to the ‘dampening’ effect on $MOE^*$ in densified bamboo tissue, and this change likely has a small role in the relative reduction.

An additional explanation for the relative reduction of the densified materials’ properties relates to differences in microfibril angle (MFA) between the inner and outer culm wall. A study by Wang et al. (2012b) found a substantially higher average MFA in the inner region of the culm
wall than that of the middle and outer region of the culm wall. This MFA difference could be related to the difference in properties of the densified (inner culm wall) and high density natural (outer culm wall) materials. However, other studies, which use a different definition of average MFA, found little variation radially across the culm wall (Yu et al. 2007; Wang et al. 2010, 2014a). This suggests the MFA difference found by Wang et al. (2012b) may be related to the mesoscale changes in the tissue (i.e. the increase in fiber volume fraction across the culm wall) opposed to actual changes in the MFA of the fibers. Ahvenainen et al. (2017) measured the MFA of the parenchyma and fibers separately in moso bamboo, and they found very different MFA distributions of the two tissues, suggesting this possibility. Furthering this argument is the work of Wang et al. (2014a), which found the mechanical properties of fibers from different positions in the culm vary little. The MFA explanation seems directly linked to the fiber volume fraction reasoning.

The reduced moduli and hardness values of the fibers, measured in the nanoindentation tests, are similar in both the natural and densified moso material (Table 6.1). Two-sample t-tests also show no statistically significant differences between the two groups’ reduced modulus (p-value of 0.117) and hardness (p-value of 0.263) values.

<table>
<thead>
<tr>
<th></th>
<th>Reduced Modulus (GPa)</th>
<th>Hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>15.7 ± 2.2</td>
<td>341 ± 78</td>
</tr>
<tr>
<td>Densified</td>
<td>16.1 ± 1.5</td>
<td>330 ± 58</td>
</tr>
</tbody>
</table>

Note values are written as mean ± standard deviation

Table 6.1 Nanoindentation Results
These nanoindentation results indicate that both the reduced modulus and hardness of the natural and densified fiber materials statistically have no significant difference, suggesting that the mechanical properties of the cell wall substance are unchanged by the VTC process. It is well known that thermal treatments generally decrease the mechanical properties of wood (Yildiz et al. 2006; Borrega and Kärenlampi 2008; Esteves and Pereira 2009). Studies that have found that the $MOE^*$ and $MOR^*$ of moso bamboo decrease considerably after thermal treatments have used temperatures of 160°C and above, for longer durations than the VTC process used in this study (Zhang et al. 2013). It is also noted that steam treatments at temperatures of 180°C and 200°C for as long as 8 minutes were found to reduce the bending properties of Cryptomeria japonica by less than 10% (Inoue et al. 1993). In the densification procedure of this study, the bamboo was only exposed to steam for roughly 2.5 min.

In densified wood, the longitudinal $MOE^*$ and $MOR^*$ seem to fall more closely to the range of properties for naturally dense wood (Kamke 2006; Kutnar et al. 2008; Forest Products Laboratory 2010). This is logical given the honeycomb-like and more homogeneous structure of wood (Sjöström 1993; Gibson and Ashby 1997; Wegst 2011). Under densification, wood should be expected to primarily densify the fibers (i.e., increase the ratio of wood fiber (or tracheid) cell wall material to that of lumen), opposed to the more complex phenomenon of increasing fiber volume fraction through parenchyma densification as in bamboo. The engineered density change in wood more closely matches that of natural increases in wood density than that in bamboo.

The models have significant limitations. Non-fiber cells of the vascular bundles are treated as the parenchyma; as noted, the volume fraction of such cells is likely small. The properties of the
solid fiber, from literature values, extrapolated from tests on bamboo, are assumed not to change during densification; the nanoindentation results support this assumption (Table 6.1). The parenchyma contributions to the mechanical properties are neglected entirely; the overall agreement between the models and mechanical data suggest this to be a reasonable assumption in all cases but that of the densified bamboo’s $MOR^*$. No lateral expansion is assumed in densification; as previously noted, Semple et al. (2013) report only slight lateral expansion at a compression of 50%. Vascular bundle shape and distribution in the bamboo tissue is not considered in this treatment. Details regarding the parenchyma structure are similarly not taken into account. These assumptions cause breakdowns in the modeling of densification with natural tissue with high fiber volume fractions. A clear breakdown of the model occurs with natural tissue when the fiber volume fraction equals $C$ (0.50 in this case). This tissue would densify to entirely fiber, which is clearly not possible. The model breaks down before this limit when the natural fiber volume fraction equals $\frac{(\rho_p^*/\rho_s)_p - C}{(\rho_p^*/\rho_s)_p - 1}$, which corresponds to the parenchyma’s relative density increasing beyond 1 during densification. In this study, this limit occurs at a natural fiber volume fraction of roughly 0.36 corresponding to a natural material density of roughly 750 kg/m$^3$. The densification of higher density bamboo tissue cannot be modeled in this framework; however, densification of already high density tissue is of less interest. The rule of mixtures treatment of the $MOR^*$ is not rigorous, as mentioned. Despite these many simplifications, the models satisfactorily reflect the density, longitudinal $MOE^*$, and longitudinal $MOR^*$ of both the natural material and the densified material in this study.
Data for the $MOE^*$ and $MOR^*$ of moso glulam and scrimber, with slightly higher moisture content (in the range of 6 to 8%) than the materials of this study, from four point bending tests from the work of Sharma and her colleagues (2015b, c) are plotted on Fig. 6.3 for comparison. The glulam beam dimensions were: width 60 mm, depth 120 mm and length 2400 mm; while the scrimber beam dimensions were: width 40 mm, depth 40 mm, length 800 mm.

The moisture content of the different groups of specimens shown in Fig. 6.3 is not constant. The effect of adjusting the MC to a constant value on the $MOE^*$ and $MOR^*$ can be estimated from the effect of varying MC on the $MOE^*$ and $MOR^*$ of wood (Bodig and Jayne 1982). The natural specimens tested in this study had a MC of 7%, the glulam specimens tested by Sharma et al. (2015b, c) had MC of 6-8% and the natural specimens of Chapter 2 had a moisture content of 4%. For an adjusted MC of 7%, the natural data of the previous study is estimated to increase in density by roughly 3% and to decrease in $MOE^*$ and $MOR^*$ by roughly 6% and 11%, respectively. The densified specimens tested in this study had a MC of 5% while the scrimber specimens had a moisture content of 7% (Sharma et al. 2015b). For an adjusted MC of 7%, the density of the densified specimens is estimated to increase by roughly 2% while the $MOE^*$ and $MOR^*$ would decrease by 4% and 8%. Adjusting for a constant MC does not greatly change the data with respect to each other or the models.

Over the density range 640 to 690 kg/m$^3$, the glulam has $MOE^*$ values between 10-12 GPa (Sharma et al. 2015b, c), similar to the natural bamboo and the model at this density range, as expected (Fig. 6.3(a)). In both the glulam and the natural material, the fiber volume fraction primarily governs the density and the longitudinal $MOE^*$; similar densities equate to similar fiber
volume fractions (at similar MC), which in turn equate to similar $MOE^*$ values. The substantially larger size of the moso glulam should not affect the elastic response. However, the resin of the glulam complicates this comparison.

The modulus of rupture of the glulam and the natural bamboo are substantially different. The $MOR^*$ of the glulam is roughly 80 MPa, over a density range of 640 to 690 kg/m$^3$ while that of the model for the natural material varies from roughly 125 to 145 MPa, giving an average knockdown factor 0.59. This difference is not unexpected; the moso glulam specimens have a volume roughly four orders of magnitude larger than that of the flexural test specimens in this study. Relating the glulam and the natural material by a size effect relationship would be oversimplifying, given the materials are two different systems with a high likelihood of different underlying failure mechanisms, though ultimate failure in both cases is at mid-span on the tensile side of the beams (and impractical given only two size-property data points and the relatively small sample size from which these points are constructed and the large variability in natural materials). However, it is worth noting that for this volume difference in wood glulam, strength knockdown factors of 0.36 (Douglas-fir and other species) and 0.60 (southern pines) are calculated with glulam size adjustment expressions (Smulski 1997). Similarly, the solid lumber $MOR^*$ size effect expression for clear, straight-grained Douglas-fir gives a knockdown factor of 0.59 (Forest Products Laboratory 2010).

Both the $MOE^*$ and $MOR^*$ of moso bamboo scrimber are lower than those of the densified moso bamboo material. The scrimber $MOE^*$ is 13 GPa, while that of the densified material at around the density of scrimber, 1163 kg/m$^3$, is generally 16 to 17 GPa. Although the scrimber $MOE^*$ is
lower than that of the VTC densified bamboo material, it is in the same vicinity, suggesting parenchyma density increases leading to small increases in $MOE^*$ from the higher fiber volume fraction. The scrimber $MOR^*$ is 119 MPa, while that of the densified material ranges from 180 to 240 MPa (at around 1163 kg/m$^3$). The large scatter in the densified moso material $MOR^*$ limits the extent to which strength comparisons with scrimber can be considered. The reduction in both the $MOE^*$ and $MOR^*$ could be attributed to several factors. Bamboo scrimber is generally not densified in a way to avoid cell wall fracture, as is the case in the VTC densification of bamboo. This microstructural explanation is interesting and compelling, and warrants further exploration. However, differences in size (the scrimber specimens are roughly three orders of magnitude larger than the small densified specimens in volume), failure mechanisms, and more general differences in the systems (e.g. macrostructure) are hypothesized to have a larger role in the reduction in properties.

The bending stiffness performance index, which minimizes the mass of a beam of a given stiffness, is given by $\sqrt{E} / \rho$ (Ashby 2000). Similarly, the bending strength performance index, which minimizes the mass of a beam of given strength, is given by $MOR^{2/3} / \rho$ (Ashby 2000). The ranges of these quantities for the natural and densified material of this study, as well as average values for the glulam and scrimber, are given in Table 6.2. The densified material’s ranges are lower than those of the natural material. In the case of $\sqrt{E} / \rho$, the glulam and scrimber values fall into the ranges of their roughly-equivalent materials, the natural and VTC densified bamboo, respectively. For $MOR^{2/3} / \rho$, both materials fall just outside their respective counterparts’ ranges. It should be noted that the performance indices vary with
density, so they do not represent intrinsic material characteristics. To address this, the models have been used to estimate the performance indices at the glulam and scrimber densities for the natural and densified material respectively. The performance index comparisons, together with the previous direct comparison of properties at a given density, give a sense for the similarities and differences between the materials.

### Table 6.2 Flexural Performance Indices

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{E/\rho}$ (GPa$^{1/2}$ m$^3$/kg)</th>
<th>$MOR^{2/3}/\rho$ (MPa$^{2/3}$ m$^3$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>0.0035 - 0.0058</td>
<td>0.029 - 0.045</td>
</tr>
<tr>
<td>VTC Densified</td>
<td>0.0029 - 0.0040</td>
<td>0.022 - 0.037</td>
</tr>
<tr>
<td>Glulam</td>
<td>0.0049</td>
<td>0.028</td>
</tr>
<tr>
<td>Scrimber</td>
<td>0.0031</td>
<td>0.021</td>
</tr>
<tr>
<td>Natural model ($\rho = 668$ kg/m$^3$)</td>
<td>0.0051</td>
<td>0.040</td>
</tr>
<tr>
<td>Densified model ($\rho = 1163$ kg/m$^3$)</td>
<td>0.0036</td>
<td>0.030</td>
</tr>
</tbody>
</table>

### 6.6 Conclusions

Moso bamboo densification increases the flexural properties along the longitudinal direction of the material. However, the properties of the natural material are higher than those of the densified material at similar densities. This is primarily due to the structure of the bamboo. The dense fibers, which dominate longitudinal properties, probably experienced no significant densification in this study. During densification, the parenchyma densifies and vessels close, increasing the fiber volume fraction within the tissue, but not to an extent such that the densified bamboo’s $MOE^*$ and $MOR^*$ reach those of the natural material at the same density. The simple
models of the densification and the densified flexural properties further suggest this to be the case. A number of aspects of bamboo densification need to be considered with a more advanced model: the geometry and density variation of the fibers is certainly one, as is the distribution, the shape and flattening of the vascular bundles and the geometry of the parenchyma. A deep understanding of transverse cell wall properties (fiber and parenchyma properties and their dependence on temperature and moisture content) would have to be combined with these details of the bamboo structure for a truly complete model of densification. Moso glulam and scrimber are bamboo products somewhat analogous to the natural and THM densified Moso tissue, respectively. In this work, flexural properties are only compared simply and put into the same context. Further work is recommended to understand size effects in bamboo and bamboo products, to relate clear bamboo tissue properties with bamboo glulam properties, and to determine optimum densification levels for bamboo.
7 Application of a Model for Wood Oriented Strand Board to Moso Bamboo Oriented Strand Board
7.1 Author Contribution

The work described in this chapter appeared in the publication:


The author of this thesis (PG Dixon) performed the strand orientation characterization, as well as the modeling with the help of S Malek and LJ Gibson. KE Semple, PK Zhang, and GD Smith performed or facilitated the board vertical density profile measurements and helped with other board information.

7.2 Background

The full potential of bamboo for structural applications has yet to be realized. The design and use of structural bamboo products (SBP) allows more efficient use of this renewable resource. Bamboo glulam and scrimber were discussed in the previous chapter. Bamboo Oriented Strand Board (OSB) is another possibility for the efficient use of bamboo (Semple et al. 2015b). In particular, bamboo OSB can be used in paneling and sheathing applications, with reduced material waste compared to laminated boards. Bamboo OSB has great potential for industrial production, for example, in terms of consistent quality and efficiency of mass production (Semple et al. 2015b).

The heterogeneity and the resulting density gradient in bamboo tissue are important to consider in manufacturing and modeling of structural bamboo products. For instance, the heterogeneous
tissue of bamboo can lead to significant strand roughness, if not sliced cleanly (Semple et al. 2015c, d), which then could impact the bonding and performance of a bamboo product. In the previous chapter, the impact of the heterogeneity of bamboo on the densification and densified properties of bamboo was discussed.

Wood OSB is widely used in sheathing and other applications (Hoadley 2000; Chapman 2006). Strands, which serve as the structural elements of the product, are cut from logs, then spray coated with resin. These coated strands are then formed into a mat, which undergoes a hot-pressing procedure, consolidating the mat into a board (Chapman 2006). Several interplaying phenomena occur in the mat during the pressing operation, including heat and mass transfer, water-steam phase change, resin curing, and consolidation, densification, and stress relaxation in the wood. These phenomena give rise to a density gradient generally characterized by high-density faces and a lower density core (Kamke and Casey 1988; Wolcott et al. 1994; Xu 1999; Wang and Winistorfer 2000; Winistorfer et al. 2000). The density gradients through the thickness of such composites are commonly referred to as vertical density profiles (VDPs). The VDP is critical to the mechanical performance of a board (Wang and Winistorfer 2000; Winistorfer et al. 2000; Wang et al. 2004; Painter et al. 2006b, a).

Early models for the mechanical properties of wood OSB assumed a uniform density profile (Shaler and Blankenhorn 1990; Xu and Suchsland 1998). Subsequently, laminate theory was used to model many layered boards with varying density in the different layers, resulting from the compaction of the strands during processing (Xu 1999). Painter and colleagues (2006b) constructed a model that predicts the VDP of OSB and then uses the framework of Xu and
Suchsland (Xu and Suchsland 1998; Xu 1999) to predict the MOE (modulus of elasticity) of OSB (Painter et al. 2006a). A rigorous continuum micromechanics approach was taken by Stürzenbecher et al. (2008) to model veneer strand board, consisting of slender large area wood strands of uniform size and geometry. More recently, Malekmohammadi et al. (2015) developed a multiscale analytical modeling framework for predicting the MOE of OSB by accounting for the board’s properties at three length scales: micro, meso, and macro. The latter, more comprehensive framework provides a multiscale approach to modeling OSB, permitting adjustments for different types of plant tissues, such as bamboo, other grasses, and palms. In this study, this multiscale approach was adapted to model the flexural modulus of bamboo oriented strand board; the model is described in more detail in the modeling section.

Using moso bamboo, Lee et al. (1996) demonstrated that it is possible to manufacture bamboo OSB and that its properties could meet industrial requirements. The effects of strand orientation in the board layers, board density, and strand length on the properties of moso bamboo OSB have been reported previously (Sumardi et al. 2007, 2015; Sumardi and Suzuki 2013). Recently, the fabrication and properties of moso bamboo OSB (Semple et al. 2015b, e), as well as details regarding moso and guadua bamboo strand production and classification, have been documented (Semple et al. 2015c, d). Moso OSB is stronger than wood analogs, but similarly stiff (Lee et al. 1996; Semple et al. 2015b).

This chapter models the MOE of moso bamboo OSB, using the approach of Malekmohammadi et al. (Malekmohammadi et al. 2015) to relate the properties of bamboo tissue to those of strand-based bamboo products – specifically, the three-layer pure moso (core and surface moso furnish)
OSB manufactured by Semple et al. (2015b). These boards had average densities (700 to 720 kg/m³) and MOEs (6 to 9 GPa) (Semple et al. 2015b) along the parallel direction slightly above the ranges reported for aspen OSB (450 to 710 kg/m³ and 4 to 8 GPa) by Chen et al. (2010). Thus, they have potential for construction, and merit study. The model results are compared to previously measured values of $MOE$ for the moso bamboo OSB boards (Semple et al. 2015b). This comparison is made to only assess initial validity of the model. For full model verification a larger statistically valid sample size is needed to capture the variability of bamboo OSB. The primary objective of this chapter is to present a model for bamboo OSB built on data. The presented model would enable the design of an extensive program in the future.

### 7.3 Materials

The moso OSB boards modeled in this chapter were three-layer boards, with oriented strands in the faces and random strands in the cores, manufactured and experimentally characterized by Semple et al. (2015b). In addition to the strands, all three layers had intermediates and fines. Intermediates are smaller elements than strands, and fines are smaller than intermediates. Furnish classified as intermediates was treated as strands in the model. All of the furnish was moso bamboo, and the resin was phenol formaldehyde (PF). Two types of the boards were manufactured and modeled: one with surface strands containing no nodes, referred to as internode, and the other with surface strands containing nodes, referred to as node. Details regarding the manufacture and testing of these materials can be found in the work of Semple et al. (2015b, e).
7.4 Methods

7.4.1 VDP characterization

The distribution of density though the thickness of the boards was measured using an X-ray density profilometer (Model QDP-01X, Quintek Measurement Systems, Knoxville, TN) at intervals of 0.1 mm through the thickness of each specimen measuring 50 mm by 50 mm square. The VD profiler constructed an average profile from 10 specimens evenly distributed over the board and cut adjacent to the bending specimens, with four boards total, representing two internode boards and two node boards. Data for the density of the actual flexural test specimens were not available for model development, and so the density of the adjacent VDP specimens was considered to be representative of the density of the rest of the board and test specimens.

7.4.2 Strand orientation distribution characterization

Three 150 mm by 150 mm sections of internode moso OSB were used to characterize the in-plane strand orientation distribution. To characterize the distribution throughout the board, layers were removed by milling. Images of the boards were captured at the top surface, mid-depth in the surface layer, the initial core surface, and mid-depth in the core layer (which was mid-depth of the entire board). A digital camera (Nikon J1 Model, Melville, NY) was used to capture images, which were then analyzed manually in Image J software (National Institutes of Health; https://imagej.nih.gov/ij/) to determine the strand orientation distribution.

7.4.3 Modeling

As shown schematically in Fig. 7.1, the board properties were calculated by considering three
length scales: micro (the bamboo strand), meso (the strand and resin), and macro (a thin sublayer with a distribution of strands and the entire board). Several parameters, such as compacted strand densities and thicknesses; strand, fines, resin, and void volume fractions; and resin coverage characteristics (resin thickness and resin area coverage) in the different layers of the board were needed in this approach. In a preprocessing step, these layer parameters were back-calculated from the board data such as the board resin content, fines content, density profile, etc. These parameters were then used in the following steps. In the micro-mechanical step, the compacted strand densities (calculated in the preprocessing step), and the inputs of a density – Young’s modulus relationship and bamboo elastic constant ratios were used to calculate the strand properties in each layer. Subsequently, at the mesoscale these strand properties were used with the resin coverage characteristics (calculated in the preprocessing step) and estimated resin properties (which were inputs in this mesoscale step) to calculate the properties of the resin and bamboo composite strand. In the first macro-mechanical step, these composite resin bamboo strand properties were used with the strand orientation distribution, which was the external input of this step, to calculate layer properties. In the final step, the relevant layer properties were then integrated over the board thickness for effective rigidities, which are then used to calculate board MOEs on the parallel and perpendicular directions to the preferred strand orientation. The board and test geometry was the input of this final step. These steps of this model are discussed in more detail in this section.
In the preprocessing step, boards were divided into roughly 100 sublayers based on experimental VDPs. The four measured summary VDPs were employed for this purpose; two for boards with surface layers with internode strands and two for boards with surface layers with nodes in the strands.

The densities of the sublayers were determined from the VDPs and were combined with board data to calculate the inputs to the model, including resin, void, fines, and strand volume fractions; compacted strand thicknesses and densities; and resin coverage characteristics of each sublayer. Note that the board data is often documented by board manufacturers; thus many of the preprocessing input parameters’ values are based on the work of Semple et al. (2015c, b, e). As previously noted, furnish classified as intermediates was treated as strands. These inputs are shown in Table 7.1.

Fig. 7.1 Schematic of Model Framework
### Table 7.1 Preprocessing Inputs

<table>
<thead>
<tr>
<th>$W_{\text{strands}}$</th>
<th>$W_{\text{fines}}$</th>
<th>$W_{\text{resin}}$</th>
<th>$W_{\text{wax}}$</th>
<th>$\rho_{\text{bamboo}}$ (parent material)</th>
<th>$\rho_{\text{resin}}$</th>
<th>Strand length</th>
<th>Strand width</th>
<th>Strand thickness (uncompacted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81%</td>
<td>13%</td>
<td>6%</td>
<td>0%</td>
<td>745</td>
<td>1400</td>
<td>130</td>
<td>12.9</td>
<td>0.65</td>
</tr>
</tbody>
</table>

$W$ refers to weight fraction. Furnish classified as intermediates is treated as fines. References: 1 (Semple et al. 2015b), 2 (Semple et al. 2015e), 3 (Malekmohammadi et al. 2015), 4 (Semple et al. 2015c)

The densities of the sublayers from the VDPs, PF resin weight fraction of 6% (Semple et al. 2015b, e), and assumed resin density of 1400 kg/m$^3$ (Malekmohammadi et al. 2015) were used to calculate resin volume fractions in each layer. Void volume fraction was then calculated similarly, with a parent material density of 745 kg/m$^3$ (Semple et al. 2015b) and assuming no densification in the core (minimum density layer in middle region of the board depth). The strand to fines weight ratio of the furnish was used with resin and void volume fractions to calculate their volume fractions and compacted densities (density of the fines and strands are equal in each layer) in each of the layers. Strand dimensions were taken simply by using moso strand dimension averages noted by Semple et al. (2015c), namely 0.65 mm for uncompacted thickness, 12.9 mm for width, and 130 mm for length. These dimensions (thickness corrected for compaction) and the calculated strand volume fraction were then used to estimate resin thickness, $t_r$. This thickness was then used with the resin volume fraction to calculate the resin area coverage. Further information on the preprocessing step can be found in Malekmohammadi et al. (2015).

In the micro-mechanical step, in contrast to Malekmohammadi et al. (2015), the longitudinal Young’s moduli of the strands was estimated using the linear density – Young’s modulus relation.
relationship given in Chapter 2 for internode material (see Fig. 7.2). The linear fit was used, as opposed to the very similar model for the longitudinal Young's modulus built from microstructural observations.

The details of the data from which this fit was developed can be found in Chapter 2. The longitudinal $MOE^*$ was approximated as the longitudinal Young’s modulus, $E^*$; shearing effects were negligible because the span to depth ratio of the beams was no less than 20. Any discrepancy in the numerical fit on Fig. 7.2 and that in Chapter 2 (in terms of solid properties) is from rounding.

While the density – Young’s modulus relationship that was used in the model is empirical, it has microstructural justification. This justification is also given in Chapter 2; the result is shown below.

$$
E^* = \frac{E_f - E_p}{\rho_f - \rho_p} \rho^* + \frac{E_p \rho_f - E_f \rho_p}{\rho_f - \rho_p}
$$

(7.1)

This was a departure from the approach of Malekmohammadi et al. (2015), accounting for the different microstructures of wood and bamboo, while retaining the analytical nature of the wood micro-mechanical relationship of Gibson and Ashby (1997) used in the framework of Malekmohammadi et al. (2015). This relationship, developed from internode material, was applied to the boards composed of surface strands both without and with nodes; the nodes were not accounted for at the microscale. Notably, other linear fits with different constants for bamboo developed in the future (be it for tissue of other species, harvested from a particular location, etc.) could be easily exchanged here in this framework.
Fig. 7.2 Moso Bamboo $E^*$ - $\rho$ Relationship
Moso bamboo longitudinal $MOE^*$ from Chapter 2 approximated as longitudinal $E^*$

The ratios of the Young’s moduli along the tangential and radial directions and all the shear moduli to the longitudinal Young’s modulus for moso bamboo are given by Bai (1996) in Table 7.2. These ratios were used to calculate the radial and tangential Young’s moduli and the shear moduli of the strands. These ratios were assumed constant at all densities. Likewise, the Poisson’s ratios were taken as constants at all densities (Bai 1996).
Table 7.2 Elastic Constant Rations (Bai 1966)

<table>
<thead>
<tr>
<th>$E_T/E_L$</th>
<th>$E_R/E_L$</th>
<th>$G_{LT}/E_L$</th>
<th>$G_{LR}/E_L$</th>
<th>$G_{RT}/E_L$</th>
<th>$\nu_{LT}$</th>
<th>$\nu_{LR}$</th>
<th>$\nu_{RT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.053</td>
<td>0.069</td>
<td>0.085</td>
<td>0.079</td>
<td>0.028</td>
<td>0.341</td>
<td>0.390</td>
<td>0.308</td>
</tr>
</tbody>
</table>

$E$ refers to Young’s modulus, $G$ to shear modulus, and $\nu$ to Poisson’s ratio. L, T, and R refer to the longitudinal, tangential, and radial directions of the wood respectively. The Poisson’s ratios are defined $\nu_{ij} = -\epsilon_j/\epsilon_i$ with $i$th direction that which the loading is applied.

In the mesoscale step, analytical micromechanics equations, developed by Malekmohammadi et al. (2014), were then applied to calculate the properties of the unit cell, namely, a bamboo strand covered in resin. These equations were developed, by Malekmohammadi et al. (2014), from the application of iso-stress conditions followed by iso-strain conditions on a strand completely covered with resin. They are given below.

\[
\frac{E_i}{E_r} = \lambda_i + \left( \frac{\lambda_{ij} + 1}{\xi_i + \xi_j + \xi_k} \right)
\]

\[
G_{ij} = \lambda_{ij} + \left( \frac{\lambda_{ij} + \lambda_{kl}}{\xi_i + \xi_j + \xi_k} \right)
\]

Where

\[
\lambda_i = \frac{E_{is}}{E_r} \quad \xi_i = \frac{L_i}{t_r} \quad \lambda_{ij} = \frac{G_{is}}{G_r}
\]
The subscripts $i$, $j$, and $k$ refer to one of three principal strand dimensions, longitudinal, tangential, and radial, $s$ refers to the pure bamboo strand, and $r$ to the resin. $L_i$ refers to the pure bamboo strand dimension on the $i$-th direction, and $t_r$ is the resin thickness. $E_i$ and $G_{ij}$ without a $s$ or $r$ subscript designation refer to those of the combined resin and bamboo composite strand. The resin’s Young’s modulus, $E_r$ (GPa), was taken to be 7.60 GPa, the value taken by Malekmohammadi et al. (2015) to model experimental boards also made with PF resin manufactured by Chen et al. (2010); assuming isotropy and using a Poisson's ratio of 0.3, its shear modulus was taken to be 2.92 GPa. It is also noted the values of these elastic properties and the resin density of 1400 kg/m³ are quite typical when the properties of phenol formaldehyde resins are viewed in CES Selector 2016, materials selection software by Granta Design (Cambridge, UK). Correction for partial strand coverage by the resin, given by Malekmohammadi et al. (2014) and shown below, was made.

$$E_{r,eq} = R_a E_r \quad (7.5)$$

$$G_{r,eq} = R_a G_r \quad (7.6)$$

Equivalent resin elastic moduli (subscript $r$, $eq$) are calculated using the resin area coverage $R_a$ (calculated in the preprocessing), and they are substituted into Eq (7.2 – 7.4). Poisson’s ratios of the unit cell, developed with similar treatment, are more involved expressions, which can be found in Malekmohammadi et al. (2014). For simplicity, in this work the Poisson’s ratios of the combined bamboo and resin strand were taken to be the same as those of the bamboo strand (Table 7.2).

In the macroscale step, the local (meaning local to the strand as opposed to global of the board)
stiffness and compliance matrices, $C_{ij}$ (GPa) and $S_{ij}$ (GPa$^{-1}$), respectively, were transformed to those of the strand at an orientation angle $\phi$ (°), $C_{ij,\phi}$ and $S_{ij,\phi}$, and then weighted, based on the experimentally determined strand orientation distribution, to obtain the matrices for the sublayer, $\overline{C}_{ij}$ and $\overline{S}_{ij}$. Several researchers simply used the Hankinson formula (Shaler and Blankenhorn 1990; Xu and Suchsland 1998; Barnes 2000; Painter et al. 2006a), while matrix transformation is a more general approach that Malekmohammadi et al. (2015) employed.

The surface-core boundaries were determined from the core and surface full layer densities and total board densities noted by Semple et al. (2015b). Matrices were transformed at angles, $\phi$, of -85° to 85° in 10° increments and weighted by frequency (count fraction), $f_\phi$, in the surrounding 10° of the rotation angle. For the core sublayers, a uniform distribution was used rather than the experimentally obtained one; i.e., a constant weight was used for all angles. This weighting assumed the count fraction (i.e., the frequency) equals the volume fraction, and strand geometry, size, and size distribution were not considered in the averaging. This is a considerable, but practical, simplification.

Only stiffness averaging was used in the framework of Malekmohammadi et al. (2015).

Similarly, previous OSB models took only an upper bound approach (Xu and Suchsland 1998; Painter et al. 2006a). However, in this model, the stiffness averaging was used for the relatively aligned faces for the parallel MOE model (for loading parallel to the preferred strand orientation), but the compliance averaging method is used for the faces for the perpendicular MOE model (for loading perpendicular to the preferred strand orientation). The logic is based on the faces’ relatively high alignment with the parallel loading direction. For the randomly oriented
core sublayers, there is no preferred strand orientation, and the effective elastic properties are expected to lie between those obtained from stiffness or compliance averaging. Therefore, both averaging methods were applied to the core. Expressions for the averaging methods are shown below. Equation (7.7) is the stiffness averaging equation, and Eq. (7.8) is the compliance averaging equation (Pastore and Gowayed 1994),

\[
\bar{C}_{ij} = \sum f_\phi C_{ij,\phi}
\]

(7.7)

\[
\bar{S}_{ij} = \sum f_\phi S_{ij,\phi}
\]

(7.8)

where \( f_\phi \) is the fraction from the distributions, \( C_{ij,\phi} \) and \( S_{ij,\phi} \) are the transformed strand matrices, and \( \bar{C}_{ij} \) and \( \bar{S}_{ij} \) are the sublayer matrices. The local \( C_{ij} \) and \( S_{ij} \) are inverses of each other, and thus equivalent matrices, as are the transformed matrices, \( C_{ij,\phi} \) and \( S_{ij,\phi} \) at a given angle \( \phi \). The averaged sublayer matrices, \( \bar{C}_{ij} \) and \( \bar{S}_{ij} \), however, generally are not.

The extraction of the relevant Young’s and shear moduli from the average matrix of each sublayer was then performed. For this purpose, the board was treated as a multilayer laminate beam, as in Malekmohammadi et al. (2015). Namely, sublayer properties were integrated over the board sections to determine the effective rigidities \((EI)_{eq}\) (GPa mm⁴) and \((AG)_{eq}\) (GPa mm²), given in Eq. (7.9) and (7.10).

\[
(EI)_{eq} = \int_{0-z}^{t-z} E_{sublayer} b z^2 dz
\]

(7.9)

\[
(AG)_{eq} = \int_{0-z}^{t-z} G_{sublayer} b dz
\]

(7.10)
In Eq. (7.9) and (7.10), $E_{\text{sublayer}}$ (GPa) and $G_{\text{sublayer}}$ (GPa) are the relevant moduli of the sublayers, $b$ is the width (mm), $t$ is the total board thickness (mm), and $z$ is the location of the neutral axis (mm). Board compliances ($\delta/P$) (mm/kN) are calculated for three-point bending, the loading configuration used in the tests by Semple et al. (2015b),

\[
\frac{\delta}{P} = \frac{L^3}{48( EI)_{eq}} + \frac{L}{4( AG)_{eq}}
\]

(7.11)

where $L$ (mm) is the span of the beam (Allen 1969). The MOEs of the board in parallel and perpendicular directions were then determined using the compliance values estimated from the above equation.

7.5 Results and Discussion

7.5.1 VDPs

The measured experimental summary VDPs are shown in Fig. 7.3. These four VDPs were used as inputs to the model. They all show the typical high density surfaces and lower density core common of oriented strand board (Xu 1999; Wang and Winistorfer 2000; Winistorfer et al. 2000). It is noted, considering the VDP and the density of the parent tissue (745 kg/m$^3$, Table 7.1), the bamboo tissue undergoes little densification, during a typical hot press cycle for OSB.
7.5.2 Strand Orientation Distribution

Fig. 7.4 shows images of board layers with the measurements made in Image J for the strand orientation overlaid. Fig. 7.5 shows the measured strand orientation distribution for the surface and the core layers. Fig. 7.5(a) is the measured surface strand orientation distribution, used to calculate average layer stiffness and compliance matrices for the surface sublayers. As previously mentioned, a uniform strand orientation distribution, opposed to the measured distribution, shown in Fig. 7.5(b), was used for calculation in the core sublayers.
Fig. 7.4 Images of (a) the Surface and (b) Core Layers
Photographs and overlaid measurement. Edges of the boards are roughly 150 mm.
7.5.3 MOE Predictions

The model estimates of the MOE of the boards, for the normal stresses in the boards parallel and perpendicular to the preferred orientation of the strands in the surface layers, are compared with the experimental values in Table 7.3, for boards with strand material from the internodes or with nodes. The densities of the individual board specimens used in the flexural tests were not measured; however, density and VDPs were measured for a series of adjacent 50 mm by 50 mm specimens of boards used to test internal bond strength, giving densities representative of the
modeled board materials and shown in Table 7.3. The model predictions are written with a deviation given $(\pm \delta)$. Note this deviation is the standard deviation of modeled results with the original and two adjusted longitudinal $E$-$\rho$ relationships. The adjustment was to multiply the constants, shown on Fig. 7.2, by 0.75 and 1.25. The standard deviation of these three results was calculated. This is the deviation shown for the modeled results; it reflects the variability in the model results as a result of natural variability. The modeled values shown are not averages of these numbers, but just that of the unadjusted model. The experimental deviation is a standard deviation of experimental results.

**Table 7.3 Board Modulus of Elasticity: Comparison of Models and Measurements**

<table>
<thead>
<tr>
<th>Model</th>
<th>Internode 1</th>
<th>Internode 2</th>
<th>Node 1</th>
<th>Node 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MOE II</td>
<td>MOE L</td>
<td>MOE II</td>
<td>MOE L</td>
</tr>
<tr>
<td>Stiffness Averaging Core (GPa)</td>
<td>9.6 ± 2.3</td>
<td>2.7 ± 0.6</td>
<td>8.5 ± 2.0</td>
<td>2.4 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>8.8 ± 2.1</td>
<td>1.9 ± 0.4</td>
<td>9.2 ± 2.2</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>Compliance Averaging Core (GPa)</td>
<td>8.6 ± 2.0</td>
<td>1.7 ± 0.4</td>
<td>7.6 ± 1.8</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>8.4 ± 2.0</td>
<td>1.4 ± 0.3</td>
<td>8.7 ± 2.0</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>770</td>
<td>697</td>
<td>695</td>
<td>710</td>
</tr>
<tr>
<td></td>
<td>8.09 ± 0.54</td>
<td>1.58 ± 0.52</td>
<td>6.67 ± 0.49</td>
<td>1.4 ± 0.38</td>
</tr>
<tr>
<td>Board Type Density (kg/m³)</td>
<td>713.4</td>
<td>706</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Model results written as main model result $\pm \delta$, where $\delta$ is the standard deviation of the model results with an $E$-$\rho$ relationship adjusted by 0.75, 1 (so including the main model in the standard deviation calculation), and 1.25. Experimental results from Semple et al. (2015b) written as mean $\pm$ standard deviation. II – parallel to preferred strand orientation, L – perpendicular to preferred strand orientation
There is relatively good agreement between the experimental values and the model predictions for the $MOE$ of the OSB with internode strands, for loading parallel to the preferred strand orientation, especially for the case with the lower density VDP of internode board no. 2 as input, which is probably closer to the density of the tested boards. The agreement is less good for the OSB with surface strands containing nodes, for loading parallel to the preferred strand orientation; this was probably due to a reduction in the strand stiffness associated with the nodes and also interference of the more heterogeneous node tissue in bonding and board consolidation during pressing. For loading perpendicular to the preferred strand orientation, there is good agreement between the model and the experimental values for both the OSB with internode strands and strands with nodes, if compliance averaging is used to estimate the core properties in the model. It should be clearly noted that this comparison between the modeled and experimental board $MOE$ is preliminary and qualitative in nature, the sample size is too small for statistical comparison. However, the similarities and differences between the results will be discussed further to illustrate aspects of the model and bamboo.

For boards made with internode strands and with strands with nodes, the model predictions are similar. The linear density – Young’s modulus relationship of moso bamboo used in the model was obtained for internode material only. The presence of nodes in strands may reduce their $MOE$, as postulated by Semple et al. (2015b). The effect of nodes on the bending properties of bamboo is not yet clearly understood; the literature is mixed on their effect (Lee et al. 1994; Hamdan et al. 2009; de Vos 2010; Shao et al. 2010b; Semple et al. 2013). Hamdan et al. (2009) found that nodes generally decrease both the longitudinal $MOE$ and $MOR$ (modulus of rupture) in Gigantochloa scortechinii bamboo specimens in bending, but in general, the decrease was
statistically significant only for the MOE. Conversely, Lee et al. (1994) found that only the MOR is influenced by the presence of a node. Similarly, Semple et al. (2013) using small bar (5 mm thick by 19 mm wide) flexural tests found nodes significantly reduced MOR in raw dry moso bamboo tissue, but the effect was small and not significant for MOE. When the tissue was compressed to 50% thickness under controlled steam injection conditions, the difference in MOR between internode and node tissue was amplified, but there was still relatively little effect on MOE (Semple et al. 2013).

Even if strands with nodes did not have lower longitudinal MOE of the moso tissue itself, nodes are sites of roughness and unevenness in strands reducing adhesion and consolidation, and contributing to lower board properties. This might be expected to also reduce experimental MOE perpendicular to the direction of strand orientation, relative to the internode values, and little reduction for loading in the perpendicular direction is observed (Semple et al. 2015b). However, the high degree of surface strand alignment along the parallel direction minimized the interlocking of strands along the perpendicular direction resulting in much lower perpendicular MOE and MOR values for boards, likely masking the node-induced bonding and consolidation effects influencing the parallel flexural properties. It is also possible that MOE does become affected by node tissue if the test specimen is very thin, such as a strand, which was not accounted for by the model. As Semple et al. (2015b) note, the effect of nodes on the mechanical and bonding behavior of strands needs to be understood in future research, in order to best address the problem of lower board MOE as a result of nodes in a practical manner, i.e., without removing all nodes from the material used for furnish.
A more detailed view of the results gives additional insights. The different averaging methods in the core lead to a difference in the model $MOE$ for loading parallel to the preferred orientation of the strands of 0.4 to 1 GPa, or an average difference of roughly 10%, for boards made from internode strands. For loading in the perpendicular direction, for boards with internode strands, the difference in averaging methods gives a difference similar to that for loading in the parallel direction in absolute value and thus much higher in relative terms. This result is unsurprising, given that in the perpendicular loading direction, the denser faces do not dominate the $MOE$ as they do in the parallel direction; the core, even with its uniform (random) orientation distribution, contributes significantly to the board $MOE$. The model $MOEs$ of the boards made from strands with nodes show less difference between compliance and stiffness averaging methods in the core for both loading directions. The smaller difference, here, is due to the thicker surfaces of the boards, which were obtained with the general values given for the total board, surface, and core layer densities by Semple and her co-workers (2015b).

The model results using compliance averaging method in the core predict the experimental results better, especially so for loading in the perpendicular direction. This would suggest compliance averaging is the appropriate method for estimating the elastic properties of the core. However, there are a number of aspects in the modeling, for which an overprediction of $MOE$ might be expected. Chief among these is the uncertainty in the bamboo strand elastic properties. Uncertainty in the longitudinal Young’s modulus and the elastic constant ratios of the bamboo strands as a result of moso bamboo’s natural variability could increase or decrease the predicted results relative to the experimental data. In addition, the MC of the bamboo specimens, for which the $E-\rho$ relationship was obtained, was quite low (~4%); the MC of the bamboo strands in the
boards is uncertain, but likely higher given the conditioning at two weeks at 65% relative humidity at 20 °C (Semple et al. 2015b, e). Jiang et al. (2012) found a 1.56% average change in the longitudinal tensile Young’s modulus (1.49% for bending) with 1% change in moisture content. Bai (1996) notes a MC of roughly 12% for their bamboo elastic properties tests, and the moisture content of bamboo strands in the board may well be lower, leading to possible under predictions of the other elastic properties. This suggests that the error stemming from moisture content differences, while uncertain, is likely small.

A more likely contributor to the possible overprediction by the model is that the $E-\rho$ relationship was obtained for strands cut from a bamboo culm; these values do not account for any damage to the tissue resulting from processing. In the model, compaction increases the properties as would a natural density increase; this is the same as in the approach used for wood OSB (Malekmohammadi et al. 2015). However, for bamboo, this assumption is more problematic. In wood, differences in density stem from differences in the cell wall thickness relative to the cell wall lumen size (Gibson and Ashby 1997), whereas in natural bamboo, density differences are in large part due to differences in the fiber volume fraction. Given bamboo’s heterogeneous structure and the high density of the bamboo fibers in many species (Parameswaran and Liese 1976; Liese 1987) in mature tissue (Liese and Weiner 1996; Gritsch et al. 2004), the densification of bamboo would likely primarily densify the parenchyma, resulting in a larger fiber volume fraction, but one that is not as large as that of the natural material at this density. This differential densification would result in lower properties at a given density. The phenomenon that densification processing gives flexural properties lower than those of natural bamboo tissue of similar density was observed by Semple et al. (2013) and discussed
considerably in Chapter 6.

These issues in the modeling, the small data set, and other issues (e.g., intermediates’ treatment as strands) limit the assessment of the core averaging methods. However, along the parallel direction the two different methods give very similar model results, and along the perpendicular direction the results are qualitatively similar. Further exploration of compliance averaging for both the properties of uniformly (randomly) oriented layers and the layer properties perpendicular to the aligned direction is warranted.

7.6 Conclusions

The $MOE$ of moso bamboo OSB was predicted using a comprehensive multiscale approach for wood, with a simple microscale adjustment accounting for the different structures of wood and bamboo. Despite simplifications and limitations, the parallel $MOE$ of the three-layer moso boards made with internode strands is predicted quite well, showing an average relative error (average of both internode VDP models and averaging methods in the core) of roughly 10%. The parallel $MOE$ in the boards made with strands with nodes are overpredicted by the model, suggesting the presence of nodes in surface strands negatively impacts bamboo boards’ $MOE$. Model results for loading perpendicular to the preferred strand orientation qualitatively predicts the experimental results for both board types. However, along the perpendicular direction, the modeled results vary considerably based on the averaging method used in the core. Compliance averaging in the core sublayers gives results which give a good description of the measured values. It is hoped this model (or aspects of it) will be used in further studies to assess the model
and increase understanding of bamboo OSB.
8 Conclusion
8.1 Conclusions

This thesis examined the ultrastructure, mesostructure and microstructure, and the mechanical properties of bamboo and selected structural bamboo products. The primary focus was moso bamboo; comparisons between the flexural performance of moso, guadua and Tre Gai were also made. The structure and flexural properties of densified bamboo were related to those of natural bamboo, as well as to common comparable structural bamboo products, bamboo scrimber and glulam. Bamboo oriented strand board (OSB) was modeled with knowledge of the structure and properties of bamboo tissue and the board structure.

In the studies of the natural tissue, the internode tissue of moso bamboo was chiefly investigated. Bamboo tissue resembles a fiber-reinforced composite with vascular bundles embedded in a matrix of foam-like parenchyma. The vascular bundles consist of sclerenchyma fibers and thin walled vessels. In the moso bamboo tissue studied, the fibers were nearly fully dense, which seems typical in bamboo. The volume fraction of vascular bundles and the fraction of solid fibers within the vascular bundles increase radially from the inside to the outside of the culm wall. The density and longitudinal flexural properties (modulus of elasticity \( MOE \) and modulus of rupture \( MOR \)) and longitudinal compressive strength increased with this gradient, increasing considerably from the inside to the outside of the culm wall in internode tissue. These longitudinal properties were found to increase linearly with density, as expected given the tissue’s fiber reinforced composite structure. Models for the mechanical properties based on the microstructure and extrapolated solid cell wall properties were created. The longitudinal mechanical properties of the bamboo tissue were modeled using the rule of mixtures, accounting
for the properties of the sclerenchyma and the parenchyma (a simplification in the case of strength). The sclerenchyma and parenchyma were modeled with the same extrapolated cell wall properties but different cellular level mechanical behavior. These models described the observed results well.

Further, a simple cell wall model for moso bamboo was developed. This model accounted for the chemical composition and cellulose microfibril angle (MFA) of the moso bamboo. When the average MFA of the sclerenchyma fibers in the literature was used in the model, a longitudinal cell wall Young’s modulus of 36.6 GPa was found, consistent with the extrapolated value of 39.8 GPa from the data in Chapter 2 and with experimental measurements available in the literature. When the average MFA of the parenchyma in the literature was used in the model, a longitudinal cell wall Young’s modulus roughly one-fourth of that of the sclerenchyma was found. The results imply the cell wall elastic properties of the two constituents are very different.

Understanding the mechanical properties of bamboo parenchyma is difficult. The vascular bundles present in bamboo tissue limit the size of parenchyma regions for mechanical tests. The tissue is soft and compliant making extraction of small specimens difficult. Additionally, the appropriate cellular solid model (honeycomb, closed-cell foam, or open-cell foam) is not clear from the structure of parenchyma. In order to better understand the parenchyma, a novel method was developed. 3D printed models were fabricated quite directly from micro X-ray computed tomography image slices of moso bamboo parenchyma, obtained with synchrotron radiation. Mechanical tests of these models indicated that their Young’s moduli scaled with relative density raised to a power slightly above two, suggesting that the cell walls deform primarily by bending.
The curvature in the cell walls of the parenchyma appears to give rise to bending deformation. Thus, bamboo parenchyma seems to be appropriately modeled as an open-cell foam, similar to closed-cell metallic foams with curved cell walls. The parenchyma of bamboo appears to have a lower longitudinal Young’s modulus (and highly related $MOE$) than the sclerenchyma fiber tissue due to differences in cell wall structure and cellular level structure.

The structural characteristics and flexural properties of two other species of bamboo, guadua and Tre Gai, were compared with those of moso bamboo. The $MOE$ and $MOR$ increased with density in fairly linearly fashion for all three species ($r^2$: 0.58 – 0.91). The $MOE$ of guadua was found to be the highest, both in general and at given density. The higher $MOE$ of the guadua at given density appears due to its stiffer fiber cell wall, as suggested by the nanoindentation results and its higher cellulose content. The $MOR$ of all species was similar at a given density.

Two structural bamboo products were directly considered in this thesis: densified bamboo and bamboo oriented strand board. Densification is an important phenomenon in the processing of some structural bamboo products, particularly in the high density product, bamboo scrimber. Densification of moso bamboo increased its longitudinal flexural properties. However, the properties of natural material at the same density were found to be higher than those of the densified material. The dense fibers in bamboo likely underwent little densification. Vessels closed and the parenchyma densified. This increased the fiber volume fraction in the tissue and so the properties increased compared to the original tissue, but much of the density increase stemmed from a denser parenchyma which did not contribute substantially to the longitudinal $MOE$. The longitudinal $MOE$ of moso bamboo glulam and scrimber found in literature were
similar to those of small natural and densified specimens, respectively, at similar density. This provides some additional evidence of density reflecting the volume fraction of sclerenchyma fiber cell wall.

The $MOE$ of moso bamboo OSB (with specific structure measured and found in the literature) was predicted using an analytical multiscale modeling framework developed for wood. A modification to account for the cellular level structure of bamboo was made to the model, using the earlier findings of this thesis. Model predictions qualitatively agreed with measured values found in the literature, along directions both parallel and perpendicular to preferred surface strand orientation of the boards. The prediction was particularly good along the parallel direction of the OSB for boards without nodes in the surface strands, differing from experimental values by roughly 10%. The $MOE$ of boards with surface strands containing nodes were overpredicted by the model, suggesting the nodes negatively affect the board $MOE$.

### 8.2 Recommendations for Future Research

For bamboo and moso bamboo in particular, investigations of properties less commonly found in the literature, such as the transverse and shear properties, viscoelastic properties, fracture properties, and fatigue properties are needed. The structure and mechanical properties of additional timber bamboo species, suitable for structural bamboo products (of which there are many), should be studied. A coordinated program across multiple countries and regions would enable a large comparative study, allowing the effect of variations in the bamboo structure on mechanical properties to be determined.
On a more fundamental level, the creation of hierarchical, multiscale models for bamboo, starting from the chemical constituent length scale up to the bamboo culm or structural bamboo product length scale are suggested. This thesis presents models: a simple cell wall model for sclerenchyma fiber and parenchyma cell walls, cellular level models of bamboo tissue, and a multiscale model for bamboo OSB that reflects the cellular level nature of bamboo. These models may serve as components or provide aspects for consideration in such modeling approaches.

Bamboo scrimber, while heavy and likely underperforming natural high density bamboo tissue, permits large elements of higher properties than is sometimes possible with natural bamboo materials. Determining optimal densification methods and levels, failure modes, and size effects in bamboo scrimber would be beneficial. Research designed to study the size effect in the $MOR$ of moso bamboo glulam and the relation of glulam and natural tissue properties, would also be beneficial. Research focused on moso bamboo OSB to assess strength properties and verify constructed models is suggested. Studies aimed at understanding the role of nodes in the mechanical properties of structural bamboo products are also recommended.

With all studies recommended for both the natural tissue and products, density should be noted. Studies do not need to have a special focus on density, as was the case throughout this thesis, but it should be noted. Density has a direct correspondence with weight; it places bamboo into a larger context and seems fairly reflective of the sclerenchyma fiber volume fraction in bamboo. Furthermore, as in this thesis, density allows structural bamboo products (in which it may be
difficult to measure fiber volume fraction) to be considered in relation to the natural material in a straightforward way.
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