Chapter 2

Literature Review

2.1   Bamboo

2.1.1   Introduction

Bamboo is one of the oldest building materials used by mankind [7]. The bamboo culm, or stem, has been made into an extended diversity of products ranging from domestic household products to industrial applications. Examples of bamboo products are food containers, skewers, chopsticks, handicrafts, toys, furniture, flooring, pulp and paper, boats, charcoal, musical instruments and weapons. In Asia, bamboo is quite common for bridges, scaffolding and housing, but it is usually a temporary exterior structural material. In many overly populated regions of the tropics, certain bamboos supply the one suitable material that is sufficiently cheap and plentiful to meet the extensive need for economical housing [17]. Bamboo shoots are an important source of food, and a delicacy in Asia. In addition to its more common applications, bamboo has other uses [30], from skyscraper scaffolding and phonograph needles to slide rules, skins of airplanes, and diesel fuels. Extractives from various parts of the plant have been used for hair and skin ointment, medicine for asthma, eyewash, potions for lovers and poison for rivals. Bamboo ashes are used to polish jewels and manufacture electrical batteries. It has been used in bicycles, dirigibles, windmills, scales, retaining walls, ropes, cables and filament in the first light bulb. Indeed, bamboo has many applications beyond imagination. Its uses are broad and plentiful.

With the advancement of science and technology and the tight supply of timber, new methods are needed for the processing of bamboo to make it more durable and more usable in terms of building materials. Studies have been done on the basic properties [3-7], and processing bamboo into various kinds of composite products [9-15]. More studies are needed to aid and promote its application in the modern world.

Some information on the basic properties of Calcutta bamboo were documented, however its properties particularly in relation to their applications as the raw material for composite products is very limited. Calcutta bamboo is exploited in such a way that its full potential is not being used. This research is needed to determine those potentials and promote Calcutta bamboo as an alternative to the commonly used raw materials.

2.1.2 Taxonomy, Resources and Habitat

Bamboo is a perennial, giant, woody grass belonging to the group angiosperms [18] and the order monocotyledon [7]. The grass family Poaceae (or Gramineae) can be divided into one small subfamily, Centothecoideae, and five large subfamilies, Arundinoideae, Pooideae, Chloridodeae, Panicoideae, and Bambusoideae. In distinction to its name, bamboos are classified under the subfamily Bambusoideae [18, 19]. Wang and Shen [20] stated that there are about 60 to 70 genera and over 1,200 – 1,500 species of bamboo in the world. About half of these species grow in Asia, most of them within the Indo-Burmese region, which is also considered to be their area of origin [22]. Some examples of

bamboo genera are *Bambusa, Chusquea, Dendrocalamus, Phyllostachys, Gigantochloa* and *Schizostachyum.* Table 1A of Appendix A, shows other genera, species, and some English names adapted from the common names of bamboo. Most of the bamboos need a warm climate, abundant moisture, and productive soil, though some do grow in reasonably cold weather (below –20°C)[20]. According to Grosser and Liese [22], bamboos grow particularly well in the tropics and subtropics, but some taxa also thrive in the temperate climate of Japan, China, Chile and the USA. Lee et al. [14] stated that the smaller bamboo species are mostly found in high elevations or temperate latitudes, and the larger ones are abundant in the tropic and subtropic areas. Bamboo is quite adaptable. Some bamboo species from one country have been introduced to other countries. The most popular and valuable bamboo species in Asia, *Phyllostachys pubescenes* or the Moso bamboo has been grown successfully in South Carolina and some other Southeastern states in America for more than 50 years [12]. Bamboos are also adaptable to various types of habitat. They grow in plains, hilly and high-altitude mountainous regions, and in most kinds of soils, except alkaline soils, desert, and marsh [20]. Abd.Latif and Abd.Razak [2] mention that bamboo could grow from sea level to as high as 3000 meter. Bamboo is suitable on well drained sandy to clay loom or from underlying rocks with pH of 5.0 to 6.5.

2.1.3   Morphology and Growth

Wong [23], McClure [17] and Dransfield [24] illustrate the morphological characteristics of bamboo. Figure 1A in Appendix A, represents the general structure of bamboo. Bamboo is divided into 2 major portions, the rhizomes and

the culms. The rhizome is the underground part of the stem and is mostly sympodial or, to a much lesser degree, monopodial. This dissertation is concerned with the upper ground portion of the stem, called the culm. It is the portion of the bamboo tree that contains most of the woody material. Most of bamboo culms are cylindrical and hollow, with diameters ranging from 0.25 inch to 12 inches, and height ranging from 1 foot to 120 feet [14]. It is without any bark and has a hard smooth outer skin due to the presence of silica [36]. The culm is complimented by a branching system, sheath, foliage leaves, flowering, fruits and seedlings. Bamboo is distinguishable from one another by the differences of these basic features, along with the growth style of the culm, which is either strictly erect, erect with pendulous tips, ascending, arched or clambering. Several published materials extensively described the morphology and structure of bamboo [17-24, 30, 36, 41].

Bamboo is a fast growing species and a high yield renewable resource. Bamboo growth depends on species, but generally all bamboo matures quickly. Aminuddin and Abd.Latif [8] stated that bamboo might have 40 to 50 stems in one clump, which adds 10 to 20 culms yearly. Bamboo can reach its maximum height in 4 to 6 months with a daily increment of 15 to 18 cm (5 to 7 inches). Wong [23] stated that culms take 2 to 6 years to mature, which depends on the species. It is suggested that with a good management of the bamboo resource, the cutting cycle is normally 3 years. According to Lee et al. [14], bamboo mature in about 3 to 5 years, which means its growth is more rapid than any other plant on the planet. Some bamboo species have been observed to surge skyward as fast as

48 inches in one-day [30]. The fast growth characteristic of bamboo is an important incentive for its utilization. Due to the fact that it is abundant and cheap, bamboo should be used to its fullest extent.

2.1.4   Harvesting Technique

The basic cultivation and harvesting methods for plantation bamboo have been explained by Farrelly [30]. However, a satisfactory and systematic harvesting technique of wild bamboo has not yet been well established. There is no consideration for its final intended usage when bamboo is harvested. The high initial moisture content of bamboo may easily cause splitting. The uncertainty of age of the harvested bamboo will create problems in processing and utilization. Some of the factors that should be taken into consideration for the improvement of the harvesting technique are age, desired quality, and the properties of the end-uses. Various harvesting methods have been reported [17, 20, 30].

2.1.5   Anatomical Structure

Introduction to Anatomy

Many studies have been published on the anatomical features of bamboo [3, 5, 7, 22, 25]. Its anatomical features directly affect bamboo physical and mechanical properties. These features affect seasoning, preservation and the final application. It is expected that these anatomical features will affect the interaction between bamboo and adhesive. A general anatomical structure of bamboo will be

discussed, and the anatomical structure of the bamboo chosen for this project will be highlighted.

The bamboo culm is divided into segments by diaphragms or nodes. The nodes separate the culm into several sections termed internodes. The culms outermost layer, the bark, consists of epidermal cells that contain a waxy layer called cutin. The innermost layer is wrapped by sclerenchyma cells. The tissue of the culm contains parenchyma cells and the vascular bundles. Vascular bundles are a combination of vessels and sieve tubes, with companion cells and fibers [26]. This is shown in Figure 2A in Appendix A. Grosser and Liese [22] used the presence and location of fiber strands on the cross-section to distinguished different types of vascular bundles from 14 bamboo genera. Figure 3A, Table 5A and Table 6A in Appendix A, illustrate the basic vascular bundle types and the anatomical classification groups depicted by the authors. Having only vascular bundle type I, the bamboo genera like *Arundinacea*, *Phyllostachys* and *Tetragonocalamus* are classified under group A. Group B is further classified into two sub-groups B1 and B2. The genera *Cephalostachyum* is classified under group B1 because it has only type II vascular bundles, whilst the genera *Melocanna, Schizostachyum* and *Teinostachyum* are classified in group B2 for having type II and type III vascular bundles. Group C is the classification that has only type III vascular bundles. An example of bamboo genera under group C is *Oxytenanthera*. The genera like *Bambusa, Dendrocalamus, Gigantochloa* and *Thyrsostachys* are classified in group D for having type III and type IV vascular bundles.

The bamboo node cells are transversely inter-connected, whilst the cell at the internodes are axially oriented. Being a monocotyledon, the bamboo culm lacks the secondary thickening, and further not possessing radial cell elements like timber.

Anatomical Analysis

Chew et al. [9] analyzed the fiber of Buloh Minyak (*Bambusa Vulgaris)*. The macerated fiber was stained with safranin-C and mounted on slides. They then measured 300 fibers for their length, width and lumen width using a visopan projection microscope. Their study shows that the fiber is long and slender, with a narrow lumen. The average fiber length and width was found to be 2.8 mm and 0.013mm, whilst the lumen width and cell-wall thickness was 0.003mm and 0.005mm respectively.

Abd.Latif and Tarmizi [5] studied the anatomical properties of three Malaysian bamboo species, 1 to 3 year old *Bambusa vulgaris* (buluh minyak)*, Bambusa bluemeana* (buluh duri) and *Gigantochloa scortechinii* (buluh semantan)*.* The bamboo was cut at about 30 cm above the ground level. Each stem was marked and cut at about 4 m intervals into basal, middle and top segments. Disks were cut and used for the determination of vascular bundles distribution and fiber dimensions respectively. This study showed that the highest mean concentration of vascular bundles was observed in the top location of the 2 year old *B. bluemeana* (365 bundles/cm^2), *B.vulgaris* (307 bundles/cm^2) and *G. scortechini* (223 bundles/cm^2). The lowest mean concentration of vascular

bundles was in the middle location of the 1 year old *G. scortechini* (132 bundles/cm^2), 2 year old *B.vulgaris* (215 bundles/cm^2) and 1 year old *B. bluemeana* (200 bundles/cm^2. The radial/tangential ratio, which was used earlier by Grosser and Liese [22] is the ratio of radial diameter (length of vascular bundle) to the tangential diameter (width of the vascular bundle). According to this study, age does not significantly affect the radial/tangential ratio, and the trend is a decrease with height except for *G. scortechini.* It was concluded by this study that vascular bundle size is larger at the basal and gradually decreases to at the top. The fiber length between the three species were significantly different. Age does not significantly affect fiber length. The author also observed the variation of fiber wall thickness, which is measured as the fiber diameter minus the lumen diameter divided by two. The fiber wall thickness was significantly different among the bamboo species. *G. scortechinii* was observed to be in the range of 0.006mm to 0.01mm, *B. vulgaris* in the range of 0.006mm to 0.008mm and 0.004 to 0.006mm for *B.bluemeana*. From the analysis done in this study, it was observed that there is variation of the anatomical characteristics of bamboo, however there are certain patterns between and within culms.

Bamboo Anatomy in Relation to Mechanical Properties

The anatomical characteristics in relation to the mechanical properties of Malaysian bamboo have been studied by Abd.Latif et al. [7]. The three species, 1 to 3 year old *Bambusa vulgaris, Bambusa bluemeana* and *Gigantochloa scortechinii* were used again in this paper. They concluded that vascular bundle

size (radial/tangential ratio) and fiber length correlated positively with modulus of elasticity (MOE) and stress at proportional limit. The authors implied that the increase in the size (mature stage), and fiber length could be accompanied by an increase in strength properties. They mentioned that bamboo that posses longer fiber might be stiffer, if it has a greater vascular bundle size. The correlation between fiber length and shear strength was negative. The fiber wall thickness correlates positively with compression strength and MOE, but negatively with modulus of rupture (MOR). There was also a correlation between lumen diameter and all of the mechanical properties, except compression strength.

The effects of anatomical characteristics on the physical and mechanical properties of *Bambusa bluemeana* were determined [3]. The studies were carried out by using nine culms of 1, 2 and 3-year-old bamboo from Malaysia. This study found that the frequency of vascular bundles does not significantly vary with age and height of the culm. They observed that the highest mean concentration of vascular bundles was at the top location of the 2-year-old culm, and the lowest mean concentration was in the middle location of the 1-year-old culm. The high-density of vascular bundles at the top was due to the decrease in culm wall thickness (Grosser and Liese [22]). The size of vascular bundles was not significantly different with height and age. There was no correlation of vascular bundles with age, but there was a significant decreased with height of the culm. They explained that the reason for the higher ratio of vascular bundle size near the basal location was due to the presence of mature tissues. The radial diameter decreases faster than the longitudinal diameter of the vascular bundles within the

height of the culm. The fiber length of the species of bamboo studied did not significantly differ with age and culm height. Fiber wall thickness is not significant by age or height of the culm. They observed that there is a decrease of lumen diameter with the increase of age and height of the culm.

2.1.6   Chemical Composition and Natural Durability

The selection of bamboo species for various applications is not only related to physical and mechanical properties but also to the chemical composition. Tomalang et. al [11] in their study found that the main constituents of bamboo culms are holocellulose (60-70%), pentosans (20-25%), hemicellulose and lignin (each amounted to about 20-30%) and minor constituents like resins, tannins, waxes and inorganic salts. The proximate chemical compositions of bamboo are similar to those of hardwoods, except for the higher alkaline extract, ash and silica contents. The carbohydrate content of bamboo plays an important role in its durability and service life. Durability of bamboo against mold, fungal and borers attack is strongly associated with the chemical composition [4]. In producing material such as cement-bonded particleboard, chemical content (starch and sugar) will retard the absorption rate of H_2O^+ ion on the cement mineral surfaces and will slow down the setting reaction. The study by Chew et al. [9] found out that *bambusa vulgaris* contains glucose 2.37%, fructose 2.07% and sucrose 0.5%. The total sugar before and after soaking was 4.94% and 0.28% respectively. This study showed that by the technique of soaking the sugar content could be reduced below 0.5%, a permitted level for the production of cement-

bonded particleboard. This paper explained that a bamboo sample that contained more than 0.6% total sugar will produce low quality cement-bonded particleboard, unless treated

2.1.7 Physical and Mechanical Properties

Physical and mechanical properties of several bamboo species of the world are presented in Table 2A and Table 3A of Appendix A. Physical and mechanical properties of bamboo depend on the species, site/soil and climatic condition, silvicultural treatment, harvesting technique, age, density, moisture content, position in the culm, nodes or internodes and bio-degradation [14]. Many studies had been carried out in order to highlight and observe these fundamental characteristics, as well as to maximize bamboo utilization [3, 7, 14, 25]. Abd.Latif et al. [3] studied the effect of anatomical characteristics on the physical and mechanical properties of *B.bluemeana*. According to this study, age and height do not significantly affect moisture content. The range of green moisture content was 57% to 97%. Younger bamboo showed higher moisture content compared to an older bamboo. The paper explained that it could be the effect of the thick wall fiber and higher concentration of vascular bundle of the older bamboo. There was no significant difference for density along the culm height of the 3-year-old culm. The radial and tangential shrinkage of *B.bluemeana*, did not differ significantly through age and height. The radial and tangential shrinkage ranges from 5.4% to 9.5% and 6.4% to 20.1% respectively. The older bamboo (3-year-old) is more dimensionally stabled compared to the young ones (1-year-old). The 1-year-old

bamboo was observed to shrink more at an average of 15% to 22%. The radial and tangential shrinkage at basal height of a 2 year old *B.bluemeana* culm is found to be 8% to 19% respectively, and top location at approximately 6% to 12% respectively.

In this study, most of the mechanical properties varied significantly with age and culm location. Shear, compression parallel to grain, and bending stress at proportional limit increased gradually with age and height. MOR decreased with age and height. However, MOE was not significantly affected by age. It was concluded by this study that the insensitivity of MOE with age could be an advantage in the use of *B.bluemeana* in a product where it is hard to pre-select old and young bamboo. Tewari [36] explained that bamboo start to shrink both in the wall thickness and diameter as soon as it starts to loose moisture. This behavior is unlike wood, where most of the properties will start to change when it reaches the fiber saturation point.

The specific gravity of bamboo varies from about 0.5 to 0.79, and this would make the density about 648 kg/m^3 (40.5 lb/ ft^3)[21]. Other article claimed that the average specific gravity of bamboo ranged from 0.3 to 0.8 [14]. Chew et al. [9] gives the density of *B.vulgaris* at 630 kg/m^3, which is relatively light compared to other bamboo. Density is the major factor that influences the mechanical properties, and it is closely related to the proportion of vascular bundles. Shear, compression parallel to grain, bending at proportional limit and MOE are correlated with density and moisture content. The observation is that as moisture content decreases the mechanical properties increase, and as the density

decreases the mechanical properties also decrease. This behavior is similar to mechanical properties of wood. Vascular bundle distribution is positively correlated with all the strength properties except for MOR. Abd.Latif et al. [3] implied that this behavior may be due to the increase of the number of sclerenchyma and conductive cells, and thus results in an increase in density. Vascular bundle size (radial/tangential ratio) and fiber length are positively correlated with compression strength, bending stress at proportional limit and MOE. The decrease in tangential size of the vascular bundle (mature stage or higher radial/tangential ratio) was accompanied by an increase in strength properties. Abd.Latif suggested that longer fiber will decrease the shear strength, which was due primarily to cell wall thickness or density rather than the percentage of the parenchyma fibers. The cell wall thickness has a positive correlation with compression strength, bending stress at proportional limit and MOE, but negetively correlated to MOR. This study found out that fiber dimensions except lumen diameter, correlate strongly with mechanical properties. Bamboo is as strong as wood in tension, bending and compression strength, but is weaker in parallel to the grain shear.

Lee et al. [14] determined the physical and mechanical properties of giant timber bamboo (*Phyllostachys bambusoides)* grown in South Carolina, USA. This study concluded that moisture content, height location in the culm, presence of nodes and orientation of the outer bark affect the mechanical and physical properties. This study found that the greatest shrinkage occurred in the radial direction, which was about twice as great as shrinkage in the tangential direction,

while longitudinal shrinkage was negligible. Average green moisture content of the bamboo species studied was 137.6%, with a green specific gravity of 0.48. It was found that there were no significant differences of the moisture content and specific gravity between the different locations of the culm and between the different stems. Compressive, tension and bending strength of the giant timber bamboo was also studied. It was found that the presence of nodes, moisture content and culm location had a significant effect on strength. The presence of nodes reduced the compression, tension strength and MOR, but did not significantly affect MOE. The top location of the culm exhibited higher compression strength, tension strength, MOR and MOE. In bending, radial or tangential loading had a significant affect on MOR and MOE. Bamboo, according to Lee et al. [14] is similar to wood in regard to anisotropic shrinkage. The authors compared the physical and mechanical properties of bamboo with loblolly pine, which showed a similarity.

2.2 Calcutta Bamboo

2.2.1 Introduction

Dendrocalamus strictus is commonly recognized as Calcutta bamboo [30], but also known as male bamboo [36], and solid bamboo [43]. Local names for this species are bans, bans kaban, bans khurd, karail, mathan, mat, butu mat, salis bans, halpa, vadur, bhiru, kark, kal mungil, kiri bidaru, radhanapavedru, kauka, myinwa, Phai Zang, bambu batu and pring peting[21,30,43]. Calcutta bamboo is the most widely used bamboo in India [42], especially for the paper industry [30]. It is also being used in house construction, basket making, mats, furniture,

agriculture implements and tool handles. It is the most common species of bamboo cited in the Indian forest and is available in every state in India [38]. This species is also found in Burma, Bangladesh, Thailand, Indonesia, and Sri Langka [21,43]. Farrelly [30], reported that *D.strictus* was introduced into the United States by seed from India, and can be found in southern California, Florida, and Puerto Rico. Generally, Calcutta bamboo thrives in the inland with low relative humidity. It flourishes in places with an annual rain fall between 30 to 200 inches, and in shade temperature from 22°F to 116°F[30]. It can grow in generally all types of soils, with good drainage characteristics, except water-logged soil such as pure clay or clay mixed with lime.

2.2.2 Culm Characteristics

According to Wong [23] and Tewari [36], the color of standing *D.strictus* culm is dark green, lightly and ephemerally white-waxy, glabrous. He described *D.strictus* culm to be 16 to 26 feet (5 to 8 meters) tall when small-culmed, and 30 to 50 feet (10 to 15 meters) when bigger. The authors described the diameter as 1 to 1.5 inches (2.5 to 3.5 cm) in small culm and 1.5 to 3.0 inches (3.5 to 7.5 cm) diameter in big culm. There is no specific dimension reported for the culm wall thickness. Tewari [36] described *D.strictus* as being thick-walled and sometimes with solid culms. The average internode length is between 9 to 18 inches (25 to 45 cm). More detailed *D.strictus* plant characteristics are elaborated in Wong [23] and Tewari [36].

2.2.3 Anatomical Characteristics

D.strictus shares the typical anatomical characteristics of bamboo, featuring the presence of vascular bundles and parenchyma. This species is classified under anatomical group D for having type III and type IV vascular bundles (Figure 3A, Appendix A).

2.2.4 Physical and Mechanical Properties

Several authors [21, 24, 36, 37, 38] reported the physical and mechanical properties of *D.strictus*. Table 2A in Appendix A presents the basic physical properties of *D.strictus* in comparison to other bamboo species. Limaye [38] reported the relative density of *D.strictus* to be 0.661 in green condition (58%) and 0.757 when dry (12%). In Table 2, the relative density of *D.strictus* is high compared to other bamboo species in the green condition, but a moderate value when dry. The longitudinal shrinkage in *D.strictus* is negligible [38], at approximately 0.1%. Shukla et al [37] and Limaye [38] investigated the wall thickness and diameter shrinkage of *D.strictus*. The authors did not report directly the radial and tangential shrinkage, however the wall thickness shrinkage is actually the radial direction. Thus, this value will be used as a comparison to the radial shrinkage investigated in this dissertation. Shukla et al [37] measured the shrinkage from green to air-dry (12%), as well as green to an oven-dry condition. They reported the wall thickness and diameter shrinkage from green to air-dry to

be 11.5% and 11.9% respectively, whilst the green to oven-dry to be 14.8% and 16.0% respectively.

The mechanical properties of *D.strictus* from several studies are presented in Table 4A, Appendix A. The tests were carried out either on small specimens (split bamboo) or on full size specimens (round bamboo). Test done in this study showed that the modulus of rupture and modulus of elasticity were 12,061 psi and 1.16×10^6 psi respectively. Stress at proportional limit was 6,343 psi, whilst compression parallel to grain was 5,988 psi. Another example from Table 4A is *D.strictus* that was taken from the forest plantation in Dehra Dun, India [38]. The investigation was done on full size samples in green and dry condition. In green condition, the test showed that the modulus of rupture, modulus of elasticity and compression parallel to grain were 13,600 psi, 2.22×10^6 psi and 6,000 psi respectively. In dry condition, modulus of rupture was 18,600 psi, modulus of elasticity was 2.56×10^6 psi and compression parallel to grain was 8,850 psi. The tensile strength of a small sample was determined by the authors to be in the range of 10,000 to 50,000 psi. They did not report the average tensile strength, and commented that the value cannot be utilized in practical work, as bamboo will fail by shear long before its full tensile stress is developed. They recommended modulus of rupture and modulus of elasticity in static bending to represent the most reliable estimate of the tensile strength.

2.3 Analysis of Physical Properties

2.3.1   Introduction

The suitability of bamboo for structural composite products is demonstrated by its physical properties. These properties are the results of genetic design, as well as the affect of the climate and soil condition. Color, grain pattern and texture are among the qualitative factors that are important for the value of appearance-type products. In this dissertation, where structural application of bamboo is stressed, quantitative factors are the subject of concern. The physical properties investigated are relative density (specific gravity), equilibrium moisture content and the dimensional stability. As with many other building materials, bamboo displays variability in its physical properties. Relative density must be taken into consideration, as it is the most important single physical characteristic of woody material. The influence of moisture content, and its effects to dimensional stability, are studied as a basic concern when using any forest product (31). The drying of woody material will cause changes in dimension, the physical as well as the mechanical properties. On the other hand, according to Abd.Razak et al. [26] and Tewari [36], bamboo will start to shrink both in the wall thickness and diameter as soon as it starts to loose moisture. This behavior is unlike wood, where most of the properties will start to change when it reaches the fiber saturation point. All wood-based materials are closely affected by the amount of water present. Thus, in order to satisfactorily use bamboo as a raw material for composite products, the physical properties of relative density, equilibrium moisture content and the shrinkage and swelling are studied.

2.3.2 Relative Density

Relative density (SG) is the weight of any given volume of a substance divided by the weight of an equal volume of water [32]. The mechanical properties for American timbers are related to their relative density [31, 47]. However these properties are not affected in the same way. Table 1B and 2B in Appendix B presents the relationship between mechanical properties and relative density for softwoods and hardwoods in the U.S. Table 3B in Appendix B exhibits the relative density of some timber species. Due to the close relation of relative density to various physical and mechanical properties, lumber is graded using this single number in several developing countries. Thus, the investigation on bamboo relative density, its variation along the culm, and its affect on mechanical properties of bamboo is very important in assessing the suitability of bamboo for structural composite products. The relative density of *Dendrocalamus strictus* are determined using the standard test methods for specific gravity of wood and wood-based materials, ASTM D 2395-93 [32]. Relative density for *D.strictus* is calculated using the equation below [45]:

$$\text{Relative Density} = \frac{\underline{\text{Oven dry mass/volume}}}{\text{Density of Water}} \qquad (2.1)$$

2.3.3 Equilibrium Moisture Content

Equilibrium moisture content (EMC) is defined as the moisture content that is in equilibrium with the relative humidity and temperature of the

surrounding air [45]. EMC is an important in-service factor because wood and other woody material like bamboo is subjected to long-term and short-term variation in surrounding relative humidity and temperature. Hence, this material is always undergoing at least small changes in moisture content, due to the fluctuation of the surrounding environment. In most cases, the changes are gradual and usually effect only the surface of the substrate when briefly exposed to moisture fluctuations. Commonly, it is not desirable to have a material that changes rapidly under the moisture stress because moisture affects the physical and mechanical properties of wood and woody materials. Table 4B of Appendix B presents the equilibrium moisture content of typical wood products. As for bamboo, it is most desirable to have a comparable behavior to wood, if not better. The conditioning of bamboo to different moisture contents was carried out using the standard guide for moisture conditioning of wood and wood-based materials, ASTM D 4933-91 [51]. Moisture content is the mass of moisture in the substance expressed as a percentage of the oven-dry mass. The expression is produced below [45]:

$$\text{Moisture Content} (\%) = \frac{\text{Weight} - \text{Weight}_{od}}{\text{Weight}_{od}} \text{X } 100\% \qquad (2.2)$$

2.3.4   Shrinkage and Swelling

Bamboo, like wood, changes its dimension when it loses or gains moisture. Bamboo is a hygroscopic material, thus the moisture content changes with the changes in the relative humidity and temperature of the surrounding

environment. Dimensional stability is very crucial in structural composite products because the safety and comfort in a structure usually depends on them. Table 3B in Appendix B exhibits the volumetric, radial and tangential shrinkage of some timber species. As was mentioned in the latter section, bamboo begins to change its dimension as soon as it starts to loose moisture. This characteristic is in contrast to wood, where it will shrink or swell only below the fiber saturation point (FSP). The FSP of wood is reached when wood loses its free water and the cell wall is saturated with bound water. The immediate shrinkage behavior of bamboo was reported by several authors [26. 36], but there was no explanation of why it happens. Free water and bound water exists in bamboo, however the amount of free water may be small compare to bound water. This could explain why it starts to shrink as soon as it loses moisture. Haygreen and Bowyer [31] explained that shrinkage in wood happens as bound water molecules leave from between long-chained cellulose and hemicellulose molecules. The shrinkage occurs in proportion to the amount of water loss from the cell wall. The introduction of water molecules into the cell wall will result in swelling, although not completely reversible to the same degree. The volumetric, radial and tangential shrinkage of bamboo was carried out with the guidance of the standard methods of testing small clear specimens of timber, ASTM D 143-94 [52]. The shrinkage and swelling of bamboo in the volume (V), longitudinal (L), radial (R) or tangential (T) direction are expressed by the following equation [31]:

$$\text{Shrinkage (\%)} = \frac{\text{decrease dimension (V, L, R or T)}}{\text{original dimension}} \ X100 \qquad (2.3)$$

$$\text{Swelling (\%)} = \frac{\text{increase dimension (V, L, R or T)}}{\text{original dimension}} \text{ X100} \qquad (2.4)$$

2.4 pH and Buffer Capacity

2.4.1 Introduction

pH and buffering capacity are other important variables in the manufacture of composite products. Both of these variables measure the acidity of the material. Extractives in the woody materials influence the pH value of the surfaces. The condition is alkaline when the numerical value is greater than 7, whereas a value less than 7 describes an acidic condition. The larger the number, the more alkaline the material, and vice versa. Buffer capacity is the measurement of the resistance of the wood or woody material to change its pH level.

2.4.2 pH Value

The pH value of wood or woody materials is highly important for various applications [48]. The ability of an adhesive to cure depends greatly on the condition of the surface of the substrate. Since the rate of cross-linking of most thermosetting adhesives is pH-dependent, these adhesives will be sensitive to the pH of the substrate [64]. According to Maloney [49], in order for the resin binders to cure properly in particleboard furnish, an appropriate chemical condition must be established. Urea-formaldehyde resins particularly are rich in methylol groups and the curing is achieved by lowering the pH to trigger condensation, splitting of water, and forming methylene bridges [61]. However, most phenolic resins used

in wood composites cure in an alkaline environment. This resin is already rich in methylol groups and capable of curing without addition of other ingredients. Adhesives are formulated in accordance to the acid range of certain species, and a wide deviation of this value will create difficulties in providing a superior adhesive bond system. The pH levels of several species of timber and bamboo are presented in Table 5B of Appendix B. The determination of bamboo pH level was carried out using the cold extraction method for hydrogen ion concentration (pH) of paper extracts, TAPPI T 509 om-83 [53].

2.4.3 Buffer Capacity

According to Maloney [49], a greater amount of acid catalyst is required to reduce the pH to the level for an optimum resin cure when wood possesses a high buffering capacity. The buffering level for a single species of wood used in composite products could be an important issue if the variation is high, but becomes a critical factor when multiple species are used. The bamboo buffer capacity was determined using the method by Borden Chemical, Division of Borden [54] and are measured in term of miliequavalent (me.). The buffering capacity of several timber species used in the manufacture of composite products is presented in Table 3B in Appendix B.

2.5 Analysis of Mechanical Properties

2.5.1   Introduction

The mechanical analysis is the study of a material's behavior when subjected to loads. This results in the deformation of the materials [50]. Bamboo, being one of the oldest building material [7], has been used in many load-bearing applications, such as bridges, scaffolding and housing. It reacts in the same fashion as other building materials. However, being a naturally occurring material like timber, it is subjected to variability and complexity. Bamboo is an orthotropic material, it has particular mechanical properties in the three mutual directions: longitudinal, radial, and tangential. Figure 4A in Appendix A illustrates the three orthogonal directions of bamboo. Studies were carried out to investigate the variation between these three directions, as well as the internodes and nodes, and the variation between different locations in the culm [3-7]. Mechanical behavior of bamboo has been investigated either with full size specimens (round form) [21,37, 38, 39, 40] or small size specimens (split bamboo) [7, 14, 21,25, 36]. In this dissertation, tension parallel to grain and the static bending test for small size specimens were carried out.

2.5.2   Tension Parallel to Grain

Tension tests parallel to the grain are seldom investigated for bamboo. There was no report on tension strength for *D.strictus*. According to Limaye [38], tensile strength value cannot be utilized in practical work, as bamboo will fail by shear long before its full tensile stress is developed. They recommended modulus

of rupture and modulus of elasticity in static bending to represent the most reliable estimate of the tensile strength. However, in order to design bamboo tension members loaded in direct tension, the tension strength value is a fundamental criterion. The tension parallel to grain test carried out was adjusted from the standard methods of testing small clear specimens of timber, ASTM D 143-94 [52]. Due to the nature of bamboo, it is impossible to cut similar specimen dimensions suggested in the standard. Thus, a miniaturized version was produced. The tensile stress at proportional limit (σ_{pl}), ultimate tensile stress (σ_{ult}) and tensile modulus of elasticity (E) was calculated using the following equations [50, 55, 56]:

$$\sigma_{pl} = P_{pl}/A \quad (N/mm^2), \tag{2.5}$$

$$\sigma_{ult} = P_{ult}/A \quad (N/mm^2), \tag{2.6}$$

$$E = P_{pl}L/A\delta_{pl} \quad (N/mm^2), \tag{2.7}$$

where P_{pl} is the load at proportional limit (N), P_{ult} is the ultimate load (N), A is area (mm^2), L is the gage length (mm) and δ_{pl} is elongation at proportional limit (mm).

2.5.3   Bending

The bending strength test carried out was adjusted from the standard methods of testing small clear specimens of timber, ASTM D 143-94 [52]. Due to the nature of bamboo, it is impossible to cut the dimensions suggested in the standard. Thus, a miniaturized version was produced. The bending stress at proportional limit (SPL), modulus of rupture (MOR) or the ultimate tensile stress

(σ_{ult}) and bending modulus of elasticity (MOE) were calculated using the following equations [50, 55, 56]:

$$SPL = M_{pl}/Z \ (N/mm^2),$$ (2.8)

$$MOR = M_{ult}/Z \ (N/mm^2),$$ (2.9)

$$MOE = P_{pl} L^3/48\Delta_{pl} I) \ (N/mm^2),$$ (2.10)

where M_{pl} is the bending moment at porportional limit (N.mm), M_{ult} is the ultimate bending moment(N.mm), P_{pl} is the load at porportional limit (N), L is the span of the bending specimen (mm), Δ_{pl} is the deflection of the bending specimen (mm) and I is the moment of inertia (mm^4).

2.6 Wettability and Penetration Analysis

2.6.1 Introduction

The introduction of bamboo as the raw material for composite products requires the determination of their interaction with adhesive. The methods that had been used by many researchers are the theory of wettability and the adhesion penetration [59, 60]. Wettability and penetration are not the only factors responsible in the formation of an adhesive bond. According to Marra [61], the five steps of adhesive bond formation in a wood substance are flow, transfer, penetration, wetting, and solidification. However, it is believed that penetration of adhesive into the porous network of wood cells has a strong influence on bond strength [62]. Wettability is also believed to be related to glue-bond quality [63] and is a quick method in predicting the gluability of an unknown species [59].

2.6.2   Contact Angle

Wetting of the surface by an adhesive is a necessary prerequisite to bond formation [63]. A convenient method to measure wetting of a solid surface is through the determination of contact angle of a liquid. Figure 1B in Appendix B, illustrate the contact angle of a liquid on a solid surface. According to Collett [67], contact angle is an indicator of the affinity of a liquid for a solid. The shape of the liquid dropped on a solid surface is related to the magnitude of the cohesion forces acting between the three planes: solid, liquid, and gas [59]. There are various methods of measuring contact angle, such as the inclined wood plate in distilled water method used by Bodig [59] and Freeman [68], and the sessile liquid drop method used by Wellons [60] and Kalnins and Feist [69]. Several authors [71-76] discussed various techniques that were used for measuring contact angle. In this dissertation, the sessile drop method was adopted to determine the wettability of Calcutta bamboo. According to Herczeg [72], the technique works with minute quantities of liquids on a wood surface, which may be prepared by any mechanical method, such as microtome cutting for it is common knowledge that freshly prepared surfaces, as a rule, provide better glue joints than aged surfaces. No precise time was given for how long the specimen should be exposed, but several authors [59, 60, 72, 73], mentioned that the freshly prepared surface was used immediately for the experiment. A precise quantity of the liquid adhesive was applied on the surface in the form of a small drop. White [77] measured the contact angle of 0.18μl of liquid drop. Zhang et al. [80] used a 50μl

pipette to drop the liquid on a wood sample and immediately captured the image of the droplet with a video camera. Kalnins and Feist [69] measured the contact angle by using an automatic micropipette to dispense a 25µl droplet while capturing an image within 2 seconds of the drop. The wetting values of the surface were reported either as contact angle or by the cosine of the contact angle. Table 6B of Appendix B shows several contact angle values of timber species.

2.6.3   Adhesive Penetration Analysis

The polar nature of the initial resin and developing polymer is critical to the wetting of the substrate. The more polar is the resin, the better the penetration into the material [66]. Penetration into the coarse capillary structure of the material is possible when a good wetting condition is achieved [61]. The creation of a bond between an adhesive and the wood substrate requires adequate interpenetration of the resin and wood components, and the development of links between the resin and the exposed wood surface [91]. The mechanisms of the link between the resin and wood components, which is still being debated today, generally are thought to involve mechanical interlocking, covalent bonding, and secondary interaction, such as Van der Waals forces and hydrogen bonding [61.92]. The combination of these linking mechanisms that promotes a strong bond. Penetration, being one of the phases involves in the resin-wood contact has a strong influence on bond strength. The molecular weight, pH and temperature of the adhesive, and the moisture content, density and permeability of the bamboo or materials will affect the penetration. The flow properties of the water component

are responsible for the fluidity of the adhesive. Other variables such as the material characteristics, processing factors and the methods of heating the adhesive bond will also influence the adhesive penetration [62]. Direction of penetration, permeability, porosity, roughness, surface energy, temperature, pressure, and time are among the other wood and processing factors that could influence the adhesive penetration [61, 83, 93]. In the case of bamboo, many researchers who have investigated the anatomical, chemical, physical and mechanical properties, concentrate on the variability of bamboo between orthogonal directions, between internodes and nodes, as well as between different locations according to the height of the culm [1-8, 22, 25]. These variables in bamboo may influence the adhesive penetration and should be investigated.

The adhesive penetration definition by Sernek et al. [62] is the spatial distance from the interface of the adjoining substrate. As defined by Brady and Kamke [89], the volume containing the wood cells and adhesive is the interphase region of the adhesive bond. The depth of penetration of the adhesive determines the size of the interphase region. According to Johnson and Kamke [84], excessive penetration will result in a starved bondline. Conversely, insufficient penetration will leave a thick film of adhesive on the surface and limited surface contact with the interior surfaces for either chemical bonding or mechanical interlocking. An ideal quantity of adhesive penetration is required to restore machining damage to the wood surface and permit better stress transfer between laminates. Sernek et al. [62] studied the penetration of liquid urea formaldehyde adhesive into beech wood using an epi-fluorescence microscope. The study found

out that moisture content had a significant influence on the urea formaldehyde penetration when heated using a conventional press, but showed no significant difference when cured in a high-frequency press. This study also found out that there was a significant difference of the adhesive penetration between the radial and tangential directions. The tangential direction has a greater penetration than the radial direction. The rate of penetration was fastest at the beginning (first 4 min), then gradually decreased, and showed no difference after 16 min. According to this study, when the adhesive was spread on the surface without any pressure applied, the effective penetration decreased 3 to 4 times compared to the samples made with applied pressure. The equation used by Sernek et al. [62] to calculate the effective penetration (EP) and the maximum penetration (MP) are reproduced below:

$$EP = \sum_{i=1}^{n} A_i / x_o \qquad (2.11)$$

where A_i is the area of the adhesive object (μm), n is the number of objects and x_o is the width of the maximum rectangle defining the measurement area (1297μm).

$$MP = \sum_{i=1}^{5} (y_i + r_i - y_o) / 5 \qquad (2.12)$$

where y_i is the centroid of the adhesive object i, which represents one of the five deepest objects (μm), r_i is the mean radius of adhesive object i and y_o is the reference y-coordinate of the bondline interface (μm).

Johnson and Kamke [84] utilized fluorescence microscopy to quantitatively analyze the gross adhesive penetration in wood. The study used the adhesive droplet technique instead of a continuous bondline. The adhesive

droplets were placed on the specimen using a micropipette set at 0.5 microliters. They commented that staining the wood section with Toluidine Blue O solution suppressed the autofluorescence of the wood, while permitting the nonabsorbent adhesive to fluoresce. The techniques used by Johnson and Kamke [84] and Sernek et al. [62] were adopted in this dissertation to determine the adhesive penetration in Calcutta bamboo.

2.7 Structural Wood Composite Products

2.7.1   Introduction

A composite generally signifies two or more materials that are combined on a macroscopic scale to form a useful material [94]. Man has long used materials in the form of a composite, either for household or structural applications. In a broader sense, we continuously blend and compose materials together to try to form a better product. This behavior has been the nature and talent of man. In everyday life, we cook delicious food by blending different ingredients and we wear beautiful clothes by sewing different types of fabric together. In building structures against the environment, man has used diverse materials, either from its natural form or manufactured. Timber has long been used as a building material because it is versatile and abundant. It has been turned into paper and plywood since ancient China and Egypt. Today, wood is used in many composite products. Non-wood materials, like straw, reed grass, hemp and bagasse are also processed using existing composite technology [105-109]. Wood has been taken for granted for centuries. We are faced with diminishing resources

today. New composite products, using lesser quality timber, as well as new materials have to be formulated in order to satisfy the increasing world demand for building materials.

2.7.2   Classification of Wood Composites

In the twentieth century, several types of wood composites were introduced. Marra [61] showed the forms of wood elements commonly used in composites today. The diverse shapes and size start from the largest element to smaller element. There are 14 basic wood elements, logs, lumber, thin lumber and veneer, large flakes, chips, small flakes, excelsior, strands, particle, fiber bundles, paper fiber, wood flour and cellulose. Bodig [59] classified wood composites in 6 different groups. Table 1C in Appendix C presents the classification of wood composites. Some newer wood composites were also included in Table 1C, like parallel strand lumber (PSL), cementboard and oriented strand board (OSB). As was mentioned before, the quality and supply of timber nowadays has decreased tremendously. Newer and better composite wood products have to be invented to overcome this problem. At the same time alternative materials need to be look upon to reduce the stress on the existing timber supply. In this dissertation, Calcutta bamboo was analyzed to investigate its suitability as a raw material for structural composite products. The technology of parallel strand lumber (PSL) was adapted to manufacture bamboo parallel strip lumber (BPSL). PSL technology is highlighted in the next section.

2.7.3 Parallel Strand Lumber

Parallel strand lumber (PSL) is produced from long strands of veneer that are bound together with exterior-type plywood adhesive [31]. PSL is grouped under structural composite lumber (SCL), alongside with other products such as laminated veneer lumber (LVL) and oriented strand lumber (OSL) [49]. The manufacture of PSL involves veneer strands that are about 0.1 to 0.16 in. (2.3 to 4 mm) thick. The strands are about 0.5 in. (12 mm) wide and generally are 102 in. (2.6 m) long but pieces as short as 24 in. (61 mm) can be included in the furnish [101]. The length of the veneer strand is limited only to the length of the billet for the peeling process. The width of the strands must not be less than 0.25 in. (6.4 mm), and the average length of the strands must be a minimum of 150 times the least dimension [44, 95]. In the production of PSL in North America, Douglas-fir, southern pine, western hemlock and yellow-poplar are commonly used for PSL [31, 44, 101]. The processing of PSL is similar to the early processing stage of plywood and LVL. A standard veneer peeling technology is used [101], until it reaches the clipping process. Clipping is done on veneer to produced strands with the width mentioned above. The strand are then coated with adhesive (phenol-resorsinol-formaldehyde) and laid up randomly to form a long and continuous mat, which is then formed into a billet (lumber) in a continuous press. A microwave-type heating system is used to set the adhesive in the thick billet. The adhesive is spread on to all surfaces of the strands and effectively penetrates lathe checks and cracks. Temperature ranging from 360°F to over 400°F (182°C to 204°C) are needed. The maximum pressure applied is approximately 100 lb/in^2.

The common commercial size of the PSL billets are 11 by 14 in. (279 by 356 mm) and 11 by 16 in. (279 by 406 mm) in cross section [49]. Figure 1C of Appendix C, illustrates the manufacturing processes of PSL.

2.7.4 Testing and Evaluation of Structural Composite Lumber (SCL)

Composite lumber expected to perform in structural applications has to be evaluated in order to provide safety and reliability. The standard ASTM D5456 [95] provides procedures to develop design properties and quality assurance methods for SCL. This standard in conjunction with other standard procedures [96-100], evaluates the physical and mechanical properties, the response of the materials to the end-use environment, and establishes and conforms the quality according to the standard performance specification. Mechanical tests suggested by ASTM D5456 are bending, tension parallel to grain, compression parallel to grain, compression perpendicular to grain and longitudinal shear. The mechanical test carried out for the prototype bamboo parallel strip lumber are bending and compression parallel to grain. The water absorption and thickness swelling, linear expansion and the accelerated aging test were carried out in accordance to ASTM D 1037-96a.

2.8   Wood Adhesives

2.8.1 Introduction

Adhesives of natural origin, like starches, and animal protein have long been used to bond wood by man. However, they are not suitable for the wood

composites of today. Synthetic resins now play an important part in the development and growth of the wood composites industry. As the wood composite industry continues to expand, significant progress has been made in the development of new and superior adhesives. The majority of wood composite adhesives today are comprised of fivesynthetic thermosetting resins, phenol-formaldehyde (PF), resorsinol-formaldehyde (RF), urea-formaldehyde (UF), melamine-formaldehyde (MF) and diphenylmethane diisocyanate (MDI). In this dissertation the characteristics of PF and MDI adhesives will be highlighted. These two adhesives were used in the adhesive penetration analysis, and PF was used as the binder for the prototype bamboo parallel strip lumber.

2.8.2 Phenol-Formaldehyde (PF)

Baeyer in 1872 observed the formation of resins based on the linkage between phenol and formaldehyde. This phenolic type resin started to be seen in the industry in 1909 [113]. Ever since, this adhesive type remains to be an important adhesive system for the wood-based composite production for exterior applications. PF is the primary adhesive type used in the structural plywood industry today. It is being used in the production of oriented strand board (OSB), waferboard, laminated veneer lumber (LVL), and many other exterior composite products [117]. A report by Sellers [116] stated that the phenolic resin consumption by the North American to produce strandboard products alone in 1997 was about 275 kilotons. Both liquid and powdered forms are used. PF is waterproof, durable and comparatively less expensive compared to other exterior-

type adhesives. The other desirable properties of PF are high glass transition, high modulus and tensile strength, good dimensional stability, solvent resistance, and high mobility and penetration power. The basic components of these adhesives are formaldehyde derived from methanol, urea, and phenol [31]. In the industry, it is produced by the reaction of phenol with formaldehyde in the presence of a catalyst. Oxalic, hydrochloric, sulfuric, phosphoric and toulene sulfonic acids are the most common catalysts used in the industry [111]. There are two types of resins formulated by altering the molar ratio of phenol and formaldehyde. Resole is formed when there is more formaldehyde than phenol (molar ratio less than 1), thus creating an alkaline condition. When there is more phenol than formaldehyde (molar ratio greater than 1), creating an acidic condition, novolac is formed. Resole resin is rich with methylol groups and is capable of forming the necessary cross-linking for polymerization without additional ingredients. This type of resin immediately is ready to cure with the introduction of heat. However, its shelf's life is short, especially in the liquid form. Novolac resin has a longer shelf life because methylol group is lacking. The novolac resin is linear in nature and is unable to polymerize. Hardener (formaldehyde) has to be added in order to convert this resin to an insoluble state [61]. Extenders and fillers are used to aid the distribution of the adhesive on the wood surfaces as a thin and uniform resin spread, add bulk and hold the adhesive on the wood surface [113]. Extenders and fillers used with phenolic resins originate from nature, such as nut shell flour, bark flour, clay, dried blood and cereal flour. The use of these additives with phenolic resin is only limited to the end use and the manufacturing processes.

Acidity or alkalinity is another important chemical property of the adhesive. The pH value for most phenolic resin is between 9 to 12. Lower pH of the phenolic resin means that more time or higher temperature is needed to cure the adhesive and vice versa. Both ends of the pH value have a certain application in the wood-based industry. In the case of the low pH value of the adherend, additional catalyst like sodium hydroxide may be added to increase to alkaline state, and further increase the rate of cure. Other factors may govern the selection of phenolic resin, such as viscosity, solids content, shelf life, form, color, odor, strength and durability.

2.8.3 Diphenylmethane diisocyanate (MDI)

Isocyanate adhesives evolved during World War II in a quest for superior adhesives to bond tire cords and rubber, but were not fully explored for other applications due to high cost and toxicity [61]. In the early 1970's, Europe started to use polymeric diphenylmethane diisocyanate (PMDI) as binders for exterior and interior grade particleboard. The first commercial MDI was produced in the 1960's. In the late 1970's, the North American structural panel industry started to recognize the potential of isocyanate adhesives with its application in Elcoboard (veneer face with particle core) by Ellingson Lumber [115}. Canada began to produce structural boards using PMDI in the mid-1980's. Ever since, this adhesive type has grown significantly in the OSB/waferboard industry [118] and approximately 14 percent of the strandboard products in the United States and Canada utilize PMDI in 1997 [116]. The advantages of this adhesive are

durability, dimensional stability, higher moisture content tolerance, lower press times and temperature, and a lighter color than PF resins [114]. Moreover, to produce the same board properties as PF resins, less MDI is needed. On the other hand, there are also some disadvantages of this adhesive. According to Marra [61], MDI is known to adhere to metals, and thus could stick to cauls or press platens. It is not soluble in water and needs a special storage system due to it premature moisture reactions. There is also less tackiness in the adhesive to hold the mat together during transportation to the press.

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