PJSRR (2016) 2(1): 63-79
eISSN: 2462-2028 © Universiti Putra Malaysia Press

Pertanika Journal of Scholarly Research Reviews
http://www.pjsrr.upm.edu.my/

# Bamboo Properties and Suitability as a Replacement for Wood

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**Abstract –** The utilization of bamboo as a manufacturing material is becoming globally attractive in the wood and wood product industries today. This is due to the numerous industrial applications and uses of the bamboo plant from its fast growth, availability, unique appearance and strength. Bamboo has been popularly known for its traditional uses such as poultry cages, vegetable baskets, incense sticks, skewers and chopsticks, woven blinds and handicrafts. Very little has been done on the industrial processing of bamboo into boards. Several authors have studied and reported on the utilization, processing and the properties of this emerging material as an alternative to the increasing decline of wood in the forest. This review aims to compare and contrast some of the works done on the advancement in producing laminated bamboo timber. The properties of bamboo and its laminated products attest to its potency in substituting wood. Bamboo utilisation has increased significantly in the wood and wood product industries, with adequate retooling in most processing firms in the sector. In line with the development and use of bamboo-laminated timber for the purpose of wood in furniture production, the creation of bamboo plantations on degraded lands will meaningfully support production and mitigate the degradation of forest.

**Keywords:** Bamboo, laminated bamboo timber, physical properties, mechanical properties

## Introduction

The continuous decline of forest resources requires the use of non-wood materials such as bamboo-laminated timber (LBT) in many structural and non-structural applications previously dominated by wood. Currently, bamboo-laminated products can be safely used in the application of furniture, interior panelling, floor parquet, etc. (Chaowana, 2013). The properties of LBT have comprehensively studied. Many researchers have investigated the properties of this emerging material (Anwar, Zaidon, Hamdan & Tamizi, 2005; Hamdan, 2004; Hanim, Ziadon, Anwar, & Rafida, 2013; Nordahlia, Anwar, Hamdan, Latif, & Mahanim, 2011; Razak, Azmy, Othman, & Hashim, 2006; Razak, Mustafa, Sukhairi, & Rasat, 2013). Most of them found variations in the physical and mechanical properties within the bamboo culm. However, their studies mainly focused on individual species at different locations.

Laminated bamboo has been found by these researchers to have really no limit to its use. It can be used for chairs and other furniture. In fact, it can be used just like laminated wood, with the advantage that bamboo laminates are much lighter in weight and the manufacturing process is much the same as for conventional plywood (Ganapathy, Huan-ming, Zoolagud, Turcke, & Espiloy, 1999; Guisheng, 1987; Zhang, Jiang, & Tang, 2002). In spite of the numerous advantages of the LBT, distortions are found in the vascular bundles of the node section of the culm, leading to the variations in strength along the culm (Anwar et al., 2005; Hamdan, 2004a; Nordahlia et al., 2011; Razak et al., 2013). The related studies recommended the removal of the node to replace it with an appropriate joint. Further research is, however, needed on the appropriate jointing method, and in replacing the nodal section of bamboo to enhance its utilization in the production of high grade LBT.

**Bamboo**

Bamboo is a hollow woody plant which belongs to the grass family (Gramineae), sub-family Bambusoideae. It is noted to have about 70 genera divided into about 1,500 species of bamboo all over the world (Khalil et al., 2012). They are found in diverse climates, from cold mountains to hot tropical regions. They are found across East Asia, from 50°N latitude in Sakhalin in Russia through to Northern Australia, and west to India and the Himalayas. About 65% of bamboo grown areas are dominated in Asia as shown in *Figure 1* (Paridah, 2013).

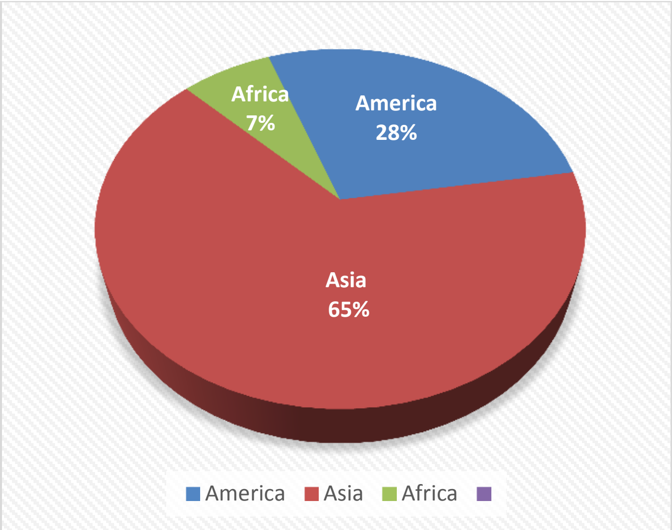


*Figure 1*: Bamboo resources according to continents

Bamboo is also found in sub-Saharan Africa, and in the Americas from the Mid-Atlantic United States south to Argentina and Chile, reaching their southernmost point anywhere, at 47°S latitude. Continental Europe is not known to have any native species of bamboo (Gratani, Crescente, Varone & Fabrini, 2008). Its height ranges from a few centimetres to over 30 metres, with a stem (culm) diameter of 3 mm to over 25 cm.

Bamboo is an exceptionally fast growing plant, which allows harvesting for construction within 4-7 years (Ashby, 2016). After a maximum life span, which varies by species and climate, the individual bamboo culm will collapse and decay, although the plant itself may survive. Furthermore, bamboo tolerates poor soils, which makes it useful for planting on degraded soils (Hunter, 2003; Muller & Rebelo, 2015).

An International Network on Bamboo and Rattan (INBAR) workshop organized for the Asian member countries emphasized on the important role of bamboo in addressing climate change of adaptation and mitigation, in addition to providing a safety net to forest-dependent communities who are most vulnerable to impacts of climate change (Kumar, 2014). The workshop also underlined bamboo's ability in maintaining a permanent canopy over the soil and it is excellent at reducing soil erosion as well as stabilizing riverbanks.

The stems of bamboo plants are very strong but hollow, with the exception of partitions at the nodes; these two qualities provide great popularity and usefulness of bamboo in everyday life especially to the Chinese, Japanese, Indo-Chinese and the West Indians.

*Specific features of bamboo*

Bamboo is structured beautifully and is unique from other plants and trees that share similar characteristics and features. The main components of a bamboo plant include rhizomes, roots, culms, branches, leaves, and flowers (Resource Centre for Natural Fibre Crafts Project, 2015).

Rhizomes are horizontal stems extending from the main plant that travel underground with the objective of colonizing new territory. As rhizomes spread through the soil, they collect and store the primary nutrients for growth (Gross, 2009). This also gives bamboo plants the ability to utilize energy created from photosynthesis and that stored in the rhizomes (Long et al., 2003; Resource Centre for Natural Fibre Crafts Project, 2015). Liese (1998) emphasized the importance of sheath that provides the plant with the protection needed to crack the surface to form a culm. He noted that healthy rhizome is usually slightly yellow or ivory in colour, although possible colours may include red, brown, green, and purple (Gross, 2009). The appearance and behaviour of rhizomes differ among species, and a rhizome is divided into three main categories including pachymorph, leptomorph and compounding.

The pachymorph (sympodial) rhizome system, which is found in clumping bamboos, expands horizontally only by short distances each year (Gross, 2009; The Behavior of Bamboo, 2012). The rhizomes are generally short and thick in appearance and curved upwards in close proximity to the domain plant. It is this feature that causes them to curve upwards and exhibit the clumping behaviour (Resource Centre for Natural Fibre Crafts Project, 2015). However, the plants can be easily controlled.

The leptomorph (monopodial) rhizome system is found in running bamboos. In contrast to the pachymorph system, the rhizomes have a tendency to branch away from the domain plant. They are invasive by design and it can be extremely difficult to remove a well-established plant as it is with genus Phyllostachys and Pleioblastus (Fu, n.d.).

The compounding type (Amphipodia) spreads as the rhizome runs along the ground with shoots emerge from the tip of the rhizome and growing upwards. A typical example is the *Guadua angustifolia* which forms clusters or clumps (Gross, 2009; The Anatomy of a Bamboo Plant, 2012).

Qisheng, Shenxue, and Yongyu (2001) also categorized bamboo into four types: monopodial, sympodial tufted, sympodial scattered and mixpodial, based on the nature of the rhizome. The monopodial type has axillary buds on the stem base that develop into thin rhizomes running horizontally for a long distance underground. Some of the buds grow into rhizomes in the soil while some turn into shoots (Kigomo, 2007). The bamboo stems of such species grow in scattered state, forming scattered bamboo bushes. *Phyllostachys* and *Pleioblastus* are common genera which thrive well in the temperate zones.

Culms are the most visibly distinguishable feature of a bamboo plant. Culms can vary in size, shape, colour, and even smell. The appearance can range from thick or thin, tall or short, erect or bent, and can exhibit irregular patterns such as those found in Tortoise Shell Bamboo (*Phyllostachys heterocycla* ‘Moso', *P. heterocycla* ‘Kiko'). Most culms are round in shape, but some species can take on a square- like appearance. The colour of the culms also has a wide range of characteristics. Although the majority of bamboos are green, they can also be brown, black, yellow, or striped.

The anatomy of the leaf itself includes a blade, sheath, and ligule. Leaves are first present in the rhizome where they almost completely comprise the sheath. At this stage, leaves serve as a protective cover to encase the rhizome as it travels underground. The blade provides the photosynthetic function of the plant by converting sunlight into energy (Liese, 1987). The appearance of leaves plays a large role in the identification of bamboo.

The major peculiarity of bamboo is that most species flower very infrequently, with intervals as long as 60 to 120 years. These species exhibit what is called mass flowering where all plants in the population flower at the same time. This phenomenon has restricted the commercialization of many species, as flowering causes the bamboo plant to die. In vegetative propagated plants, it is almost impossible to predict the flowering pattern. However, if a flowering event occurs and seedlings are utilized, flowering is not expected for another 60-120 years depending upon the species (Muller & Rebelo, 2015).

*Bamboo stem morphology*

Bamboo plant includes the rhizome, the culm, the leaves, the flowers and fruits, in which the culm is the most useful part for industrial utilization. The bamboo culm consists of three parts: stem, stem base and stem petiole. Its length, diameter, stem wall thickness and the number of nodes are varied with different bamboo species. According to Liese (1987, 1992), *P. pubescens* has the height of 10 – 20 m; its diameter is 20 – 30 cm, its stem wall thickness is about 10 mm and the nodes are more than 10. Some bamboo's diameter is only about 1 cm, 2 – 3 m in height, and stem wall's thickness is 2 – 3 mm.

The stem is always straight and cone or ellipse cone, which has visible parts comprising nodes and internodes. The internodes are hollow inside, which form stem cavities. The wall around the cavities is called stem wall. The thickness of stem wall varies greatly according to different species. According to Schroder (2011), every node has two closely positioned rings. The lower one is called sheath ring, a scar formed after the falling of sheath. The upper one is called stem ring, a scar formed after the growth-cease of inter-node tissue. The part between the rings is the node itself. The nodes help the bamboo to be straighter and they also contain water and nutrients; however, they are bad for bamboo slices (Liese & Ding, 2003; Taylor et al., 2014).

The stem base is the lower part of the bamboo stem; it extends into the soil to connect with the root system. The stem base consists of numerous short sections, and the diameter is quite significant. Its adventitious roots grow densely on the sections. On the stem bases of some bamboo species, there are up to ten alternate buds, which grow into shoots and then bamboo stems. In the industrial utilization of bamboo, particularly for making bamboo-based panels, bamboo species with large stems are selected.

Bamboos are monocotyledonous and possess only primary shoot without secondary growth (Ghosh & Negi, 1959). All the growth in bamboos occurs longitudinally and there is no lateral or radial growth as in trees. Characteristically, bamboo has a hollow stem or culm that is closed at intervals by nodes. *Figure 2* and *Figure 3* show a portion of bamboo culms consisting of nodes and internodes.

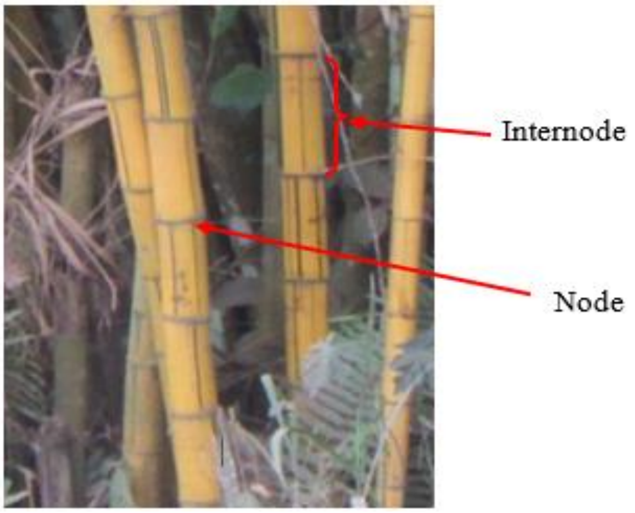


*Figure 2*: Portions of bamboo showing nodes and internodes

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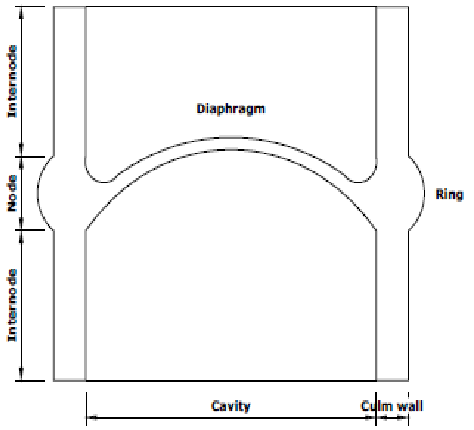


*Figure 3*: Longitudinal section of a bamboo culm

*Anatomical composition*

The properties of the culm are determined by its anatomical structure. The culm consists of internodes and nodes (*Figure 2*). At the internodes, the cells are axially oriented, whereas at the nodes, cells provide the transverse interconnections. No radial cell elements such as rays exist in the internodes. Within the nodes an intensive branching of the vessels occurs. These also bend radially inward and provide transverse conduction through the nodal diaphragms, so that all parts of the culm are interwoven (Liese, 1985). The outer part of the culm is formed by two epidermal cell layers, the inner appearing thicker and highly lignified. The surfaces of outermost cells are covered by a cutinized layer with a wax polymer coating of hydroxyl acids.

Liese (1980b) found the culm to be composed of about 50% parenchyma, 40% fibre, and 10% conducting tissues with some variation according to species. The percentage distribution and orientation of cells display a definite configuration within the culm, both parallel and perpendicularly (StudyMode.com, 2012). At the outer part of the culm the vascular bundles are smaller and more numerous while the inner parts are larger and fewer (Grosser & Liese, 1971; Mustafa et al., 2011).

Within the culm wall the total number of vascular bundles decreases from bottom towards the top, while their density increases at the same time (Kelemwork, 2008; Liese, 1980a). Espiloy (1987) found vascular bundles of *G. scortechinii* to be negatively correlated to moisture content, tangential shrinkage, stress at proportional limit and modulus of rapture. He also found similar results for *B. blumeana*. This indicates that vascular bundle distribution has an influence on the physical and mechanical properties which vary between and within species. However, he found compressive loading, the incidence of vascular bundles along culm height, to have no significant effects.

The culm tissue is mostly parenchyma and the vascular bundles are composed of vessels, sieve tubes with companion cells and fibres. Abd. Latif (1987) and Murphy and Alvin (1997) conducted a study of vascular bundles of some Malaysian bamboo and indicated that the bamboos are characterized as having fibre strands positioned with the vascular bundles but entirely surrounded by ground tissues. Also, bamboo does not possess any special cells for radial transport like the rays of dicotyledonous and gymnosperms. According to Grosser and Liese (1971), most of the bamboo species have separate fibre strands on the inner, or both on the inner and outer of the vascular bundle.

Parenchyma and conducting cells are more frequent in the inner third of the wall, whereas in the outer third the percentage of fibres is distinctly higher. In the vertical direction, the amount of fibres increases from bottom to top and that of parenchyma decreases (StudyMode.com., 2012). This is an indication that it is wasteful, leaving the upper part of a cut culm unused as is commonly done.

The bamboo culm vascular bundles consist of xylem with two large metaxylem vessels (40-120 µm) with one or two proxylem elements and the phloem with thin walled, unlignified sieve tubes connected with companion cells. The vessels are larger at the inner part of the culm and become smaller towards the outer part. Most of the species have separate fibre strands on the inner or side of the vascular bundles (Liese, 1980). The number of vascular bundles varies within species but not with age and height of bamboos and their interaction. *Figure 4* and *Figure 5* show the distribution of vascular bundles and anatomical structure of *G. scortechinii*.

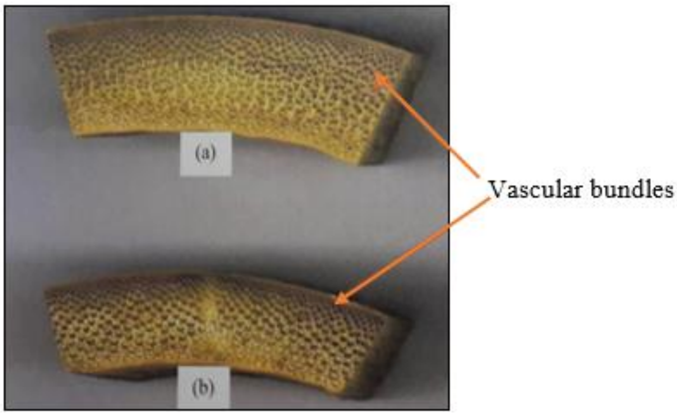


*Figure 4*: Distribution of vascular bundle structure of 4-year old *G. scortechinii* (a) at 14th internode (Anwar et al., 2005)

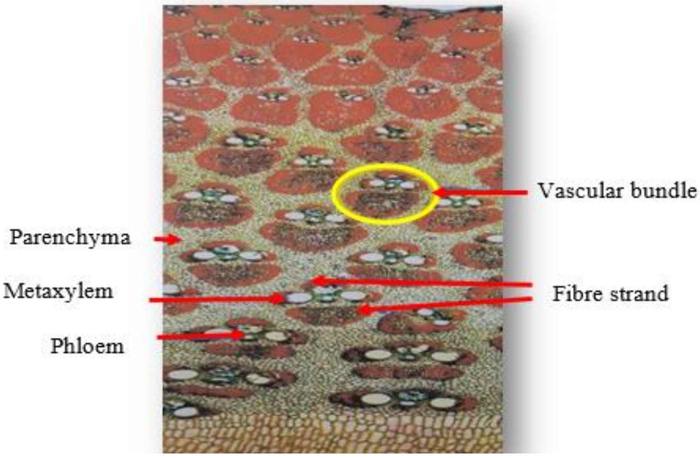


*Figure 5*: Cross-section of G. scortechinii (Anwar et al., 2005)

The fibres in bamboo are grouped in bundles and sheaths around the vessel. Kumar et al. (1994) and Tamolang et al. (1980) also noticed that fibres in both nodes and internodes tend to become shorter toward the top portion while the internodal fibres are longer than the nodal fibres. Parenchyma and conducting cells are more frequent in the inner third of the wall, whereas in the outer third the percentage of fibre is higher (Chaowana, 2013). Parenchyma tissue percentages are higher in the basal internodes and gradually decrease towards the top. The percentage of parenchyma is reduced towards the periphery and increases towards the inside of the culm (Liese, 1998).

*Chemical composition*

The properties of bamboo are demonstrated by its chemical composition and structure. The research on chemical composition is of great importance since it affects the durability of the end products. The main organic components of bamboo culms are similar to those of wood, mainly cellulose (±55%), hemi-cellulose (±20%) and lignin (±25%), which amount to over 90% of the total mass (Tomalang et al., 1980). The minor components, which vary with different parts of bamboo stem and different ages of the same bamboo stem, are resins, tannins, waxes and inorganic salts.

Compared with wood, however, bamboo has higher alkaline extractives, ash and silica contents (Chen, Qin, Li, Gong, & Ni, 1985). Yusoff, Abd.Kadir, and Mohamed (1992) studied the chemical

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composition of one, two, and three-year old bamboo (*G. scortechinii*). The results indicated that the holocellulose content did not vary much among different ages of bamboo. Bamboo has similar chemical composition to that of wood except its high alkaline extract, ash and silica contents. The carbohydrate content of bamboo plays an important role in its durability and service life. The durability of bamboo against mold, fungal and borers attack is strongly associated with the chemical composition (Liese, 1980).

**Physical properties of bamboo material**

*Moisture content*

The moisture content (MC) of growing bamboo is rather high; it depends on different seasons and species. The average MC of G. scortechinii at the cutting age is approximately 90% (Hamdan et al., 2009). Halis et al. (2008) found five bamboo species in Malaysia to have average initial moisture content of 67%. However, Razak et al. (2007) recorded 89% green MC for a four-year-old *B. vulgaris*. Liese (1985) found the MC within the culm wall to be higher in the middle part than the outer part of *D. stritus*.

Qisheng et al. (2001) also found the MC of a growing bamboo to be very high depending on different seasons and species. They stated that the average moisture content of *P. pubescens* at the cutting age to be approximately 80% with equilibrium MC of bamboo material after air seasoning changes in connection with atmosphere temperature and humidity as 15.7% of *P.* pubescens in the Beijing area.

The variation of MC within the culm wall was very much attributed to the distribution of vascular bundles (Qisheng et al., 2001). They further found that the vascular bundles at the peripheral zone were much more distributed than in the inner zone, and most of the cells were parenchyma, which has a better water holding capacity than the vascular bundles. Hence the higher the content of parenchyma cells in the inner zone, the higher the water holding capacity and thereby affecting shrinkage.

The equilibrium moisture content (EMC) of bamboo material after air seasoning changes according to the atmosphere's temperature and humidity. The MC of bamboo is very crucial since it can affect the physical properties especially the strength when it changes below the fibre saturation point. When moisture is reduced, strength increases and vice versa.

The MC of bamboo is the decisive factor for its use as a structural element, and as all physico-mechanical properties are functions of it (Wakchaure & Kute, 2012). The moisture content also predicts the life span of bamboo material as it easily attracts fungi and borer insects. The speedy rotting process in bamboo is a result of high water content. Bamboo is more prone to insect attack than other trees and grasses because of its high content of nutrients. The MC along the height of bamboo culm is also not constant, so are also the physical and mechanical properties.

*Density*

Density is the best and the simplest determinant of strength of wood and for that matter bamboo without defects. With increasing density, strength also increases. The relationship of density and strength varies with properties and species. The basic density of bamboo material (whole stem weight /green bamboo volume) is in the range of 0.40 - 0.9 g/cm3 and this is mainly dependent on the density of the vascular bundles and their composition.

As a rule, the density of bamboo stem increases from inner to outer part, and from lower to upper part. The density of inner layers of stem wall increases with the growth of stem and the thickness of wall, while the outer layers only change slightly. The density of nodes is higher than that of internodes and according to Razak, Janshah and Hashim (2007), the lower internodes have higher density than the upper internodes.

*Dry shrinkage*

Dry shrinkage of bamboo is a result from water evaporation in the drying process after cutting. The amount of shrinkage is proportional to the moisture lost below the fibre saturation point. It also depends on the amount of accessible cell wall materials such as vascular bundles and parenchyma cells, i.e. the basic density of the bamboo. The dry shrinkage varies in different directions. From air seasoning to full drying, when the moisture content decreases 1%, the average shrinkage rate of *P. pubescens* is as follows: lengthwise - 0.024%, tangential - 0.1822%, radial - 0.1890% (on node parts - 0.2726%, on internode parts 0.1521%). It is clear that the lengthwise shrinkage is much less than crosswise shrinkage, while the tangential shrinkage is similar to radial shrinkage. Liese (1987) reports that bamboo material shrinks as it begins to be dried. This is different from timber. When moisture content decreases to certain extent, dry shrinkage almost stops, but when drying process continues, dry shrinkage starts again.

Several authors (O. Razak & Latif, 1995; Sekhar & Rawat, 1964; Tewari, 1992) have reported the immediate shrinkage behaviour of bamboo although no scientific reason was given to explain the observations. Mansur (2000) related this to the presence of free water (water in the lumen) and bound water (water in the cell wall) in bamboo. The considerably small amount of water in the former could possibly explain shrinkage of bamboo as soon as it begins to lose moisture immediately after felling.

According to Anwar et al. (2005), the shrinkage of *G. scortechinii* from green to oven dry condition indicated that bamboo, in the form of a strip (without epidermis and inner layer), shrank more than the split (with epidermis and inner layer) and outer split in the radial and tangential directions. The term strips are defined as squared splits obtained by removing the epidermis and the inner layer of bamboo splits.

The radial and tangential shrinkage for bamboo strips were reported to be 23.7% and 19.8% respectively (Anwar et al., 2005). Bamboo splits on the other hand, experienced less radial and tangential shrinkages where the values being respectively 20.9% and 12.4%. Hamdan, Hill, Zaidon, Anwar and Abd. Latif (2007) observed that the geometry of the samples also has some effects on the sorption properties as observed in strips being more hygroscopic than splits.

*Dimensional stability*

The dimensional stability exhibited by bamboo also happens in timber ("Physical properties of Calcutta bamboo," n.d.). The behaviour is posited to have occurred in timber as a result of the orientation of most of the microfibrils (S2 layer) which is aligned parallel to the longitudinal axis. The explanation of this behaviour can also be applied to bamboo. According to the study of the anatomical structure by (Parameswaran & Liese, 1976), there are two types of microfibril orientation in bamboo, the narrow lamellae showing fibrillar angle of 80 – 90° to the axis and the broader ones with fibrillar angle almost parallel to the axis as in *Figure 6* (Wang, Ren, Zhang, Fei, & Burgert, 2012).

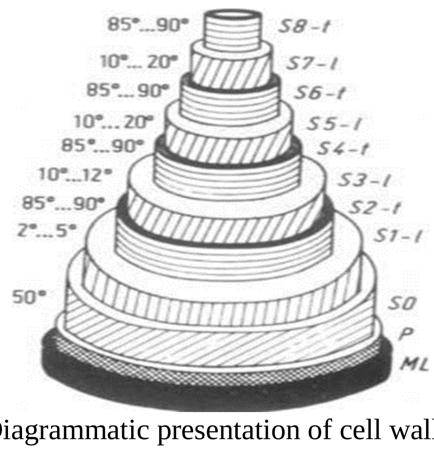


*Figure 6:* Diagrammatic presentation of cell wall in bamboo.

Although the fibres in bamboo demonstrate a polylamellate nature (8 lamellae compared to 3 lamellae in wood (S1, S2 and S3)), the broad fibril layer, which is parallel to the axis, is greater when compared to the narrow lamellae. Unlike wood, bamboo starts to shrink from the very beginning of drying (Yu, 2007). The removal of moisture in the cell wall, that is hygroscopic or bound water, causes shrinkage to take place as a result of the contraction of the microfibrillar net in proportion to the amount of liquid evaporated (Panshin & de Zeeuw, 1970). Bamboo, like wood, changes its dimensions when it loses moisture. The MC changes with changes in the relative humidity and temperature of the surrounding environment (Glass & Zelinka, 2010; Kushwaha, 2012; Sethia & Baradiya, 2014; Shaw, 2012; Simpson & TenWolde, 1999). The studies also found dimensional stability as a very crucial element in structures because the safety and comfort in a structure usually depend on them. Accordingly, Razak et al. (2013) found bamboo to begin changing its dimensions as soon as it starts to lose moisture.

Simpson and Tenwolde (1999) maintained that moisture relationship has an important influence on wood properties. Dimensional stability has been evaluated by measuring dimensional changes in load free wood specimens. Wood components were often subjected to humidity variations under mechanical force (Norimoto, 2001). The dimensional stability treatment is one that reduces or prevents swelling in wood no matter how long it is in contact with moisture or liquid water (Rowell, 2005). Stamm (1964) stated that the methods for attaining improved dimensional stability of wood fall into one or more of these types:

a. Laminating of anisotropic sheets as to restrain the dimensional changes of sheet in the direction in which swelling is the greatest by cross-sheets that swell in this direction as in plywood.
b. Applying water-resistant surface and internal coating to retard moisture adsorption.
c. Reducing the hygroscopicity of the cellulose materials, thus reducing water adsorption and swelling.
d. Bulking the fibre so as to reduce the amount of water that the component fibres can hold.
e. Cross-linking the cellulose chains of the component fibres that their separation by water adsorption is minimized.

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**Mechanical properties of bamboo**

The mechanical properties of bamboo are the measure of its resistance to external forces which tend to deform its mass. The resistance to such forces will depend on the magnitude and manner of loading (tension, compression, shear, bending, etc.). The strength of bamboo depends on species, moisture content, density, and age and culm height (Rangqui & Kuihong, 1987; O. Razak & Latif, 1995).

The strength of bamboo increases as it becomes older due to the hardening of the culm walls. Abd. Latif (1987) concluded that with age increment, mature tissues start to develop and continue to influence density, strength properties, growth of branches, and established root system in one to three-year old Malaysian bamboos. He reiterated that as bamboo matures, the culm wall thickness becomes hard resulting in maximum strength. Bamboo matures in about three years; it reaches its maximum strength (Liese, 1985; Young & Haun, 1961; Zhou, 1981). Bamboo splits and strips behave more like solid wood as the mechanical properties increase with decrease in MC (Gnanaharan, Janssen, & Arce, 1994; Hamdan, 2004a).

The increase in wall thickness is not only due to thickening of the existing cell wall, but by the deposition of additional lamellae (*Figure 6*). Liese (1998) found the 1-year-old culm to have three lamellae at the base (2.6 µm), and a 12-year-old has about eight lamellae (8 µm). Parameswaran & Liese (1976) also found multilayer-texture of different lamellae with two types of microfibril orientation in bamboo, the narrow lamellae showing fabrillar angle of 80° - 90° to the axis and the broader ones with fabrillar angle almost parallel to the axis as indicated in Figure 6.

Bamboo exhibits an excellent strength property, especially in tensile parallel to the grain. Most mechanical properties of bamboo are closely correlated with specific gravity and density. The strength, as well as the stiffness increases with specific gravity (Janssen, 1981). *Table 1* shows the strength and stiffness of bamboo culms (in round form) compared with other building materials.

*Table 1*: Comparing the efficiency of materials for strength and stiffness

| Material | Strength ($Nmm^{-2}$) | Weight by volume | Ratio* | Stiffness ($Nmm^{-2}$) | Weight by volume | Ratio* |
|---|---|---|---|---|---|---|
| Concrete | 8 | 2400 | 0.003 | 25000 | 24000 | 10 |
| Steel | 160 | 7800 | 0.02 | 210000 | 7800 | 27 |
| Wood | 7.5 | 600 | 0.013 | 11000 | 600 | 18 |
| Bamboo | 10 | 600 | 0.017 | 20000 | 600 | 33 |

*Ratio = stregth or stiffness / weight by volume, Janssen (1981)

For bamboo to be accepted as an alternative to wood, it must be able to show a considerable agreement to the various mechanical properties exhibited by wood. Bamboo, similar to wood, is a kind of heterogeneous and anisotropic material. Therefore, its mechanical properties are extremely unstable, and in certain respects it is more unstable than wood (Ogunwusi & Onwualu, 2013). According to the complexity:

a It is due to the uneven distribution of vascular bundles, density, dry shrinkage and strength changed in connection with different heights and positions. In general, the distribution of vascular bundles in the outer part of the stem wall is much closer than in the inner part, thus the strength of the outer part is higher (Chand, Shukla, & Sharma, 2008). The density of bamboo stem wall thickness increases from the lower part, consequently the strength also improves in the same direction.

b The difference in MC also affects the physical and mechanical properties. A change in MC of wood from 12% to 6% and 20% can respectively increase or decreased the compressive strength by 35%, indicating that, higher MC has detrimental effect on compressive strength (Gerhards, 1982).

c Physico-mechanical properties of node parts and internode parts are different. For instance the tensile strength of nodes is less than that of internode (Semple et al., 2015; Shao et al., 2010).

d The physical and mechanical properties of bamboo stem tend to modify with age. Normally, a 2-year old bamboo material is softer and with lower strength whereas that of 4 to 6 years is tough and with high strength. However, 7 years and above bamboo materials are brittle with a very low strength.

e Physical and mechanical properties of bamboo materials are different in radial, tangential and longitudinal directions (Ogunwusi et al., 2013). For example, the cleavage strength parallel to grain is the lowest.

However, Knudson (1992) found the removal of the naturally occurring inhomogeneity such as nodes tend to create discontinuities in the orthotropic character of bamboo, and reassembling it as is done with wood composites to lower the coefficient of variation than solid wood. This gives bamboo an advantage over solid wood as it relatively has a small variability in their mechanical properties. *Table 2* presents the strength and stiffness of common bamboo culms as compared with timber.

*Table 2*: Mechanical properties of bamboo culms and timber from different countries

| Species | Country | SG | MC (%) | MOR ($Nmm^{-2}$) | MOE ($Nmm^{-2}$) |
|---|---|---|---|---|---|
| Bamboo | | | | | |
| *Bambuas bambos* | India | 0.65 | 15.5 | 67.4 | 6500 |
| *B. blumeana* | Philippines | 0.50 | green | 30.8 | 8640 |
| *B.nutans* | Bangladesh | 0.68 | 12.8 | 87.7 | 12900 |
| *B. tulda* | India | 0.71 | 14.9 | 50.6 | 8265 |
| *B.vulgaris* | Indonesia | na | 17.0 | 86.0 | na |
| *B. balcooa* | Bangladesh | 0.74 | 12.5 | 80.3 | 10900 |
| *Dendrocalamus asper* | Indonesia | na | 15.0 | 105 | na |
| *D. strictus* | India | 0.72 | 10.7 | 118.4 | 15949 |
| Timber | | | | | |
| *Melocanna bacifera* | Bangladesh | 0.66 | 12.0 | 72.3 | 23200 |
| *Tectona grandis* | India | 0.60 | 12.0 | 95.9 | 11960 |
| *T. grandis* | Bangladesh | 0.59 | 12.0 | 100.8 | 13100 |
| *Shorea robusta* | India | 0.71 | 12.0 | 131.8 | 16204 |
| *S. robusta* | Bangladesh | 0.78 | 12.0 | 103.7 | 12800 |
| *Koompasia malaccensis* | Malaysia | na | 12.0 | 122 | 18600 |
| *Intsia palembanica* | Malaysia | na | 12.0 | 116 | 15400 |
| *Hevea brasiliensis* | Malaysia | na | 12.0 | 66 | 9240 |

Note: SG = Specific gravity; MC= Moisture content; MOR = Modulus of rapture; MOE = Modulus of elasticity; na = not available (Sattar, 1995)

*Strength in bending*

The strength of bamboo strip in bending is an important mechanical property since most of the structures constructed from bamboo are likely to be subjected to loads that may cause it to bend. This is usually expressed by modulus of rapture (MOR) which shows the highest stresses in the outmost fibres of bamboo.

Hamdan, Zaidon, and Tamizi (2009) found the MOR of *G. scortechinii* bamboo generally increases in height in both the node and the internodes from 129.2 to 123.3 $Nmm^{-2}$ and 155.8 to 151.2 $Nmm^{-2}$ respectively. These are all higher than the bamboo and timber species tested in Table 2, making it one of the strongest bamboo species. Mansur (2000) also found the mechanical properties to be greater at the top portion when nodes and internodes were tested at dry condition. They also found modulus of elasticity (MOE) is usually determined from the static than the dynamic bending tests of bamboo under dry conditions to be increased in height though with no significant difference. The static bending is preferable due to its accuracy in result values (Tsoumis, 1991).

*Strength in compression*

The strength of bamboo in compression just as in wood is also different if loads are applied parallel or transverse to the grain (Xu, Harries, Li, Liu, & Gottron, 2014). The study indicated that compressive strength falls with an increase in MC. Hamdan et al. (2009) reported a difference in failure behaviour between nodes and internodes. They further reported significantly higher values at the internodes than the nodes except for MOR tested for compression, indicating that in order to maximize the stiffness and strength during usage, the node or the internode sections of bamboo strips should be orientated.

*Strength in shear and percentage of wood failure*

Xiao, Wang, and Chui (2007) studied shear strength and percentage of wood failure of different wood species. They found the shear strength increases and the glue penetration decreases as wood density increases. Increasing initial MC of wood also has a positive effect on shear strength and glue penetration. Joints with low density and at a low MC have low shear strength due to over-penetration of glue.

Correal and Ramirez (2010) suggested that bond shear strength is not affected by bamboo species with similar densities and adhesive spread rates. Also, the amount of the adhesive applied on the wide and narrow faces does not affect the value of bond shear strength.

The presence of additives influences the penetration of the adhesive (Kamke & Lee, 2007). Therefore, the study highlighted the inclusion of castor oil in the formulation of polyurethane adhesive, which can make it less sticky and easy to penetrate. Amorim and Del Menezzi (n.d.) found a lower percentage of wood failure to be related to a higher efficiency of the adhesive. They indicated that rupture occurred most often in the panels, neither in the timber nor in the glue line. This situation provides reliability to the bonding and can be justified by the lower strength of LBT panels to the rupture when compared to solid wood

**Laminated bamboo products**

Many works have been carried out in several countries in developing laminated bamboo products. As many as 28 laminated bamboo products that combine wood and other organic materials have been reported (Ganapathy et al., 1999). Jagadeesh and Ganapathy (1995) noted that bamboo composite materials particularly mat board and plywood, can be made into potential walling materials, either as sheathing or stressed skin construction for prefabricated houses. The properties of some bamboo panel products are shown in *Table 3*.

*Table 3*: Properties of some bamboo panel products (Ganapathy et al., 1999)

| Types of bamboo product | Density ($kgm^{-3}$) | MOR ($Nmm^{-2}$) | MOE ($Nmm^{-2}$) |
|---|---|---|---|
| Bamboo Mat board (India) | 766 | 51 | 3678 |
| Bamboo Mat board (China) | 850 | 93 | na |
| Bamboo Curtain board (China) | 850 | 121 | 12500 |
| Bamboo Strip board (Vietnam) | 815 | 124 | 9600 |
| Bamboo Strip board (China) | 780 | 113 | na |
| Bamboo Parallel glulam (China) | 850 | 167 | 11500 |

Note: na = not available

Huang (1992) also made comparison between bamboo and wooden platform boards based on bending strength as shown in *Table 4*.

*Table 4*: Bending strength of bamboo and wooden platform boards

| Bending strength | | Max. Deflect / max. carrying capacity prior to breakage | |
|---|---|---|---|
| Load | | Fixed with 4 M 10 screws | Fixed with 10 M 10 screws |
| CL | BB | 44mm/27.5KN | 42mm/30KN |
| | WB | 35mm/7.5 KN | na |
| UL | BB | 51mm/30KN | 57mm/30KN |
| | WB | na | 29MM/28KN |

Notes: CL=Concentrated loading; UL =Uniform loading; BB = Bamboo board; WB= wood board; na = not available

Numerous studies have been conducted on the utilization of bamboo culms in particular for *Bambusa vulgaris* and *Gigantochloa scortechinii*. These bamboos were reported to be suitable for manufacturing cement-bonded particleboard (Chew et al., 1992), particleboard (Jamaluddin et al., 1999), laminated bamboo board (Razak et al., 1997), plybamboo (Zaidon et al., 2004; Anwar et al., 2004) and bamwood (Anwar et al., 2005), These products, however, have not been highly commercialized because of inconsistent supply of bamboos, competitiveness in land acquisition and also limited supply of quality planting stocks. Another disadvantage is that there are no established methods for harvesting, processing and product quality control (Azmy & Appanah, 1998).

The Asian region has made some progress in the development of bamboo with China taking the lead of producing a new type of bamboo composite panel (over 90% bamboo) called laminated bamboo fibrillated-veneer lumber (LBL). Among the products are ply bamboo and laminated bamboo lumber.

Mahdavi et al. (2011) see laminated bamboo lumber as a relatively new concept that involves gluing together bamboo materials in various forms either strands or mats to form rectangular boards, similar to lumber (Mahdavi et al., 2011; Ramirez et al., 2012).

Despite its commercial potentials, only a small body of research on LBL exists in the literature. Two patents exist—the first patent, by Chu, entitled "Bamboo board" [U.S. Patent No. 4,810,551 (1989)], describes a product that is similar in lay-up to plywood, and the second, by Plaehn, entitled "Parallel randomly stacked, stranded, laminated bamboo boards and beams" [U.S. Patent No. 5,543,197 (1996)], is similar in lay-up to parallel strand lumber (PSL). The second patent describes the composition of the beam as bonded bamboo segments, specifically, bamboo stalks that are split open and dried in segments ranging from 6.5 to 8.5 mm in width to approximately 1.5 – 6 m in length (Mahdavi, Clouston, & Arwade, 2012; Mahdavi et al., 2011). The core may contain gaps as a result of the cross-sectional shape of the bamboo segments and the randomness of the stacking of the segments.

## Conclusion

Laminated bamboo timber is an excellent engineering material of great extents, high strength and stiffness with small deformation and relatively stable when used in dry conditions. Its excellent strength-to-weight ratio far exceeds those of structural steel, aluminum alloy, cast iron, timber, and concrete, showing that it has a very efficient load-bearing capability. The review suggests the feasibility of using bamboo materials for boards, blocks and laminations through advanced processing technologies. However, a couple of challenges have been identified. Among them are that normal precautions should be taken for moisture and dimensional stability as would be done for wood (Mahdavi et al., 2011). Also, adequate surface treatment is required since adhesives do not bond well in bamboo.

To sum up, considerable comparison on the most common bamboo species has not been well established. The identification of the similarities among the species will promote the processing of similar species since the current bulk of supply is from the wild. Further study is also required into the improvement of processing procedures in order to produce high grade LBT.

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