# I

# RESEARCH ARTICLES

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

# EVALUATION OF THE MECHANICAL PROPERTIES OF BAMBUSA BAMBOO LAMINATES THROUGH DESTRUCTIVE TESTING

Raviduth Ramful[1]


## ABSTRACT

In this research study, *Bambusa ssp*, the utilized species of bamboo, was rendered into a more versatile construction material in the form of laminates. The laminated specimens were manufactured using simplified processing methods according to the ASTM D3039 and ASTM D143 standards. Polyvinyl acetate was the adhesive used between the 2-ply laminate. The mechanical properties of the specimens were evaluated through tensile, compressive and bending strength tests according to set standards on the Testometric M500-50AT Universal Testing Machine. The tensile strength of laminated bamboo was comparable to that of redwood, spruce, cedar and pine. The ratio of compressive strength of parallel to perpendicular fibers in compressive tests was in a close range to that of poplar, fir and pine. The correlation in compressive strength values between bamboo and wood confirmed the inherent anisotropic nature of both plant materials.



## KEYWORDS

Bamboo, Laminates, Structural, Universal Testing Machine


Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

## 1. INTRODUCTION

By 2050, with an estimated world population nearing the 9 billion, the exploitation of existing conventional construction material such as wood, concrete and metals will be further stretched to their limit (UN News 2013). In order to keep up with this increasing trend in material needs, as well as growing interests in eco-friendly development, the consideration of sustainable material as an alternative in the construction sector will alleviate the dependency on depleted resources. With continued growth and economic development worldwide, it has become essential to minimize the impact of human activities on the environment. The incorporation of sustainable development in modern infrastructures would be viable in the long run given the consideration of factors such as availability, environmental impact, resilience and so forth.

With favorable characteristics and advantages over traditional building materials such as concrete or steel, wood is still widely considered as a sustainable alternative in many engineering applications (Falk 2009). As shown in Figure 1, 47% of the world's forests have already been wiped out while preserved natural habitats account for around 20% (World Resource Institute

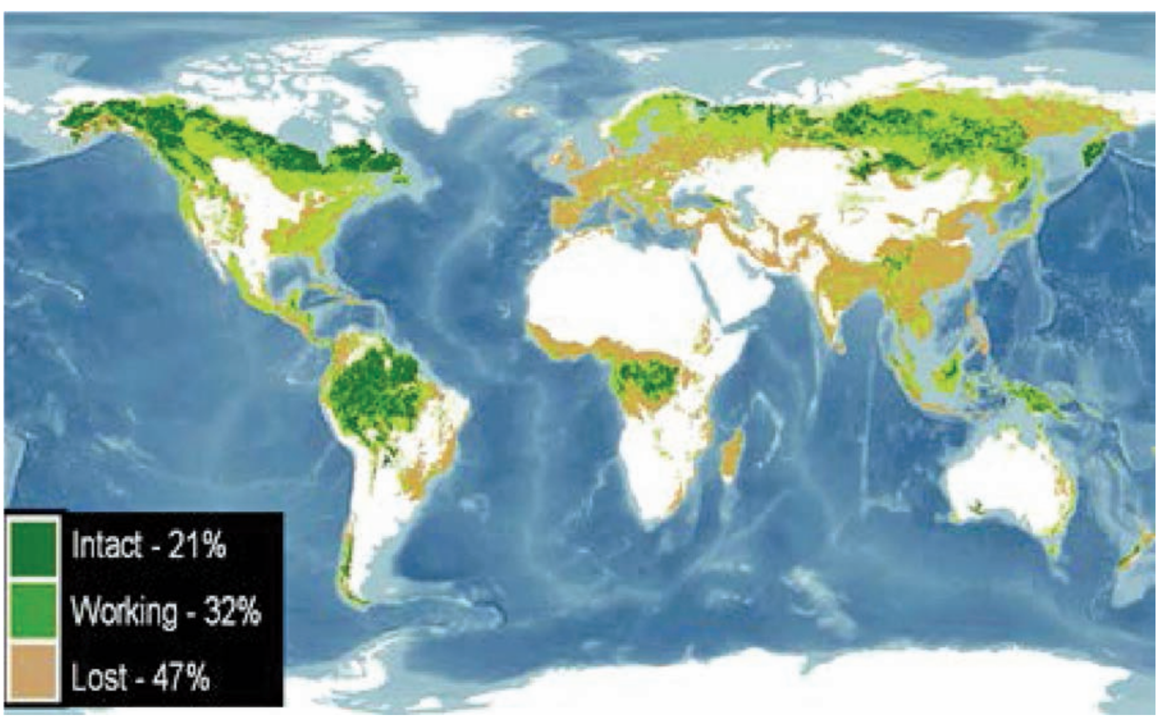
1. Mechanical and Production Engineering Department, Faculty of Engineering, University of Mauritius, r.ramful@uom.ac.mu.

2009). Despite its inherent favorable characteristics as a building material, timber can no longer be considered as a sustainable resource due to its relatively slow regeneration rate.

In order to replace wood with alternatives of the same characteristics, Graham (2011) proposed hemp, soy, cardboard, straw and bamboo. When processed into composites, products in the form of plywood and engineered-timber could be easily replicated. With its unrivalled mechanical properties, usage of bamboo as a structural building material is becoming an important subject of study. It is still widely used as a construction material in many countries (Lobovikov *et al.* 2007). Bamboo has been thoroughly studied in Asian countries and is recognized globally based on its remarkable physical and mechanical characteristics. It is categorized as grass and is part of the *Poaceae* or *Gramineae* family. Due to its tubular structure, natural bamboo does not easily fit into assemblies and requires specific joining techniques.

Another advantage of bamboo apart its remarkable strength is its regeneration rate which completely outclasses timber in that category; in fact, one bamboo species even holds the world record for fastest growing plant on Earth, i.e., up to 91 cm per day (Guinness World Records 2016). Being an invasive species, bamboo is sustainable and can reach maturity in 3 years compared to wood, which can take several decades in some cases before maturity is attained. Additionally, being also anisotropic, the mechanical properties of bamboo culms correspond to a large extent to that of wood. Investigation by Ghavami (2003) additionally supported the inherent mechanical characteristic of bamboo, namely an impressively high strength to weight ratio coupled with a high specific load bearing capacity. In addition, some of its compelling properties can be further enhanced when utilized as a composite material. As suggested by Awaludin and Andriani (2014), the material was further reinforced using fiber-reinforced plastic (FRP) technique.

**FIGURE 1.** Distribution of world's global forest.




Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

Due to the peripheral arrangement of fibers varying in the transverse, longitudinal or radial directions, it often poses a challenge to employ bamboo conventionally, namely in beam application. According to Sharma (2015), re-engineered bamboo laminates would be more suitable to form joints and connections. The usability and strength of natural bamboo can be further improved by considering processed laminates where a highly strong polymer matrix is used (Mahdavi 2011). In construction, bamboo with large diameters are mostly employed, namely *Dendrocalamus Giganteus* (Dendrocalamus), *Phyllostachys heterocycla pubescens* (Moso), *Bambusa Stenostachya* (Tre Gai) and *Guadua angustifolia* (Guadua). Laminated bamboo boards designed for construction are already the manufacturing norm in Europe and North America. Nigeria, which has an abundant amount of bamboo, is maximizing its use in the manufacture of laminates for flooring and wall application. This initiative is not only curbing the demand for wood, but is a step forward towards minimizing deforestation (Atanda 2015).

### 1.1 Bamboo Characterization

Bamboo, which is an anisotropic material, has considerable strength and rigidity throughout its axial length in contrast to its crosswise direction (Chen *et al.* 2011). The hollow culm of bamboo has longitudinal fibers that are aligned in a matrix of lignin and divided by nodes along its length. As it is not composed of the same extractives as wood, bamboo can easily be glued into laminates (Janssen 1981). However, being a hydrophilic material, bamboo tends to absorb moisture and humidity from its environment. This variation in dimension is significant and has a direct impact on the physical and mechanical properties of bamboo (Shi & Gardner 2006). According to The Food and Agricultural Research & Extension Institute (FAREI) in Mauritius, the diameter does not only vary between species but also by region. Bamboo tends to grow faster and have thicker wall diameters in wet climates such as near river banks.

The research carried out by Dixon and Gibson (2014), on the structure and mechanics of Moso bamboo revealed that the material exhibited comparable and better mechanical properties to North American softwoods. The modulus of rupture and compressive strength of the bamboo was found to be much higher than softwoods, namely white pine, Douglas fir and white spruce. In other research, the strength of the bamboo culm was observed to increase with decreasing moisture content (Mahdavi 2011). From flexural tests carried out on glued laminated timber (glulam) according to ASTM D143-09, 20 mm-thick laminae were found to exhibit similar modulus of rupture (MOR) of 70.35 MPa to that of solid wood at 69.14 MPa (ASTM D143 2014), (Umaima & Arya 2015). The research by Verma *et al.* (2014) to evaluate the tensile strength of laminated bamboo according to ASTM D3039 also revealed that the mechanical properties of laminated bamboo were comparative to that of hardwood and better than softwood (ASTM D3039 2014).

### 1.2 Bamboo Durability and Treatment

Durability of untreated bamboo depends on the species, age and the conservation actions taken (Ghavami 2003). Bamboo has a limited lifespan of up to 3 years when exposed to the atmosphere and soil, while treated bamboo without soil contact can last more than 6 years (Janssen 2000). If untreated, the material is prone to degradation due to water ingress, fungal propagation and insect infestation. Various treatment methods have been applied and tested over the years and common ones include water based, oil-based, tar application and boron-based chemicals (Jayanetti & Follett 2008).



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

A boron-based chemical mixture is an effective treatment commonly considered based on its affordability. Schröder (2014) proposed a mixture of boric acid and borax at a ratio of 1:1.5 in a 5% solution to protect against insects and fungi. The solution can be either sprayed or impregnated. A more effective mixture can be made with boric acid, borax and sodium dichromate at a ratio of 2:2:0.5, respectively, at the same concentration of 5% solution. Copper chrome arsenic (CCA), which is a fixing-type preservative, is another treatment that can be used to give a long-lasting protection in excess of 50 years. A chromium element is used for fixation and contributes to decay prevention, while the arsenic element strengthens the resistance against insects and fungi. The outer layer of bamboo, which has a high silica content, contributes to its natural resistance to water and insects. The silica layer also acts as an impermeable layer to externally applied preservatives. Thus, application of preservatives is limited to culm-ends through the transport vessels. This method of treatment application through conducting vessels loses efficiency during a 24 hour-period following harvest time (Janssen 2000).

Manalo *et al.* (2015) investigated the treatment of bamboo laminates using alkalis. The best results for bending, tensile and compressive strengths for the laminates were obtained after treatment with a 6% concentration of sodium hydroxide (NaOH). In an attempt to reduce the starch content in bamboo culms, leaching, which is a process where the raw materials are submerged in water for 3 to 4 weeks, is carried out. When harvested, raw bamboo can have a moisture content of 37%. Moisture can occur in two forms; firstly, as free water and secondly, bound to cellulose of the cell wall. Studies revealed that the mechanical strength of bamboo is affected when the moisture content is more than 12%. Sun drying is the simplest way to reduce the moisture content (Verma & Chariar 2012). Olajide *et al.* (2013) suggested that two weeks of drying will result in a decrease of the moisture content to the required 12%. They also observed that protective coatings were more effective on dry fiber as compared to moist ones, which in turn compromised the durability of fibers.

### *1.3 Lamination Stage of Bamboo*

Presently, bamboo scrimber and laminates are developed with phenol formaldehyde, a chemical that poses a threat to human health (Frihart & Hunt 2010). Bansal and Prasad (2004) evaluated the strengths of three types of adhesives, namely, phenol formaldehyde, melamine urea formaldehyde and urea formaldehyde in bambusa bamboo laminates. Their study revealed that phenol resorcinol formaldehyde and phenol formaldehyde yielded better strengths. Other adhesives that could be used in the bamboo lamination process include formaldehyde-free and soy-based adhesives (Correal & Ramirez 2010). Further evaluation of the effects of adhesive on the flexural strength of laminated timber, consisting of polyvinyl acetate, was conducted by Nadir and Nagarajan (2014) according to ASTM D905-08. Tests conducted at a speed of 5 mm/min showed that the adhesive had only 64% of shear strength as compared to that of solid wood. Another research investigation led by Anokye *et al.* (2016) on the effects of adhesives on the mechanical characteristics of bamboo laminates showed that phenol formaldehyde yielded far better results as compared to polyvinyl acetate.

Over the last few decades, several methods have been developed to undertake the lamination process. Nugroho and Ando (2001) developed strand mats by flattening boiled fibers at low press temperatures of 100°C and 130°C. Further improvement in dimensional stability was achieved by subjecting Moso bamboo culms to roller-pressing followed by a hot-pressing at elevated temperatures in the range of 150°C to 180°C. In addition to the application of a resorcinol-based adhesive, adhesion between layers were improved by discarding the inner and



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

outer layers by means of a planer. Lamination of bamboo can also be achieved by splitting treated and dried bamboo culms into smaller strips. A planer is often used to smooth the rectangular strips and to remove the outer and inner layers prior to the bonding stage (Mahdavi 2011). Sharma (2015) used a similar technique to process Moso bamboo into laminates and polyurethane was used as the binding matrix. Verma and Chariar (2012) also processed laminates out of *Dendrocalamus* bamboo using epoxy-based polymer resin. Adequate curing through solidification was ensured by means of a cold-pressed method with a die pressure of 10 kg/cm$^2$.

Lee *et al.* (1998) devised a technique whereby longitudinally-split Moso bamboo culms were flattened under a pressure of 690 kPa for a short duration. This was followed by the application of a pressure of 1380 kPa on the stacks bonded with a resorcinol-based adhesive for a further 12 hours. Rittironk and Elnieiri (2007) and Sulastiningsih and Nurwati (2009) used similar techniques to produce bamboo laminates, namely through the processes of splitting, scrapping and planing. The latter allowed the strips to be air-dried at room temperature for a duration of one week before immersion into a boron solution. Prior to the bonding stage using tannin-based resorcinol formaldehyde adhesive, further drying in the sun reduced the moisture content to 12%. Verma and Chariar (2012) found that both manufacturing cost and mechanical properties of bamboo laminates surpassed that of teak. The mechanical properties of laminates evaluated by Olajide *et al.* (2013) under the ASTM D143-52 standard proved to be superior to conventional timber (ASTM D143 2014).

According to FAREI, over 20 species of bamboo are present in Mauritius, namely *phyllostachys*, *bambusa*, *fargesia*, *dendrocalamus*, *sasaella* and *chimonobambusa*. In the local context, however, bamboo has not been widely exploited. It is mostly used in the manufacturing of blinds and as decorative artisanal products. With a land area of 2000 km$^2$, the consideration and implementation of sustainable and alternative resources will undoubtedly be beneficial for an insular nation like Mauritius. The aim of this research study was to employ alternate and traditional techniques to devise industrial grade laminated bamboo specimens. An attempt was made to render raw bamboo culms into a more versatile form while maintaining an overall lower manufacturing cost in contrast to highly expensive Bamboo laminated veneer lumber (BLVB) products. This research investigation, which is perfectly in line with the concept of Mauritius as a sustainable Island, was carried out to evaluate the mechanical properties of laminated bamboo.

## 2. METHODOLOGY

### 2.1 Specimen Preparation

In this study, bambusa spp was selected based on its large diameter and wall thickness, which is ideal for structural application. According to FAREI, this abundantly available species across Mauritius is well suited for future mass exploitation. In the lamination process, bamboo should have a maturity ranging between 3 to 5 years, since the strength of the fibers depend on the age of the grass. Hence, culms with an average diameter of 100 mm, thickness 10 mm, and with a maturity age of 3 to 4 years were harvested. As wall thickness and density of fibers decrease with height, the lower ground-portion of the culm, of about 1m in length, was cut by the use of a machete. To prevent further degradation of the material after the lamination process, treatment of raw bamboo is essential to protect against insect attack and fungi development due to the presence of starch and a high moisture content.

In this research, a mixture of boric acid and borax was selected based on cost-effectiveness. The culms were soaked in a 5% solution of boric acid and borax at a ratio of 1:1.5, prepared by

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

mixing 25 litres of water with 0.75 kg of borax and 0.5 kg boric acid. A two-week soaking period was utilized to allow for a good penetration of the solution into the culms. In order to reduce the moisture content and improve adhesion, the culms were sun dried for an additional period of two weeks. This exposure time reduced the moisture content in the culms to an acceptable amount of 12%, suitable for lamination (Olajide *et al.* 2013).

In view of minimizing the overall costs of laminated products, locally available glues, used traditionally by carpenters to bond wooden materials, namely Monatex, Pekay and Pattex, were preliminarily selected. Prior to the bonding phase, an initial evaluation to compare the effectiveness of bonding strengths of all three adhesives was conducted through tensile tests. Pekay WD 91 is a water-based, white acrylic adhesive, while Pattex-wood glue and Monatex are synthetic resin glues based on polyvinyl acetate that is suitable for bonding plywood and any compounded boards. Bamboo, cut in strips of length 70 mm, width 25 mm, and thickness 10 mm, were bonded at the 25 mm by 10 mm cross section (Figure 2). The three specimens were subjected to tensile tests on the Testometric M500-50AT Universal Testing Machine (UTM), which had a maximum capacity of 50 kN force. Tensile tests were carried out using continuous load application at a test speed of 1 mm/min (Table 1). The principal purpose of this preliminary test was to characterize the basic mechanical properties of the adhesive material prior to its selection. Tests were conducted until the complete delamination of bonding surfaces.

Test observations revealed solid adhesion between all three adhesives and bamboo surfaces. Failure resulted within the bulk of the adhesive material only. Based on the tensile test results obtained from Table 1, Pekkay WD 91 was found to withstand a maximum force of 240 N with an elongation of 0.15 mm. However, selection was conducted based on time to failure. Consequently, Monatex proved to be the most ductile adhesive material when compared to the others and was thus selected for the rest of the investigation.

Prior to the mechanical test characterization, all specimens were carefully prepared according to the test standards as specified in Table 2. The first stage of the simplified lamination process consisted of three main steps, namely splitting, sawing and planing. Raw bamboo was

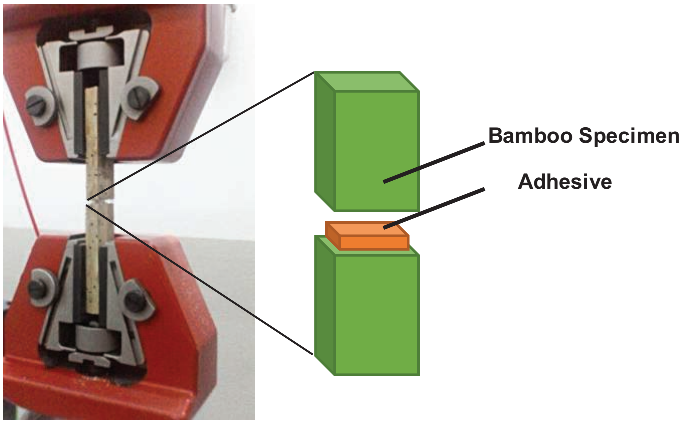
**TABLE 1.** Adhesive specifications.

| No. | Adhesive | | Test Speed/ mm/min | Time to Failure/S | Maximum Force/N | Young's Modulus/ N/mm$^2$ |
|---|---|---|---|---|---|---|
| | Common Name | Specification | | | | |
| **1** | Monatex | Synthetic resin—Polyvinyl acetate | 1.0 | 207 | 205 | 1233.0 |
| **2** | Pekkay WD 91 | Water-based—white acrylic | 1.0 | 68 | 240 | 2469.0 |
| **3** | Pattex | Synthetic resin—Polyvinyl acetate | 1.0 | 96 | 39 | 87.0 |



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

**FIGURE 2.** Tensile test conducted at a test speed of 1.0 mm/min.




first split into smaller strips using basic hand tools, namely hammer and machete. The inner and outer layers, which are weak in adhesion, were then removed on a bench saw machine. The resulting material consisted of a smoother surface finish, which is ideal for good adhesion. The surfaces were further smoothed by the combined use of a bench saw and an electric planer (Figure 3). Based on each category of test method, single ply strips were reduced to thicknesses in the range of 8 mm, 10 mm and 12.5 mm, respectively, by the use of an electric planer.

In industry, a standard laminate orientation code is used to ensure the standardization of ply stacking and laying-up sequence. The orientation code denotes the angle, in degrees, between the plies while the stacking sequence is denoted in brackets. The directional strengths and stiffness of the laminate can be altered by changing the ply orientation. In this study, all laminae specimens used for further evaluation had a similar sequence listed from the first to the last as follows:

$$[0/0] \tag{1}$$

where 0 indicates the angle between the lamina and X axis of the specimen taken in the span-wise direction. The angle of each ply is separated by a slash (AMHC(AW) *et al.* 1993).

**TABLE 2.** Test standards for mechanical characterization of bamboo laminates.

| Standard | Test method | Direction | Specimen size (L × W × H)/mm | Test speed/ mm/min |
|---|---|---|---|---|
| **ASTM D3039** | Tension | Parallel to grain | **250 × 16 × 10** | 1.0 |
| **ASTM D143** | Compression | Parallel to grain | **60 × 20 × 20** | 0.6 |
| | | Perpendicular to grain | **60 × 20 × 20** | 0.6 |
| **ASTM D143** | Three-point bending | Parallel to grain | **400 × 25 × 25** | 1.3 |



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

**FIGURE 3.** Planing process of bamboo strips.

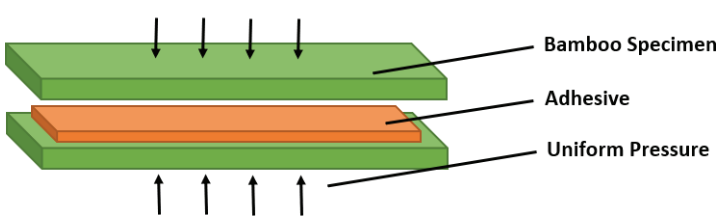
Using a [0/0] stack configuration, bamboo strips were stacked and bonded to each other to form a 2-ply layered laminate. Monatex adhesive was uniformly applied between the contact interface (L × H) of the bamboo specimen along the grain direction. Uniform pressure, applied for a period of 12 hours by means of G-clamps and a pair of plates, provided adequate adhesion time for a rigid yet durable bond (Figure 4).

### *2.2 Mechanical Characterization*

Mechanical characterization of bamboo specimens was conducted through a series of mechanical tests, namely tensile, compressive and flexural tests as per set standards on the Testometric M500-50AT Universal Testing Machine (UTM). ASTM standards, as specified in Table 2, were considered in the mechanical tests. Additionally, due to a noticeable lack of standards for the testing of bamboo, ASTM D143, which is used to evaluate the different strengths and properties of wood was used in the compression and three-point bending test. For the tensile test, however, ASTM D3039, which is the standard test method for tensile properties of polymer matrix composite materials, was used (ASTM D143 2014), (ASTM D3039 2014).

In the tensile test, the Universal Testing Machine, equipped with a load cell of 5000 kg, was set up at a constant test speed of 1.0 mm/min. Prior to test initiation, specimens were tightly secured between the grips of the tensile tester as shown in Figure 5(a). Furthermore, in compressive tests, the same load cell and test speed was selected while a uniform compressive force was applied to the specimen by the use of flat plates as shown in Figure 5(b). A flexural test, on the other hand, was conducted according to ASTM D143 with test specimens of 400 mm in length. Supports in the three-point bending test-setup were 300 mm apart while a test speed of 1.3 mm/min was maintained (Figure 5(c)). Graphical results in terms of force against

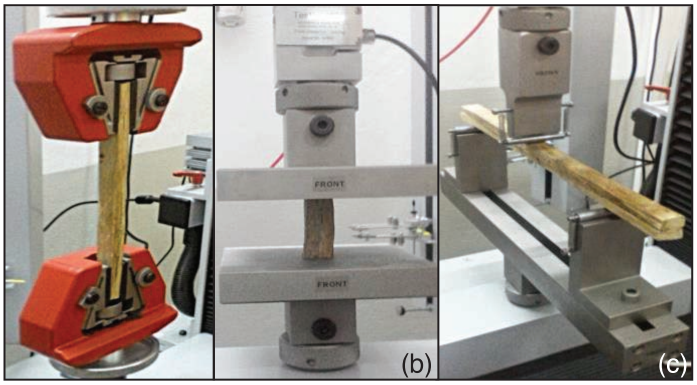
**FIGURE 4.** Bonding stage of bamboo strips.






Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

**FIGURE 5.** (a) Tensile, (b) Compressive and (c) Flexural test setups.




deflection curves of each test were directly generated by the UTM. All tests were conducted until ultimate failure of specimens.

## 3. RESULTS

### 3.1 Tensile Test Results

The tensile test results of 4 samples of bamboo laminates are displayed in Table 3. Samples were divided into two categories, namely green (specimens 1 and 2) and dried bamboo (specimens 3 and 4). The maximum force until failure and the material's Young's Modulus were key parameters directly generated by the software of the UTM. Additionally, the ultimate tensile strength of the laminate was determined using equation (2).

$$\text{Tensile strength} = \frac{\text{Maximum force}}{\text{Cross-sectional area}} \quad (2)$$

The linear portion of the graphs revealed proportional elongation with respect to the force applied. Beyond the ultimate tensile strength point, minimal plastic deformation signaled near complete failure of the specimen. Eventually, failure occurred in terms of brittle fracture. The load-slip curves of green specimens are displayed in Figure 6. Post-test observations as shown

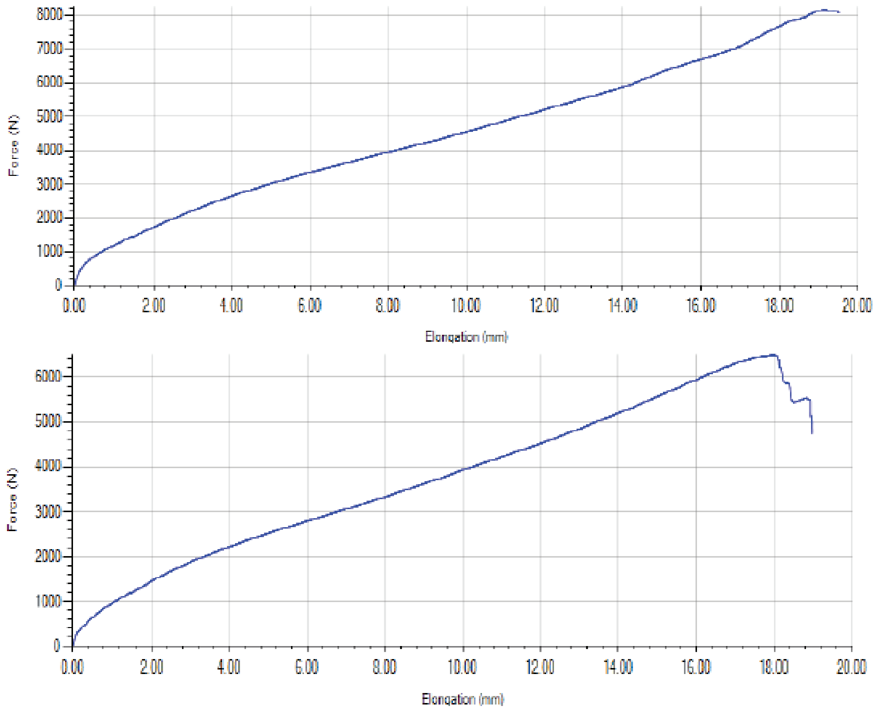
**TABLE 3.** Tensile test results.

| Specimen | Setup | Maximum force/N | Young's Modulus/MPa | Tensile Strength/MPa |
|---|---|---|---|---|
| **1** | Parallel to grain | 8163 | 802.0 | 51.0 |
| **2** | Parallel to grain | 6495 | 806.0 | 40.6 |
| **3** | Parallel to grain | 4900 | 314.8 | 30.9 |
| **4** | Parallel to grain | 4200 | 464.4 | 26.3 |



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

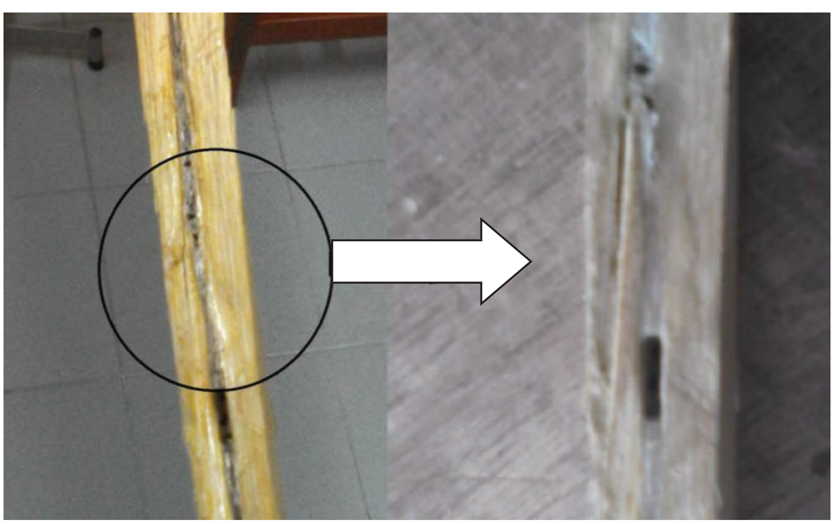
**FIGURE 6.** Load-slip curve of green bamboo laminates in tensile tests.




in Figure 7, and revealed that crack formation preceded failure, occurring along the grain in the longitudinal direction which ultimately led to split of that section. Moreover, based on the graphical results, failure was attributed as a result of the brittle nature of the laminate mainly due to the minimal plastic deformation characteristic displayed by the material prior to failure.

Discrepancies in the test results of the two categories of specimens occurred as a result of many factors. The preparation stage of dried samples was critical to ensure material was free of

**FIGURE 7.** Crack observation in failed specimen.





Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

excessive moisture content. During the drying process, the free water within bamboo is targeted. An approximate moisture content (MC) of 12% roughly indicates the complete evaporation of free water. Even though the material tends to become brittle, the overall mechanical strength is improved following the drying stage. However, in cases where samples have been excessively dried beyond the fiber saturation point (MC < 12%), the cellulose molecular structure would be affected. This would in turn result in subsequent alteration to the composition within the bulk of the material. If cellulose, which is a key contributor to the mechanical strength in bamboo structure, is affected, the overall structural rigidity of the material could be highly compromised. Furthermore, as a highly anisotropic inhomogeneous material, the properties of bamboo mainly vary with its orthotropic geometrical aspects. Non-uniform planing process might have also contributed to irregular orthotropic planes, primarily in the longitudinal direction along the grain.

Despite yielding better results, green bamboo is unsuitable for direct application given its poor resistance characteristics to outdoor conditions. As an organic material, green harvested bamboo is susceptible to deterioration when subjected to environmental factors, namely rain, cyclic moisture variation and ultra-violet radiation. Fungi propagation and insect attack additionally compromise the structural integrity of the material if left untreated. Discernible bored holes on dried laminated samples confirmed the presence of insect attack.

### *3.2 Compressive Test Results*

Compressive test results of 4 samples of bamboo laminates, sized according to ASTM D143, are displayed in Table 4. Samples were divided into two categories, namely green (specimens 1 and 2) and dried bamboo (specimens 3 and 4). The maximum force till failure, the material's Young's Modulus and compressive strength are key tabulated parameters. Compressive strength is the maximum strength that the specimen could withstand when loaded prior to the plastic deformation phase. As per ASTM D143, compressive test specimens were prepared and tested along the direction of the grain. As shown in the top graph of Figure 8 and given the inherent strength of bamboo in the longitudinal direction along the grain, dried laminated specimens were able to withstand compressive loads above 13 kN. The highly anisotropic characteristic of bamboo was confirmed by the far inferior Modulus of Elasticity in the transverse direction of the material. Crack initiation occurred prior to maximum force and was observed to propagate unstably until final failure (Figure 9).

**TABLE 4.** Compressive test results.

| Specimen | Setup | Maximum force/N | Cross-section Area/m$^2$ | Young's Modulus/MPa | Compressive Strength/MPa |
|---|---|---|---|---|---|
| **1** | Parallel to grain | 3655 | 0.0004 | 276.0 | 9.1 |
| **2** | Parallel to grain | 3699 | 0.0004 | 323.0 | 9.2 |
| **3** | Parallel to grain | 13600 | 0.0004 | 1436.3 | 34.0 |
| **4** | Perpendicular to grain | 11646 | 0.0025 | 95.8 | 4.7 |



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

**FIGURE 8.** Load-slip curve of dried bamboo laminates in compressive tests (Parallel & Perpendicular to grain).

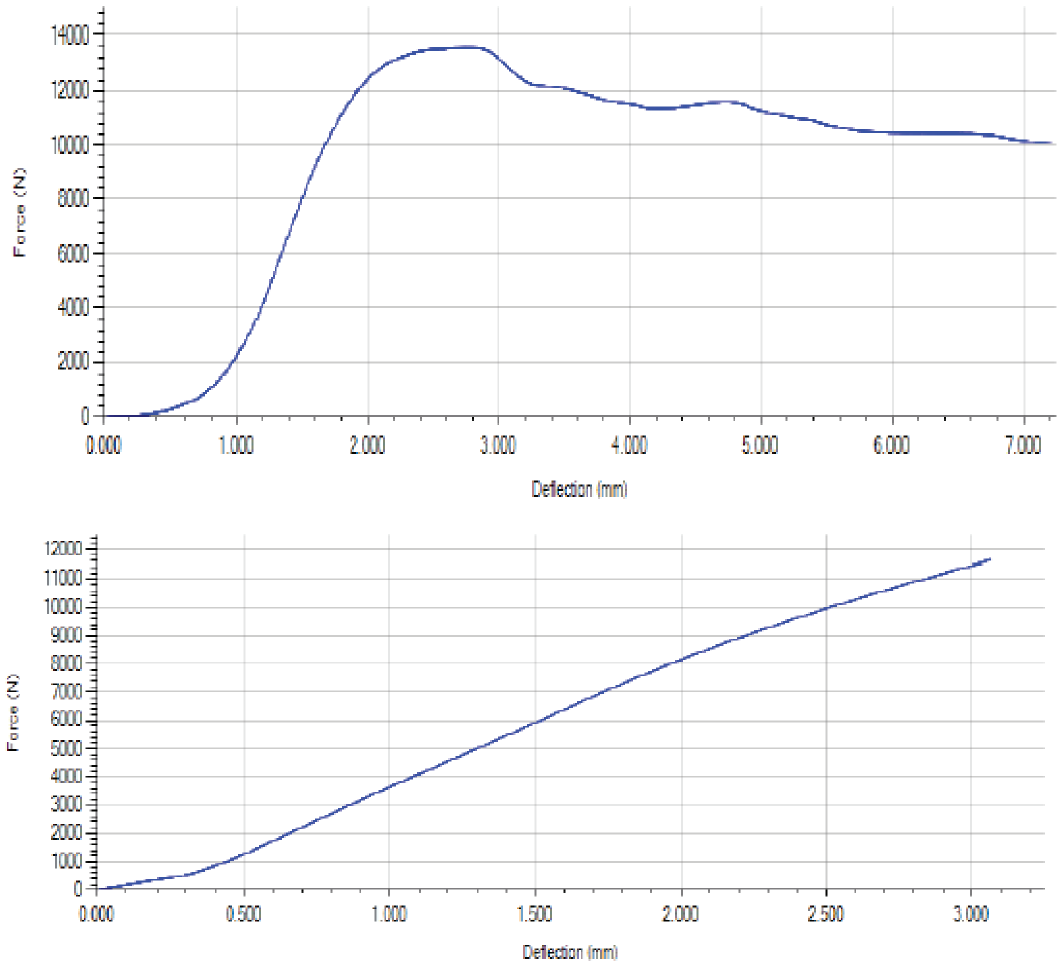



**FIGURE 9.** Deformed specimens in compressive tests; (a) Parallel to grain and (b) Perpendicular to grain.



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

### *3.3 Bending Test Results*

Results of the 3-point bending flexural test were conducted as per ASTM D143 and are tabulated in Table 5. Based on equation (3), the flexural strength was calculated using the maximum force recorded during the test and by taking into consideration the geometrical parameters of specimens, namely length between supports, width and thickness. As shown in Figure 10(b) and as per the graphical results of Figure 11, linear deflection was observed in the first instance of both cases of flexural tests. Crack initiation was confirmed through cracking noise observed around 30% into the linear elastic region. It was assumed that cracks propagated stably until maximum force was reached. Unstable crack propagation continued through the plastic deformation region and was confirmed by more frequent and random cracking sounds. Testing continued until complete delamination of bulk fibers whereby final fracture of the specimen occurred. Discrepancies occurred due to numerous factors, namely distribution of fibers and anisotropy of material. Additionally, based on the test results, green specimens tended to be less brittle and displayed an overall lower strength than dried specimens.

$$\text{Flexural Strength} = \frac{3FL}{2bt^2} \tag{3}$$

where; $F$ = Maximum force in N, $L$ = Distance between supports, $b$ = width of sample and $t$ = thickness of sample.

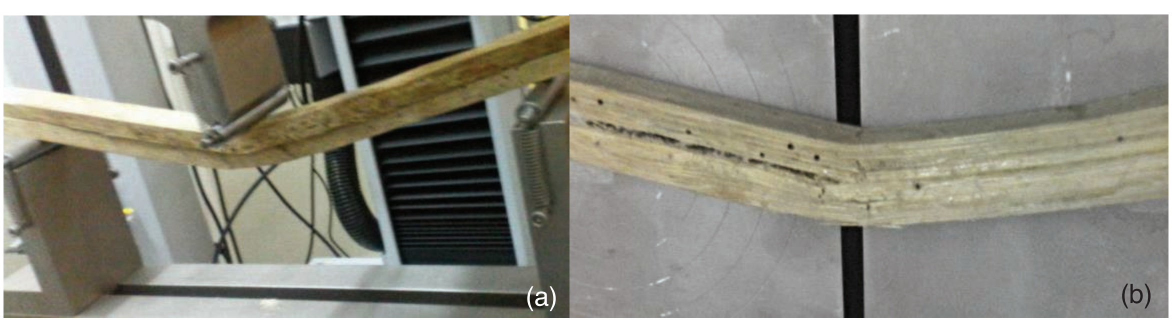
## 4. DISCUSSION

Based on the literature, the tensile strength of laminated bamboo (51–26 MPa) is comparable to that of redwood, spruce, cedar and pine (62–40 MPa) (Green *et al.* 1999). The ratio of compressive strength of parallel to perpendicular fibers in compressive tests at 7:1 roughly

**TABLE 5.** Flexural test results.

| Specimen | Maximum force/N | Bending Modulus/MPa | Bending Strength/MPa |
|---|---|---|---|
| **1** | 740 | 1974.6 | 21.3 |
| **2** | 400 | 722.3 | 11.5 |

**FIGURE 10.** (a) 3-point bending flexural tests of green bamboo laminates and (b) Failed Specimen.

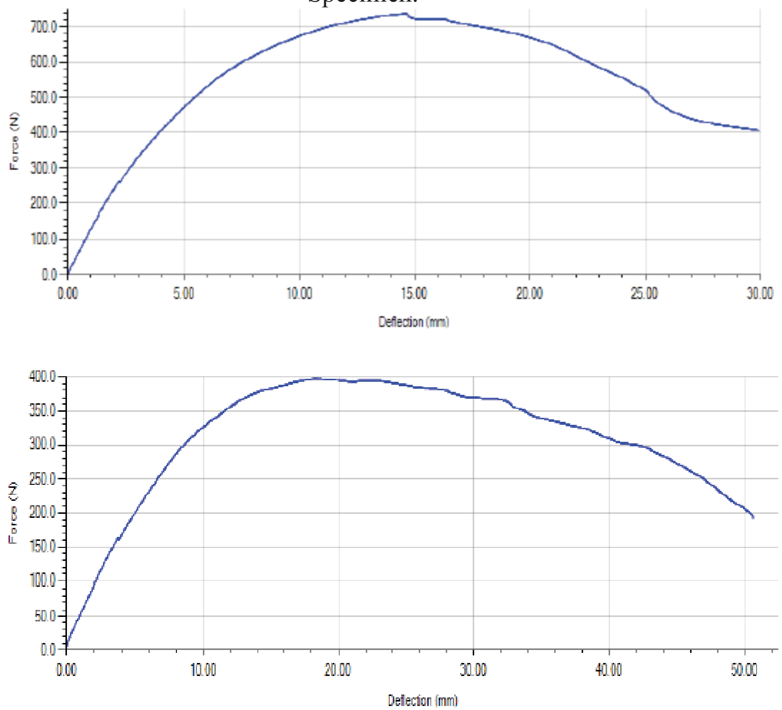





Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

**FIGURE 11.** Load-slip curves of green bamboo laminates in 3-point bending flexural tests.

Specimen.




approached to the ratio of poplar, fir and pine of 10:1 (Aydin *et al.* 2007). This correlation in compressive strength values between bamboo and wood indicates the inherent similarity in the fibers' distribution within the bulk of the material structure. Being inhomogeneous bio-composite materials, both wood and bamboo display anisotropic characteristics. Both materials have evolved into self-supported, vertical-type structures capable of withstanding high wind loadings. Consequently, they have developed greater reinforcement in the longitudinal direction, specifically provided by the bulk of aligned cellulose fibers, hence confirming the surplus strength along the grain.

The flexural strength of bamboo laminates was approximately half the magnitude of poplar, fir and pine (Aydin *et al.* 2007). In general, a full-culm bamboo plant has developed into a very resilient structure against transverse loadings. When processed into strips, part of this resilience is lost as key load-bearing fibers within the geometrical structure are modified and removed. The hollow cylindrical tubular shape of bamboo culms also significantly contributes to its high flexural resistance given a highly favorable second moment of area.

In order to reduce the overall cost of laminated bamboo products in this research study, several challenges were encountered in the process of developing laminates through simplified processing methods. These challenges could as well be the cause behind the large discrepancy observed in the mechanical characterization results of laminates. For instance, in the planing process stage, dense fibers in the outermost layers were removed in order to reduce the curvature in strips. The remaining middle-core fibers were less dense and consequently weaker in mechanical strength. Additionally, the adhesive used was beyond comparison with industrial grade epoxy resin, which are widely used as a matrix component in composite engineered



Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

bamboo and timber products. Other causes leading to inferior properties could be attributed to a lack of adequate treatment and drying methods.

## 5. CONCLUSION

The aim of this research study was achieved on 2-ply laminated specimens which had an overall lower manufacturing cost as a result of simplified processing methods. The reliability of the engineered material was evaluated in terms of basic mechanical characteristics, namely flexural, tensile and compressive strengths, according to the established ASTM D3039 and ASTM D143 standards. Discrepancies observed in the test results were attributed to the distribution of fibers and inherent anisotropic nature of the material. Other factors involved in the treatment and lamination stage also contributed to the premature deterioration and delamination of the test specimens respectively. Further investigation could be conducted on fiber distribution with respect to the mechanical strength of laminates. Evaluation of the effect of multi-ply laminates as a function of orientation would also contribute towards the goal of rendering bamboo into a more versatile and strong material. Additionally, the durability properties against mechanical strength could be further discussed, namely when sustainable treatment methods are utilized as alternatives to current industrial-based chemical treatments.

## REFERENCES


AMHC(AW) Humrichouser, AMHC Ervin AMCS Biel (1993) *Aviation Structural Mechanic (H & S) 3 & 2*, USA: US Navy.

Anokye, R., Bakar, E.S., Ratnasingam, J., Yong, A.C.C. and Bakar, N.N. (2016) 'The effects of nodes and resin on the mechanical properties of laminated bamboo timber produced from Gigantochloa scortechinii', *Construction and Building Materials*, 105(), pp. 285–290.

ASTM D143 (2014) *Standard Test Methods for Small Clear Specimens of Timber*, West Conshohocken, PA: ASTM International.

ASTM D3039 (2014) *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, West Conshohocken, PA: ASTM International.

Atanda. J. (2015) 'Environmental impacts of bamboo as a substitute constructional material in Nigeria', *Case Studies in Construction Materials*, 3(), pp. 33–39.

Awaludin, A. and Andriani, V. (2014) 'Bolted bamboo joints reinforced with fibers', *Procedia Engineering*, 95(), pp. 15–21.

Aydin, S., Yardimci, M.Y. and Ramyar, K. (2007) 'Mechanical properties of four timber species commonly used in Turkey', *Turkish Journal of Engineering and Environmental Sciences*, 31(1), pp. 19–27.

Bansal, A.K. and Prasad, T.R.N. (2004) 'Manufacturing laminates from sympodial bamboos—an Indian experience', *Journal of Bamboo and Rattan*, 3(1), pp. 13–22.

Chen, F.M., Wang, G., Li, X.J. and Cheng, H.T. (2011) 'Mechanical properties of a woven ramie fabric under multidimensional loadings', *Textile Research Journal*, 81(12), pp. 1226–1233.

Correal, J.F. and Ramirez, F. (2010) 'Adhesive bond performance in glue line shear and bending for glued laminated Guadua bamboo', *Journal of Tropical Forest Science*, 22(4), pp. 433–439.

Dixon, P.G., Gibson, L.J. (2014) 'The structure and mechanics of Moso bamboo material', *Royal Society*, 11(99)

Falk, R.H. (2009) 'Wood as a sustainable building material', *Forest products journal*, 59(9), pp. 6–12.

Frihart, C.R. and Hunt, C.G. (2010) 'Adhesives with wood materials, bond formation and performance', in *Wood Handbook Wood as an Engineering Material*. USA: USDA Forest Service, pp. 10–24.

Ghavami, K. (2003) *Eco-construction and infrastructure*, Rio de Janeiro, Brazil: World Climate & Energy Event.

Graham, S. (2011) *10 materials that could replace wood one day*, Available at: http://www.networx.com/article/10-materials-that-could-replace-wood-one (Accessed: 29th October 2015).

Green, D.W., Winandy, J.E. and Kretschmann, D.E. (1999) *Mechanical properties of wood. Wood handbook : wood as an engineering material*, Wisconsin, USA: USDA Forest Service, Forest Products Laboratory.




Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

Guinness World Records (2016) *Fastest growing plant*, Available at: http://www.guinnessworldrecords.com/world-records/fastest-growing-plant (Accessed: 15th March 2016).

Janssen, J.J.A. (1981) *Bamboo in Building Structure*, Netherlands: Doctoral Thesis the Eindhoven University of Technology.

Janssen, J.J.A. (2000) *Design and building with bamboo*, Eindhoven, The Netherlands: International Network for Bamboo and Rattan.

Jayanetti, D.L. and Follett, P.R. (2008) 'Bamboo in Construction', *Modern Bamboo Structures*, (), pp. 23–32.

Lee, A.W.C., Bai, X. and Bangi, P. (1998) 'Selected properties of laboratory-made laminated bamboo lumber', *Holzforschung*, 52(), pp. 207–210.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H. and Wu, J. (2007) *World bamboo resources A thematic study prepared in the framework of the global forest resources assessment 2005*, Italy: FAO

Mahdavi, M., Clouston, P.L. and Arwade, S.R. (2011) 'Development of laminated bamboo lumber: review of processing, performance, and economical considerations', *Journal of Materials in Civil Engineering*, 23(7), pp. 1036–1042.

Manalo, A.C., Wani, E., Zukarnain, N.A., Karunasena, W. and Lau, K. (2015) 'Effects of alkali treatment and elevated temperature on the mechanical properties of bamboo fibre–polyester composites', *Composites Part B: Engineering*, 80(), pp. 73–83.

Nadir, Y. and Nagarajan, P. (2014) 'The behavior of horizontally glued laminated beams using rubber wood', *Construction and Building Materials*, 55(), pp. 398–405.

Nugroho, N. and Ando. N. (2001) 'Development of structural composite products made from bamboo II: fundamental properties of laminated bamboo lumber', *Journal of Wood Science*, 47(3), pp. 237–242.

Olajide, O.B., Ogunsanwo, O.Y. and Aina, K.S. (2013) 'Strength properties of thermal treated glue lam of bamboo bambusa vulgaris', *International Journal of Advanced Biological Research*, 3(2), pp. 281–288.

Rittironk, S. and Elnieiri, M. (2007) 'Investigating laminated bamboo lumber as an alternate to wood lumber in residential construction in the United States', *Proceedings 1st International Conference on Modern Bamboo Structures*, Taylor & Francis, Abingdon, UK, pp. 83–96.

Schröder, S. (2014) *Durability of Bamboo*, Available at: https://www.guaduabamboo.com/preservation (Accessed: 29th October 2015).

Sharma, B., Gatóo, A., Ramage, M.H. (2015) 'Effect of processing methods on the mechanical properties of engineered bamboo', *Construction and Building Materials*, 83(), pp. 95–101.

Shi, S.Q. and Gardner, D.J (2006) 'Hygroscopic thickness swelling rate of compression molded wood fiberboard and wood fiber/polymer composite', *Composites Part A: Applied Science and Manufacturing*, 37(), pp. 1276–1285.

Sulastiningsih, I.M. and Nurwati. (2009) 'Physical and mechanical properties of laminated bamboo board', *Journal of Tropical Forest Science*, 21(3), pp. 246–251.

Umaima Muhammed, C.K. and Arya, R. (2015) 'Analytical study on flexural behaviour of glued laminated timber', *International Journal of Innovative Research in Science, Engineering and Technology*, 4(4), pp. 2485–2493.

UN News (2013) *World population projected to reach 9.6 billion by 2050*, Available at: http://www.un.org/en/development/desa/news/population/un-report-world-population-projected-to-reach-9-6-billion-by-2050.html (Accessed: 10th April 2016).

Verma, C.S. and Chariar, V.M. (2012) 'Development of layered laminate bamboo composite and their mechanical properties', *Composites Part B: Engineering*, 43(3), pp. 1063–1069.

Verma, C.S., Naresh, Kr. Sharma., Chariar, V.M., Maheshwari, S. and Hada, M.K. (2014) 'Comparative study of mechanical properties of bamboo laminae and their laminates with woods and wood based composites', *Composites: Part B*, 60(), pp. 523–530.

World Resource Institute (2009) *State of the World's Forests*, Available at: http://www.wri.org/map/state-worlds-forests (Accessed: 30th January 2016).


Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access