Bamboo as future bio-industrial material: Physical behaviour and bending strength of Malaysia’s Beting bamboo (Gigantochloa levis)

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Abstract. In this paper, bending strength and physical properties (specific gravity, dimensional stability and equilibrium moisture content) of a Malaysian bamboo locally known as Beting bamboo (Gigantochloa levis) are addressed. Characterizations of physical and bending strength of G. levis in terms of the variability of location along culm height (top, middle, bottom), culm section (nodes and internodes), fiber orientation (longitudinal, tangential and radial) and culm layer (outer and inner) were conducted. Comparison of these properties is also made to some bamboo and commercial timber species. It was found that G. levis has favorable physical and mechanical properties although the specific gravity of G. levis has tendency to be on the higher side. The characteristics studied were found to have some variability at different locations, sections, and directions. There was variability in terms of bending strength along with the culm height of bamboo. It is indicated from this study that the bending strength and physical properties of G. levis were found to be satisfactory.

1. Introduction
As a result of growing awareness of eco-friendly biomaterials, bamboo has acquired popularity as potential alternative to synthetic fibers, in composite for construction and automobile applications [1,2]. These are some of the benefits of bamboo over traditional materials. Bamboo has high specific gravity and excellent tensile strength to weight ratio compared to steel and can endure compressive strength better than concrete. Bamboo, as a natural hierarchical cellular material, has exceptional mechanical properties such as flexibility and fracture toughness, excellent mechanical properties, including tensile and flexural strength along the fiber direction [3,4]. Bamboo is also beneficial as a solution for several environmental issues. Due to the shrinking accessibility of timber and growing interest among end-users of wood-based products about the threat to the environment if certain natural forest stands are depleted, it is an excellent alternative to wood [5]. 59 species of bamboo have been classified in Malaysia, consist of 25 introduced species, while 34 others are indigenous [6].

Study on utilization of bamboo as raw materials for many types of composite products such as parallel strand lumber [7,8], oriented strand board [1,9], bamboo I-beams fabricated from oriented strand
board [10] and oriented strand lumber [11] have been conducted previously and has generated promising results. Some previous researchers even utilized bamboo with a combination of other materials (aluminum/glass fabrics) to create super hybrid eco-material with good recyclability and improved properties [12,13]. Because bamboo is a biological material, its mechanical, physical, and natural durability properties can vary depending on various of factors such as growing conditions and genetics. A thorough understanding of bamboo's mechanical behavior allows for a safe design that extends the material's service life. Detailed study on mechanical properties of several bamboo species has been conducted as in [14] that work focused on the physical and mechanical properties of Calcutta bamboo or Dendrocalamus strictus. Yu et al., (2008) reported the physico-mechanical characteristics of of Moso bamboo (Phyllostachys pubescens) [15]. Physical and mechanical properties of four bamboo species, Bambusabalcooa, Bambusa tulda, Bambusa salarkhanii and Melocanna baccifera was also available in literature [16]. There is also literature on the effect of accelerated ageing on some physical and mechanical properties of bamboo (Phyllostachys bambusoides) [17]. Nordahlia et al., (2012) reported the effect of age and height on selected properties of Malaysian bamboo [18]. Mechanical properties of bamboo, Dendrocalamus asper or Petung putih through measurement of culm physical properties is also available in literature. In the study, correlation between mechanical properties such as tensile strength, modulus of rupture and modulus of elasticity in flexural and tension, and also physical properties of bamboo culm (Dendrocalamus asper) was reported [3].

Demand for wood products will soar in the near future, and hence, the quest for an alternative source of wood must be continued to meet the market demand. This study aims to highlight the physical properties and bending strength of G. levis as one of the possible renewable materials in fabrication of composite materials. Physical analysis was conducted in terms of specific gravity (SG), dimensional stability (DS) and equilibrium moisture content (EMC)

2. Materials and methods

2.1. Raw materials

Bamboo (Three-year-old) G. levis was harvested in bulk from the forest in Pahang, Malaysia by local supplier. Bamboo culms were divided into three sections when they arrived, with each section approximately 1.80m long (6 ft) as shown in Figure 1 and left to air dry for two weeks.

![Figure 1. Bottom, Middle and Top Section of G. levis.](image)

2.2. Specific gravity and dimensional stability

Specific gravity (SG) of bamboo was determined according to standard (ASTM D2395 - 93) [19]. A minimum of 30 specimens were taken from each section along the culm height (B-bottom, M-middle, and T-top). SG was determined based on oven dry mass. Before SG was measured, specimens are covered with thin layer of wax to prevent any water absorption. In this study, water immersion electronic densitometer Alfa Mirage EW 300 SG) was used to determine the SG of specimens.

Specimens for shrinkage and swelling properties were taken from internodes section along the culm height (B, M, and T). The specimen dimension was equivalent to 20mm x 25mm x thickness. For two weeks, specimens were first conditioned at 20°C ±5°C and RH of 65% ±5% to achieve 10-12% MC,
before being dried using laboratory oven. Comparisons were made between three main directions; Lo-longitudinal, Ra-Radial and Ta-Tangential. By immersing the specimens in distilled water for 24 hours, the swellings were measured from oven dry to wet conditions [13].

2.3. Equilibrium Moisture Content
Equilibrium moisture content (EMC) was determined under five different relative humidity (RH) conditions that were 20%, 33%, 65%, 85% and 95%. Conditioning was conducted by using a combination of humidity chamber and saturated salt solution. Moisture content (MC) of bamboo was determined based on standard (ASTM D4442-92) [20]. Specimens were obtained along the culm height (B, M and T). After conditioning for 3 weeks at specific relative humidity, specimens were weighed and subsequently dried in oven at 103°C ±2 for 24 hours.

2.4. Bending strength
Bamboo was cut, and outer skin was removed using abrasive planer machine to achieve uniform thickness. Each section of bamboo culms (B, M and T) was cut for bending specimen using band saw. Dimension of bamboo specimens for three-point bending test was equivalent to 1cm x 16 cm x thickness (3-10mm). Thickness of bending specimens varied due to changing nature of bamboo along the culm height. For each section, specimens were taken from nodes and internodes. Specimens were conditioned at 20°C 5°C and a RH of 65% ±5% until the weight stabilized before testing. Three-point bending test was performed according to standard (ASTM D143-09) [21] with slight modification on dimension to suit the original thickness and nature of bamboo culms. Experiment was carried out using Universal Testing Machine (Instron 5582 Universal Testing Machine equipped with Bluehill® processing software) with cross head speed of 25mm/min (=0.98 inch) with the dense layer of fiber (outer layer) facing upward.

3. Results and discussion
3.1. Specific gravity, dimensional stability and equilibrium moisture content (EMC)
The average SG of bottom section of bamboo equivalent to 0.74 (standard deviation, SD = 0.05); while specimens obtained from higher section (M and T) are higher, 0.86 (SD = 0.03) and 0.90 (SD = 0.02) respectively. Analysis of Variance (ANOVA) indicated that there was a significant difference in the SG of specimens obtained from different sections (F-value = 109.69). The wall thickness of G. levis decreased from lower to higher culm height. The SG of G. levis increased due to the fact that the number of vascular bundles increased from basal to top. [14–16].

It is found that the G. levis has relatively high specific gravity, almost equivalent to the SG of Gigantochloa scortechinii (Semantan bamboo) [22]. SG is a significant factor because it influences material behaviour, particularly physical and mechanical properties. When compared to other species of timber, SG of bamboo can be considered high. High SG may be a drawback of G. levis over much lower specific gravity materials as heavy composite material is more difficult to work with and may add unnecessary weight to composite material made from G. levis. Nevertheless, G. levis might be utilized as core material where good density and sound mechanical characteristics are required [14].

Comparison of dimensional stability in terms of shrinkage and swelling was conducted along culm height (B, M, T) and between three main directions of bamboo, the Lo-longitudinal, Ra-Radial and Ta-Tangential. Average swelling at Lo for top, middle and bottom specimens was 0.54%, 0.71% and 0.94% respectively. The difference was significant in Lo swelling (24 hours) along the culm height (F-value= 7.51). In Ta direction, swelling was equivalent to 6.41%, 6.13% and 8.17% for top, middle and bottom specimens respectively. In Ra directions, swelling was equivalent to 12.22%, 16.76% and 21.11% respectively. There was a significant difference between Ta along the culm height (F-value- 14.20) and Ra directions along culm height with F-value equivalent to 14.20 and 19.13 respectively.
EMC of Sitka spruce (*Picea sitchensis*), Beting bamboo (*G. levis*), Calcutta bamboo (*D. strictus*) and Semantan bamboo (*G. scortechinii*) is shown in Figure 4. The sitka spruce isotherm curve is widely used to predict the timber EMC value in many parts of the world [5]. Beting bamboo exhibit lower initial and final MC compared to Sitka spruce, Calcutta bamboo and Semantan bamboo. However, Beting bamboo behave almost similarly to the two bamboo species and as well as this timber species. MC of Sitka spruce and Calcutta bamboo at 15% RH were 3.5% and 4.2% respectively, while at 12% RH, MC of Semantan bamboo was 2.15%. The initial MC of Semantan bamboo (3.85% MC, 23%RH) and Beting bamboo (2.75% MC, 20% RH) is considered quite low compared to Calcutta bamboo and Sitka spruce at 15% RH. MC of Sitka spruce and Calcutta bamboo was 6.4% and 6.6% at 32.5% RH respectively while Beting bamboo and Semantan bamboo was 4.3% and 4.69% respectively. This shows a similar pattern at 60% RH where Sitka spruce and Calcutta bamboo both exhibit 9.5% MC while Beting bamboo was at 8.16% MC at 60% RH. At the same level of RH, MC of Semantan bamboo was 8.5%. Growth of fungi was observed during the experiment on Calcutta bamboo conditioned at 20ºC and 77% RH. In this study, fungi growth on the specimens occurred when the RH exceeding 95% at 20ºC [14].

**Figure 2.** Average dimensional stability of *G. levis* at different heights and directions.

**Figure 3.** Average dimensional stability of *G. levis* at different heights and directions.
3.2. Bending strength analysis

The average MC for the bending specimens was equivalent to 10.95%. Figure 5 shows the mean bending strength at different section (height) and location (nodes and internodes) of *G. levis*. For specimen with nodes, the mean Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and Stress at Proportional Limit (SPL) was 13576.40 N/mm² (SD=3703.22), 90.02 N/mm² (SD=26.52) and 53.85 N/mm² (SD=20.68) respectively. For internodes specimens, the mean MOE, MOR and SPL was equivalent to 21363.31 N/mm² (SD=2574.82), 148.38 N/mm² (SD=33.56) and 97.42 N/mm² (SD=27.08) respectively.

There was a significant difference detected along the culm height of bamboo for nodes specimens in terms of MOE, MOR and SPL at 95% confidence intervals (MOE: F=11.26, MOR: F=7.26 and SPL: F=7.64). On the other hand, there was no significant difference detected in MOE along the culm height of bamboo for internodes specimens (F=1.35) at 95% confidence intervals. For MOR and SPL, there was a significant difference traced along the culm height of bamboo (MOR: F=45.97, SPL: F=50.15) at 95% confidence intervals. Comparison was also made between the inner and the outer layer of the bottom internodes specimen. The inner layer of *G. levis*, the mean MOE, MOR and SPL for inner layer was equivalent to 11265.57 N/mm² (SD=4345.40), 91.88 N/mm² (SD=39.09) and 56.56 N/mm² (SD=25.75) respectively. For the outer layer of *G. levis*, the mean MOE, MOR and SPL was 19851 N/mm² (SD=4112.43), 152.36 N/mm² (SD=34.26), and 101.71 N/mm² (SD=25.25) respectively. The composition and distribution of bamboo's vascular bundles and parenchyma tissues have a significant impact on its mechanical properties. The volume of vascular bundles and the content of parenchyma cells increased as the distribution density of vascular bundles decreased from the bamboo outer layer to the inner layer [23,24].
3.3. Failure modes under bending

Typical pattern of failure of pure bending had been identified (Figure 6) for clear specimen of bamboo with and without existence of nodes. Simple tension as shown in Figure 6b was the most common failure type of bamboo samples without node in bending. Crease line appeared on the external side of the indicate stress line at the compression side where the fiber crushed into each other as shown in Figure 6a. For samples with nodes, the stress line at the compression side was not well defined as due to abnormality of fiber structure at nodes as shown in Figure 6c. Bodig & Jayne, (1982) [25] explained this type of failure usually make their appearance at loads less than ultimate, but tension breaks will eventually appear below the neutral plane as both types of failure will appear at the end of the test.

At tension side, cross grain tension was the most common failure modes that occur due to the abnormality of fiber structure at nodes. At ultimate (breaking) stress, the fibers are pulled out from the matrix (parenchyma) (Figure 6d). Fibers pull – out are more obvious at tension side of samples with nodes, indicating low fiber pull-out strength of vascular bundle from the matrix (parenchyma). One possible explanation for this phenomenon according to Ding & Liese, (1997) [26] and Sulthoni, (1989) [27] is vascular bundles in nodes are oriented randomly and also said to be short, forked crossing each other compared to internodes which contains axial orientation of cells and greater fiber length compared to nodes.

![Figure 6. Failure mode of bamboo under bending loading.](image)

4. Conclusions

The specific gravity (SG) of *G. levis* was discovered to be higher than that of the majority of commercially available timber species. As a result, this could have an impact on *G. levis*'s use as a composite material's raw material. Nonetheless, *G. levis* can be useful in a condition where combination of high SG and mechanical properties is needed. *G. levis* may be suitable for laminated composite products or composite products that do not require extensive compression during material pressing. When exposed to different relative humidity, *G. levis* showed an almost identical pattern to Calcutta bamboo and Sitka spruce, despite the fact that the initial and final MC of *G. levis* was lower than that of Calcutta bamboo and Sitka spruce. *G. levis* exhibited excellent dimensional stability when compared to wood species with high shrinkage when dried from green to oven dry and large differences in instability in the radial and tangential directions. *G. levis* exhibit excellent bending strength where the value of MOE was found to be higher than most commonly used timber species. *G. levis* exhibit different failure mode behaviour in bending for specimen with existence of nodes and without nodes. At tension side, cross grain tension was the most common failure modes that occur due to the abnormality of fiber structure at nodes. At ultimate (breaking) stress, the fibers are pulled out from the matrix (parenchyma).

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