Original Article
J. Korean Wood Sci. Technol. 2024, 52(4): 383-392
https://doi.org/10.5658/WOOD.2024.52.4.383

Journal of the Korean Wood Science and Technology
pISSN: 1017-0715 eISSN: 2233-7180
http://www.woodj.org

Physical and Mechanical Properties of Laminated Board from Betung Bamboo (*Dendrocalamus asper*)

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ABSTRACT

Laminated bamboo is an engineered bamboo technology to maintain its mechanical durability for both construction and furniture materials. This study was conducted to assess the properties of laminated bamboo made from Betung bamboo at different culm positions and laminate orientations. The materials used in this study were 4-year Betung bamboo (*Dendrocalamus asper*) obtained from a community forest in Yogyakarta and polyvinyl acetate resin as adhesive. Two factors were applied for this study, i.e., culm position (lower, middle, and upper) and laminate orientations (vertical and horizontal direction). To examine the mechanical properties, a static bending test and the hardness test were performed in accordance with ASTM D1037-99. Moisture content and density were determined in accordance with BS 373-1957. The results indicated that there was no interaction between the culm position and laminate orientation on the moisture content, density, static bending properties and hardness. The culm position affected the static bending and hardness, with the higher position of the culm resulting a greater strength. The laminate orientation also affected the strength of laminated bamboo, with the vertical direction resulting in higher strength than the horizontal.

Keywords: Betung bamboo, culm position, laminate orientation, laminated board, physical and mechanical properties

1. INTRODUCTION

Bamboo is a multifunctional plant classified as a type of grass (family: Poaceae) and has been widely used by the Indonesian community for construction materials and furniture. In general, bamboo can be used for laminated boards when it is 2–3 years old, and as a construction material when it is 3–6 years old (Raj and Agarwal, 2014). This is in contrasts to wood, which typically requires 40–50 years to reach maturity before achieving the desired strength. However, bamboo culm generally has strong, impermeable outer surface (exodermis), hollow stems, and uneven thickness, where the thickness is relatively thin at the base, thicker in the middle, and thinner again towards the one-third end of the bamboo culm, leading to non-uniform mechanical properties (Kasmudjo, 2013). The bamboo culm also consists of the nodes and internodes which cause to the different tensile strength

Date Received March 5, 2024; Date Revised April 3, 2024; Date Accepted May 2, 2024; Published July 25, 2024
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(Darwis *et al*., 2023). It should be noted that due to its high sugar and starch content, bamboo has poor biological durability, therefore some treatments or modification are needed (Arsyad *et al*., 2020; Lee and Lee, 2021; Maulana *et al.,* 2021; Qi *et al*., 2019).

Laminated bamboo is an engineered bamboo formed by bonding multiple bamboo strips to enhance the uniformity of mechanical properties compared to natural bamboo (Setyo *et al*., 2014), which are glued parallel to the fiber direction (Qisheng *et al.,* 2002). As a result, laminated beams exhibit greater strength than single layers with minimal dimensional changes (Morisco, 2006; Setyo *et al.,* 2014). Several studies have investigated the production of laminated bamboo using various methods for preparing raw materials (Galih *et al.,* 2020; Guan *et al.,* 2022; Kim *et al.,* 2003; Nugroho and Ando, 2001; Putri *et al.,* 2023; Sumardi *et al.,* 2022). The physical and mechanical properties of bamboo are generally influenced by the type and age of the bamboo, moisture content, nodes and internodes, and culm position (Janssen, 2000).

In this study, laminated boards were manufactured by utilizing Betung bamboo (*Dendrocalamus asper* Backer ex K.Heyne). This bamboo variety was selected for its extensive use in construction and furniture manufacturing in Indonesia. It can reach as high as 20–30 m with an internode length of about 20–45 cm and a diameter of 8–20 cm. The wall thickness of the culm is around 6–22 mm (Javadian *et al*., 2019). The wall thickness of Betung bamboo (5 years old) at the top, middle, and bottom was 11.2 mm, 21.1 mm, and 27.4 mm, respectively (Maulana *et al*., 2022). Irawati and Saputra (2012) summarized the mechanical properties of Betung bamboo. It indicated the modulus of rupture (MOR) of 134.87 MPa and modulus of elasticity (MOE) of 12.89 GPa. Based on a study of Adam and Jusoh (2019), Betung bamboo has basic density of 0.48–0.73 g/cm^3, MOR of 48–228 MPa, and MOE of 1.16–10.67 GPa depending on the culm position.

Liese (1985), Praptoyo and Yogasara (2012) similarly revealed that bamboo culms can manifest diverse properties along their axial direction, specifically at the base, middle, and top. Therefore, evaluating the position of bamboo culm is crucial to determine its optimal mechanical properties. In addition to culm position, it is imperative to consider differences in mechanical properties concerning the laminate direction technique. According to Sharma *et al.* (2015), the orientation of lamination significantly influences the bending properties. Using vertical lamination, for example, can improve bending properties by up to 18% compared to horizontal lamination. As reported by Kariuki *et al.* (2014), the mechanical properties of laminated bamboo were affected by fiber orientation. Nugroho and Ando (2001) also stated that vertical orientation could increase the strength of laminated bamboo.

This study aimed to explore how culm position and lamination direction affect the mechanical properties of laminated boards made from Betung bamboo. The objective was to gather insights into the anticipated mechanical characteristics of laminated Betung bamboo, providing guidance for producing boards with optimal mechanical strength by considering the recommended culm position and lamination direction.

2. MATERIALS and METHODS

2.1. Materials preparation

The type of bamboo used in this study was Betung bamboo (*D. asper),* which is commonly known as giant bamboo, obtained from Sleman Regency, Yogyakarta. The specified dimensions of the bamboo include mature culms aged over 3 years, with a length of 9 meters (measured from the base of the cut) divided into three sections: base, middle, and top, each measuring 3 meters. The minimum diameter was 15 cm, minimum internode length was 35 cm, and minimum wall thickness was 2 cm. The bottom 0.5 m from the ground of the bamboo culm was removed, and both outer and inner skin were stripped. The adhesive used was Crossbond X4, a branded adhesive based on polyvinyl acetate (PVAc) from Bioindustries, Yogyakarta. The specification of the adhesive was pH of 4.1, specific gravity of 1.15, solids content of 44% and viscosity of 3,500 cps.

2.2. Laminated board manufacturing

The bamboo underwent a conventional solar drying process for one month until it reached an air-dry condition. This drying method was chosen for Betung bamboo because it is simple and can reduce operational costs (Sumardi *et al*., 2024). After drying, the bamboo was split into slats with a width of 1.5 cm. The slats obtained were then further split into smaller pieces, resulting in bamboo slats measuring 35 cm in length, 1.5 cm in width, and 0.5 cm in thickness. Before lamination, the bamboo slats were first preserved with mixture of borax and boric acid in a ratio of 3:2 at a concentration of 10% and boiled at 55℃–60℃ for 2 hours (Sulistyawati, 1997 with modifications). As reported, the application with boron did not significantly affect the density and mechanical properties of laminated Betung bamboo (Aini *et al*., 2009; Sumawa *et al*., 2019). Some studies also reported that the preservative treatment on wood with boron did not reduce the density and flexural properties of samama wood (Cahyono *et al.,* 2020) and light red meranti wood (Lee *et al*., 2024). The bamboo slats were drained and dried again until they reached a moisture content of about 15%. The conditioned bamboo slats were taken randomly and then arranged to form a board measuring 30 cm in length, 30 cm in width, and 3 cm in thickness, then bonded using PVAc adhesive with glue-spread of 280 g/m^2 and clamped with a hydraulic press at a pressure of 1 MPa. The bamboo slats were glued horizontally and vertically (Fig. 1). The bamboo assembly was cold pressed for 24 hours and conditioned for one week prior to testing.

2.3. Physical and mechanical properties testing

The physical and mechanical properties tested were moisture content and density according to BS 373 (BSI, 1957), static bending strength consisting of MOR and MOE, and hardness test based on ASTM D1037 (ASTM, 1999). The static bending tests were conducted using a sample size of 30 cm × 2 cm × 2 cm (l × w × t), while hardness testing uses a standard with a sample size of 5 cm × 5 cm × 5 cm. The testing was performed using the Universal Testing Machine (UTM) Instron Model 3360.

3. RESULTS and DISCUSSION

3.1. Moisture content and density

The results of testing the moisture content and density of laminated bamboo indicate that the moisture content

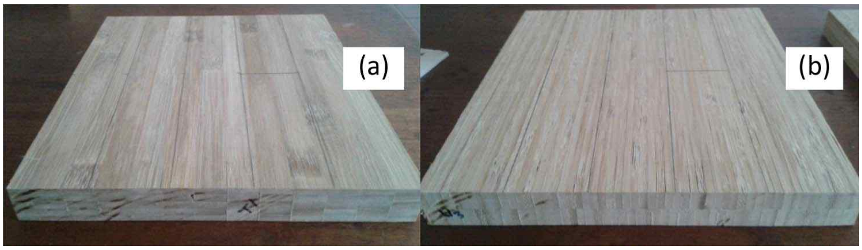

Fig. 1. Laminated board pattern. (a) Horizontal orientation, (b) vertical orientation.

of the produced laminated bamboo ranges from 14.19% to 15.86%, with an average value of 15.25%. These values are consistent with the typical range of air-dry moisture content found in Indonesia. Furthermore, the density of laminated bamboo has an average value of 0.66 g/cm³. This is higher compared to the generally observed density of common bamboo, which has an average basic specific gravity of 0.61 as reported by Kasmudjo (2013). However, this value was lower than the original Betung bamboo in the study of Irawati and Saputra (2012), which resulted in an average density of 0.72 g/cm³. The difference in density is suspected to be caused by the presence of remaining bamboo skin and the existence of adhesive material that binds between bamboo laminates. Tho and Morisco (2008), elucidated that the mechanical properties are influenced by the presence of skin layers on the strips compared to those without. In general, the values of moisture content and specific gravity of the produced laminated bamboo were not influenced by the variation of culm position and laminate direction.

3.2. Static bending properties

The mechanical properties serve as a measure of an object's resistance to external forces that tend to alter its original shape (Bowyer *et al*., 2007). In this study, the static bending strength test was conducted to obtain the values of MOE and MOR for the produced laminated bamboo. The average MOR values and the results of the variance analysis are presented in Tables 1 and 2. Based on the analysis of variance, the MOR test results indicated no significant differences in the factors of stem position, lamination direction, or their interaction. Therefore, in terms of MOR, there was no significant influence observed in either the culm position or lamination

Table 1. Average MOR of laminated bamboo at different culm position and lamination direction (MPa)

Lamination direction	Culm position			Average
	Lower	Middle	Upper	
Vertical	91.48 (7.87)	98.14 (26.89)	131.68 (5.92)	107.10 (13.50)
Horizontal	76.34 (39.99)	109.57 (9.28)	96.06 (6.50)	93.99 (28.09)
Average	83.91 (23.93)	103.86 (18.08)	113.87 (6.21)	100.55 (18.02)

Numbers in parentheses are SD.
MOR: modulus of rupture.

Table 2. Variance of MOR of laminated bamboo at different culm position and lamination direction

Source of diversity	Sum of squares	Db	Median square	*F* count	Sig.
Culm position (B)	772.791	1	772.791	1.820^{ns}	0.202
Lamination direction (L)	2,790.707	2	1,395.354	3.286^{ns}	0.073
Interaction (B × L)	1,669.629	2	834.815	1.966^{ns}	0.183
Error	5,095.159	12	424.597		
Total	10,328.287	17			

^{ns} Not significantly different.
MOR: modulus of rupture.

direction to the MOR values, although it can be seen in Table 1 that the higher culm position resulted in higher MOR (83.91 MPa, 103.86 MPa and 111.87 MPa for lower, middle and upper culm position, respectively) and vertical lamination resulted in higher average MOR (107.10 MPa) than that of horizontal lamination (93.99 MPa). Nevertheless, the average MOR value reaches 100.55 MPa. As a comparison, the MOR values of this study were lower than the study of Setyo *et al*. (2014) which resulted in an average MOR of 130.98 MPa by using UF resin as adhesive. However, the result of MOR value was higher compared to the general MOR of whole bamboo culms, which is 33.58 MPa (Kasmudjo, 2013). This improvement in strength is attributed to the lamination process and bonding technology, as highlighted by Setyo *et al.* (2014).

The average MOE values and the results of the analysis of variance were presented in Tables 3 and 4. Based on the analysis of variance, the MOE test results show significant differences in culm position and lamination direction, but the interaction between these two factors does not yield significant differences. The results of honestly significant different (HSD) test at significant level of 1% test results indicate significant differences between the lower position and both the middle and upper positions, while the middle position does not show significant differences from the upper position. Figs. 2 and 3 presented the histogram of the relationship between culm position, lamination direction and MOE of laminated bamboo board. The middle and upper position of bamboo culm resulted in MOE of 12.54 and 12.43 GPa, respectively. It was higher than the lower culm position of 10.01 GPa. Similar findings are also mentioned by Oka *et al.* (2014), indicating that the culm

Table 3. Average MOE of laminated bamboo at different culm position and lamination direction (GPa)

Lamination direction	Culm position			Average
	Lower	Middle	Upper	
Vertical	10.74 (0.54)	12.37 (0.26)	13.95 (1.58)	12.36 (0.79)
Horizontal	9.27 (2.34)	12.70 (1.02)	10.91 (1.00)	10.96 (1.40)
Average	10.01 (1.44)	12.54 (0.64)	12.43 (1.29)	11.66 (1.12)

Numbers in parentheses are SD.
MOE: modulus of elasticity.

Table 4. Variance of MOE of laminated bamboo at different culm position and lamination direction

Source of diversity	Sum of squares	Db	Median square	*F* count	Sig.
Culm position (B)	24.550	2	12.275	7.100**	0.009
Lamination direction (L)	8.708	1	8.708	5.037*	0.044
Interaction (B × L)	8.565	2	4.283	2.477ns	0.126
Error	20.747	12	1.729		
Total	62.571	17			

* Significantly different at 5% test level; ** Significantly different at 1% test level; ns not significantly different.
MOE: modulus of elasticity.

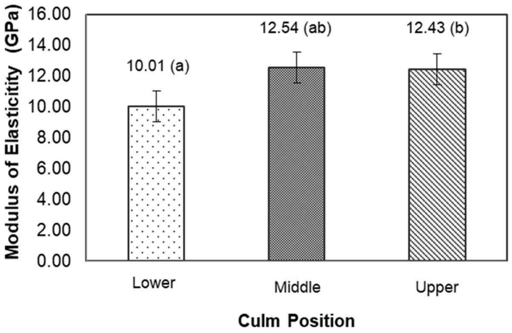

Fig. 2. Histogram of the relationship between culm position and modulus of elasticity of laminated bamboo. [a,b] Values followed by the same letter indicate no significant difference.

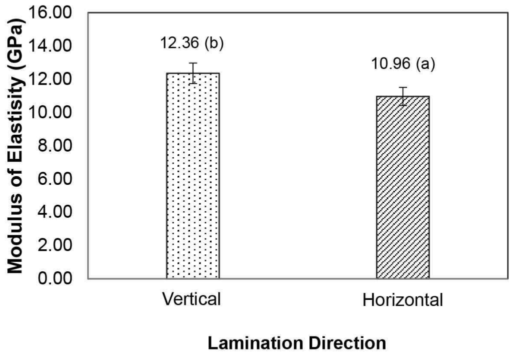

Fig. 3. Histogram of relationship between lamination direction and modulus of elasticity of laminated bamboo. [a,b] Values followed by the same letter indicate no significant difference.

position of bamboo significantly affects mechanical properties, especially in tensile, compressive, and shear strength tests. The difference shows that vertical lamination provides 12.77% higher flexural modulus than horizontal lamination. The vertical direction resulted in an average MOE of 12.36 GPa, while the horizontal one resulted in an average MOE of 10.96 GPa. This follows the finding that vertical laminate increases static flexural strength (Nugroho and Ando, 2001; Sharma *et al.*, 2015). However, the results of this study are slightly lower than the expression of Sharma *et al.* (2015), who mentioned that the vertical laminate arrangement direction improved the average MOE value by 18%. Compared to the study of Setyo *et al.* (2014), the average MOE values of this study were quite lower (11.66 GPa compared to 12.42 GPa). It was understandable since they used UF resin in laminated bamboo production.

3.3. Hardness

The results of the hardness testing for different culm positions and lamination directions were presented in Table 5. To determine the variation of the average hardness value based on the factors of stem position and lamination direction, the variance analysis is presented in Table 6. The histogram depicting the relationship between culm position, lamination direction and hardness of laminated bamboo board was presented in Figs. 4 and 5. Based on the analysis of variance, the hardness results showed highly significant differences in both and

Table 5. Average hardness of laminated bamboo at different culm position and lamination direction (kgf/cm^2)

Lamination direction	Culm position			Average
	Lower	Middle	Upper	
Vertical	986.87 (100.39)	1,284.13 (132.54)	1,422.80 (266.53)	1,231.27 (166.48)
Horizontal	625.53 (86.71)	1,019.11 (76.21)	939.12 (105.70)	861.25 (89.54)
Average	806.20 (93.55)	1,151.62 (104.375)	1,180.96 (186.115)	1,046.26 (128.01)

Numbers in parentheses are SD.

Table 6. Variance of hardness of laminated bamboo at different culm position and lamination direction

Source of diversity	Sum of squares	Db	Median square	*F* count	Sig.
Culm position (B)	521,234.724	2	260,617.362	12.695**	0.001
Lamination direction (L)	616,101.431	1	616,101.431	30.010**	0.001
Interaction (B × L)	36,027.539	2	18,013.770	0.877ns	0.441
Error	246,357.491	12	20,529.791		
Total	1,419,721.185	17			

** Significantly different at 1% test level; ns not significantly different.

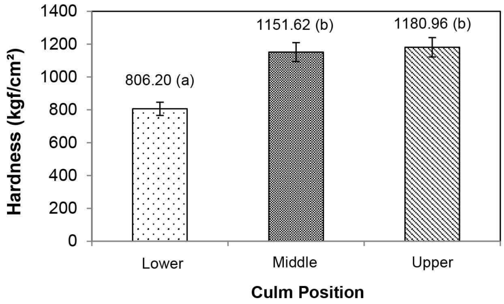

Fig. 4. Histogram of relationship between culm position and hardness of laminated bamboo. [a,b] Values followed by the same letter indicate no significant difference.

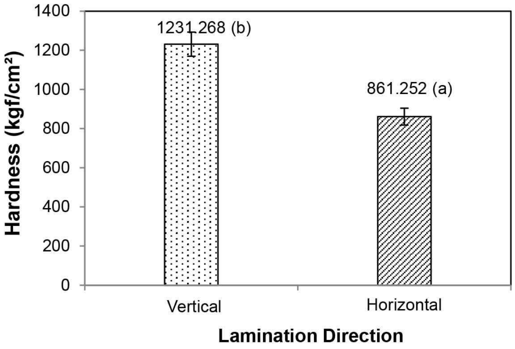

Fig. 5. Histogram of relationship between lamination direction and hardness of laminated bamboo. [a,b] Values followed by the same letter indicate no significant difference.

culm position and lamination direction, while the interaction between the two did not yield significant differences. The HSD 1% test results indicate highly significant differences between the base position and both the middle and end positions. Regarding lamination direction, the HSD 1% test results show highly significant differences between the vertical and horizontal lamination directions. Therefore, considerations for hardness properties also consider both culm position and lamination direction, even though only one of them is being considered. The overall average total hardness value for lamination direction was 1.046 kgf/cm², a value significantly higher than the natural hardness of Betung bamboo, which is only 250 kgf/cm² (Kasmudjo, 2013). This improvement in strength was attributed to the bonding process in lamination technology, as highlighted by Setyo *et al.* (2014).

4. CONCLUSIONS

Research on the effect of different culm positions and lamination directions on the physical and mechanical properties of laminated Betung bamboo resulted in the average moisture content of 15.25%, density of 0.66 g/cm³, MOR of 100.55 MPa, MOE of 11.66 GPa and hardness of 1.046 kgf/cm². Furthermore, it is concluded that there is no interaction between culm position and lamination direction concerning the physical and mechanical properties of laminated bamboo. In MOE and hardness, the higher the stem position, the greater the strength value, while the vertical lamination direction has greater strength than the horizontal lamination direction. Culm positions with a high likelihood of being utilized for laminated bamboo boards are primarily the middle and upper sections, particularly for applications in building materials and high-strength furniture. The lamination direction with the feasibility of being used was the vertical lamination direction.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGMENT

The authors would like to thank Universitas Gadjah Mada for funding this research project through Indonesian Research Collaboration based on contract number of 2658/UN1/DITLIT/Dit-Lit/PT.01.03/2023. The comments and suggestions from anonymous reviewers are greatly acknowledged.

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