Bamboo Hybrid Laminate Board (*Gigantochloa apus*) Strip with Falcata Veneer (*Paraserianthes falcataria*) in Selected Fiber Directions

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This study investigated the physical and mechanical properties of bamboo hybrid laminate boards (BHLB) in various fiber directions as a potential wood-replacement structural material. This study used dry bamboo (*Gigantochloa apus*) processed into thin strips with a thickness of 4 mm and falcata veneer (*Paraserianthes falcataria*). The BHLB were arranged based on different fiber directions (*i.e.*, perpendicular and parallel) in cold pressing (30 min; 22.2 kgf/cm^2) and hot pressing (6 min; 15 kg/cm^2). The adhesive used was urea-formaldehyde (UF) resin (glue spread rate of 250 g/m^2 and inter veneer 170 g/m^2). Physical and mechanical properties were observed to validate the feasibility of preparing BHLB from bamboo strips and falcata veneers. The results showed that the arrangement of the fiber direction affects dimensional stability, MOE (modulus of elasticity), MOR (modulus of rupture), shear strength, and screw withdrawal strength. Falcata veneer as the board core material resulted in lower density, low dimensional stability, and higher water absorption. However, the mechanical properties were not much different and fulfilled the standard for structural use. This study concludes that bamboo can be used for making composite BHLB as an alternative to wood-based composites for structural use.

Keywords: BHLB; Bamboo laminated; Strip bamboo; LBL; Ply-bamboo; Hybrid

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INTRODUCTION

The production of high-quality wood is considered difficult because its structural development requires a long time and the availability in natural forests is declining. Therefore, a wood substitute to fulfill the market demand is needed. Bamboo is a good wood substitution due to its fast life cycle of around 3 to 4 years and the abundant availability of bamboo in Indonesia (INBAR 2005).

Bamboo is a material with good mechanical properties. However, its round and hollow shape have made the use of bamboo limited. Therefore, a dimensional modification process is needed, such as those resulting in composite bamboo. Composite bamboo is a way to process products by combining several parts of bamboo with the help of adhesives. The modification process results in a more flexible bamboo shape that can be used as a structural or non-structural material (Sharma *et al*. 2015). Numerous composite bamboo products have been successfully made and reported in several studies, *i.e.*, particleboard (Widyorini *et al*. 2015), strandboard (Sumardi *et al*. 2015), scrimber (Sharma *et al*. 2015), bamboo laminated (Li *et al*. 2013), and bamboo composite lumber (Sulastiningsih *et al*. 2018).

The bamboo laminate board is an alternative form of modification that can increase the use of bamboo as a raw material (Sulastiningsih *et al*. 2018). The use of bamboo laminate boards as structural and non-structural applications has been developed, such as furniture, interior panels, parquet, and other applications (Anokye *et al.* 2016). There are also several studies related to laminated bamboo development, *i.e.*, laminated bamboo lumber (Mahdavi *et al*. 2012), laminated bamboo zephyr (Nugroho and Ando 2001), bamboo-bundle laminated veneer (Chen *et al*. 2014), and laminated bamboo strips (Rassiah *et al*. 2014).

Another way to change the bamboo dimension is by splitting it into usable pieces, *i.e.*, bamboo strips. Bamboo in the strip form has a low thickness, depending on its stem diameter. The bamboo laminated board is bamboo strips glued to other wood and pressed. The combination of bamboo and wood can enhance mechanical properties, which are essential to structural use (Verma and Chariar 2012). Several kinds of wood and bamboo combination have been successfully made, *i.e.*, bamboo bundle lamination poplar wood veneer (*Populus ussuriensis*) (Chen *et al*. 2017), bamboo strip laminate with larch and poplar particle wood (Xiao *et al*. 2014), and laminated bamboo strips with matting (Ali *et al*. 2016).

Falcata (*Paraserianthes falcataria*) and urea formaldehyde (UF) have an important role in the Indonesian timber industry. The adhesive UF is widely used in Indonesia in the plywood industry as the main bonding agent. This type of adhesive has a detrimental effect on the environment, but is still used because of its relatively cheap price, colorless, water soluble and quick drying (Pizzi *et al.* 2005; Jovanovic *et al*. 2019; Jeong and Park 2019) On the other hand, falcata wood is a fast growing tree that has a low density and low mechanical properties. Falcata wood has many industrial uses, for example for pulp and paper, furniture, and light construction. However, falcata wood utilization is often for products requiring medium to low-density wood (Krisnawati *et al*. 2011). The combination of bamboo with falcata veneer is a feasible solution to produce a lightweight board and to increase its structural use. The use of bamboo as a face and back layer has been shown to increase the stiffness and strength of laminated boards (Chen *et al*. 2017). The direction of the fiber arrangement on the laminate board affects the mechanical properties (Kariuki *et al*. 2014). Therefore, the study of the effect of the core layer using falcata veneer in various fiber directions on the physical and mechanical properties of the bamboo laminate board is discussed in this paper.

EXPERIMENTAL

Materials

This study used materials, *i.e.*, water, borax (PT Adimitra Prima Lestari, Jakarta, Indonesia), falcata veneer (*Paraserianthes falcataria* (L.) Nielsen) (PT SGS Plywood Industry, Tangerang, Indonesia), urea formaldehyde adhesive (PT Pamolite Adhesive Industry, Probolinggo, Indonesia), and 4-year-old bamboo (*Gigantochloa apus* (J. A. & J. H. Schultes) Kurs.) culms obtained from the Sumedang area, West Java, Indonesia.

Bamboo culms and strips preparation

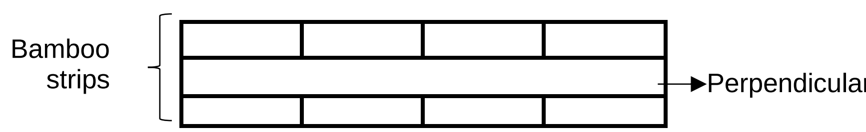
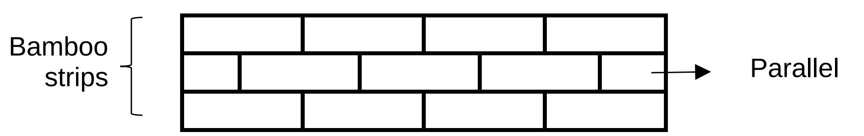
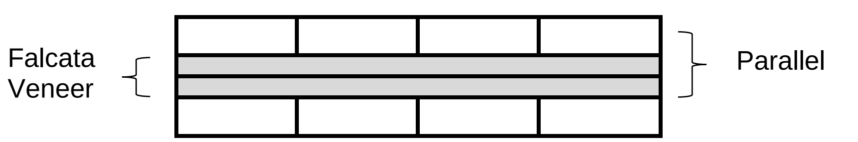
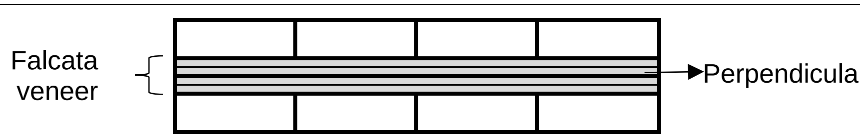
Fresh bamboo culms were cut to pieces of ± 40 cm. Bamboo was preserved by soaking with a borax solution ($Na_2B_4O_7.5H_2O$) for 7 days. The preparation of bamboo strips was completed by drying it at room temperature for 7 days or until it reached 20%

water content. Then, each bamboo column was removed from the outer and inner parts and cut into 20 pieces of 40 cm long, 2 cm wide, and 0.4 cm thick, then arranged into sheets of bamboo strips.

Producing laminated bamboo boards

The lamination boards were made with a final size of 40 cm x 40 cm x 1.3 cm (length x width x thickness) with variations in the core layer and fiber direction (Table 1). Variations in the core constituent materials were hybrids using four layers of falcata veneers of 2 mm thick and three layers of bamboo strips. The direction of arrangement was parallel to the fiber, namely LBL (laminated bamboo lumber) and perpendicular to ply-bamboo. Prior, urea formaldehyde (UF) adhesives were mixed with 20% wheat flour and 0.5% hardener. Each layer was coated with UF adhesive with a double spread technique with a glue spread rate of 250 g/m^2 and between veneers of 170 g/m^2. Cold pressing was performed for 30 min at a pressure of 22.2 kgf/cm^2 followed by hot pressing for 6 min at 15 kg/cm^2 pressure and a temperature of 110 °C. The laminate boards were then conditioned for 7 days before testing.

Table 1. Laminated Bamboo Board Arrangement and Combination

Type of Laminated Board	Illustrated Cross-section
Strip Ply-bamboo	
Strip LBL[a]	
Hybrid LBL[a]	
Hybrid Ply-bamboo	

[a] Laminated bamboo lumber

Physical and Mechanical Properties Testing

The bamboo hybrid laminate board (BHLB) was evaluated for its water content, density, water absorption, swelling-shrinkage, and delamination. Determination of water content and density followed JAS 003 (2014) for plywood and JAS for laminated veneer lumber. Accordingly, the moisture content and density were recorded after the board was air-dried. The shrinkage and water absorption testing were according to the modified ASTM D1666-64 (1981) standard. The shrinkage test was conducted after 24 h of soaking for changing in thickness and length. The thick dimension was the side of the bamboo laminate board, while the long dimension was in the direction of the fiber (face and back layers).

The mechanical properties of ply-bamboo and laminated bamboo lumber (LBL) tested were modulus of elasticity (MOE), modulus of rupture (MOR), shear strength, and screw withdrawal strength. The determination of the MOE/MOR ply-bamboo board was completed in the long and cross direction of the sample following JAS 003 (2014) for plywood. Then, the determination of MOE/MOR LBL was completed in the flat and edge directions of the sample according to JAS 2773 (2013) for laminated veneer lumber. The testing of shear strength was performed according to JAS 003 (2014) for plywood standard with a ply-bamboo sample size of 81 mm x 25 mm. The LBL horizontal shear strength was performed according to the JAS 2773 (2013) standard for laminated veneer lumber in two testing directions, *i.e.*, flat direction (81 mm x 39 mm), and edge direction (99 mm x thickness). The standard used in determining screw withdrawal strength was SNI 03-2105 (2006) with a sample size of 5 cm x 10 cm and a screw depth of 0.7 mm.

Data Analysis

The design of the experiment was following the completely randomized design method with two factors, *i.e.*, a combination of raw materials and variations in the fiber direction. Each treatment used four replications. Data were analyzed using the independent sample T-test with $\alpha \leq 0.05$. Data analysis was performed with SPSS 16.0 software (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Moisture Content and Density

The results of the moisture content test and the density of the bamboo laminate board are shown in Table 2. The moisture content values ranged from 10 to 12% and met the required standard for plywood (14% maximum; JAS 003 (2014)). The density of bamboo strip laminate boards ranged between 0.7 to 0.72 g/cm^3; meanwhile, the hybrids ranged between 0.85 to 0.86 g/cm^3.

Table 2. Physical Properties of Laminated Bamboo Boards

Laminate Bamboo Board Type	Moisture Content (%)	Density (g/cm^3)	Delamination (%)
Strip ply-bamboo	11.07 (1.16)	0.86 (0.01)	0
Strip LBL	10.44 (1.01)	0.85 (0.03)	0
Hybrid ply-bamboo	11.40 (0.81)	0.70 (0.01)	0
Hybrid LBL	11.13 (0.49)	0.72 (0.01)	0

The bamboo strip laminate board strength produced in this study is within the range of the strong class II (0.6 to 0.9 g/cm^3) as per SNI 03-3527 (1994). The hybrid density values were higher than the specific gravity of falcata wood (0.24 to 0.49) as per SNI 7973 (2013) and the specific gravity of rope bamboo or *G. apus* (0.65) as per the study by Suryokusumo and Nugroho (1994). The wood modification aimed to improve the physical and mechanical properties of the raw material. These results showed that the hybrid laminates increased the density and strength class of bamboo and falcataria wood. The density of the hybrids was smaller than the strip due to the substitution of bamboo with falcata veneer because the composition of the laminate material affects the density value of the bamboo composite board (Sulastiningsih 2008).

Dimensional Stability

Dimensional stability was measured using changes in thickness and length, *i.e.*, expansion and shrinkage. The shrinkage test was conducted after 24 h of soaking. The thick dimension was the side of the bamboo laminate board, while the long dimension was in the direction of the fiber (face and back layers). In this case, thick changes were greater than the length due to the high shrinkage in the tangential direction characteristics of bamboo. Part of the long direction was the longitudinal bamboo, where the shrinkage was minimal. This result was consistent with the result of Odebunmi *et al.* (2019), where the development in the longitudinal direction was approximately 0.19 to 0.52%, the development in tangential direction was 5.56 to 8.34%, shrinkage in the longitudinal direction was 0.24 to 0.37%, and shrinkage in the tangential direction approximately 3.82 to 6.99%.

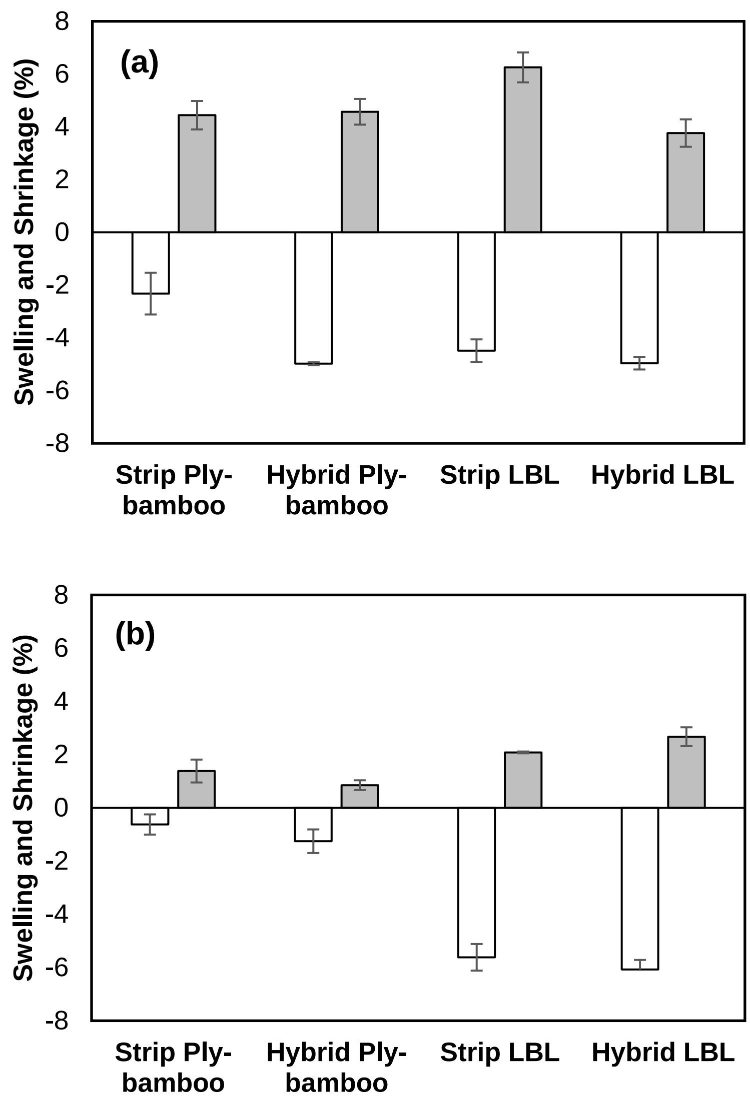


Fig. 1. Swelling and shrinkage of (a) thickness and (b) length of the four different laminated bamboo boards

Figure 1a shows the total value of thick changes in both shrinkage and development, *i.e.*, 10.74% for strip LBL, 9.55% for hybrid ply-bamboo, 8.72% for hybrid LBL, and 6.76% for ply-bamboo strips. The value shows that the change in the thickness direction value was the lowest on the ply-bamboo strip and highest in the LBL strip. This result was influenced by the direction of the arrangement of the fiber. Meanwhile, there were no significant differences in the hybrid core layer. The direction of the perpendicular fibers can reduce the thickness change due to the differences in the direction of the fiber so that the escape paths hold water. Additionally, the hybrid core layer thick direction stability was in the range of the core layer of the strip.

Figure 1b shows the total value of length changes from depreciation and development of four types of laminated bamboo board, *i.e.*, 8.75% for hybrid LBL, 7.70% for LBL strip, 2.11% for hybrid ply-bamboo, and 2.01% for ply-bamboo strip. The value shows that the bamboo laminate board with a parallel arrangement (LBL) had a high shrinkage value, indicating an unstable arrangement. The arrangement of ply-bamboo or perpendicular to the stability of the long direction was higher because the direction of fibers that intersect the core layer reduces the changes in length. The length changes on each layer of LBL laminate boards, meanwhile the ply-bamboo length changes on the face and back layers. The core layer of ply-bamboo has a different direction of the fiber, which resists the changes. The use of a hybrid core layer showed a higher length change than the strip. It is suspected that the two layers of falcata veneer have a lower ability to withstand changes in length than one layer of bamboo strips.

Water absorption measurement was done by measuring the weight changes after soaking to its saturation point. The increase in water absorption is presented in Fig. 2.

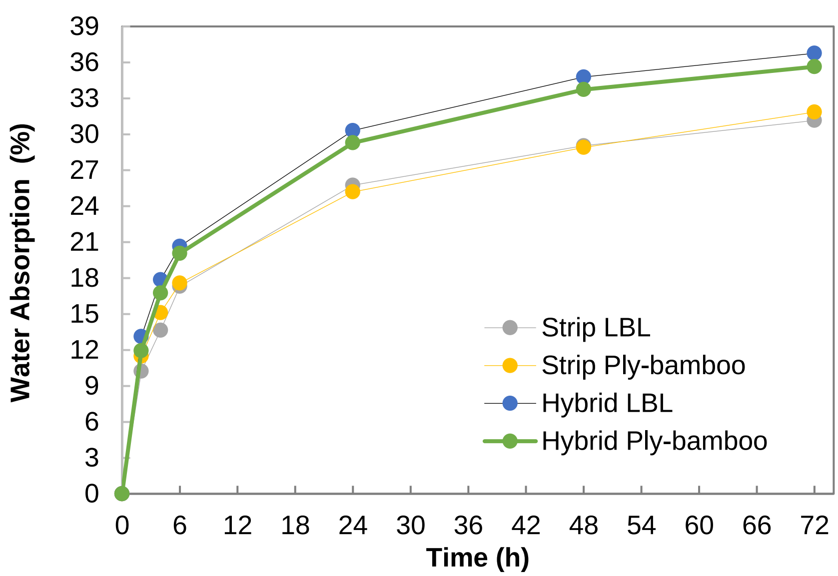


Fig. 2. Percent water absorption of four different laminated bamboo boards

The highest absorbency of bamboo was seen in the first 2 h of soaking, and after 48 h it remained stable. The stable water absorption indicated that bamboo had been saturated near the limit where the water could not enter the wood cells anymore. In this study, the water absorption for hybrids (34 to 43% of the weight before immersion) was higher than the strip (29 to 35%). One possible explanation was that the falcata saturation was higher than bamboo. The hybrid with perpendicular fiber arrangement (hybrid ply-bamboo) showed a lower water absorption than the hybrid with parallel fiber arrangement (LBL). Indeed, other studies, such as Lee *et al.* (2012), found that the arrangement of perpendicular layers of fibers has the best dimensional stability of thickness swelling and water absorption because perpendicular arrangement can stabilize the dimensions by balancing the stresses when shrinkage and expansion occur. The parallel bamboo laminate boards or LBL was compressed with a higher pressure than the hybrid ply-bamboo. When LBL is immersed, the presence of elastic strain allows it to return to its original shape, which causes changes in higher dimensions.

Modulus of Elasticity and Modulus of Rupture

The MOR value indicates the ability to withstand maximum load until the wood is broken and the MOE value indicates the value of wood stiffness. The highest MOE and MOR values were shown by LBL boards (Fig. 3). The independent T-test result showed significant differences between the MOE and MOR values, which indicates the influence of the direction of the fibers and the core layer constituent materials.

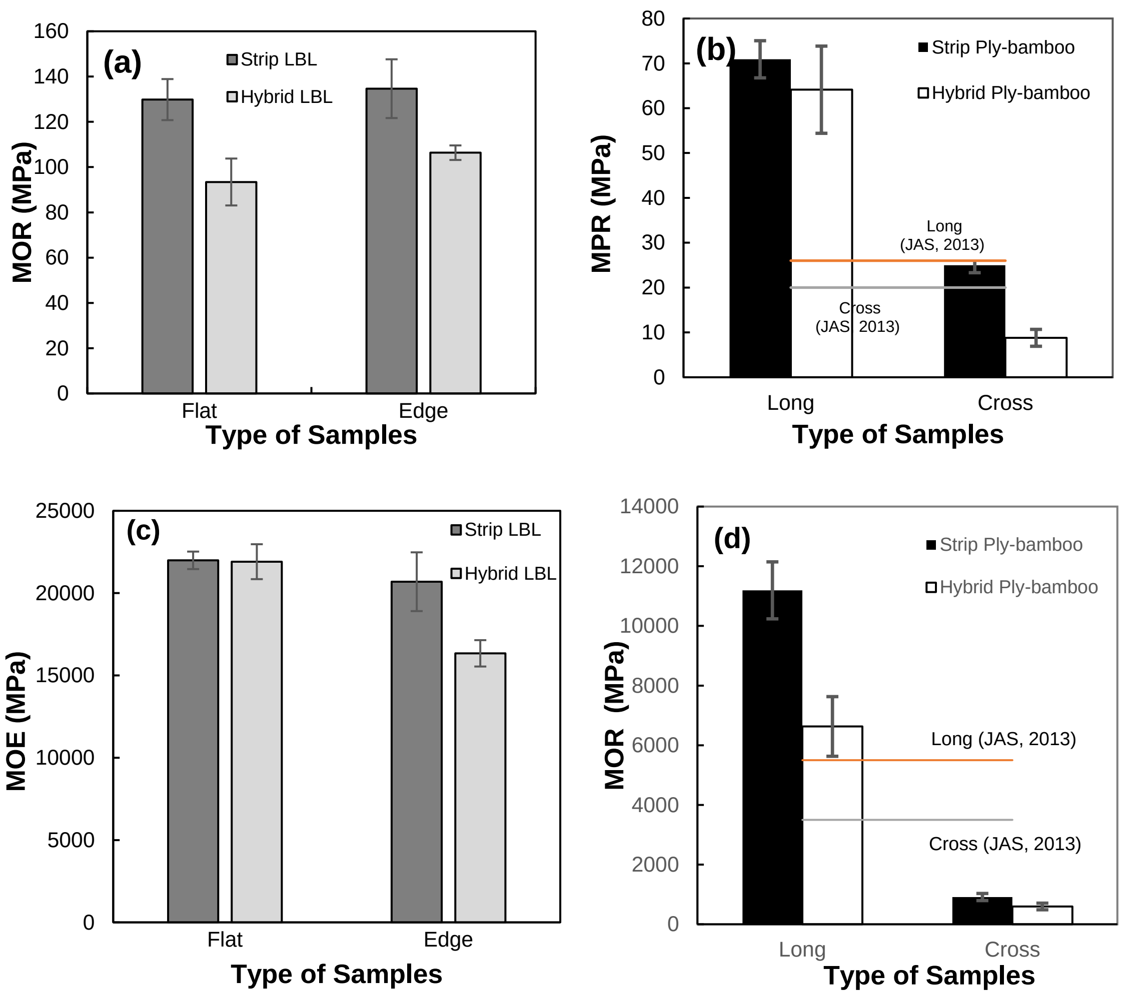


Fig. 3. Test results of laminated bamboo strip boards and hybrid variations in different arrangement of directions: (a) MOR in parallel, (b) MOR in perpendicular direction, (c) MOE in parallel direction, and (d) MOE in perpendicular direction

The MOE and MOR testing on LBL used two test areas, *i.e.*, flat and edge. The flat area is when the test is perpendicular to the board surface and the edge is perpendicular to the side of the board. The highest MOE and MOR values were shown by the LBL strip (Fig. 3a and c). The test results obtained in the flat area value MOR for strip LBL was 129.8 MPa and hybrid LBL was 93.4 MPa. Test results from the edge area for strip LBL was 134.6 MPa and for hybrid LBL was 106.4 MPa. The MOR value was lower when the falcata veneer was used as a core layer (Fig. 2) because the laminated board was not able to withstand the burden given to the face and back layers. Laminated board with bamboo strips as the core layer still had the ability to withstand the load, thus did not break immediately. This was also supported by the board's lower hybrid density. The MOR and MOE values were positively related to the wood's density; a higher density resulted in higher MOE and MOR values. High density indicates that compressing and gluing is running well because the damage of the bending test often occurs at the opening of sticky lines (Roh and Ra 2009). In this study, MOR values were higher in the edge test field, similar to a study by Kariuki *et al*. (2014), where the edge gave higher MOR and MOE values.

The MOE test results in the flat direction were 22,000 MPa for the strip LBL and 21900 MPa for the hybrid LBL. Meanwhile, the edge test area showed values for the LBL strip of 20700 MPa and LBL hybrid of 16341 MPa. Compared to the LBL hybrid, the LBL strip's MOE value was higher in the edge area (Fig. 3c) and similar in the flat area. The MOE measurement on the flat samples indicated the stiffness of the board. Thus, the measured value influenced the face and back layers of the board. This was indicated by the slight difference in the MOE value on the flat sample using falcata veneer. The core layer did not influence the flat area, whereas it decreased the MOE value on the edge area. Based on the independent T-test result, the core layer constituent materials influenced the MOE edge, MOR flat, and MOR edge. Possibly, the edge test area was in contact with veneers, resulting in a decrease in stiffness (low MOE value). Falcata wood is known to have low elasticity and can easily break. The results of MOE and MOR testing for LBL structural type A showed the highest class (class 180 E) based on JAS 2773 (2013) for laminated veneer lumber standard.

The MOE and MOR testing on ply-bamboo used two sample pieces, *i.e.*, long and cross. The long-sample piece was parallel to the direction of the fiber, and the cross-sample piece was perpendicular to the direction of the fiber on both laminate board surface (face and back). The measured MOE and MOR values were higher in the long direction and with bamboo strip cores (Fig. 4). Testing the direction of the cross-direction had little value because the first layer was a connected bamboo strip. When the tested load was in contact with these surfaces, it caused splitting at the connection. The absence of a sticky line between the strips can also cause a low cross-direction value. The damage after MOE and MOR testing and the differences in the results of the long and cross direction tests are shown in Fig. 4. After the test, the cross-direction samples tended to break at the affected part of the load, while long shear occurred between the sticky lines.

The result of the hybrid ply-bamboo MOR test in the long-direction was 64.1 MPa and the cross-direction was 8.79 MPa. The MOR value of the strip ply-bamboo in the long-direction was 70.9 MPa and the cross-direction was 25.0 MPa. The value of MOE and MOR of hybrid ply-bamboo (< 20.0 MPa in the cross-direction) and the ply-bamboo strip (> 26.0 MPa on the long; > 20.0 MPa in the cross-direction) did not meet the JAS 003 (2014) for plywood standard. The core layer constructed with bamboo had a greater MOR value than the veneer. Therefore, bamboo had a higher ability to withstand a greater load when it reaches the core layer. The result of the hybrid ply-bamboo MOE test on the long cutting area was 6630 MPa and the cross-direction was 596 MPa. The value of the ply-bamboo strip MOE in the long direction was 11200 MPa and the cross-direction was 913 MPa. Based on JAS 003 (2014) for plywood standards, the long direction fulfilled the standard because it exceeded 5,500 MPa, but the cross-direction did not meet the standard because it was less than 3,500 MPa. This result was similar to the study of Lee *et al*. (2012) on MOR and MOE.

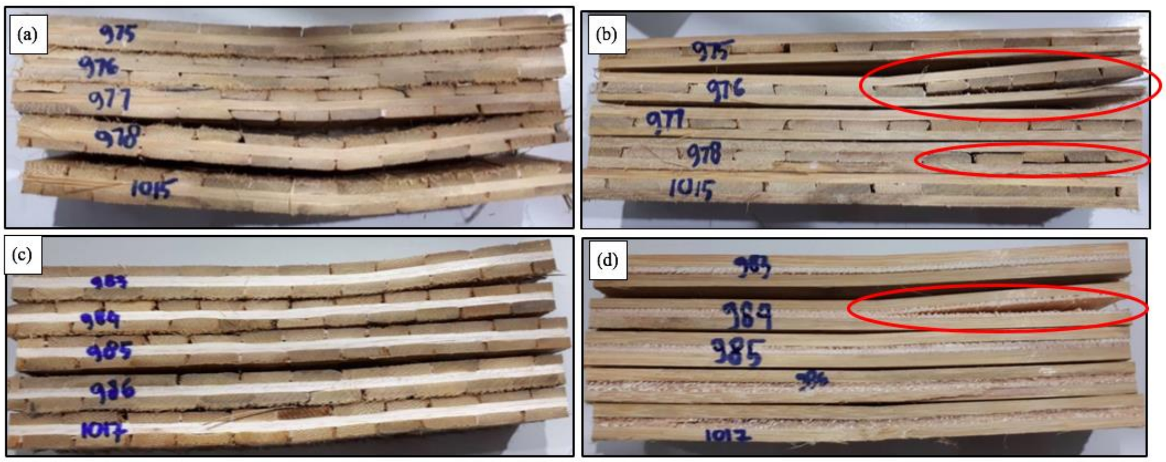


Fig. 4. Bamboo laminate board samples with perpendicular arrangement after MOE and MOR testing: (a) strip ply-bamboo cross test, (b) strip ply-bamboo long test, (c) hybrid ply-bamboo cross test, and (d) hybrid ply-bamboo long test

Shear Strength

The shear strength and delamination were studied to determine the gluing ability of the board with urea-formaldehyde resin. The number of sticky lines in the constituent material of the core layer was 2 for the strip and 3 for the hybrid. The result showed that the veneer core layer had a smaller value than the strip layer on ply-bamboo and LBL (Fig. 6). The shear strength was influenced by the adhesive and the lamina constituent. A high sample density resulted in a higher shear strength value. Additionally, the more layers in the lamina or sticky lines resulted in a higher possibility of greater shear (*i.e.*, low shear strength). The independent T-test results showed that the preparation of the sample's fiber direction influenced the value of shear strength.

The results of this study were different from Santoso *et al*. (2016), which showed that the differences in panel density can increase stickiness. Possibly, the adhesive unevenly penetrated the different layers of the laminate board; there was more adhesive entering the falcata veneer in the face and back layer and the bamboo became poor in adhesive. Falcata wood is a type of wood with high porosity and permeability that allows the adhesive to easily penetrate it. Low wood densities generally absorb a higher amount of chemicals (Ashaari *et al*. 2016). Lack of adhesive resulted in wetting and low viscous line thickness, thereby reducing stickiness (Sulastiningsih 2014). Damage that occurred on the bamboo strip laminate board was due to the separation of the connections between the bamboo strips in the core layer (Figs. 5a1 and 5b1). The connection splitting was due to the absence of adhesive applied between the strips**.**

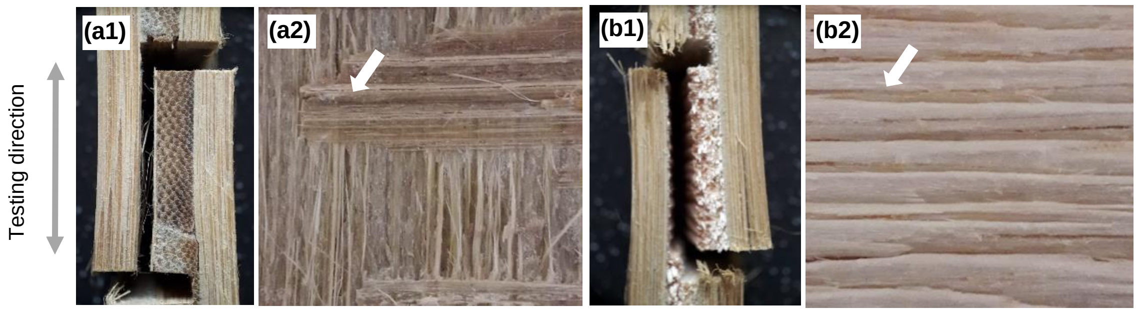


Fig. 5. Photograph (10x magnification) of bamboo laminate board samples in perpendicular arrangement after the shear stress test: (a1) strip ply-bamboo sample and (b1) hybrid ply-bamboo sample; damage after the shear testing: (a2) strip ply-bamboo samples and (b2) hybrid ply-bamboo samples. White arrows indicate the material (wood/bamboo) attached to other surfaces**.**

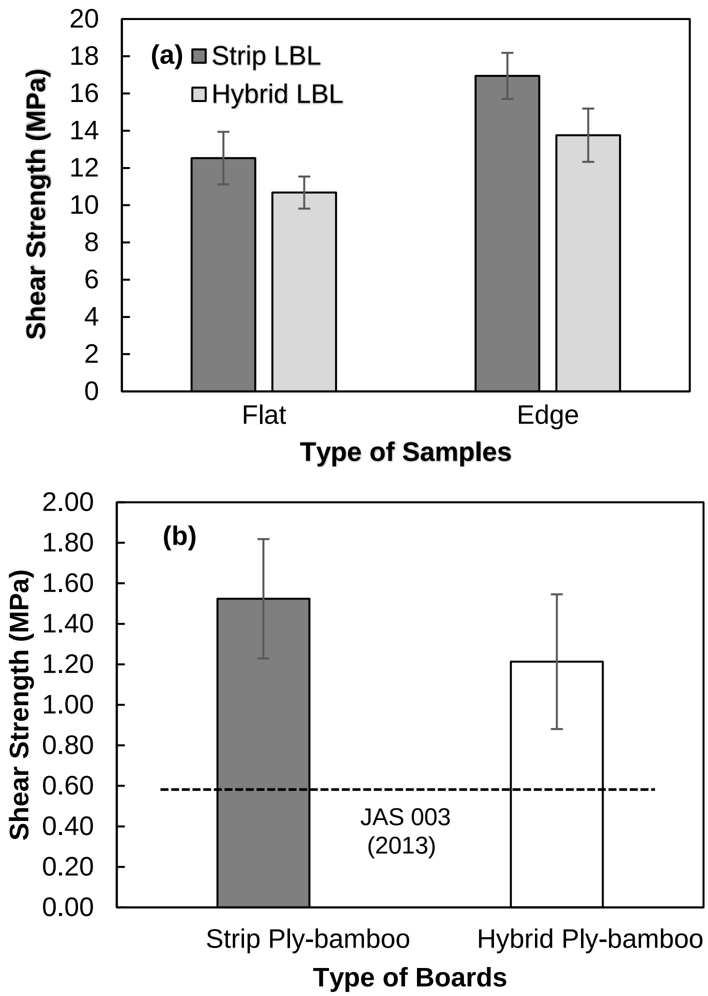


Fig. 6. The shear strength of the laminated bamboo strip board and hybrid variations in the direction of arrangement: (a) parallel and (b) perpendicular to the direction of the fiber

The test of shear strength on the parallel arrangement board was conducted using two contact areas, *i.e.*, flat and edge. The edge area has a higher shear strength (strips: 16.94 MPa, hybrid: 13.76 MPa) compared to the flat area (strips: 12.53 MPa, hybrid: 10.68 MPa; Fig. 6) because of the load given in the direction of the fiber. In contrast, the load on the flat area was given perpendicular to the fiber. The horizontal shear category class was 65 V - 55 H based on the JAS 2773 (2013) standard for laminated veneer lumber structural type A. The value of the fiber perpendicular shear constancy was 1.52 MPa for ply-bamboo strips and 1.21 MPa for hybrids. The shear strength measured in this study exceeded 0.70 MPa, thus fulfilling the JAS 003 (2014) standard for plywood. A similar result was obtained by Suryana *et al.* (2011), where the parallel shear strength was higher than the perpendicular. The study of Xing *et al.* (2019) also mentioned that the bond of shear strength in the load on the edge area was higher than the flat (both horizontally and vertically) and low on the perpendicular fibers. The results of this shear strength are supported by the good delamination value. The delamination value of the bamboo laminate board was 0% (Table 2) with no peeling on the layer, resulting in a good adhesion quality when UF adhesive was used.

Screw Withdrawal

The screw withdrawal strength test was conducted on the face layer, perpendicular to the first layer. The next layer depends on the arrangement of the direction of the fibers and the constituent materials of the core layer, *i.e.*, falcata veneer or bamboo. The result showed that all boards tested fulfilled the SNI 03-2105 (2006) particleboard standard and JIS A 5908 (2003) standard (screw withdrawal strength > 500.14 N). The LBL boards had a smaller screw withdrawal strength value (strip: 701.3 N, hybrid: 507.62 N) than ply-bamboo boards (strip: 1300.63 N, hybrid: 927.66 N; Fig. 7) because bamboo has a longer and more continuous fibers.

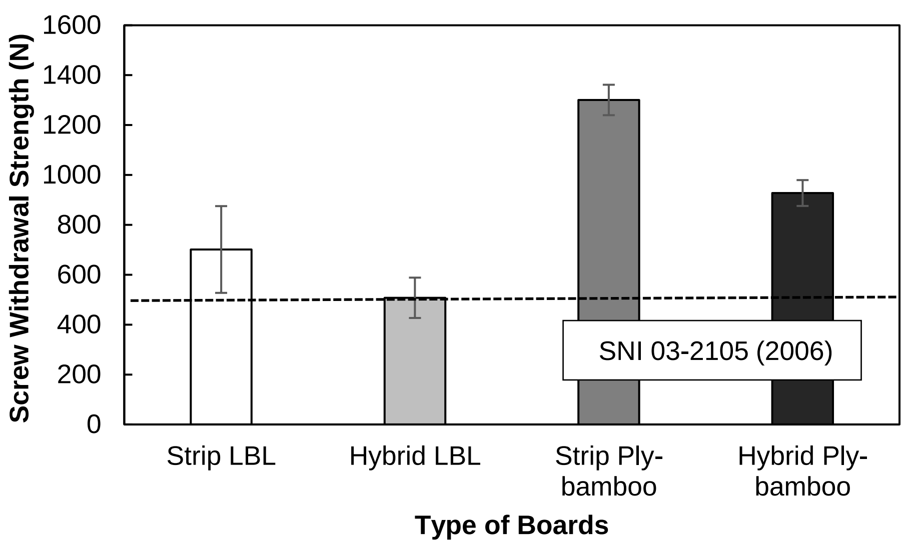


Fig. 7. The screw withdrawal strength value of the four types of board

The screw insertion and retraction divide the LBL, contrary to the perpendicular arrangement where the core layer holds the structure. The results of the independent T-test showed that the core layer constituent material influenced the screw withdrawal strength for ply-bamboo boards. The screw withdrawal strength also influenced by the preparation of the fiber direction. A similar result was shown by the study of Eshaghi *et al*. (2013), where the fiber direction influenced the screw retention by the opening of the layer, which weakens the screw connection. Furthermore, screw withdrawal strength was also affected by the density of the coating material (Fig. 7). Due to its low density, the falcata veneer core layer tends to have a lower screw withdrawal strength because low wood density cannot withstand screw loads. Indeed, other studies also showed the positive correlation of wood density and the screw withdrawal strength (Erdil *et al.* 2002; Bal *et al*. 2017).

CONCLUSIONS

1. Arrangement of fiber direction affects dimensional stability, MOE, MOR, shear strength, and screw withdrawal strength. Arrangement of perpendicular direction produces good dimensional stability and screw withdrawal strength, while parallel produces better MOE, MOR, and shear strength.
2. Bamboo hybrid laminate board (BHLB) results in lower density, lower dimensional stability, and higher water absorption. Bamboo hybrid laminate board reduces mechanical properties but does not differ greatly and has met the standard as a structural use.

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