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# THE EFFECT OF LAMINA CONFIGURATION AND COMPACTION PRESSURE ON MECHANICAL PROPERTIES OF LAMINATED GIGANTOCHLOA APUS COMPOSITES

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***This study aims to investigate the mechanical properties of bamboo apus (gigantochloa apus) as a natural reinforced composite material. Bamboo's laminates of gigantochloa apus were used as reinforcement on the epoxy resin matrix. The parameters examined in this study are the configuration of lamina and compaction pressure. Laminate configuration varies in the number, thickness and direction of the lamina. Compaction pressures of 1.5 MPa, 2 MPa, and 2.5 MPa were used to fabricate the Laminated Bamboo Composites (LBCs). The stem of bamboo with a length of 400 mm was split to obtain bamboo lamina with a size of 400×20 mm. The thickness of bamboo lamina is varied between 1 mm, 1.5 mm, and 2 mm. The bamboo lamina is then preserved by watering it with a preservative solution in the form of 2.5 % sodium tetraborate solution and dried in an oven until the water content reaches 10 %. LBCs were made with a hand lay-up method. After the LBCs were molded, they were pressed with 3 variations of dies compaction 1.5 MPa, 2 MPa and 2.5 MPa. The tensile and bending tests were carried out on the LBCs. Tensile testing is performed in accordance with ASTM standard D3039 and the bending tests were conducted based on ASTM standard D7264. The results show that at each compaction pressure, the highest tensile and bending strength was achieved by LBCs with a thickness of 1 mm of bamboo lamina and 7 layers of bamboo laminates. The LBC with thinner bamboo lamina reinforcement and more layers has the highest tensile strength and bending strength, even it has a lower mass fraction. The LBCs with laminates oriented 0° exhibited greater tensile and bending strengths than the LBCs with laminates structured –45°/+45° and 0°/90°. The LBCs with the 0° laminates direction is matrix fracture followed by lamina fracture. In the 0°/90° direction, matrix fracture is followed by delamination in the 90° and 0° laminates direction. Delamination and lamina clefting were observed in LBCs with laminates oriented +45°/–45°***

***Keywords: Laminated Bamboo Composites, Gigantochloa Apus, Tensile Strength, Bending Strength***

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## 1. Introduction

Bamboo is a group in the true grass family Poaceae, subfamily Bambusoideae, tribe Bambuseae. There are more than 1.450 bamboo species found in cold mountains to hot tropical regions. Bamboo can be harvested in 3–4 years after planting, compared to the traditional timbers that need decades between planting and harvesting [1, 2]. Bamboo has specific mechanical properties that are superior to other types of natural fibers due to the longitudinal arrangement of the fibers. The small microfibrillar angles of the bamboo fibers support high volume stability and excellent mechanical properties [3–5]. The advantages of the mechanical properties of bamboo and the availability of abundant materials have attracted many researchers to use bamboo as reinforcement in composite materials. The use of bamboo fibers as a reinforcing material provides many benefits. Natural fibers that are low in density can be employed as a useful lightweight engineering material compared to synthetic fibers like glass fibers or carbon fibers [6]. Unfortunately, as for the area of bamboo composites characterizations in thermoset setting, only a handful of studies have looked into laminate-based bamboo composites. The use of bamboo as a composite material provides solutions in the development of the materials industry. The tensile strength of bamboo is about twice as high as the tensile strength of lumber, with the compressive strength being approximately 1.5 times stronger than lumber. The strength to weight ratio of bamboo is higher than lumber and plain steel [7]. Bamboo fiber has the potential to replace glass fibers as reinforcing composites. The bamboo fiber has a specific young modulus (Specific E) comparable with the E-glass fiber. It means that the bamboo fiber has a high stiffness with minimum weights [8, 9]. A rather recent study concerning bamboo strips had successfully characterized several imminent properties, for example, tensile, flexural, impact strength, and hardness of bamboo composite in a comprehensive manner [10].

Indonesia is a tropical country with various species of bamboo plants, including petung bamboo (*dendrocalamus asper*), wulung bamboo (*gigantochloa atroviolacea*), yellow bamboo (*bambusa vulgaris*), spotted bamboo (*bambusa maculata*), apus bamboo (*gigantochloa apus*) and others. Bamboo is widely used for flooring, roof construction, crafts/furniture, and fabrics. Apus bamboo (*gigantochloa apus*) is a type of bamboo that has the advantage of being easy to divide and cut up to the thickness of 1 mm. At this time, apus bamboo is widely used for handicraft materials such as bamboo fans, bamboo baskets, ceiling/home asbestos and woven crafts. Apus bamboo has a tensile strength of 230 MPa with a density of 0.6 gr/cm$^3$. The strength to weight ratio of Apus bamboo is higher than woods. The abundant availability of apus bamboo and its good mechanical properties can be used to replace wood in various structural applications. The limitation of bamboo for engineering applications is due to its shape.

Bamboo engineering with lamination by developing Laminated Bamboo Composites (LBCs) is a method to increase the application of bamboo as an engineering material. Laminated bamboo is a processed bamboo based composite manufactured by gluing bamboo strips/laminas under controlled temperature or pressure. Therefore, the development and improvement of the manufacture of LBCs by studying the effect of pressure, number, thickness and direction of the Apus bamboo lamina with improved characteristics is the number one priority of researchers in this field.

## 2. Literature review and problem statement

Bamboo fiber was used as reinforcement of composite. The mechanical behavior of short untreated and treated with NaOH bamboo fiber reinforced epoxy resin composites was studied. Bamboo fibers with various lengths and contents are reinforced with epoxy resin to produce a composite. The results showed that the mechanical properties such as tensile strength, flexural strength, and impact strength of composites were influenced by the NaOH treatment. The tensile strength of the composite with three layers of treated fiber is 18.07 MPa and 16.51 MPa for three layers of untreated fiber [11]. Treating the apus bamboo (*gigantochloa apus*) laminas by soaking them in methanol solution increases the tensile and flexure strength of laminated bamboo composites by about 10 % [12]. The results have shown that treatment of bamboo by NaOH or methanol solution will enhance the mechanical properties of bamboo composites. However, the effect of the number, thickness, direction of the lamina and compaction pressures has not been investigated in the study.

The use of gigantochloa scortechinii woven bamboo fibers as reinforcement in composite materials has been investigated. Bamboo matting is made from sheets of bamboo layers measuring: 0.5 mm thickness and 5.0 mm width. Composites with 2 to 6 bamboo layers were made with a hand lay-up method by using unsaturated polyester (UP) as the matrix. The results indicate that increasing the thickness of bamboo strips increases the tensile stress and modulus of the laminated UP/BF. This is attributed to the bamboo's increased physical interaction with an unsaturated polyester matrix [13]. Bamboo sheets made from thin-wall bamboo culm and isocyanate adhesive have been used to produce laminated bamboo esterilla sheets (LBES). LBES were fabricated by manual compaction and hydraulic compaction. Manual compaction of laminated bamboo was handled using a hand-tightened bolt without measuring the amount of applied pressure. Hydraulic compaction was conducted on the laboratory-scale Weili MH3848(A) 100 T hydraulic pressing machine. The results show that different compaction methods resulted in different properties of LBCs. Manual compaction yields lower MOR than hydraulic presses [14]. The results of this study indicate that in composites with a single laminate, increasing lamina thickness increases the mechanical properties of the composite. The method and amount of compaction in the manufacture of LBCs affect the tensile and bending strength of LBCs. Research to examine the effect of the interaction between the matrix and the bamboo lamina in composites with more than one layer needs to be carried out. A study is required to investigate the characteristics of the effect of the amount of compaction pressure used as a parameter in the manufacture of LBCs.

Laminated composites (LBCs) using four laminas of dendrocalamus strictus cold-pressed using epoxy resin result in maximum stress of LBCs of about 210 MPa. The specimens used had a cross-section of 16×10 mm. This study reported that compressive strengths of LBCs range between 55 MPa and 88 MPa. The fracture mode of LBCs found that the matrix failure occurs followed by fibers failure with a metallic sound of anyone layer and subsequently other layers in specimens. There are good agreements between the theoretical values and experiment results for stiffness and strength [15]. Laminated Bamboo Composites (LBCs) of *dendrocalamus strictus* bamboo culms were manufactured from laminas and laminates using an epoxy resin matrix. The mechanical properties of LBCs have been evaluated with different loading conditions. The results show that the mechanical properties of LBCs are better than teak wood, which is one of the strongest woods [16]. The work [17] reported significant differences in strength and behavior between small specimens sourced from different growth portions with the full-size structural members (cross-section 100×100 mm) constructed from laminated bamboo sourced from different growth portions of the culm. This study found that the bamboo laminate sourced from the middle growth section has the largest elastic modulus. The study of tensile properties of single and two ply laminated bamboo at various off-axis loading angles and laminates configurations has shown that composite laminate theory is applicable to LBCs composite and may be used for the design of products and structures [18]. Researches are needed to fill the gap in existing knowledge of laminated bamboo composites, in order to characterize the mechanical behavior of single and multi ply laminates with off-axis loading angle, as well as laminate configuration.

Based on previous studies, it can be concluded that the use of bamboo as an engineering material can be enhanced by developing Laminated Bamboo Composites (LBCs). Compaction pressure, the number of laminas, the thickness of the lamina, and the orientation of the laminates are critical fabrication variables for achieving a high strength of LBCs. The present study investigates epoxy resin reinforced with bamboo laminates. The type of bamboo studied was Apus bamboo (*Gigantochloa apus*). Apus bamboo was chosen because it has flexible properties and is easy to make into thin sheets. The research was conducted by varying the thickness, number of laminas, direction of laminates and compacting mold pressure. A detailed characterization, including the tensile and bending strength of the LBCs, was performed.

## 3. The aim and objectives of the study

The aim of this study is to determine the effect of lamina configuration and compaction pressure on the tensile and bending strength of laminated *gigantochloa apus* (*Apus bamboo*) composites.

The following objectives have been formulated:

– to investigate the effect of the number of bamboo laminates, direction of laminates and compaction pressure on the tensile strength of Laminated Bamboo Composites (LBCs);

– to investigate the effect of the direction of bamboo laminates on the tensile strength and bending strength of Laminated Bamboo Composites (LBCs);

– to investigate the fracture of tensile and bending photo macrograph of Laminated Bamboo Composites (LBCs);

## 4. Materials and Methods

### 4. 1. Material

Bamboo's lamina of *gigantochloa apus* was used as primary reinforcement material. The bamboo used is three years old with an average diameter of 150 mm. The selected part of the bamboo stem, 1 m to the base to 4 m, was used to make the lamina. The epoxy Bakelite® EPR 174 and resin hardener V-140 were used as a matrix and hardener.

### 4. 2. Methods

The process of making bamboo lamina begins with cutting the bamboo stalks to obtain a stem length of 40 cm. The bamboo stalks are then split into blades, making the bamboo slats by removing the outer shell. Then the splitting process is carried out to obtain a bamboo blade with a size of 40 cm×20 mm. The formation of bamboo lamina blades is carried out using the four-side planning tool. This process is carried out to obtain the thickness of 1 mm, 1.5 mm, and 2 mm. Fig. 1 shows the bamboo lamina-making process.

The bamboo laminas are then preserved by watering them with a preservative solution in the form of 2.5 % sodium tetraborate solution. After preservation, the bamboo laminas are dried. The bamboo lamina is dried in an oven until the water content reaches 10 %. A moisture meter measured the percentage of water content in the bamboo laminas. Drying takes approximately 2–4 weeks in an oven, depending on the weather. Dry bamboo slats are grouped according to their thickness and then sanded to smooth the surface using a sandpaper machine. The photo of bamboo lamina is depicted in Fig. 2.

The dried bamboo laminas are then used as reinforcing composites to make Laminated Bamboo Composites (LBCs). An epoxy resin polymer is used as a matrix/adhesive material. LBCs were constructed by the hand lay-up method with three different numbers of laminas: 3, 5, and 7. Additionally, LBCs are manufactured in a variety of laminates directions: 0, –45°/+45° and 0°/90°. The configuration of the directional arrangement of the laminates in the composite is shown in Table 1. After the hand lay-up process, LBCs were compacted using a hydraulic pressing machine with a variation of compaction pressure: 1.5 MPa; 2.0 MPa; 2.5 MPa. The LBCs were pressed for 24 hours. Table 2 shows the resulting composites with variations in compaction pressure and the number of lamina forming LBCs. This process produces a composite with a size of 400×250 mm with various thicknesses.

Table 1

Configuration of laminates direction in Laminated Bamboo Composites

| | 0° | –45°/+45° | 0°/90° |
|---|---|---|---|
| 3 layers | 0°; 0°; 0° | –45°; +45°; –45° | 0°; 90°; 0° |
| 5 layers | 0°; 0°; 0°; 0°; 0° | –45°; +45°; –45°; +45°; –45° | 0°; 90°; 0°; 90°; 0° |
| 7 layers | 0°; 0°; 0°; 0°; 0°; 0° | –45°; +45°; –45°; +45°; –45°; +45°; –45° | 0°; 90°; 0°; 90°; 0°; 90°; 0° |

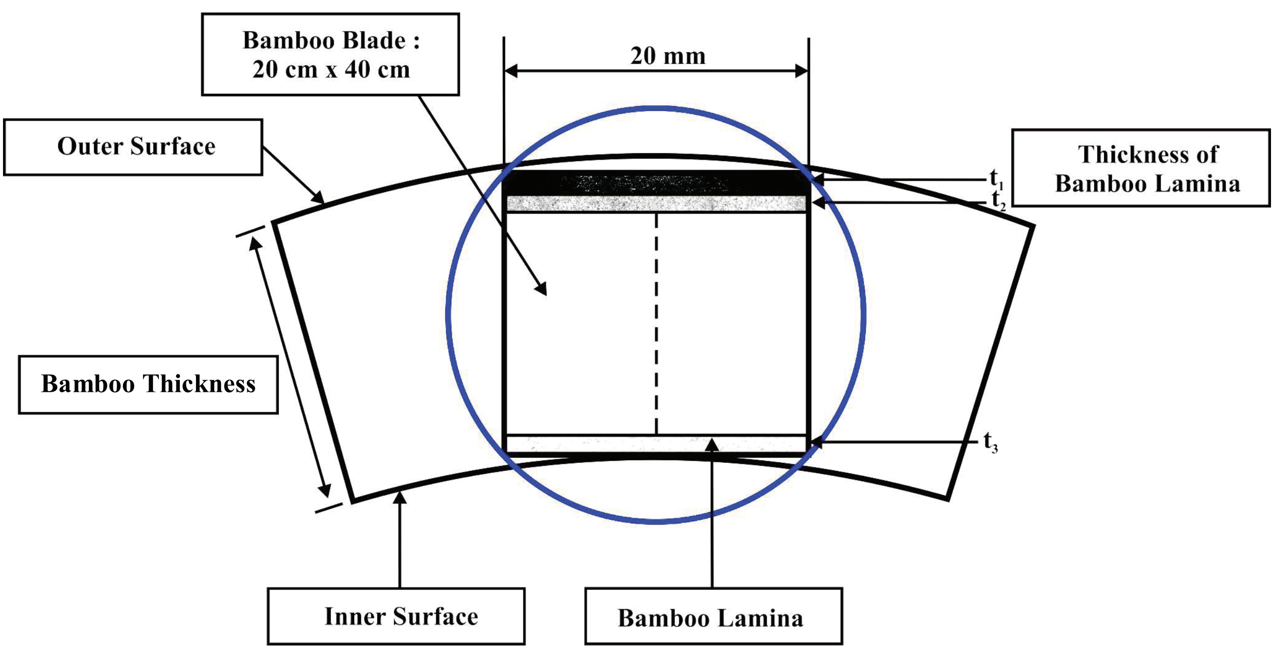


Fig. 1. Formation of the bamboo apus lamina (*gigantochloa apus*)

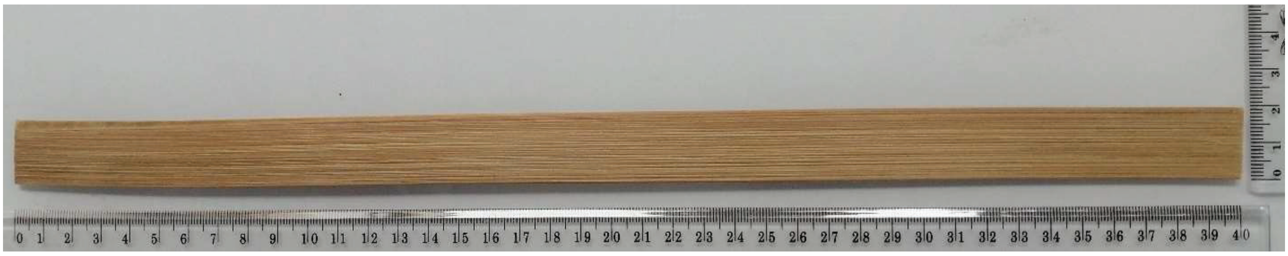

Fig. 2. Bamboo lamina

Table 2

Weight fraction of bamboo fibers and the epoxy resin matrix of the composites

| No. | Compaction pressure (MPa) | Lamina (layer) | Lamina thickness (mm) | LBCs thickness (mm) | Bamboo mass fraction (kg/cm$^3$) | Epoxy resin mass faction (kg/cm$^3$) |
|---|---|---|---|---|---|---|
| 1 | 1.5 MPa | 3 | 2.0 | 7.0 | 0.70 | 0.30 |
| 2 | | 5 | 1.5 | 7.0 | 0.65 | 0.35 |
| 3 | | 7 | 1.0 | 7.0 | 0.60 | 0.40 |
| 4 | 2.0 MPa | 3 | 2.0 | 6.5 | 0.75 | 0.25 |
| 5 | | 5 | 1.5 | 6.5 | 0.70 | 0.30 |
| 6 | | 7 | 1.0 | 6.5 | 0.65 | 0.35 |
| 7 | 2.5 MPa | 3 | 2.0 | 6.0 | 0.80 | 0.20 |
| 8 | | 5 | 1.5 | 6.0 | 0.75 | 0.25 |
| 9 | | 7 | 1.0 | 6.0 | 0.70 | 0.30 |


Fig. 3. Tensile test specimens


Fig. 4. Bending test specimens

The tensile test refers to the ASTM standard D3039 with a specimen size of 250×25×$t$ mm. The bending test was carried out using the ASTM standard D7264 with a 130×13×$t$ mm specimen size. The test specimens were prepared using water jet cutting. Tensile and bending testing uses a Universal Testing Machine (UTM) type WE-1000B, with a maximum capacity of 1000 KN. For each variation, five specimens were tested. Fig. 3–5 present photos of tensile and bending test specimens.

## 5. Results of the effect of lamina configuration and compaction pressure on the mechanical properties of laminated gigantochloa apus composites

**5. 1. Effect of the number of bamboo laminates, direction of laminates and compaction pressure on the tensile strength of Laminated Bamboo Composites**

Table 3 and graphs in Fig. 5–7 show the results of the tensile test of LBCs for variations in the number of laminates (3, 5, 7), laminates directions (0°, –45°/+45°, 0°/90°) and compaction pressure (1.5 MPa, 2 MPa, 2.5 MPa) and effect on the tensile strength of LBCs. It can be noticed from Fig. 5–7 that the tensile strength of LBCs is influenced by the number and direction of laminates. It is shown in Fig. 5 that at a compaction pressure of 1.5 MPa, direction of laminates 0° (on axis) increasing the number of laminates also increases the tensile strength of the LBCs. LBCs with 3 laminate layers have a tensile strength of about 115 MPa, increasing by about 7 % (124 MPa) with the number of laminate layers of 5. The highest tensile strength of LBCs at the 0° direction and 1.5 MPa compaction pressure is 139 MPa at 7 lamina layers. The same phenomenon is obtained in the fiber direction –45°/+45°, 0°/90° that as the number of layers in the LBCs increases from 3 to 7, the tensile strength also increases. LBCs with the direction –45°/+45° and 0°/90° gain the highest tensile strength of 76 MPa and 107 MPa, respectively with 7 laminate layers. The lowest tensile strength of LBCs is 58 MPa (about 41 % of the highest value) with 3 lamina layers and –45°/+45° laminates direction.

LBCs with a pressure of 2 MPa produce the highest tensile strength of 185 MPa with 7 laminates with the laminates direction 0° (Fig. 6). Besides, the laminates direction –45°/+45 yields the highest tensile strength of 88 MPa and LBCs with the laminates direction 0°/90° resulted in the highest tensile strength of 156 MPa. LBCs with the laminates direction –45°/+45, 3 lamina layers and 2 mm lamina thickness yield the lowest tensile strength value of 76 MPa (41 % of the highest tensile strength value).

The graph in Fig. 7 shows that at a pressure of 2.5 MPa, the highest tensile strength of LBCs is achieved by the composite with the direction of laminates 0° valued 180 MPa. The highest tensile strength is also achieved by LBCs with the laminates direction 0° (on axis laminates), 7 lamina layers and 1 mm lamina thickness. The increase in the number of laminate layers from 3, 5, 7 results in an increase in the tensile strength of 164 MPa, 175 MPa, and 180 MPa, respectively. The lowest tensile strength value of LBCs is 71 MPa (39 % of the highest value) also found in LBCs with 3 laminate layers and laminates direction –45°/+45.

Table 3

Tensile strength of LBCs

| Pressure | 1.5 MPa | | | 2.0 MPa | | | 2.5 MPa | | |
|---|---|---|---|---|---|---|---|---|---|
| Layers | 3 | 5 | 7 | 3 | 5 | 7 | 3 | 5 | 7 |
| 0° | 115 | 124 | 139 | 168 | 177 | 185 | 164 | 175 | 180 |
| –45°/+45° | 58 | 64 | 76 | 76 | 81 | 88 | 71 | 78 | 87 |
| 0°/90° | 91 | 99 | 107 | 135 | 149 | 156 | 131 | 141 | 151 |

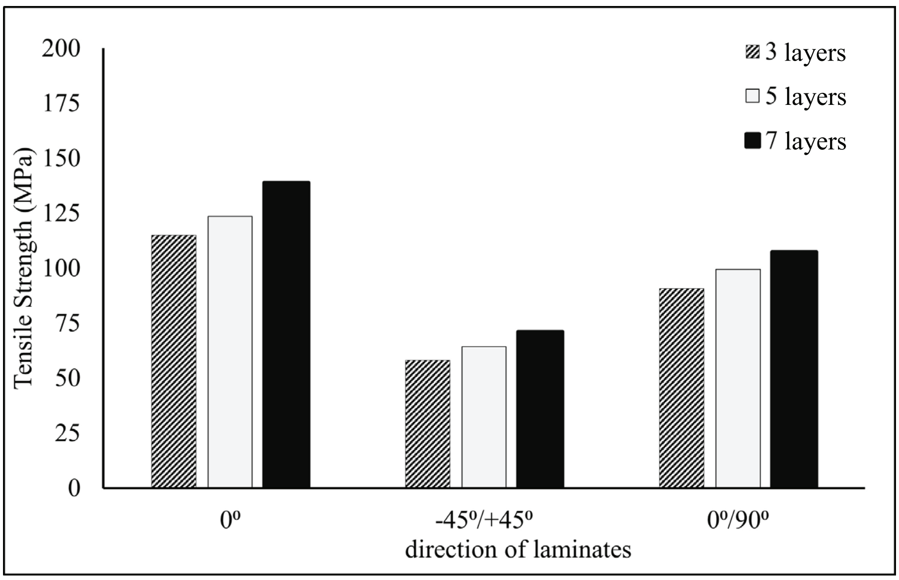


Fig. 5. Tensile strength of LBCs with 1.5 MPa compaction pressure

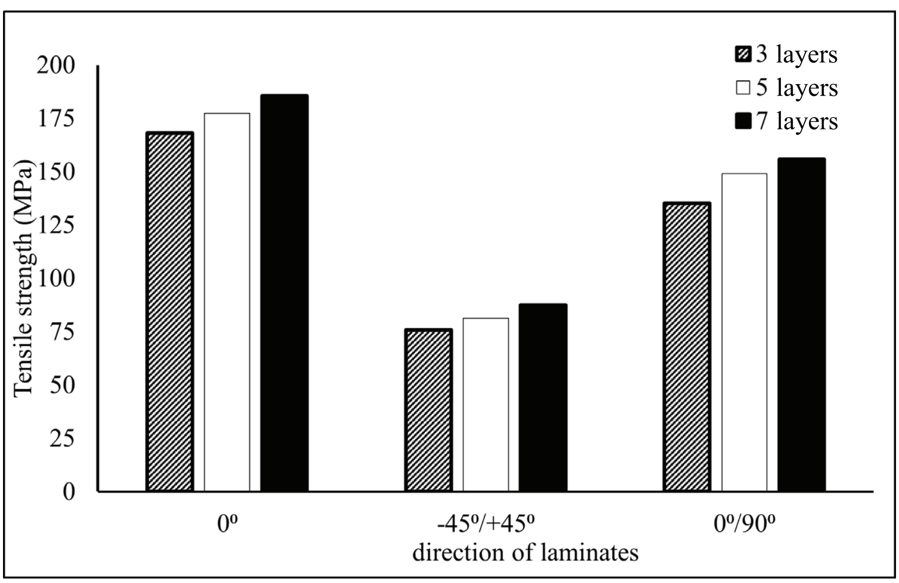


Fig. 6. Tensile strength of LBCs with 2 MPa compaction pressure

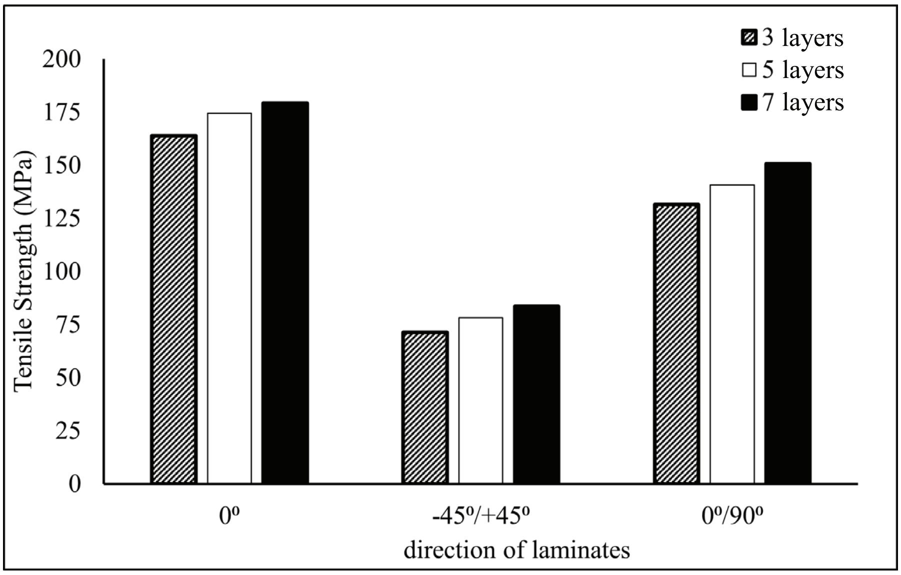


Fig. 7. Tensile strength of LBCs with 2.5 MPa compaction pressure

At all pressure variations, LBCs with the 0° laminates direction have a higher tensile strength than LBCs with the direction –45°/+45° and 0°/90°. LBCs with the laminates direction –45°/+45° produced lower tensile strength than the others. The effect of mass fraction of bamboo laminates and tensile strength of LBCs in composites with the direction of 0° is shown in Fig. 8. LBCs with 7 laminate layers, 1 mm lamina thickness and 1.5 MPa compaction pressure produce composites with % wt. reinforcement 60 %. At a compaction pressure of 2.0 MPa and 2.5 MPa, % wt. of LBCs with 7 laminate layers, 1 mm lamina thickness is 65% and 70 %, respectively. The tensile strengths of LBCs with seven layers are 139 MPa, 185 MPa, and 180 MPa at 1.5 MPa, 2.0 MPa, and 2.5 MPa compaction pressures, respectively. LBCs with 3 layers and 2 mm lamina thickness yield a composite with % wt. reinforcement higher than LBCs with 7 layers and 1 mm lamina thickness. LBCs with three layers and 1.5 MPa, 2.0 MPa, or 2.5 MPa compaction pressure produce LBCs with tensile strengths of 115 MPa, 168 MPa, and 164 MPa, respectively.

The graph in Fig. 9 also shows the effect of compaction pressure on the tensile strength of LBCs at the mass fraction of 70 %. This analysis selected a mass fraction of 70 % wt. because a mass fraction of 70 % wt. was generated for all variations studied (Fig. 8). Fig. 9 shows that increasing the compression from 1.5 MPa to 2.0 MPa increases the tensile strength of LBCs by 55 % in the 0° laminates direction, 40 % in the –45°/+45° laminates direction, and 64 % in the 0°/90° laminates direction. Increasing the compaction pressure from 2 MPa to 2.5 MPa did not significantly increase the tensile strength of the LBCs. The differences of tensile strengths are smaller than the standard deviation of the test. Therefore, it can be concluded that the increase in pressure from 2 MPa to 2.5 MPa does not significantly affect the tensile strength of LBCs.

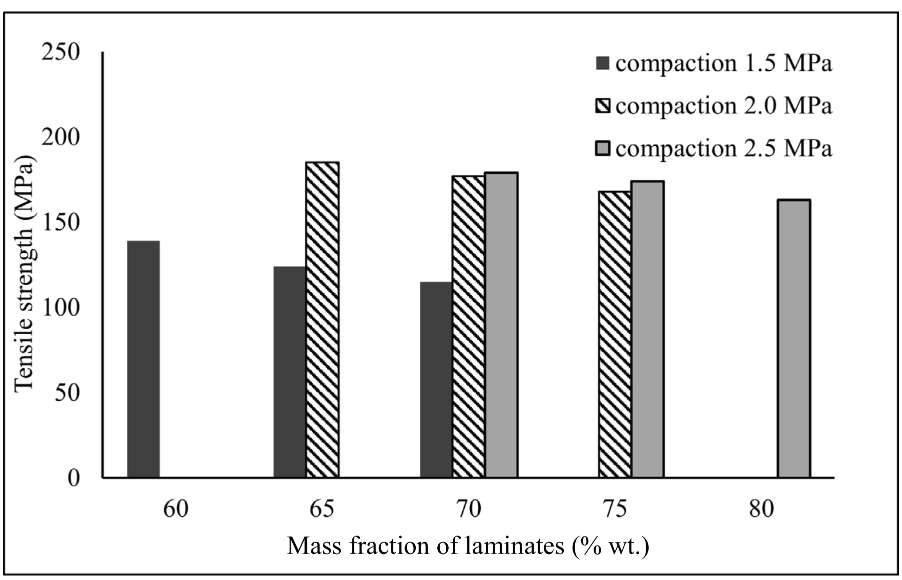


Fig. 8. Effect of the mass fraction of bamboo laminates on the tensile strength of LBCs in composites with the direction of 0°

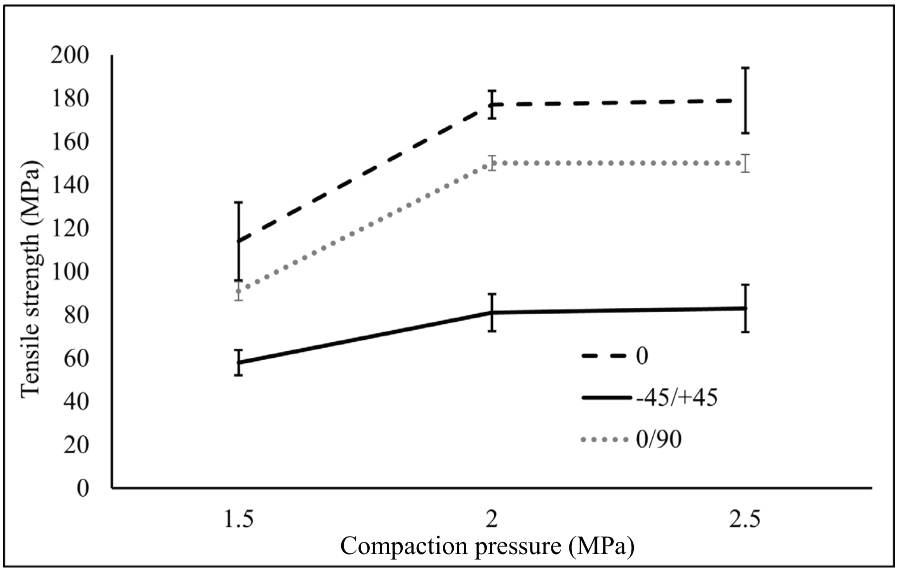


Fig. 9. Effect of compaction pressure on the tensile strength of LBCs at 70 % mass fraction

**5. 2. Effect of the number of bamboo laminates, direction of laminates and compaction pressure on the bending strength of Laminated Bamboo Composites**

Table 4 and Fig. 10–12 show the bending strength of LBCs with variations of the direction of laminates: 0°, –45°/+45°, 0°/90° and variations in the number (3, 5 and 7) and thickness (1 mm, 1.5 mm and 2 mm) of apus bamboo lamina with a variation of compaction pressures of 1.5 MPa, 2.0 MPa and 2.5 MPa. Fig. 10 shows that LBCs with the direction of laminates 0° resulted in higher bending strength than LBCs with the laminates direction 0°/90° or –45°/+45°. The bending strength of LBCs with the 0° laminates direction is approximately 8 % higher than either of LBCs with the 0°/90° laminates direction and approximately 12 % greater than that of LBCs with the –45°/+45° laminates direction. At a compaction pressure 1.5 MPa, the highest bending strength of LBCs is 265 MPa, the lowest bending strength is produced by LBCs with the laminates direction –45°/+45° valued 218 MPa (approximately 82 % of the highest bending strength).

Table 4

Bending strength of LBCs

| Pressure | 1.5 MPa | | | 2.0 MPa | | | 2.5 MPa | | |
|---|---|---|---|---|---|---|---|---|---|
| Layers | 3 | 5 | 7 | 3 | 5 | 7 | 3 | 5 | 7 |
| 0° | 251 | 257 | 265 | 295 | 315 | 321 | 280 | 298 | 306 |
| –45°/+45° | 218 | 229 | 232 | 245 | 266 | 271 | 234 | 239 | 259 |
| 0°/90° | 233 | 241 | 240 | 274 | 284 | 294 | 261 | 268 | 279 |

The bending strength of LBCs with a compaction pressure of 2.0 MPa and 2.5 MPa is shown in Fig. 11, 12, respectively. The value of the bending strength of the composite with a compaction pressure of 2.0 MPa ranged from 245 MPa to 321 MPa. LBCs have a bending strength between 234 and 306 MPa when compressed to 2.5 MPa. The composite with the 0° layer direction and 7 lamina layers produces the highest bending strength.

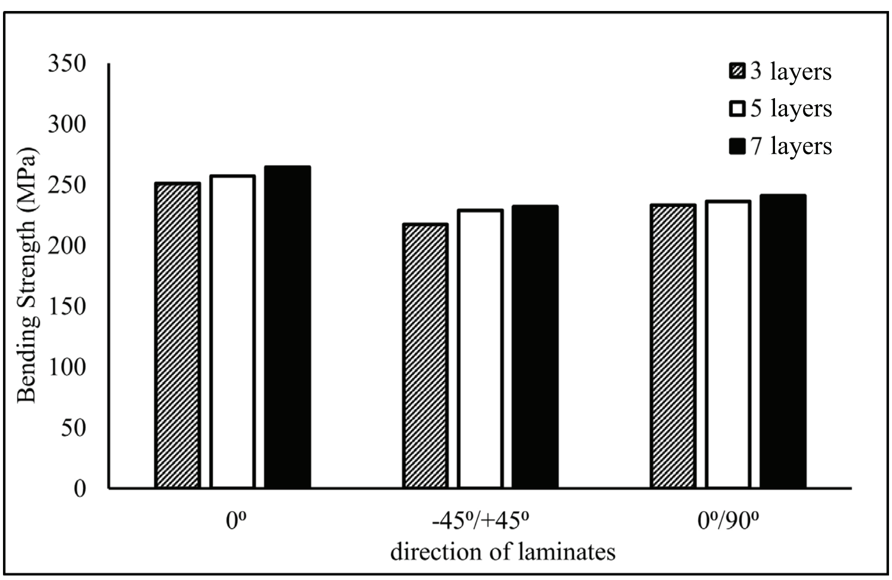


Fig. 10. Bending strength of LBCs with a compaction pressure of 1.5 MPa

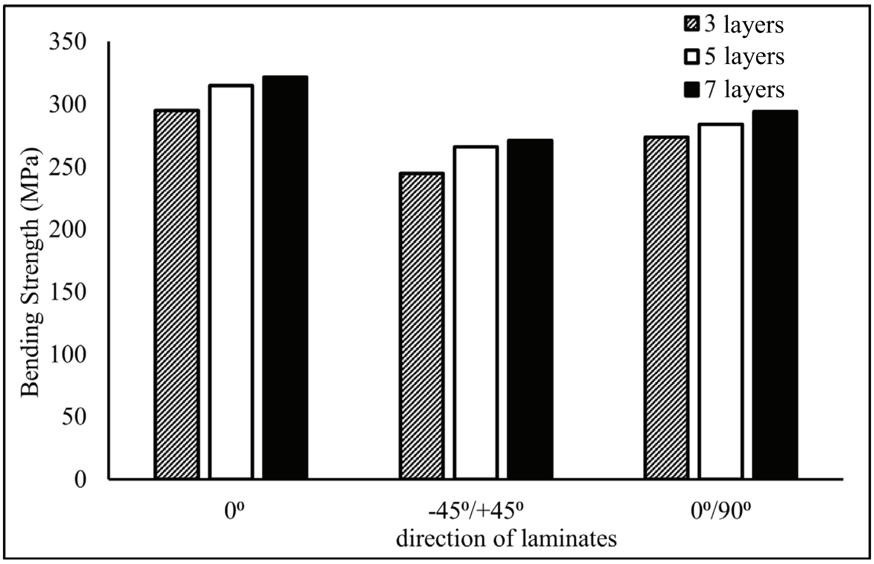


Fig. 11. Bending strength of LBCs with a compaction pressure of 2.0 MPa

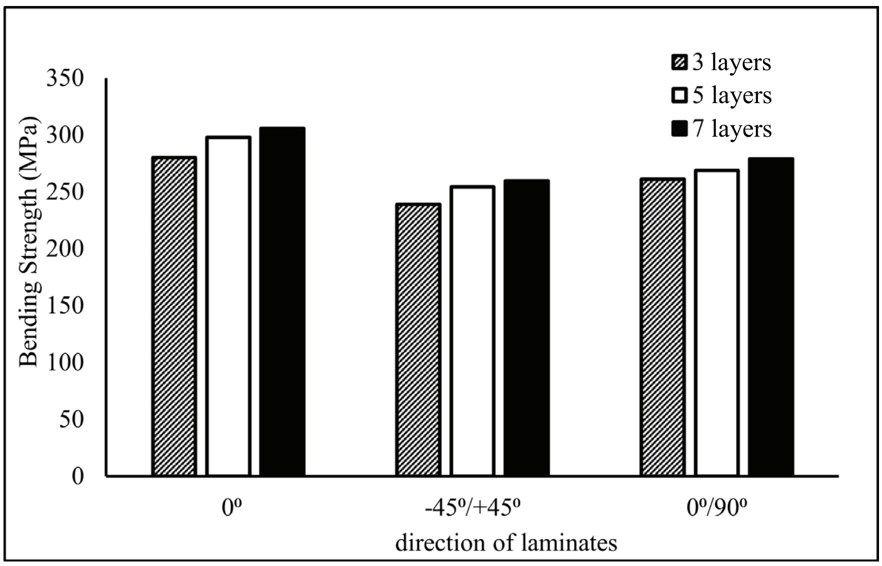


Fig. 12. Bending strength of LBCs with a compaction pressure of 2.5 MPa

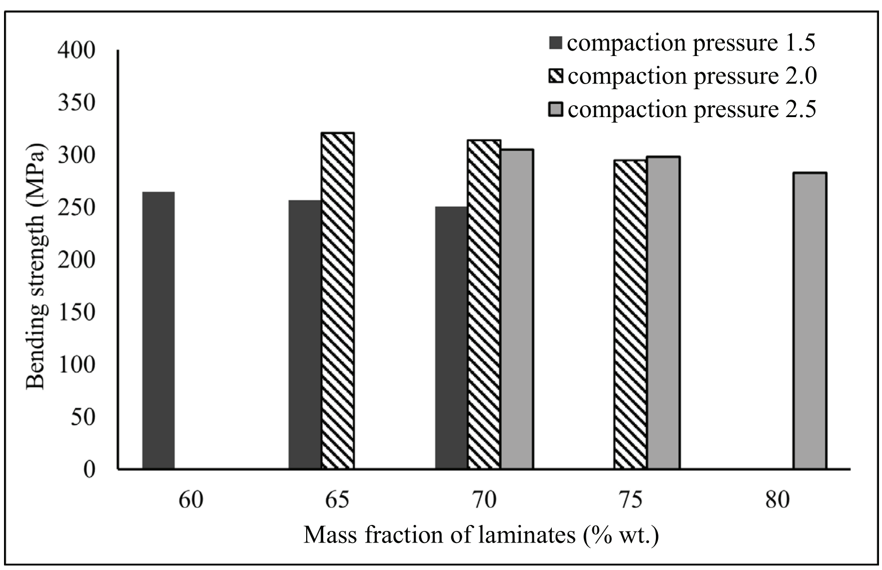


Fig. 13. Effect of mass fraction of laminates on the bending strength of LBCs with the 0° direction

The relationship between the bending strength of LBCs and their mass fraction with the laminates on-axis (0°) direction is shown in Fig. 13. At 1.5 MPa compaction pressure, LBCs with a mass fraction of 60 % have structured 7 layers of lamina with a thickness of 1 mm, yielding the highest bending strength of 265 MPa. At compression pressures of 2.0 MPa and 2.5 MPa, LBCs with 7 lamina layers exhibit the highest bending strength, with values of 321 MPa and 306 MPa, respectively. From the graph in Fig. 13, it can be concluded that the highest bending strength is in the composite with thinner bamboo reinforcement and a higher number of layers even at a lower mass fraction.

The graph in Fig. 14 also shows the effect of compaction pressure on the bending strength of LBCs at the mass fraction of 70 %. By increasing the compaction pressure from 1.5 MPa to 2 MPa, the bending strength of LBCs increases by 25 % in the 0° laminates direction, 22 % in the 45°/+45° laminates direction, and 21 % in the 0°/90° laminates direction. As with the tensile tests, increasing the compaction pressure from 2 MPa to 2.5 MPa has no noticeable effect on the bending strength of LBCs.

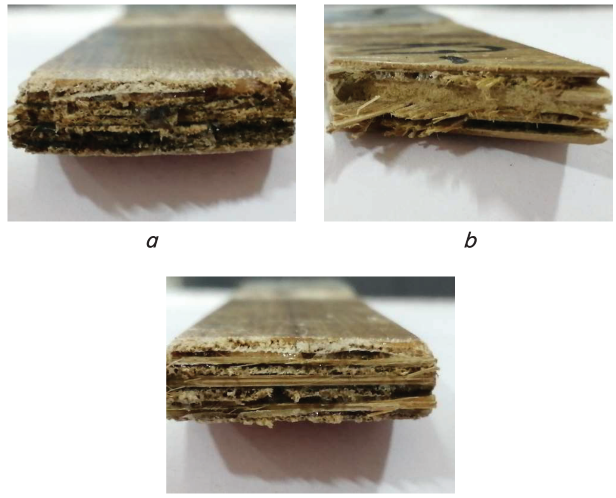

Fig. 15. Photo macrography of the fracture of cross-section of the tensile test of 7-layer Laminated Bamboo Composites (LBCs): *a* – direction of laminates 0°; *b* – direction of laminates –45°/+45°; *c* – direction of laminates 0°/90°

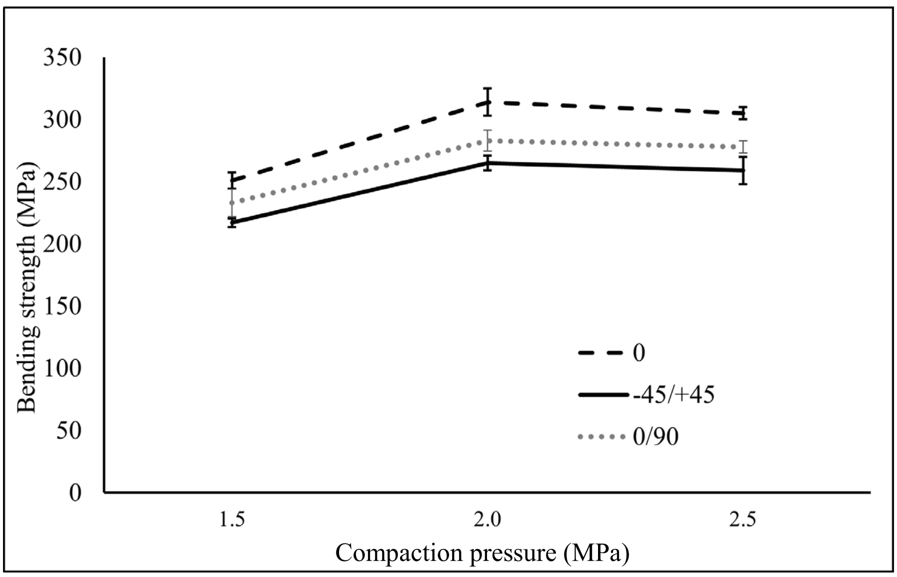


Fig. 14. Effect of compaction pressure on the bending strength of LBCs at 70 % mass fraction

The macro photographs of the LBCs after the bending test are shown in Fig. 16. Fig. 16, *a* shows that the bending test of LBCs with the 0° laminates direction produced the fracture of the matrix followed by the fracture of laminates. Fracture photographs of LBCs with the layers direction –45°/45° (Fig. 16, *b*) shows that at the bottom of the specimen, fracture occurs due to lamina delamination. Failure continues with delamination and the lamina splits due to shear stress. The failure of the specimen with the lamina direction of 0°/90° as shown in Fig. 16, *c* indicates that the failure due to bending started with matrix fracture and lamina fracture at the bottom (outer) of the specimen. Failure is followed by delamination of the lamina in the 90° direction.

**5. 3. Investigation of fracture of tensile and bending photo macrograph of Laminated Bamboo Composites (LBCs)**

Fig. 15 shows a macro photograph of the surface fracture of LBCs after tensile testing. Fig. 15, *a* shows the fracture of LBCs with the laminates direction 0°. The surface fracture of the LBCs with the direction of laminas –45°/+45° (Fig. 15, *b*) and the surface fracture of the LBCs with the direction of laminas –0°/90° (Fig. 15, *c*). The LBCs with the 0° direction of laminates, the first phenomenon when tensile tested is matrix fracture, followed by load transfer to bamboo laminas and subsequent bamboo lamina fracture. Fig. 15, *b* shows the fracture of the matrix followed by delamination of lamina in the 90° direction, and finally fracture of lamina in the 0° direction. In LBCs with laminates orientation +45°/–45°, matrix fracture was followed by delamination and lamina clefting.

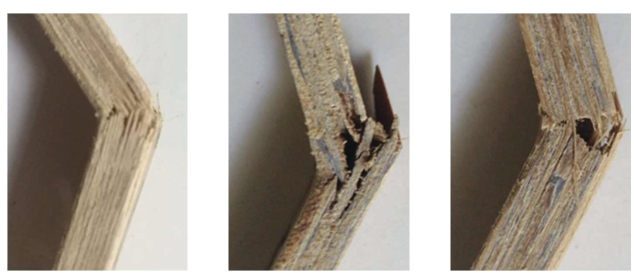

Fig. 16. Bending test results of specimens of laminated bamboo composites (LBCs) from 7 layers: *a* – layers direction of 0°; *b* – layers direction –45°/45°; *c* – layers direction 0°/90°

## 6. Discussion of the effect of lamina configuration and compaction pressure on the mechanical properties of laminated gigantochloa apus composites

The effect of direction, thickness, number of laminas on the tensile strength of LBCs at a compaction pressure of 1.5 MPa; 2.0 MPa; 2.5 MPa is shown in Fig. 5–7, respectively. These results indicate that the increased number of layers and the reduced lamina thickness increase the tensile strength of LBCs. The highest tensile strength was achieved by LBCs with a thickness of the bamboo lamina of 1 mm and 7 layers of bamboo lamina. It can be concluded that the highest tensile strength is in the composite with thinner bamboo reinforcement and more layers, even at a lower mass fraction. Increasing the tensile strength properties of LBCs in the thinner bamboo lamina reinforcement with a higher number of composites forming layers is an important concern in this study. This is caused by the ability of the epoxy resin to enter the thinner pores of the apus bamboo fiber, thereby increasing the interface strength of the composite-forming bamboo layer. The other works also reported that increasing the number of laminas forming the Layered Laminated Bamboo Composites (LLBCs) will increase tensile and flexural stress [7]. The tensile strength of laminated composites is dependent on the interfacial properties of natural fibers and polymer composites. Additionally, the tensile properties are influenced by the direction of laminas [19]. The study on the mechanical properties of laminated bamboo composites with different bamboo and matrices (gigantochloa scortechinii and unsaturated polyester) showed that the thicker the bamboo blades, the higher the tensile stress and flexural stress [20]. Fig. 5–7 also depict that the direction configuration of the composite laminates also affects the tensile strength of LLBCs. The configuration of the laminates with the direction 0° yields a higher result of tensile strength compared to the configuration of the direction of the fiber crossed –45°/+45° and 0°/90°. Thus, the tensile strength of the LBCs decreases with increasing the angle of the laminates under the tensile stress. According to the Tsai–Hill criterion, the tensile and compressive properties of the composite will continue to decrease due to changes in the fiber orientation angle that increases from 0° [21]. This study's results prove that the direction of the lamina 0° provides the higher tensile strength compared to the direction of the laminates –45°/+45°, 0°/90°.

The compaction pressure applied to the manufacture of LBCs affects the mass fraction (wt.) of the epoxy resin matrix contained in the LBCs. The compaction pressure will drive the epoxy resin out of the LBCs mold while the mass fraction of the bamboo laminates is steady [9]. Higher compression pressure will reduce % wt. epoxy resin and increase % wt. lamina (Fig. 8). The compaction pressure of LBCs from 1.5 MPa to 2.0 MPa can reduce the weight fraction of epoxy resin in LBCs by 5 % of the initial mass fraction, but it can increase the tensile strength of LBCs by 55 % at the laminates direction 0°, 40 % in the direction of laminates –45°/+45° and 64 % in the direction of laminates 0°/90°. The numerical analysis results demonstrate that the ultimate tensile loading increases as adhesive thickness decreases [22]. The optimum tensile stress of Laminated Bamboo Composites (LBCs) was obtained at a 2 MPa compaction pressure variation with a mass fraction (wt.) of lamina of 70 % and a mass fraction (wt.) of epoxy resin of 30 %. The application of compaction pressure above 2 MPa on LBCs didn't affect the tensile stress value. It can be concluded that compaction pressure of 2.0 MPa also produces the optimum thickness of the epoxy resin matrix in bamboo laminas. The anatomy of bamboo has a maximum limit for compaction or is caused by decreased matrix bonds because of reduced mass fraction (% wt.) of the epoxy resin matrix contained in the respective LBCs each by 5 % for each variation of the tested specimens.

Apus bamboo (gigantochloa apus) lamina has a tensile strength of 230 MPa and an epoxy resin with a tensile strength of 57 MPa after being formed into a composite LBCs was able to produce the highest tensile strength of 185 MPa with a ratio of 70 % bamboo lamina mass fraction and 30 % epoxy resin. This result is higher than in previous research that reported composites used gigantochloa scortechinii (semantan reed) woven bamboo as reinforcement with a ratio of 33 % of the mass fraction (wt.) of bamboo laminates and the mass fraction (wt.) of 77 % epoxy matrix was only able to produce a maximum tensile strength of 89 MPa [11].

Bending test results for LBCs with varying lamina orientations 0°, –45°/+45°, 0°/90°; number of laminas (3, 5 and 7) and thickness of lamina (1 mm, 1.5 mm and 2 mm) with a variation of compaction pressures of 1.5 MPa, 2.0 MPa and 2.5 MPa are depicted in Fig. 10–12. LBCs with the direction of laminates 0° resulted in higher bending strength than LBCs with the laminates direction 0°/90° or –45°/+45°. These results show that increasing the number of lamina with thinner lamina increases the bending strength of LBCs. The LBCs with 7 layers of bamboo laminas, 1 mm thickness, 0° fiber direction and 2 MPa stress yield the highest bending strength valued 321 MPa. It's approximately 20 % stronger than LBCs with a compaction pressure of 1.5 MPa and 5 % higher than LBCs with 2.5 MPa compaction pressure. Apus bamboo (gigantochloa apus) with a bending strength of lamina 348 MPa and epoxy resin with a bending strength of 175 MPa, after being manufactured into a composite LBCs, these materials yield the highest bending strength of 321 MPa with a ratio of mass fraction (wt.) of 70 % and mass fraction (% wt.) epoxy resin 30 %. Gigantochloa scortechinii (semantan reed) woven bamboo with a ratio of 33 % of the mass fraction (wt.) of bamboo laminates and the mass fraction (wt.) of 67 % epoxy matrix was only able to produce a maximum bending strength of 120 MPa [11]. The bamboo allowed large flexural deformations because its outer part retains the tensile stress while the softer inner part undergoes large compressive deformation [23]. The configuration of the 0° laminates direction yields the higher bending strength compared to the configuration of 0°/45° and 0°/90° crossed laminates [21].

The bending stress of laminated bamboo composites is also influenced by the direction (orientation) of the bamboo laminates and the number of layers. At each variation in the direction of the bamboo laminates and stress, the bending strength of the LBCs increased with the increasing number of layers of bamboo laminas. In the number of layers, the bending strength of LBCs with the laminates direction of 0° has the largest bending strength, followed by the crossed fiber direction of 90° and the lowest bending strength is the LBCs with the –45°/+45° fiber direction.

Laminated Bamboo Composites (LBCs) with more layers of laminas produce higher tensile and bending strength compared to LBCs with a lower number of laminas. The thinner lamina provides a higher adhesive contact surface area than the thicker lamina. The higher adhesive contact area provides better stress transfer to the lamina [24].

Fig. 15, 16 show the surface fracture of LBCs after the tensile and bending test. The same mechanism of fracture in both of surface tests is found. The cross-section of the surface fracture of the tensile and bending test of LBCs with the on axis laminas direction (0°) shows the phenomenon of fracture in the lamina due to the load transmitted by the matrix. Bamboo lamina can fully withstand the load transferred by the matrix. This causes LBCs with the 0° laminates direction (on axis) to be stronger than LBCs with the off axis laminated direction. The cross-section of fracture photograph demonstrates that the fracture mechanism is a matrix fracture followed by the breaking of the bamboo laminates. On the LBCs with laminas orientation –45°/+45° and 0°/90° fracture mechanism of LBCs, there is delamination of lamina caused by debonding of adhesion between laminas. The fracture's cross-sectional images demonstrate the lamina delamination behavior.

## 7. Conclusions

1. LBCs with the 0° direction of laminas yield higher tensile strength than LBCs with the off axis direction of laminates (–45°/45°; 0°/90°). Increasing the number of laminas increases the tensile strength of LBCs. LBCs with thinner lamina provide a higher adhesive contact surface area than the thicker lamina and yield higher tensile strength of LBCs. The rise of the compaction pressure from 1.5 MPa to 2.0 MPa increases the tensile strength of LBCs by 55 % in the 0° laminates direction, 40 % in the –45°/+45° laminates direction, and 64 % in the 0°/90° laminates direction. Increasing the compaction pressure from 2.0 MPa to 2.5 MPa did not significantly increase the tensile strength of the LBCs. The highest tensile strength of LBCs with the value of 185 MPa is produced by LBCs with the 0° direction, 7 laminas, 1 mm lamina thickness with compaction pressure of 2 MPa.

2. The highest bending strength of LBCs, 321 MPa, is achieved with LBCs in the 0° direction, 7 laminas, 1 mm lamina thickness, and 2 MPa compaction pressure. LBCs with laminates oriented on axis (0°) have a greater bending strength than composites with the orientation of laminates off axis (–45°/45°; 0°/90°). LBCs' bending strength increases as the number of laminates increases. The bending strength of LBCs increases by 25 % in the 0° laminates direction, 22 % in the 45°/+45° laminates direction, and 21 % in the 0°/90° laminates direction when the compaction pressure is increased from 1.5 MPa to 2.0 MPa. Increased compaction pressure from 2.0 to 2.5 MPa has no perceptible effect on the tensile strength of the LBCs.

3. The LBCs with the 0° laminates direction, the first phenomenon when tensile tested is matrix fracture, followed by bamboo lamina fracture. In composites with the 0°/90° laminates direction, the fracture of the matrix was followed by delamination of lamina in the 90° direction, and finally fracture of lamina in the 0° direction. In LBCs with laminates orientation –45°/+45°, matrix fracture was followed by delamination and lamina clefting.

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