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Mechanical Properties Evaluation of Laminated Composites of Petung Bamboo (*Dendrocalamus asper*) and Coconut Coir Fiber as Ship Construction Components

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ABSTRACT

The high demand for steel and wood as the primary shipbuilding materials will increase market prices due to decreasing supplies each year. To address this issue, new alternative materials that are more environmentally friendly and inexpensive, such as natural fibers like bamboo and coconut fiber, must be explored. This study aimed to investigate how the directional arrangement (0° unidirectional and 90° unidirectional) of laminated Petung bamboo (*Dendrocalamus asper*) affects the compressive and flexural strength of ship construction. The compressive strength on the X, Y, and Z-axis was measured to determine the laminated beam's strength ratio on each side. In contrast, the flexural strength was only observed on the Y and Z-axis due to testing equipment limitations. The results showed that the directional arrangement of laminated Petung bamboo with different test axes significantly impacted the compressive and flexural strength of laminated beams made of Petung bamboo and coconut coir fiber. Laminated Petung bamboo and coconut coir fiber with 0° unidirectional fiber had better compressive and flexural strength values than those with 90° unidirectional fiber. Based on the data testing, the combination of Petung bamboo and coconut coir fiber materials can be categorized into different strength classes. These findings have important implications for using laminated bamboo in shipbuilding applications. The use of laminated bamboo with a 0° lamina direction could be recommended for ship components that require high levels of strength than laminated bamboo with a 90° lamina direction.

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1 Introduction

Wood is a popular raw material for shipbuilding and is heavily exploited, particularly in Indonesia, where fishing vessels account for 10% to 15% of the country's wood demand, or more than 2.5 million m³/year [1]. This high demand for wood is one of the main drivers of deforestation, and Indonesia has the highest deforestation rate (1021 km²/year) of any country in the world [2]. To mitigate this issue, one of the solutions is to replace wood material with laminated bamboo as a traditional shipping material. Various types of bamboo, such as Petung (*Dendrocalamus asper*), Apus (*Gigantochloa apus*), and Black (*Gigantochloa atrovioleacea*), can be used as laminated boards or beams, resulting in reduced consumption of high-quality wood and lower production costs.

Bamboo is known for its strength and durability, making it a suitable choice for various applications. Additionally, it is a renewable resource that can be grown and harvested quickly, making it a more sustainable alternative than wood. The versatility and sustainability of bamboo make it an attractive option for shipbuilding, and future research can explore how different bamboo types and laminating techniques can further improve the properties of this material for shipbuilding purposes. Petung bamboo fiber, one of the bamboo types found in Indonesia, is a natural fiber that can be combined with other materials such as oil palm, banana, coconut coir, and silk into a biocomposite material [3]. The use of bamboo fiber, which has low density, can be used for lightweight engineering materials, then compared with those synthetic fibers such as glass or carbon fiber [4]. Therefore, there is no doubt

that bamboo fiber is a superior competitor as a reinforcement in composite materials.

Due to their desirable mechanical properties and environmental benefits, laminated bamboo composites have been increasingly researched as alternative materials for traditional ship construction components. Combining bamboo and other natural fibers as alternative ship material are reviewed. Several studies have investigated the mechanical properties of laminated bamboo composites as ship structural components. Research conducted by Manik et al. [5] has demonstrated that laminated Petung bamboo can be a viable material for wooden ships when combined with meranti wood. It can be found that laminated Apus bamboo and meranti wood can be recommended as ship structural components such as stern, stern block, framing system, keel plate, floor, deck structure, deck plating, deck beam, web frame, and side shell plating [5]. This discovery is noteworthy as it presents an opportunity for the shipbuilding industry to explore alternative materials, which have become increasingly important in the modern era [6].

Additionally, Supomo et al. [7] conducted a study on the selection of glue type and adhesiveness for bamboo composite in the side hull of a 20 GT fishing boat. They found that Epoxy Polyamide EWA120 is the most suitable glue for this purpose, as it is strong enough to withstand seawater and is ideal for constructing a small fishing boat. This particular glue was chosen for various reasons, such as its practicality, affordability, quick curing time, acceptable viscosity, thin consistency, colorlessness, and lack of odor. Anokye et al. [8] examined the mechanical characteristics of LBT panels made from *G. scortechinii* bamboo using various adhesive types, adhesive spreading rates, and node interval configurations. Their findings demonstrate that the bending ability of laminated bamboo timber with nodes is enhanced when the node spacing is increased.

Further, Rindo et al. [9] analyzed the effect of the arrangement and orientation of the Petung bamboo fiber laminates on the interfacial bonding of the laminated bamboo composites for a traditional fishing vessel. The compression test results show that the arrangement of parallel fibers is better than that of woven, brick, and perpendicular. The average compressive test is 30.71 MPa, categorized as Strength class III according to the regulations of the Indonesian Classification Bureau (BKI) wooden vessel. It can be used on ships' ivory, leather, decks, masts, deck boards, girders, and above-water construction. Another study also found that the thinner the thickness of the bamboo lamina applied for ship structures, the greater the value of the interfacial/ bond strength [10]. **Another study discussed improving the quality of Apus bamboo fiber with alkali and silane treatment for the application of hull skin in fishing vessels [11]. The test results obtained showed that the mechanical properties improved by soaking in a methanol solution. The mechanical properties of Apus laminated bamboo in this study were categorized as Strength class II and III. They can be used in the keel, ivory, ivory boards, deck beams, leather, deck housings, deck boards, and construction**

above the waterline. In addition, the mechanical behavior of different joint types of laminated bamboo composite, such as scarf joint, butt joint, finger joint, desk joint, and tongue and groove joint, was investigated. Based on the data analysis findings, desk joint connections may be utilized as ship hull material since they meet the minimal standards imposed by BKI [12]. In addition, several researchers have investigated the impact of several factors, such as layer arrangement, bamboo species, oil treatment, and adhesive type, on the mechanical characteristics of laminated bamboo boards. They have determined that the bamboo strips possess exceptional mechanical properties [13-17].

Natural fibers are essential for weight reduction to save fuel use and increase the payload in the transportation industry [18]. **Adding Waru fiber improved the mechanical properties of the laminated bamboo composites [19]. Another eco-friendly natural fiber is coconut coir fiber.** This ductile and energy-absorbing material has the potential to be employed in composites for a variety of engineering applications [20]. Coconut coir fiber has the advantage that it is light, strength, abundant, renewable, cost-effective, can easily withstand heat, and is resistant to saltwater [21]. Several researchers have studied coconut coir fiber as a potential construction material. For instance, Yadav and Singh [22] investigated using coconut fiber in reinforced concrete, which can be particularly beneficial in areas prone to seismic activity.

Meanwhile, Ariff et al. [23] manufactured and analyzed motorcycle helmet shells using coconut fiber composites, which were found to be a cost-effective and effective alternative to Expanded Polystyrene Styrofoam (EPS) in terms of stress absorption. Widnyana et al. [24] examined the tensile characteristics of coconut coir fibers treated with alkali. According to their findings, the fiber behaved like a linearly elastic material and did not exhibit ductility. The fracture surface of the composite clearly displayed all types of fiber reinforcement, such as overload, pullout, delamination, and matrix flow. The studies as mentioned earlier highlight the versatility of coconut coir fiber in various construction applications and its potential to replace conventional materials with more sustainable and eco-friendly options.

Based on the aforementioned literature, limited research is available on the specific use of laminated bamboo composites for constructing traditional ships. Furthermore, there is a lack of comprehensive studies investigating laminated bamboo composites' mechanical properties and durability when utilized for ship construction components. Thus, this study addresses this research gap by examining the development of a novel laminated bamboo composite material using combined Petung bamboo and coconut coir fiber for ship structures. The primary objective is to enhance the material's mechanical properties by analyzing the impact of lamina direction (unidirectional 0° and unidirectional 90°) on mechanical characteristics. To achieve this, various tests such as density, moisture content, bending, and compressive tests will be conducted to investigate the mechanical behavior of the laminated bamboo composites.

2 Materials and Method

2.1 Material Selection and Properties

Bamboo is a plant commonly found in rural areas of Indonesia and is utilized for various purposes such as construction, vegetable baskets, paper, musical instruments, handicrafts, and even shipbuilding. Among the different bamboo species, Petung bamboo is known to have slightly dense clumps and is larger and taller than other bamboo types. It has a density of 0.71 g/cm³, air-dry moisture content of 12-15%, and good mechanical strength, as shown in Table 1. In addition to bamboo, coconut coir fiber has also been studied for its mechanical properties. Table 2 presents the main mechanical properties of coconut coir fiber reviewed from previous studies [25-27]. These materials have been identified as promising alternative materials for shipbuilding due to their potential advantages, such as being more environmentally friendly and cost-effective than traditional materials like wood and steel. However, more research is needed to fully explore their potential and ensure they meet the ship construction standards.

The adhesive material utilized in the bamboo lamination process was epoxy resin adhesive material, widely employed in repairing wooden ships and constructing fiberglass ships. A type of glue was thermosetting epoxy resin. Epoxy comprised two components: epoxy resin and hardener, mixed in a 50/50 (by weight) ratio. Epoxy Bakelite® EPR 174 and resin hardener V-140 purchased from Justus Kimiaraya, Indonesia, and under license from Germany were used as a matrix and hardener, respectively. The epoxy resin is a glycidyl ether of bisphenol A (DGEBA) with an equivalent epoxy weight of 189 ± 5 g/eq. The hardener is a cycloaliphatic amine (EPH 555), mainly containing 3-aminomethyl-3,5,5 trimethyl cyclohexylamine with an amine hydrogen equivalent weight of 86 g/eq and a viscosity of 0.5–1 poise at a room temperature. The chemical composition of epoxy resin is shown in Table 3.

Table 1 Mechanical properties of Petung bamboo [9].

Mechanical Properties	Value (MPa)
Flexural strength	134.97
Tensile strength parallel fiber	228
Compressive strength parallel fiber	49.21
Compressive strength perpendicular fiber	24.18
Shear test parallel fiber	9.59
Flexible modulus of elasticity	12,888

Source: Rindo et al. Effect analysis of the direction of fiber arrangement on interfaces of laminated bamboo fiber as a construction material for wood vessel hulls [9].

Table 2 Mechanical properties of coconut coir fiber [25-27].

Mechanical Properties (unit)	Value
Fiber length (mm)	8-337
Diameter (µm)	69-870
Fiber density (g/cc)	1.40
Flexural modulus (dyn-cm ²)	150-250
Young’s modulus (GPa)	4-6
Single fiber breaking elongation (%)	15-37
Moisture regain (% , at 65 R.H. 27°C)	8-12.5

Source: Author’s collection based on several material properties data from reference numbers [25-27].

Table 3 Composition of epoxy resin [5].

Compositions	Percentage (%)
Bisphenol A	80 - 90
Modified Epoxy Resin	5 - 15
Alkyl Glycidyl Ether	5 - 15
Mercapton Polymer	50 - 60
Tertiary Amine	5 - 10
Polyamide Resin	30 - 35
Triethylene Tetramine	< 3
Aliphatic Amine	1 - 10

Source: Authors

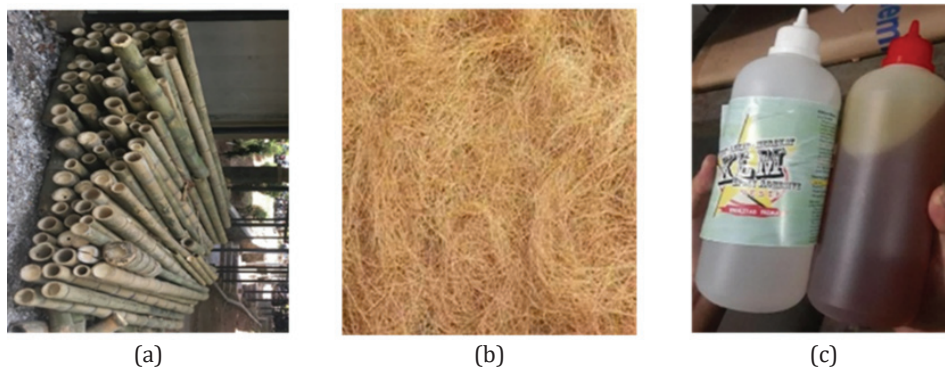


Figure 1 Materials a) Petung bamboo, b) coconut coir fiber, c) Epoxy Bakelite® EPR 174.

Source: Authors

2 Procedure of Specimen Manufacture

The specimens were made at Morisco Bambu Manufactory, Yogyakarta, Indonesia. Manufacturing laminated bamboo composite specimens involved several steps. The first step was bamboo selection. This step selected high-quality bamboo culms with uniform dimensions and free from any damage, decay, or insect infestation. In the second step, the bamboo culms were cut into strips of the desired dimensions and shaped into the desired geometry, such as flat, circular, or square cross-sections. The bamboo Petung material was cut 10 mm in width and 5 mm in thickness and glued together using epoxy resin so that the total width was 50 mm, as shown in Figure 2a. The coconut coir fiber was prepared using a mechanical method to

have the same size as the Petung bamboo material with a thickness of 1475 mm, as shown in Figure 2b. Then, the blades were arranged with two lamina direction variations, 0° unidirectional and 9° unidirectional, as in Figure 3. The bamboo slats and coconut coir fiber were then glued with epoxy resin with reasonably high adhesion (Figure 2d).

A compaction process was carried out to strengthen the bond of the two materials so that there was no air space between the blades. The last step was drying, as seen in Figure 2f. Drying was conducted to reduce the moisture content. Moisture content is the mass of water to the mass of solids in a specimen, expressed as a percentage. According to ISO 22157-1-2004, the moisture content had to be below 12% [28]. After drying, the composite

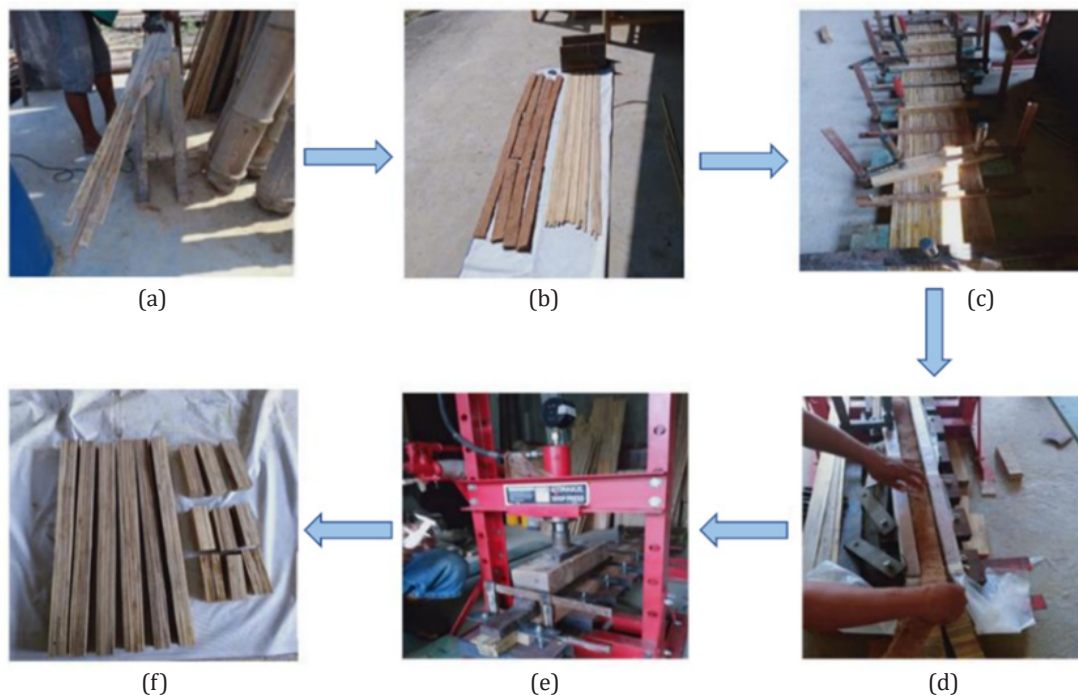


Figure 2 Laminated bamboo specimen manufacturing process.

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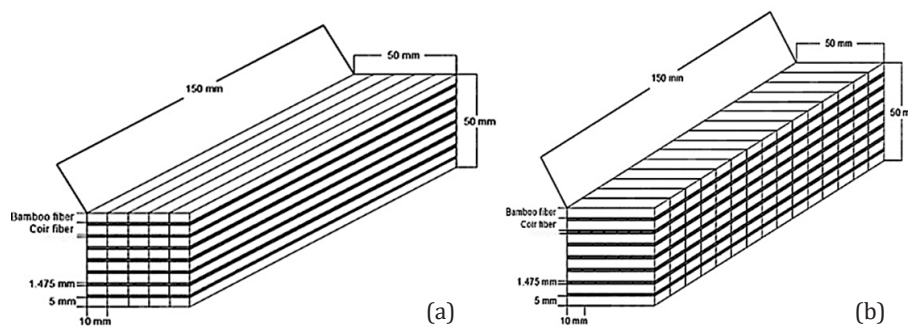


Figure 3 The direction of lamina a) unidirectional (0°), b) unidirectional (90°).

Source: Authors

block was trimmed to the desired shape and size, then sanded to achieve a smooth and even surface. The laminated bamboo composite specimens were allowed to cool and equilibrate to the ambient temperature and humidity level. This process helped prevent warping, cracking, or deformation during subsequent use or testing. The laminated bamboo composite specimens were inspected for defects, such as delamination, voids, or surface roughness. Any samples that failed to meet the specified quality standards were rejected.

2.3 Flexural Testing Specimen and Procedure

The flexural strength of the beam was defined as the maximum tensile stress that it could endure before experiencing failure [29]. This study employed the SNI 03-3959-1995 standard for flexural testing [30]. The Laboratory for Welding and Ship Materials at the Department of Naval Architecture, Universitas Diponegoro, Semarang, Indonesia, conducted the tests. The three-point bending method was utilized to measure the strength of the material, and a Universal Testing Machine (UTM) type WE-1000B, manufactured by Zhejiang in China, was used for the tests. The test was carried out with a 2.0 mm/min crosshead movement rate. The specimens had dimensions of 150 mm in length and 50 mm in width and thickness, as depicted in Figure 5. Five specimens were tested, and the average bending strength and modulus values were calculated. Figure 4 shows the schematic diagram of the flexural test conducted on the Y and Z-axis.

By using the three-point bending method to determine the flexural strength of laminated Petung bamboo and coconut coir fiber, this study provided valuable insights into the suitability of these materials for shipbuilding purposes. The bending strength and modulus were critical parameters that determined a ship's structural integrity and load-bearing capacity. As such, the findings of this study had significant implications for the shipbuilding industry, particularly in the context of reducing reliance on wood and other conventional materials. Moreover, the use of UTMs for flexural testing allowed for accurate measurement of the strength properties of the material being tested. In future research, other testing methods could be used to validate this study's findings further and explore the properties of other alternative materials for shipbuilding.

2.4 Compressive Testing Specimen and Procedure

The greatest compressive stress that a specimen could sustain before rupturing or deforming by a specific amount was known as compressive strength [31]. The compression test used the SNI 03-3958-1995 standard [32]. Compressive testing was carried out to obtain information on the strength of the material using the three-point bending method in a UTM WE-1000B type, Zhejiang, China, with a maximum capacity of 1000 kN, conducted at the Laboratory for Welding and Ship Materials of the De-

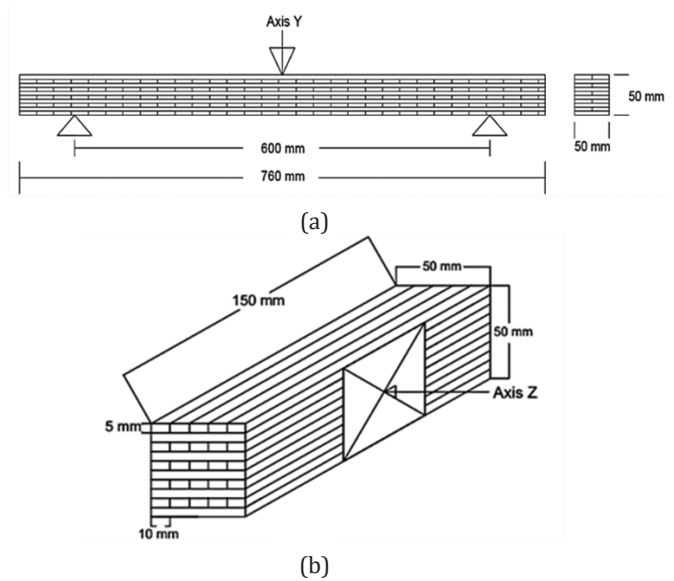


Figure 4 Bending test under different loading directions (a) Y-axis direction, (b) Z-axis direction.

Source: Authors

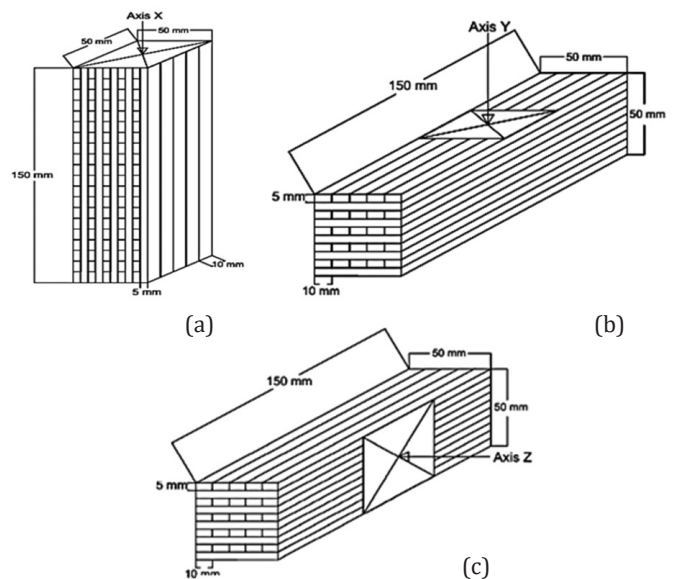


Figure 5 Compressive tests under different load directions (a) X-axis, (b) Y-axis, (c) Z-axis.

Source: Authors

partment of Naval Architecture, Universitas Diponegoro, Semarang, Indonesia. The specimen's dimension was 150 mm in length, 50 mm in width, and thickness, as seen in Figure 5. To obtain compressive test data, each variation was tested using five specimens. Different loading scenarios of the compressive test, such as parallel to the fiber (X-axis) and the loading direction perpendicular to the fiber (Y and Z-axis) can be seen in Figure 5.

3 Result and Discussion

3.1 Result of Moisture Content and Specific Density

Moisture content is a crucial factor in determining the quality and strength of materials for shipbuilding [33]. The presence of water can weaken the structural integrity of a material, leading to deformation or failure under loading conditions. The study conducted by Amatosa et al. [34] concluded that when the composite specimen had a high percentage of water content, it weakened Moisture content using ISO 22157-1-2004 standard and was measured using a Moisture Meter. For wooden ships, the BKI has set a specific density range of 0.60 – 0.90 gr/cm³ for its Strength Class II classification [35]. This standard assumes that denser wood will be strengthened and more durable, which is generally true. However, this assumption does not consider the specific properties of different wood species or alternative materials. Petung bamboo had a specific density of the fresh volume of 0.57 – 0.69 gr/cm³ and air dry volume of 0.65 – 0.78 gr/cm³ [36].

For instance, Petung bamboo, which was used in this study, has a specific density that falls within the BKI standard. However, it is essential to note that the strength and durability of bamboo are not solely dependent on its density. Other factors, such as the age and maturity of the bamboo, the harvesting and processing methods, and the environmental conditions during growth, can also affect its mechanical properties. Therefore, while specific density is an crucial factor to consider when selecting materials for shipbuilding, it should not be the sole criterion for determining their suitability. Instead, a comprehensive analysis of the material's properties and performance under various loading conditions is necessary to ensure its suitability for the intended application. The moisture content and specific density of the Petung bamboo specimens tested in this study met the BKI Strength Class II classification standard.

3.2 Results of Mechanical Tests

The maximum stress a composite material can endure before breaking when stretched is known as tensile or ultimate tensile strength. This strength is typically assessed by conducting a tensile test and recording strain and stress value changes. The peak of the stress-strain curve is referred to as the ultimate tensile strength. Unlike the size of the material, the strength value is determined by the

material's type. The flexural strength data obtained from this study provides valuable insights into the suitability of Petung bamboo and coconut coir fiber for shipbuilding purposes. The findings of this study indicate that the laminates of Petung bamboo and coconut coir fiber possess sufficient flexural strength and can be a suitable alternative to traditional wood materials for shipbuilding. This suggests that Petung bamboo and coconut coir fiber laminates can be used in various shipbuilding applications, such as decks, bulkheads, and frames.

It can be found that tensile strength has a different value based on lamina direction. The results indicate that the 0° lamina direction in both loading directions showed an increased flexural strength value compared to the 90° lamina direction. It can be found that the highest flexural strength, with a value of 94.81 MPa, can be found in a specimen with 0° lamina direction with load in Z-axis (LZA). In contrast, the lowest flexural strength can be found in a specimen with 90° direction with Y-axis load (LYB), with a value of 36.91 MPa. As the angle of the laminates increases under the bending test, the bending strength of the material decreases. The Tsai-Hill criterion indicates that as the fiber orientation angle increases from 0°, the composite's tensile and compressive properties will continue to decline [37]. Similar result can be found in the previous study that laminated bamboo materials achieve the highest tensile strength with the laminates' direction 0° (on-axis laminates) compared to 45°/-45° and 0°/90° layer orientations [12,19]. The flexural strength in the present study is lower than in previous studies due to the use of thicker bamboo. To enhance the strength properties of the material, it is recommended to use thinner bamboo that is laminated with a higher number of bamboo layers, as suggested by ref. [12]. Furthermore, the research found that laminated boards without joints and a fiber direction of 0° showed the highest strength, while those with a fiber direction of 45° or 90° experienced a decrease in tensile strength of 52% and 15.7%, respectively. This finding was reported in an earlier study [38].

This finding is significant since it implies that the material's mechanical properties can be optimized by orienting the laminates in a specific direction during the lamination process. Some recommendations were given by Supomo et al. [39], where the stalk diameter and thickness of the bamboo skin decreased with increasing height. It was found that the bending strength of the laminated slats decreased when the material was taken from the top of tree trunks.

Table 4 Comparison of flexural strength and modulus of elasticity (MOE) under different lamina directions.

Specimen Code	Flexural Strength (MPa)	MOE (MPa)
0° direction with load in Y-axis (LYA)	51.42	4588.15
90° direction with load in Y-axis (LYB)	36.91	1530.25
0° direction with load in Z-axis (LZA)	94.81	4106.63
90° direction with load in Z-axis (LZB)	39.24	1911.16

Source: Authors

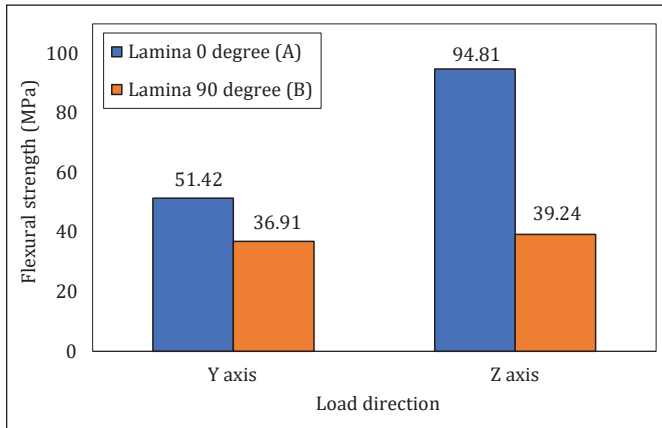


Figure 6 The average flexural strength under different lamina directions.

Source: Authors

In addition, the bending MOE of wood is a critical parameter in the grading of wooden structures and the design of wood [40]. Bending MOE measures a material’s resistance to elastic deformation when a force is applied to the specimen. The MOE of a specimen is defined as the slope of the stress–strain curve in the elastic deformation region. The average bending MOE value of the specimen for the Y and Z-axis bending test results can be seen in Figure 7. As such, the bending MOE value obtained from this study for Petung bamboo and coconut coir fiber laminates can be used in the grading process and structural design of wooden shipbuilding. Figure 7 shows that the bending MOE value of the Petung bamboo and coco fiber laminates, which had the smallest bending MOE value in the 90° lamina direction specimen with the Y-axis load direction, obtained a value of 1530.25 MPa. The highest bending MOE value can be found in the 0° lamina direction at the Y-axis loading direction, with a value of 4588.15 MPa. These data indicate that the 0° lamina direction has a better bending MOE value than the 90° lamina direction because the strain value in the 0° lamina direction is smaller than the 90° lamina direction.

The compressive strength test is an pivotal mechanical property that needs to be evaluated to assess the suitability of bamboo composites for structural applications. The results of this study show that the orientation of the laminates significantly affects the compressive strength of the bamboo composite. The 0° lamina direction generally had higher compressive strength values than the 90° lamina direction when compressed in the load direction of the X and Y axes. This is consistent with the flexural test results, where the 0° lamina direction had a better bending MOE value than the 90° lamina direction.

However, in the Z-axis direction, the compressive strength of the 90° lamina direction was slightly higher than the 0° lamina direction. This may be due to the fact that in the Z-axis direction, the load is applied perpendicular to the plane of the laminates, and the orientation of the laminates may not have as significant an effect on the compressive strength. In summary, the results of this study indicate that

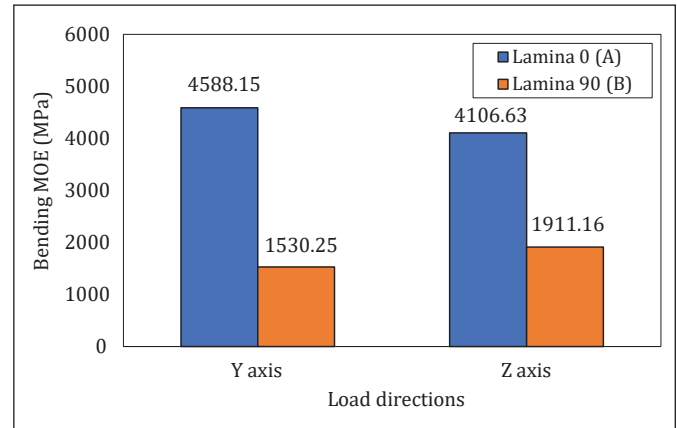


Figure 7 Comparison of MOE under different lamina directions.

Source: Authors

Table 5 Compressive test results under different load directions.

No	Specimen Codes	Compressive strength (MPa)
1	0° direction with load in X-axis (TXA)	28.50
2	90° direction with load in X-axis (TXB)	25.13
3	0° direction with load in Y-axis (TYA)	72.52
4	90° direction with load in Y-axis (TYB)	50.09
5	0° direction with load in Z-axis (TZA)	10.37
6	90° direction with load in Z-axis (TZB)	52.12

Source: Authors

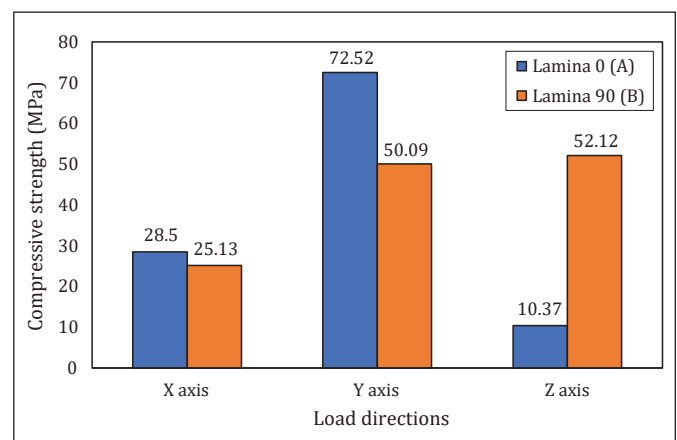


Figure 8 Compressive strength under different lamina direction.

Source: Authors

the orientation of the laminates has a significant effect on the mechanical properties of the bamboo composite, including bending MOE and compressive strength. These findings can be used to optimize the design and manufacturing process of bamboo composites for structural applications, such as in the construction of wooden ships, where strength and durability are critical factors.

3.3 Comparison of Material Properties Between Different Laminated Beam Types

The compressive and flexural strengths of laminated beams made of Petung bamboo and coconut fiber were compared to previous tests on laminated Petung bamboo beams [41]. The comparison revealed that the laminated Petung bamboo and coconut fiber beams had higher compressive strength values parallel to the Y-axis, at 78.27 MPa, compared to the Petung bamboo beams, which only had a parallel compressive strength of 26.85 MPa. The flexural strength of laminated Petung bamboo and coconut fiber beams was 94.81 MPa, almost the same as that of laminated Petung bamboo beams, at 95.08 MPa. Furthermore, the comparison showed that the laminated Petung bamboo and coconut wood beams had a flexural strength of 95.98 MPa, which was almost the same as the laminated Petung bamboo and coconut fiber beams. These findings suggest that adding coconut fiber to the laminated Petung bamboo increases the strength of the laminated beam.

In addition to increasing the strength of the laminated beam, the effect of adding coconut fiber was also found to reduce the thermal conductivity of the composite specimens, which could potentially reduce damage caused by heat during compression or bending tests [21]. This is an important finding as it suggests that adding coconut fiber could improve the durability and resilience of laminated bamboo beams, particularly in high-temperature environments. Further research could explore the optimal ratio of bamboo to coconut fiber and the potential applications of these composite materials in various industries.

3.4 Comparison of BKI Wooden Strength Standard

The construction of critical wooden vessels requires the use of wood that meets certain minimum requirements. Specifically, the laminated wood must be glued with water-resistant glue, tested and stamped by the BKI, or made according to recognized standards [35]. Table 7 shows the wood strength class according to BKI wooden ship 1996. The wooden ship can be categorized into four different strength classes with a specific density, compressive and flexural strength. Each Strength class has a different application of the ship structure.

The findings of Table 8 provide insight into the strength classes of various specimens based on their flexural strength. The results show that specimens with different loading directions have been classified into different strength categories. Notably, the laminated bamboo specimen with a fiber direction of 0° was classified in strength class I and II, indicating a high level of strength. On the other hand, the specimen with a fiber direction of 90° was classified in strength class III, indicating a lower strength level than the former.

These results have important implications for using laminated bamboo in various application of ship structural components. For instance, laminated bamboo with a fiber direction of 0° can be recommended for ship applications with high strength. This could include the keel, machine foundation, web frame. On the other hand, using laminated bamboo with a fiber direction of 90° may be more suitable for applications where lower levels of strength are acceptable, such as in ship decks and construction parts above the waterline.

Table 6 Comparison of material properties between laminated bamboo types.

Tests	Petung Bamboo and Coconut Fiber	Petung Bamboo	Petung Bamboo and Coconut Wood
Moisture Content (%)	11.90	12.83	13.08
Specific Density (gr/cm ³)	0.77	0.63	0.64
Compressive Strength Parallel to the Y-axis (MPa)	78.27	26.85	-
Flexural Strength (MPa)	94.81	95.08	95.98

Source: Authors

Table 7 Acceptance criteria of wood strength class according to BKI wooden ship 1996 [35].

Strength class categories	Dried specific density (gr/cm ³)	Compressive strength parallel to Y-axis (kgf/cm ²)	Flexural strength (kgf/cm ²)
I	≥ 0.90	≥ 1100	≥ 650
II	0.60 - 0.90	725 - 1100	425 - 650
III	0.40 - 0.60	500 - 725	300 - 425
IV	0.30 - 0.40	360 - 500	215 - 300
V	≤ 0.30	≤ 360	≤ 215

Source: Authors

Table 8 Categorization of strength class of different specimens based on flexural strength.

Specimen Code	Flexural strength (kgf/cm ²)	Strength class categories
0° direction with load in Y-axis (LYA)	524	II
90° direction with load in Y-axis (LYB)	376	III
0° direction with load in Z-axis (LZA)	967	I
90° direction with load in Z-axis (LZB)	400	III

Source: Authors

Table 9 Categorization of strength class of different specimens based on compressive strength.

Specimen Codes	Compressive strength (kgf/cm ²)	Strength class categories
0° direction with load in X-axis (TXA)	291	V
90° direction with load in X-axis (TXB)	256	V
0° direction with load in Y-axis (TYA)	739	II
90° direction with load in Y-axis (TYB)	511	III
0° direction with load in Z-axis (TZA)	106	V
90° direction with load in Z-axis (TZB)	531	III

Source: Authors

Table 9 presents the categorization of the strength class of various specimens based on their compressive strength. Similar to the results from Table 8, the specimens with different loading directions have been classified into different strength categories. Notably, the laminated bamboo specimen with a fiber direction of 0° was classified in strength classes II and V, indicating a high level of compressive strength. In contrast, the specimen with a fiber direction of 90° was classified in strength classes III and V, indicating a lower level of compressive strength compared to the specimen with a fiber direction of 0°.

These findings have important implications for the use of laminated bamboo in shipbuilding applications. For instance, the use of laminated bamboo with a fiber direction of 0° could be recommended for ship components that require high levels of strength, such as the keel, machine foundation, web frame, and hull plate. On the other hand, the use of laminated bamboo with a fiber direction of 90° may be more suitable for ship components where lower levels of strength are acceptable, such as ship deck, deck plate, and construction parts above the waterline. The findings suggest that laminated Petung bamboo and coconut fiber beams could be a suitable and sustainable alternative to traditional wooden beams in shipbuilding, particularly in critical areas of the ship where strength and durability are of utmost importance.

4 Conclusion

Several tests, such as moisture tests, flexural and compressive tests, were conducted experimentally to investigate material behavior under different loading directions and lamina stackings. Several conclusions can be drawn.

Based on the results of the analysis of specimen testing, the laminated beams of Petung bamboo and coconut coir fiber met the requirements so that they could be used as alternative materials to replace wood and glass fiber. Variations in the 0° and 90° laminated direction of laminated bamboo with different test axes significantly affected the compressive and flexural strength of laminated beams of Petung bamboo and coconut coir fiber. Laminated Petung bamboo and coconut coir fiber with 0° oriented direction laminated bamboo was the most robust specimen compared to specimens with 90° oriented direction laminated bamboo. The highest average compressive strength value was 72.52 MPa, and the highest average flexural strength value was 94.81 MPa. Laminated bamboo could be utilized in ship components requiring varying strength levels based on fiber direction. For instance, if high levels of strength are necessary, laminated bamboo with a fiber direction of 0° could be recommended for components such as keels, machine foundations, web frames, and hull plates. Conversely, suppose lower strength levels are acceptable. In that case, laminated bamboo with a fiber direction of 90° could be more appropriate for ship components like the ship deck, deck plate, and construction parts above the waterline.

It is also important to note that further research could be conducted to investigate the effects of other factors on the strength of laminated bamboo. This could include factors such as the thickness and number of layers in the laminated bamboo, as well as the moisture content of the material. By better understanding the factors that influence the strength of laminated bamboo, it may be possible to develop even stronger and more durable materials for a wide range of applications.

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