

The Mechanical Properties of Laminated Bamboo with Different Types of Adhesive and Compression Pressures

Zulmahdi Darwis

Department of Civil Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia |
Department of Civil Engineering, Faculty of Engineering, Sultan Ageng Tirtayasa University, Indonesia
zulmahdi.darwis@student.uns.ac.id

Achmad Basuki

Department of Civil Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia
achmadbasuki@staff.uns.ac.id (corresponding author)

Muhammad Yani Bhayusukma

Department of Civil Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia
muhammadyani@staff.uns.ac.id

Stefanus Adi Kristiawan

Department of Civil Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia
stefanus.kristiawan@staff.uns.ac.id

Kuncoro Diharjo

Department of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia
kuncorodiharjo@ft.uns.ac.id

Cahyo Hadi Wibowo

Department of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia
cahyo.haw@student.uns.ac.id

Fathony Nada Saputro

Department of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia
fathony_saputro@student.uns.ac.id

Faishal Machfudz Majid

Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Surakarta,
Indonesia
fmm463@ums.ac.id

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ABSTRACT

Laminated bamboo, having a high strength -to-weight ratio, is getting popular for structural applications. This study evaluates how adhesive type (epoxy, polyurethane, and polyvinyl acetate) and compression pressure affect the mechanical properties and failure morphology of laminated bamboo (*Dendrocalamus asper*). The laminates were fabricated using the Multi Double Glue Layer (MDGL) method with cold pressing for 24 h. Tensile and shear tests were conducted in accordance with ASTM D143 to characterize mechanical behavior. Fracture surfaces were examined by macrophotography to classify failure modes.

The results indicate that the epoxy adhesive provides the greatest tensile and shear strength, with failure occurring within the bamboo substrate, indicating an effective adhesive bond. Polyurethane (PUR) exhibited multiple failure modes coupled with intermediate mechanical performance, while Polyvinyl Acetate (PVAc) showed adhesive failure and offered the lowest strength. The optimum compression pressure was found to be 3.5 MPa, which allowed for effective adhesive infiltration between bamboo pores without causing excessive extrusion. Exceeding the pressure limit resulted in strength reduction due to the formation of voids, adhesive thinning, and microcracking of the substrate. Epoxy exhibited the highest Young's modulus, due to its rigid and highly cross-linked molecular structure.

Keywords-mechanical properties; laminated bamboo; adhesive; compression pressure

I. INTRODUCTION

Advanced materials are replacing conventional ones in industrial and structural applications [1]. Bamboo has great potential as a processed structural material because of its high strength, low weight, and abundance [2]. However, effectively using bamboo requires appropriate manufacturing techniques to ensure consistent and reliable performance [3]. Laminated bamboo, is produced by arranging and bonding bamboo strips in layers along the length, in order to reduce natural variability and obtain a more uniform material [4]. The strength of laminated bamboo is influenced by its characteristics, the adhesive's specific properties, and the amount of pressure applied, whereas the quality of lamination is affected by the density and moisture content. Increased density creates a larger contact area between laminae. Maintaining the moisture content below 12% ensures that the laminae remain stable during curing [5]. The type of adhesive also affects the interlaminar mechanical properties, which govern stress transfer and lamination failure mechanisms [6]. When subjected to shear force, brittle adhesives tend to fail, and adhesives that are too soft may deform over time [7]. Popular glues for bamboo lamination include epoxy, PUR, and PVAc. Epoxy adhesives have high tensile and shear strength, and good thermal stability, forming covalent bonds with hydroxyl groups in cell walls [8]. PUR consists of hard and soft segments containing urethane and urea groups which establish a hydrogen-bonded network that acts as a physical crosslink. This molecular architecture imparts toughness and flexibility and ensures reliable performance under humid conditions, thereby minimizing the likelihood of delamination failure [9]. PVAc is notable for its low cost, medium viscosity, and rapid drying at room temperature. Authors in [10] reported that epoxy adhesives produced the greatest shear strength in laminated bamboo boards and passed the JAS 234:2003 standard. In contrast, PVAc adhesives failed the delamination test, indicating their unsuitability for dry interior applications. Authors in [11] found that PUR adhesives resulted in a higher proportion of wood failure than Phenol Resorcinol Formaldehyde (PRF) adhesives, indicating superior bond quality. These findings demonstrate the significant influence of adhesive type on the performance of laminated bamboo. Applying pressure during the fabrication of laminated bamboo allows for better penetration of adhesives, improves contact between laminae, increases adhesive flow into cell wall pores, and partially densifies parenchyma tissue [12]. These effects increase density and minimize void formation, thereby improving the mechanical properties of laminated bamboo composites [13]. Insufficient pressure can result in glue-starved lines due to inadequate adhesive penetration [14]. Conversely,

excessive pressure can result in adhesive over-extrusion, lumen structure damage, and residual stresses from trapped vapor release [15]. Authors in [16] reported that increasing compression pressure from 1.5 MPa to 2.0 MPa improved the tensile strength of laminated bamboo composites by 22.5%. This improvement was attributed to deeper adhesive penetration and enhanced interfacial bonding. This study examines the influence of compression pressure variations on laminated bamboo bonded with three commonly used adhesives: epoxy, PUR, and PVAc. The mechanical properties were evaluated using tensile and shear tests conducted in accordance with ASTM D143 standards. Surface failure observations were made using macro photography. The results are expected to reveal the optimal compression pressure for each adhesive, thereby improving the mechanical performance of laminated bamboo.

II. MATERIALS AND METHODS

A. Materials

Three- to five-year-old *Dendrocalamus asper* bamboo was obtained from Turgo, Sleman Regency, Indonesia. Three types of adhesives were used in this study: epoxy-based, PUR-based, and PVAc-based. The epoxy-based adhesive was Roland epoxy adhesive, produced by UD Rai Suntama. The PUR-based adhesive was MRLUX PUR adhesive, produced by MRLUX Indonesia. The PVAc-based adhesive was PRESTO PVAc, produced by PT Polychemie Asia Pacific Permai Indonesia.

B. Preparation of Adhesive

Each adhesive was prepared using 50 Multilayer Double Glue Line (MDGL) [17]. The adhesive composition was calculated using:

$$GPU = \frac{S \times A}{2048.3} \quad (1)$$

where GPU is the gram pick-up (g), S is the amount of adhesive applied in pounds (based on MDGL), and A is the area of the surface being bonded (cm^2). In this study it was 25 cm^2 for each side of the sample, so the total coated surface area was 50 cm^2 for both sides. The adhesive requirement for both sides of the bamboo was 1.23 g for PUR-based adhesive and PVAc-based adhesive. Epoxy-based adhesive used a 1:1 mixing ratio between the epoxy base and hardener, so each component was weighed at 0.61 g.

C. Preparation of Laminated Bamboo

The bamboo culms were stripped of their outer skin and cut into $100 \text{ cm} \times 2.5 \text{ cm} \times 1 \text{ cm}$ rectangular pieces. Deltamethrin was dissolved in water at a ratio of 2.5 ml to 1 L. The strips were immersed in this solution for three days to prevent termite

attack. After treatment, the strips were oven-dried at 105 °C for 4 H until the moisture content reached approximately 12%. Then, the dried strips were assembled into laminated bamboo panels using three types of adhesives: CBEP (epoxy-based), CBPU (PUR-based), and CBPA (PVAc-based). Each adhesive was applied to the bamboo strips and subjected to cold compression at 3.5 MPa, 5 MPa, and 7 MPa for 24 h, as shown in Table I. The resulting laminated panels were cut into test specimens with specified dimensions.

TABLE I. SAMPLE DESIGN OF LAMINATED BAMBOO

No	Sample	Adhesive	Compression pressure (MPa)
1	CBEP 3.5	Epoxy	3.5
2	CBEP 5	Epoxy	5
3	CBEP 7	Epoxy	7
4	CBPU 3.5	PUR	3.5
5	CBPU 5	PUR	5
6	CBPU 7	PUR	7
7	CBPA 3.5	PVAc	3.5
8	CBPA 5	PVAc	5
9	CBPA 7	PVAc	7

D. Experiment

This study evaluated the mechanical properties through tensile and shear testing, using a 50-ton Universal Testing Machine (UTM) with specimens prepared according to ASTM D143 [18]. Tensile tests were conducted at a crosshead speed of 2.5 mm/min until failure; shear tests were conducted at a crosshead speed of 0.6 mm/min until failure. Figure 1 presents the tensile and shear dimensions of the samples.

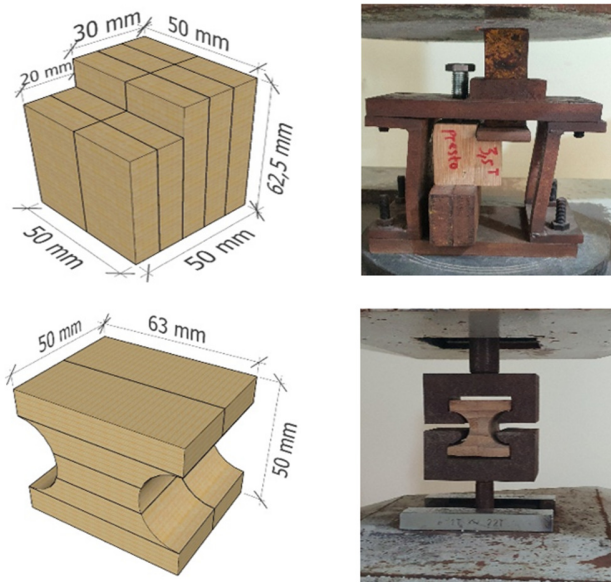


Fig. 1. Shear and tensile test samples based on ASTM D143.

Macro photography was conducted using an Olympus ZX7 stereo microscope to examine the fracture surface morphology and bond-line quality following mechanical testing. This provided a basis for evaluating failure mechanisms and bond integrity. Figure 2 shows a flowchart of the experiments conducted in this study.

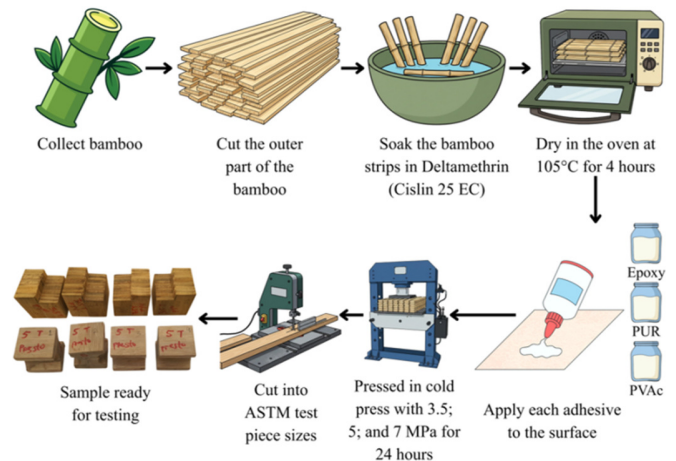


Fig. 2. Flowchart summarizing the experimental procedure.

III. RESULTS AND DISCUSSION

A. Failure Surface Morphology

Figure 3 illustrates macro-observations of fracture surfaces from shear tests on laminated bamboo specimens bonded with different adhesives. Specimens bonded with CBEP adhesive exhibited a favorable failure pattern in which fracture occurred within the bamboo substrate rather than at the adhesive interface. Peeling and tearing occurred on the substrate surface in the bonding region, indicating that the adhesive bond's strength exceeded that of the bamboo. Under applied load, the weakest region was within the bamboo matrix rather than the adhesive layer. This behavior is attributed to strong physicochemical interactions between the epoxy resin and the lignocellulosic components of the bamboo substrate [19]. The tensile and shear strength values confirm these findings, showing that CBEP-bonded specimens had the highest results compared to specimens bonded with other adhesives. According to [20], epoxy adhesives can prevent micro-gaps between bamboo fibers. Furthermore, epoxy penetration creates a rough texture on the fiber surface, improving mechanical interlocking and minimizing slippage. The specimens bonded with CBPU adhesive exhibited a combination of failure modes. Cohesive failure was observed due to damage within the bamboo substrate, as well as adhesive failure, characterized by the presence of residual adhesive on the bonding interface. The inherent flexibility of PUR enhances bond durability under varying moisture conditions, contributing to improved long-term interfacial stability. In contrast, specimens bonded with CBPA adhesive demonstrated a clear adhesive failure pattern. The adhesive layer remained intact on the surface with minimal damage, and there was no visible damage to the bamboo substrate. This failure pattern signifies a weak adhesive bond. Different adhesives have different abilities to distribute moisture-induced stress within the bond line, resulting in distinct failure mechanisms [21]. Adhesives can typically be categorized into two main types: polymerized and pre-polymerized. These classifications result in unique mechanical behaviors. Adhesives that have undergone polymerization are relatively rigid due to their highly cross-linked polymers. In contrast, pre-polymerized adhesives, such as polyurethane, are flexible.

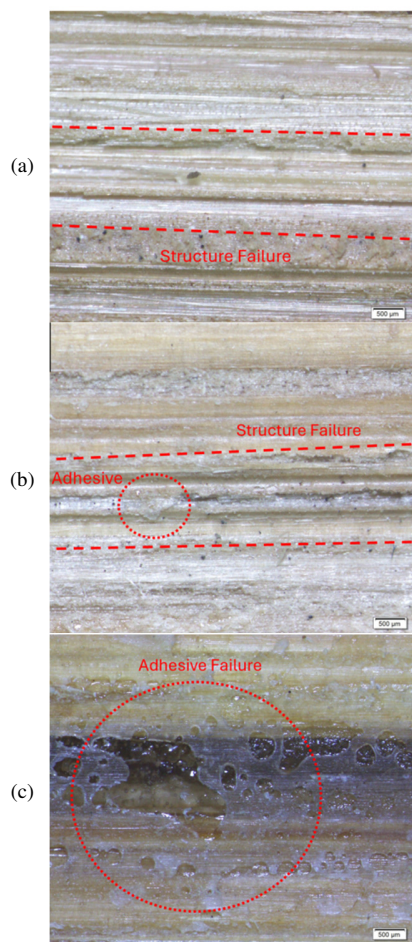


Fig. 3. Macro photograph of the surface of laminated bamboo fractures in shear testing: a) CBEP adhesive, b) CBPU adhesive and c) CBPA adhesive.

B. Shear Strength

Figure 4 displays the shear strength performance of laminated bamboo specimens created using various adhesive types and compression pressures. Given that all specimens were oriented longitudinally in relation to the loading direction, the species of bamboo used did not have a significant effect on the shear strength. However, the type of adhesive utilized and the compression pressure applied during fabrication significantly influenced shear strength. Examining the graph reveals a trend in which shear strength diminishes as compression pressure increases. Among the adhesives tested, CBEP demonstrated the highest shear strength, followed by CBPU and CBPA. This suggests that compression pressure directly impacts bond quality. The ideal compression pressure was determined to be 3.5 MPa. Increased pressure levels could potentially lead to microcracking within the bamboo's internal structure [22]. These microcracks may serve as initial points for larger cracks to propagate, leading to premature structural failure.

Furthermore, applying excessive pressure can squeeze out the adhesive at the interface, reducing the amount remaining between the bonding surfaces. This results in a thinner adhesive layer and leads to failure due to insufficient wetting and poor

adhesion to the bamboo substrate [23]. Macro-photographic evidence supports this phenomenon by showing the absence of adhesive residue on the bamboo surface and a lack of fiber damage, which indicates inadequate adhesive interaction at the bond line. The adhesive plays a crucial role in forming a strong bond between the substrate and the laminate and facilitating efficient load transfer across the joint [24]. Stress induced during deformation was more uniformly distributed in polyurethane-bonded specimens, which helps maintain the integrity of the adhesive joint due to polyurethane's inherent ductility [25]. In contrast, PVAc adhesives demonstrated the lowest shear strength. This behavior can be attributed to their molecular structure consisting of long polymer chains that lack cross-linking and allow the molecules to easily slide past one another [26]. The weak molecular structure of PVAc renders the material unable to withstand continuous loads due to creep, making PVAc adhesives unsuitable for structural applications.

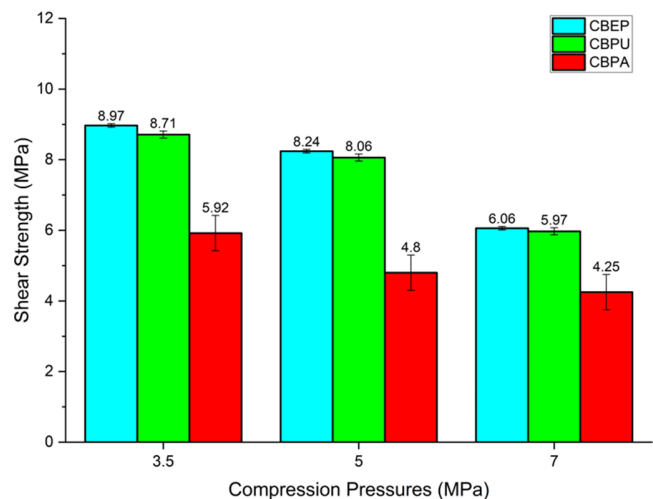


Fig. 4. Shear strength of samples.

C. Tensile Strength

The results of the analysis of how adhesive type and compression pressure affect the tensile strength of laminated bamboo are presented in Figure 5. The former match the shear test results, which showed that specimens bonded with CBEP adhesive and compressed at 3.5 MPa exhibited the highest tensile strength. Authors in [27] found that epoxy polyamide adhesives provide superior bonding strength compared to other types of adhesives. Additionally, reducing the compression pressure was related to an increase in tensile strength. This behavior can be attributed to an optimal compression pressure of approximately 3.5 MPa. This pressure allows the liquid adhesive to adequately fill the voids within the bamboo fibers without excessively squeezing out from the bonding interface. Typically, applying moderate pressure results in a thicker adhesive layer, but excessive pressure can cause adhesive loss from the bamboo interface. Reducing adhesive loss decreases the solid content and weight fraction of the bonding material, resulting in lower overall panel density [28]. Furthermore, high compression pressure may result in fiber plasticization, leading to inadequate adhesive anchorage within the substrate [29].

Among the evaluated adhesives, epoxy exhibited superior strength compared to PUR and PVA. This superiority can be attributed to epoxy's molecular structure, which forms strong, rigid, cross-linked bonds, though it tends to display brittle-elastic behavior [30]. In contrast, the CBPA adhesive exhibited a clear adhesive failure pattern, as evidenced by macrophotographic observations, resulting in lower strength than the other specimens. This type of failure is likely caused by voids that lead to a poor interfacial bond between bamboo fibers.

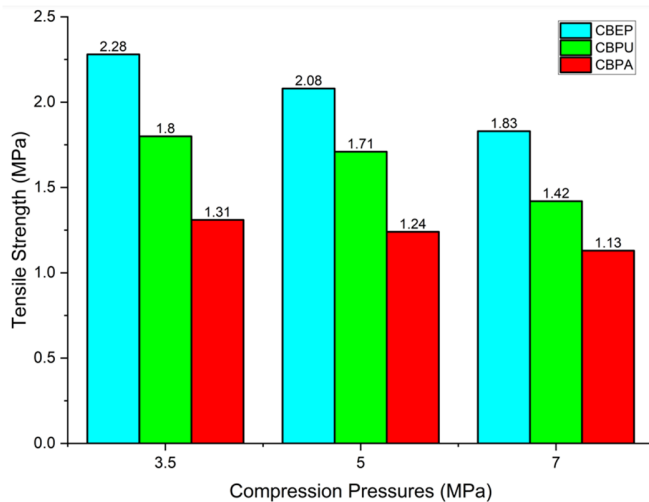


Fig. 5. Tensile strength of samples.

D. Young Modulus

Figure 6 shows that the specimens bonded with epoxy adhesive had the highest Young's modulus, those bonded with CBPA had the second highest values, and those bonded with CBPU had the lowest values. However, an inverse relationship was observed between modulus and compression pressure during fabrication. This reduction is primarily due to changes in the interfacial contact conditions between the bonded surfaces. While applying pressure is essential for promoting adequate adhesion, excessive pressure can force the adhesive out of the bonding interface. Excessive pressure can also result in the adhesive being forced out of the bonding interface, having a negative effect on uneven substrates with porous structures and height differences. Consequently, when two high points on the surfaces meet, a void in the adhesive can be formed, resulting in imperfect bonding and reducing the material's overall stiffness. Another factor that influences Young's modulus is the inherent characteristics of the adhesive used. During the curing process, the epoxy resin develops a robust, cross-linked network of covalent bonds that immobilize the polymer chains. This chemical structure locks the polymer chains in place, preventing them from shifting when a force is applied. Consequently, rigid and strong bonding is formed, as evidenced by the highest modulus value observed for epoxy adhesives [31]. Authors in [32] reported that chemical and physical interactions between the epoxy adhesive and the substrate create an interfacial boundary zone. Within this zone, the adhesive molecules near the substrate surface become more

ordered and concentrated than in other regions. In comparison, PUR adhesives are more elastic than other types. This is because PUR has a different chain structure than epoxy. Although both have cross-links, the primary molecular chains in PUR consist of hard and soft segments. This configuration leads to lower cross-linking density, resulting in high flexibility and reduced stiffness and modulus values [33].

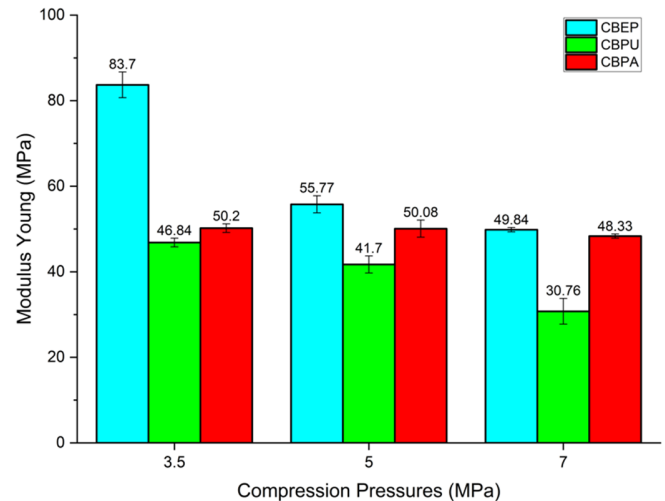


Fig. 6. Young modulus of samples.

IV. CONCLUSIONS

This study concludes that the type of adhesive and compression pressure are critical factors that influence the mechanical properties and failure modes of laminated *Dendrocalamus asper*:

- Epoxy (CBEP) adhesive yielded the highest mechanical performance (tensile and shear strength), with failure occurring in the bamboo substrate rather than the bond.
- The optimal compression pressure for all adhesives was 3.5 MPa.
- Pressures exceeding 3.5 MPa negatively impacted strength, likely due to excessive adhesive extrusion and microcracking of the substrate.
- Polyvinyl acetate (PVAc) performed the poorest, exhibiting clear adhesive failure.
- Epoxy's rigid structure resulted in the highest stiffness, while the flexible structure of Polyurethane (PUR) resulted in the lowest.

These results confirm that optimally fabricated laminated bamboo is a high-performance, sustainable alternative to conventional materials. However, potential disadvantages, such as long-term creep, must be addressed for use in large-span structural systems.

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