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Evaluation of Web Diameter, Flange Thickness, and Adhesive Type on the Physical and Mechanical Properties of Siam Bamboo I-Joist

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ABSTRACT

This study investigated the effects of geometric and adhesive variables on the physical and mechanical properties of I-joist beams using Siam bamboo (*Thyrsostachys siamensis*) as the web and *Acacia mangium* as the flange. This study combined two experimental studies focusing on (1) the influence of web diameter (3 and 4 cm) and flange thickness (2, 2,5, and 3 cm) and (2) the effect of adhesive type (epoxy and polyurethane) and penetration depth (½, ¾, and full thickness of flange). All materials were conditioned to a moisture content of 12–14% before fabrication. Physical testing included moisture content and density, while mechanical testing included flexural strength (MOE and MOR), tensile withdrawal strength, and failure mode analysis. The results showed that increasing the web diameter and flange thickness contributed to higher density, MOE, and MOR values, with the best performance observed at a diameter of 3 cm and a flange thickness of 3 cm. Meanwhile, using epoxy adhesive with ¾ penetration depth significantly improved the bonding strength and stiffness, achieving MOE values up to 22,361 kgf/cm² and MOR up to 132 kgf/cm². The most common failure modes were flange cracking and web detachment, particularly in beams with shallow penetrations and large diameters. This combined investigation confirms that optimizing the geometric configuration and joint adhesion can significantly enhance the structural performance of bamboo-based I-joists, offering a viable solution for eco-friendly construction.

Keywords: bamboo I-joist, mechanical performance, sustainable construction, web dimension

INTRODUCTION

The use of timber structures on a large scale has been increasing worldwide owing to their advantages of easy installation and good energy efficiency. However, the availability of high-quality, large-diameter sawmill timber required for roof and floor frameworks in civil and industrial buildings is becoming increasingly limited and expensive (Tupenaite *et al.* 2023). Engineered Wood Products (EWPs) offer a strategic solution to address the limitations of wood resources while opening up opportunities for the development of wooden building structures. EWPs are engineered wood-based materials composed of fibers, particles, veneers, boards, or strands of wood that are combined through gluing or mechanical bonding processes to form larger elements such as beams, boards, or other structural components. These are then produced and tested according to national or international standards to ensure structural strength and durability (Ding *et al.* 2023). EWPs are available in various sizes and dimensions, including I-joists (Yadav and Kumar 2021).

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According to a life cycle analysis conducted by the USDA Forest Products Laboratory (Bergman 2020), composite I-joists exhibit a high strength-to-weight ratio with a significantly lower use of raw materials than solid wood beams, thereby contributing to sustainable and efficient construction practices in resource utilization.

Bamboo is a reliable, sustainable, and engineerable material. Bamboo exhibits mechanical performance comparable to conventional materials such as steel, concrete, and timber, offering a sustainable and renewable construction alternative in rural and urban areas (Hossain *et al.* 2021). *Thyrsostachys siamensis,* commonly known as Siam bamboo, is one of the most widely cultivated bamboo species in Southeast Asia and is recognized for its high mechanical performance. Based on its excellent strength properties, bamboo is well-suited for use as a structural element in engineered wood products, particularly as a web component in I-joist beams. Experimental studies have reported that after the drying process, Siam bamboo can achieve tensile and flexural strengths of up to 118,14 MPa and 208,08 MPa, indicating its strong potential for structural applications (Chaiunachai 2017).

The selection of an appropriate wood species is a critical factor in determining the appearance, strength, and durability of engineered wood products. Fast-growing timber can be an alternative material for wood composites because of its renewable nature and underutilized potential (Olaga *et al.* 2024). One such promising species is *Acacia mangium.* According to Krisnawati *et al.* (2011), this wood species has a density ranging from 0,45 to 0,69 g/cm³ at 15% moisture content. It is commonly used for structural purposes and is classified as durability class II and strength classes II to III.

Most previous research on the development of I-joist beams has focused on the use of engineered materials such as laminated veneer lumber (LVL), oriented strand board (OSB), and medium-density fiberboard (MDF) as web elements (Ghazijahani *et al*. 2020; Chen *et al.* 2021; Jiloul *et al.* 2024). While these studies have shown promising results, research on the influence of geometric parameters, particularly web diameter, flange thickness, web depth, and adhesive type,on bamboo-based I-joist beams remains limited. Therefore, this study aimed to evaluate the effects of these four variables on the physical and mechanical properties of I-joist beams made from *Thyrsostachys siamensis* bamboo and fast-growing *Acacia mangium* wood, to identify the configuration material and optimal joint that enhances structural integrity and promotes sustainable construction.

METHODS

Materials

The materials used in this study included Siam bamboo (*T. siamensis*) aged 3–5 years, sourced from the vicinity of Bogor Agricultural University, and *Acacia mangium* wood boards harvested from trees aged 9–10 years.

Experimental Design

This study was conducted in two stages. The first test aimed to evaluate the effects of web diameter and flange thickness. The second round of testing was conducted based on these results to evaluate the web depth and adhesive types used. In the first stage, Siam bamboo was employed as the web material in the form of solid cylindrical pieces with diameters of 3 and 4 cm. Each flange was prepared with a recess to a depth of ¼ of its thickness to accommodate the bamboo web before bonding. The length of the bamboo was adjusted to match the required specimen dimensions (5,5 cm, 6,25 cm, and 7 cm). *Acacia mangium* wood served as the flange material, and the overall dimensions of the I-joist beams for the bending tests were 200 cm × 6 cm × 10 cm (Figure 1 (a)), with flange thicknesses of 2, 2.5, and 3 cm. The distance between the webs was consistently maintained at 15 cm across all specimens. For the tensile joint tests, specimens measuring 7 cm × 8 cm × 10 cm were used, as shown in Figure 1(b). Epoxy adhesive was used as the sole bonding agent to ensure consistency in adhesive performance. The bamboo and wood components were then assembled into an I-joist.

In the second stage, Siam bamboos with a diameter of 3 cm were used as the web material. *Acacia mangium* wood serving as the flange was prepared with dimensions of 200 cm × 6 cm × 10 cm for bending tests and 7 cm × 8 cm × 10 cm for tensile tests, using a constant flange thickness of 2 cm. Two types of adhesives were applied in this stage: epoxy resin and polyurethane. The joints between the web and flange were constructed with three penetration depths: ½, ¾, and full flange thickness. The overall spacing between the webs was maintained at 15 cm for all specimens prepared in this stage. All materials were conditioned to a moisture content of 12–14% before the assembly and testing processes.

Physical and Mechanical Testing

The physical properties, including moisture content and density, were tested. Moisture content was tested according to ASTM D4442-14, and density was measured based on ASTM D2396-14. The mechanical properties were evaluated, including flexural strength (modulus of elasticity/MOE and modulus of rupture/MOR), using a two-point loading bending test with a span length of 170 cm. The loading was applied using a two-point load model with a distance of one-third of the span, as specified by ASTM D5055-16. The I-joist Nail withdrawal strength was tested according to ASTM D1037-06, and damage patterns were observed based on the classification outlined in ASTM D5055-16.

Data Analysis

The data obtained from the tests, which included physical properties (moisture content and density) and mechanical properties (MOE/MOR), nail withdrawal strength, and damage patterns, were analyzed using a factorial Completely Randomized Design (CRD) with two factors to assess the effects of web diameter, flange thickness, adhesive type, and penetration depth on the performance of Siam bamboo and *Acacia mangium*-based I-joist beams. This factorial design involved three replicates for each treatment combination to test the individual effects of each variable and their interactions. Duncan's Multiple Range Test (DMRT) was performed at a 5% significance level to determine if significant differences between treatments were found.

RESULTS AND DISCUSSION

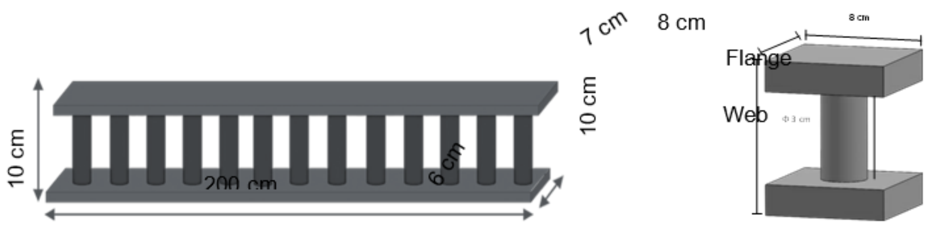
Effect of Web Thickness and Diameter
Physical Properties

The physical properties of a product, such as density and moisture content, significantly influence its mechanical performance (Bahtiar 2010). Based on

Figure 2, Moisture content and density of I-joist beams with variations in flange thickness and web diameter, the results show the moisture content and density of the I-joist beams with variations in the flange thickness and web diameter. The average moisture content of the I-joist beams ranges from 14,34% to 15,80%, which is lower than that of solid acacia wood, with a moisture content ranging from 15,9% to 17,6% (Nurhasybi and Sudrajat 2019). An increase in the moisture content was observed with an increase in the flange thickness. For the web diameter factor, D2 exhibited slightly higher values than D1. However, based on the analysis of variance (Table 1 Analysis of Variance for Physical and Mechanical Properties of I-Joist Beams), the results indicate that the moisture content does not significantly affect the increase in the flange thickness and web diameter in the I-Joist beams.

Based on the density values, the density of the I-joist beams increased from 0,53 g/cm³ to 0,63 g/cm³. The obtained values are comparable to the density of Siam bamboo (0,4–0,7 g/cm³) and Acacia wood (0,43–0,69 g/cm³) (Narasimhamurty *et al.* 2013; Viet *et al.* 2020). The highest density for the I-joist beams was observed in D2T3, with a value of 0,63 g/cm³, indicating an increase in density with increased flange thickness and web diameter. This increase in density is attributed to the dimensional enhancement of the web diameter and flange thickness, which resulted in a higher mass and volume of the I-joist beam. Furthermore, the larger dimensions and surface area may have facilitated the use of a greater amount of adhesive. However, the analysis of variance indicated that the web diameter and flange thickness did not significantly affect the density of the I-joist beams (Table 1). This finding is consistent with the research by Odebunmi *et al.* (2019), who demonstrated that increasing the number of thin laminas in bamboo glulam, with thicknesses ranging from 2 to 8 mm, enhanced the contact area and adhesive volume, thus affecting the density, which reached values of 0,57–0,61 g/cm³. However, lamina thickness did not significantly affect the density owing to the relatively stable adhesive absorption at each lamina, aligning with the findings of the present study, which showed that variations in web diameter and flange thickness did not significantly affect the density of the I-joist beams.

Based on the findings of several studies, the moisture content and density of I-joist beams are generally influenced by the characteristics of the raw materials (such as wood/bamboo type, material composition, and porosity) and the drying process (temperature, relative humidity, and drying time), rather than by geometric dimensions such as web diameter or flange thickness (King *et al.* 2019; Islam *et al.* 2017; Wan *et al.* 2022). The physical dimensions affect mechanical aspects such as stiffness and bending strength, but do not significantly impact the moisture content and density of I-joist beams. Therefore, variations in the web or flange dimensions did not considerably affect the moisture content and density of the I-joist beams.



(a) (b)

Figure 1 Sample structure for testing a) Bending and b) Tensile strength.

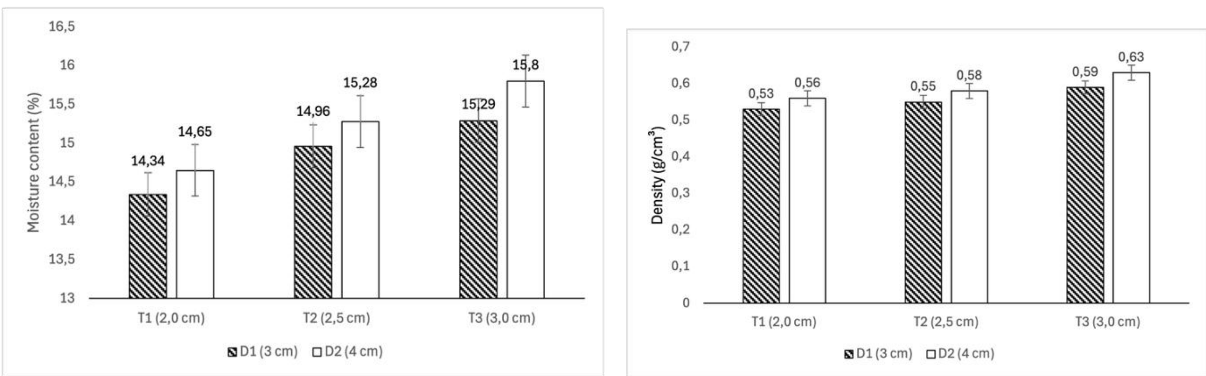


Figure 2 Moisture content and density of I-joist beams with variations in flange thickness and web diameter.

Mechanical properties

Mechanical property tests were conducted to evaluate the effects of flange thickness and bamboo web diameter on the flexural performance of the I-joist beams, as indicated by the modulus of elasticity (MOE) and modulus of rupture (MOR). Based on the results of the MOE and MOR tests of the I-joist beams presented in Figure 3, the highest MOE value was obtained for beam D1T3, with an average of 23,812 kgf/cm², whereas the lowest value was observed in beam D2T1, at 11,602 kgf/cm². The highest MOR value was obtained for beam D1T3, with an average of 129,5 kgf/cm², whereas the lowest value was recorded for beam D2T1, at 72,3 kgf/cm². The variance analysis results shown in Table 1 indicate that the flange thickness has a highly significant effect ($p < 0.01$) on both MOE and MOR. This confirms that the flange is the primary structural component governing the flexural stiffness and bending strength of I-joist beams. This aligns with the findings of Sukanya and Rajeevan (2022), who stated that increasing the flange thickness significantly enhances the flexural capacity of beams, as the flange is the primary component responsible for bearing most of the bending moment in I-beams.

At each flange thickness level, the combination of a 3 cm web diameter (D1) consistently yielded higher MOE and MOR values than the 4 cm web diameter (D2). This difference suggests that a smaller web diameter tends to provide better flexural performance. This finding is consistent with that of Ding et al. (2023), who investigated steel-bamboo composite beams and found that increasing the web height can enhance the flexural capacity. However, increasing the width-to-thickness ratio of the web component increases the potential for local deformation, such as instability. A more uniform bending stress distribution in the smaller diameter web helps reduce eccentricity and improves the effectiveness of the stress transfer between the web and flange.

Nevertheless, the variance analysis results indicate that the web diameter does not significantly affect the MOE or MOR ($p>0.05$). This aligns with the study by Duan et al. (2021) on steel-bamboo composite I-beams, who found that the effect of web dimensions on bending deflection is minimal when deformation remains in the elastic range. The dominant influences are the interface connections and the contribution of the flange to the flexural stiffness. Therefore, the variance analysis in Table 1 suggests that within the 3–4 cm diameter range, variations in the web diameter do not significantly affect the flexural stiffness or strength of the I-joist beams.

After determining the optimal geometric configuration for the flange and web dimensions, namely a flange thickness of 3 cm and a web diameter of 3 cm, the next phase of this study will focus on evaluating the influence of joint characteristics, including adhesive type and web penetration depth into the flange, to examine the contribution of adhesion factors in improving the mechanical performance of bamboo-based I-joist beams.

Effect of Adhesive Type and Penetration Depth

Physical Properties

The results of the moisture content testing of the I-joist beams in the bending and tension tests with various combinations of adhesive types and web penetration depths are shown in Figure 4 Moisture

Table 1 Analysis of variance for physical and mechanical properties of I-Joist Beams

Physical and mechanical properties	Factor (*P-Value*)		
	Web diameters	Flange thickness	Diameter x thickness
Moisture content	0.302	0.086	0.964
Density	0.631	0.166	0.286
MOE (Modulus of elasticity)	0.154	0.000**	0.652
MOR (Modulus of rupture)	0.258	0.000**	0.713

Note: ** = significant difference at 95% confidence level.

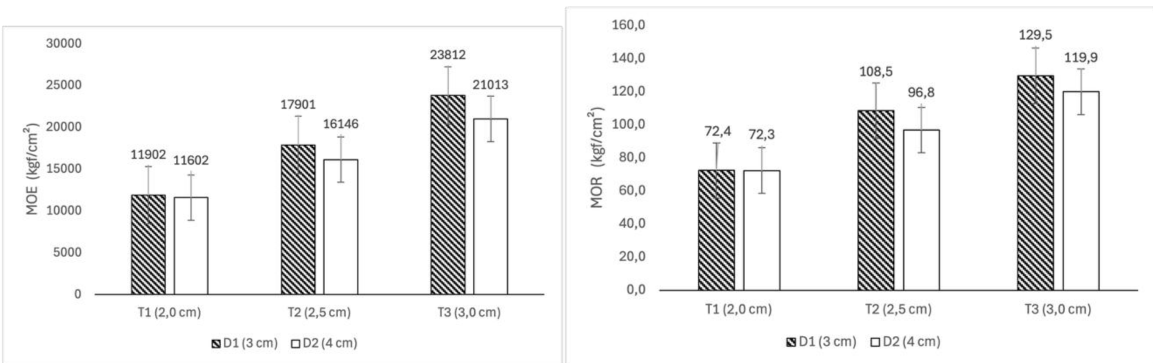
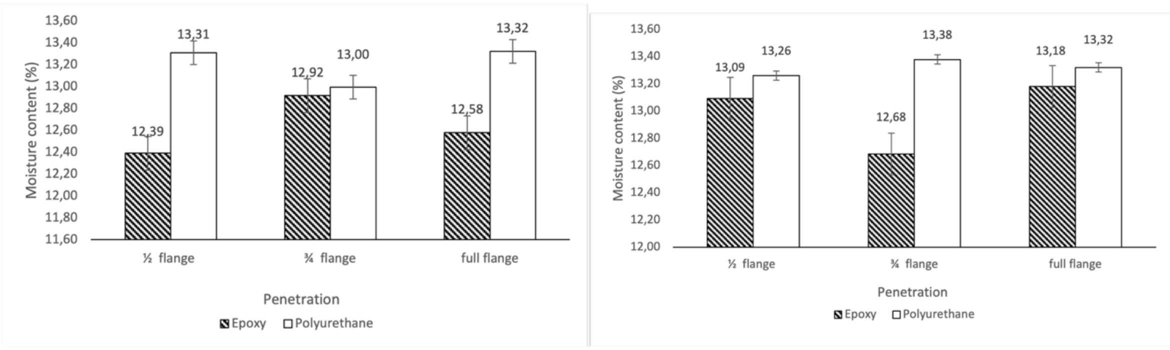


Figure 3 Modulus of elasticity (MOE) and modulus of rupture (MOR) values of I-Joist for various combinations of web diameter and flange thickness.

content of I-Joist Beams for sample a) Bending Test, b) Tension Test. In general, the average moisture content ranged from 12,39% to 13,38% across all treatments. In the bending test, the moisture content for the epoxy adhesive ranged from 12,39% to 12,92%, while for polyurethane, it ranged from 13,00% to 13,32%. These results indicate that the adhesive type affects the moisture content, with samples using polyurethane adhesive tending to have a slightly higher moisture content than those using epoxy.

Variance analysis (Table 2) shows that the adhesive type factor has a significant effect on moisture content (p = 0,012). In contrast, the penetration factor and the interaction between adhesive and penetration did not significantly impact (p > 0,05). The difference in moisture content between the adhesive types is likely related to the differences in the chemical properties and moisture affinity of each adhesive. Polyurethane has a higher hygroscopic property than epoxy because of the larger number of active polar groups, making it more susceptible to moisture absorption, whereas epoxy is more chemically stable and resistant to water penetration because of its dense structure, which is less prone to water diffusion (Xu *et al.* 2023; Yunus *et al.* 2018). However, the overall moisture content range remained within the safe limits for wood mechanical testing according to the ASTM D4442 standards.

The results of the density tests are shown in Figure 5 Density of I-Joist Beams for samples: a) Bending Test; b) Tension Test**.** The density values range from 0,48 g/cm³ to 0,62 g/cm³ across all treatments. In the bending test, the density of the beams with epoxy adhesive ranged from 0,52 to 0,57 g/cm³, while that with polyurethane adhesive ranged from 0,52 to 0,62 g/cm³. Evidently, the use of polyurethane results in a generally higher density than that of epoxy. This can be explained by the differences in viscosity and adhesive spreading characteristics during the manufacturing of



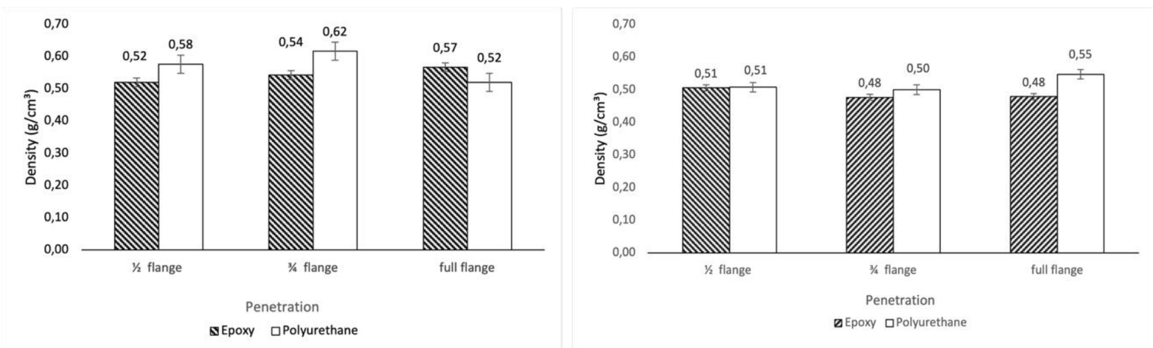
(a) (b)

Figure 4 Moisture content of I-Joist Beams for samples: a) Bending Test; b) Tension Test.

Table 2 Analysis of variance for physical and mechanical properties of I-Joist Beams

Physical and mechanical properties	Faktor (*P-value*)		
	Adhesive	Penetration	Adhesive x penetration
Moisture content	0.012**	0.885	0.221
Density	0.001**	0.086	0.122
MOE (Modulus of elasticity)	0.075	0.000**	0.323
MOR (Modulus of rupture)	0.205	0.001**	0.234

Note: ** = significant difference at 95% confidence level.



(a) (b)

Figure 5 Density of I-Joist Beams for Samples. a) Bending test and b) Tension test.

the composite product (Grmusa *et al.* 2012). More fluid polyurethane adhesives tend to penetrate more easily into wood pores and interface gaps, increasing the total mass and density of the composite (Li *et al.* 2023; Ren *et al*. 2024).

The results of the variance analysis (Table 2) show that the adhesive type had a significant effect on density (p = 0,001). However, the penetration factor and its interaction did not significantly affect the density (p > 0,05). This indicates that the volume of adhesive absorbed into the material is more controlled by the adhesive type used, whereas the web penetration depth into the flange does not significantly affect the density. These findings align with those of Odebunmi (2019), who suggested that in bamboo lamination, variations in layer thickness or adhesive volume have a limited contribution to the total density when the adhesive distribution is sufficiently homogeneous.

Mechanical properties

The results of the modulus of elasticity (MOE) and modulus of rupture (MOR) tests on I-joist beams with varying adhesive types and penetration depths are shown in Figure 6 Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) values for various treatments**.** In general, both MOE and MOR showed increased values with deeper web penetration into the flange. The highest MOE value was achieved at full penetration (thick flange) with epoxy adhesive, 22,361 kgf/cm², followed by polyurethane at 20,156 kgf/cm². A similar trend was observed for MOR, where the highest value was recorded for full penetration with epoxy adhesive, which was 132 kgf/cm², followed by polyurethane at 116 kgf/cm².

The results of the variance analysis (Table 2) indicate that web penetration significantly influenced both the modulus of elasticity (MOE) (p = 0,000) and the modulus of rupture (MOR) (p = 0,001). In contrast, adhesive type and the interaction between adhesive and penetration did not exhibit statistically significant effects (p > 0,05). These findings highlight that the depth of adhesive penetration is the primary factor affecting the stiffness and bending strength of the I-joist beams. As the penetration depth of the web increases and the contact area of the joint expands, the effectiveness of the bending stress transfer between the components significantly improves (Hu *et al.* 2010). Although the variance analysis results indicated that the adhesive type did not have a statistically significant effect, epoxy generally tended to yield higher MOE and MOR values than polyurethane. This is attributed to the superior mechanical properties of epoxy, which exhibits higher shear strength at the adhesive bond than polyurethane, thereby enabling more effective stress transfer (Nugroho *et al*. 2009).

The load and deflection analysis results for the I-joist beams with different flange thickness combinations are presented in Figure 7 Deflection of Samples at different treatment: a) Epoxy Adhesive, b) Polyurethane Adhesive**.** The deflection load testing results indicated that all treatments experienced a gradual increase in

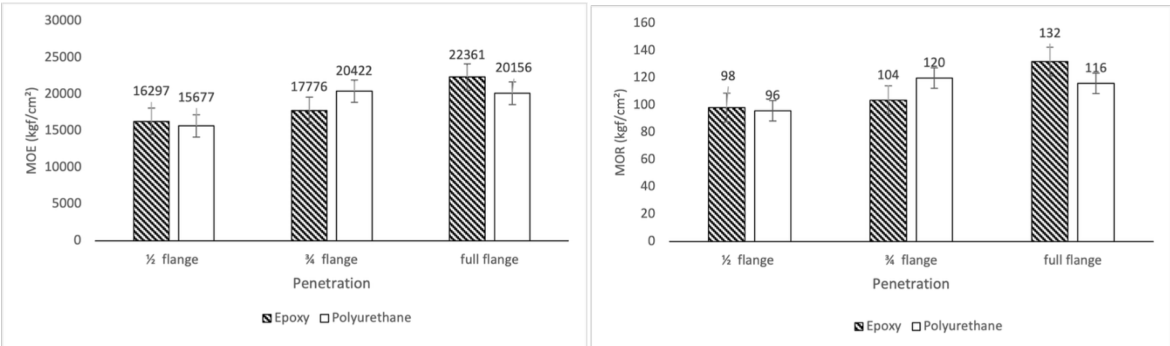
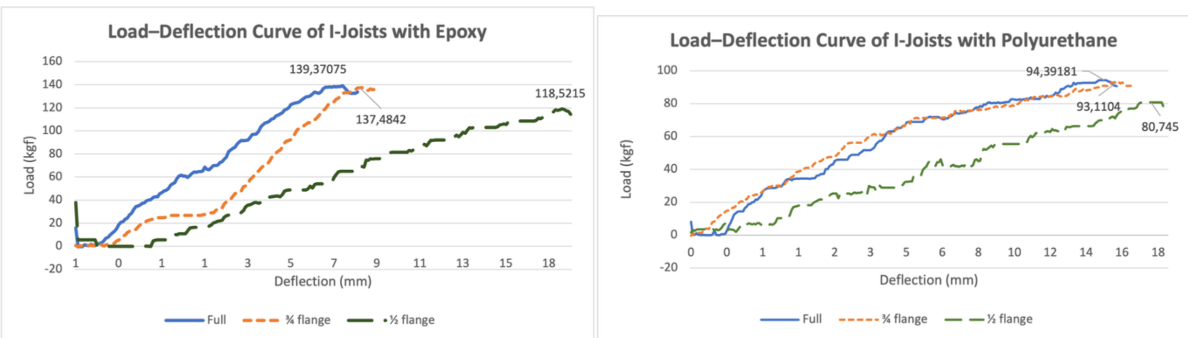


Figure 6 Modulus of elasticity (MOE) and modulus of rupture (MOR) values for various treatments.



(a) (b)

Figure 7 Deflection of Samples with various treatments. a) Epoxy adhesive and b) Polyurethane adhesive.

deformation as the load increased, reaching their maximum capacity before bending failure occurred. For the beams with epoxy adhesive, the highest maximum load capacity was recorded at full penetration (flange thickness), measuring 139,37 kgf, followed by ¾ flange penetration at 137,48 kgf, and the lowest at ½ flange penetration at 118,52 kgf. Additionally, full penetration resulted in more controlled and stable deformation up to the peak load, reflecting an optimal stress transfer efficiency across the adhesive zone (Shehada *et al.* 2024). The maximum deflection at full penetration was also smaller than that at partial penetration, suggesting that an increased adhesive contact area improves the stress distribution and bending stability (Alachek *et al.* 2019). A similar pattern was observed for the beams with polyurethane adhesives. The highest maximum load capacity occurred at full penetration, registering 94,19 kg, followed by ¾ flange penetration at 93,11 kg, and the lowest at ½ flange penetration at 80,74 kg. Compared with epoxy, polyurethane exhibited more gradual and plastic deformation, allowing for substantial deformation before failure, reflecting the mor e flexible adhesive properties of polyurethane that enable it to accommodate greater deformation prior to failure (Duan *et al.* 2021).

Tensile Strength

The results of the tensile strength testing of the adhesive joints of the I-joist beams with varying penetration depths and adhesive types are shown in Figure 8 Tensile Strength Values for various treatment variations**.** In general, the resulting pattern shows that an increase in the penetration depth does not always lead to a linear increase in the tensile strength. The highest tensile strength values were obtained at ¾ flange penetration, with 12,39 kgf/cm² for epoxy adhesive and 9,15 kgf/cm² for polyurethane adhesive. A similar finding was reported in adhesive joint testing on laminated bamboo with epoxy adhesive, where the optimization of the overlap depth resulted in a more uniform stress distribution and maximum tensile strength (Kang *et al.* 2024). The increase in the contact area of the joint owing to deeper penetration can theoretically improve the tensile strength. However, if the penetration is too deep, such as full penetration. In this case, the stress distribution along the joint area becomes uneven, which can cause stress concentration at the joint edges, triggering early failure (stress concentration). This is similar to the research on bamboo bio-composites with in situ lignin adhesives, where Meng *et al.* (2023) stated that the imbalance in stress leads to premature failure at the adhesive edge, which results in reduced tensile strength at full penetration, despite the increased adhesive contact area.

This led to a reduction in the tensile strength at full penetration, despite the increased adhesive contact area. The results of the variance analysis (Table 3 Analysis of Variance for Physical Properties and Tensile Strength) show that neither the adhesive type, penetration, nor their interaction had a statistically significant effect on tensile strength (p > 0,05).

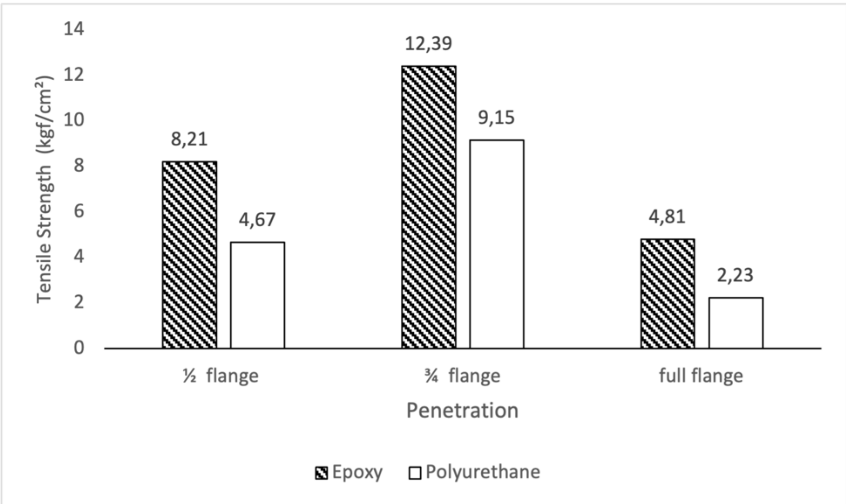


Figure 8 Tensile Strength Values for various treatment variations.

Table 3 Analysis of variance for physical properties and tensile strength

Physical and mechanical properties	Faktor (*P-value*)		
	Adhesive	Penetration	Adhesive x penetration
Moisture content	0.056	0.529	0.303
Density	0.801	0.436	0.130
Tensile strength	0.145	0.052	0.946

Note: ** = significant difference at 95% confidence level.

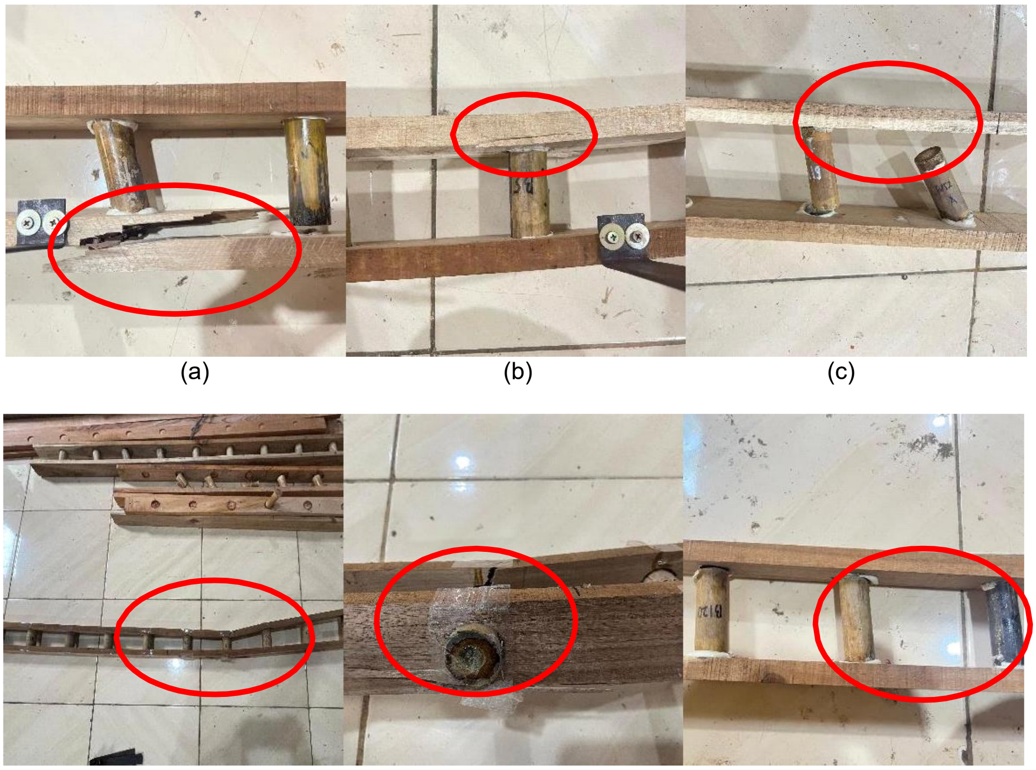
Nevertheless, epoxy consistently resulted in a higher tensile strength than polyurethane at all penetration levels. A similar pattern was observed in the adhesion testing of Acacia wood with epoxy adhesive, where the high shear modulus of epoxy facilitated more efficient interfacial tensile force transfer, even though the variation in parameters was not statistically significant (Fakhri *et al.* 2020). The superiority of epoxy can be attributed to its higher adhesive bond strength, better shear modulus, and ability to withstand interfacial tensile forces more effectively than polyurethane (Kim and Netravali 2013). The tensile test results indicate that the adhesive joint strength is not only dependent on the contact area but is also significantly influenced by the quality of the interfacial bonding and the characteristics of the local stress at the joint. I-joist beams with ¾ flange penetration can be considered optimal for tensile joints, as the adhesive contact area is sufficiently effective in enhancing the tensile strength without causing excessive stress concentration. Epoxy remains the adhesive of choice, consistently demonstrating superior tensile performance.

Failure Pattern

According to the damage classification code in ASTM D5055-15, six types of failure are commonly observed. Figure 9(a) corresponds to Flange Failure in Buckling (FCB), which is flange damage caused by buckling owing to inadequate lateral support. Figure 9(b) shows the Flange Failure in Flexural Compression (FC), which is flange damage due to compressive forces, where the damage occurs in the area where the test load is applied**.** Figure 9(c) corresponds to Poor Bonding (PB), indicating damage ranging from 30% to 70% in the bonding area. Figure 9(d) corresponds to Flange Failure in Tension (FT), which is flange damage caused by tensile forces, where the damaged area significantly affects the flange, and the damage length is measured according to visual specifications. Figure 9(e) corresponds to No Glue Transfer (NGT), where the adhesive is applied but does not penetrate or bond effectively on both adhesive surfaces. Figure 9(f) shows the Web Joint Vertical Shear Failure (WVSF), where the web experiences shear failure owing to tensile forces directed toward the support load. Generally, damage to I-joist beams consists of shear cracks and failures at the bonding lines. The common cause of failure is the tensile strength in the span, which leads to damage and crack formation (Shiba *et al.* 2018).

CONCLUSION

This study demonstrates that the geometric configuration and adhesive joint characteristics significantly affect the structural performance of Siam bamboo and *Acacia mangium* based I-joists. The optimal configuration was identified at a flange thickness of 3 cm and web diameter of 3 cm, which



(a) (b) (c) (d) (e) (f)

Figure 9 Variations of damage in bending testing.

resulted in high bending performance, with modulus of elasticity (MOE) values reaching 23,812 kgf/cm² and modulus of rupture (MOR) values up to 129.5 kgf/cm². Increasing the adhesive penetration depth enhanced the bending stiffness and strength, with full penetration yielding the highest MOE (22,361 kgf/cm²) and MOR (132.06 kgf/cm²) when epoxy adhesive was applied. However, the tensile joint performance was maximized at a penetration depth of ¾ of the flange thickness, whereas full penetration led to a reduction in tensile strength. Although the effect of adhesive type was not statistically significant, epoxy adhesives consistently exhibited higher mechanical performance than polyurethane adhesives. Overall, the combined use of a 3 cm flange thickness, 3 cm web diameter, penetration depth of ¾ to full flange thickness, and epoxy adhesive provides an optimized I-joist configuration with improved stiffness, strength, and joint stability, supporting its potential application in sustainable lightweight structural systems.

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