Research Paper

The Effect of Epoxy Resin on the Compressive Strength of Short Laminated Bamboo Columns

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Abstract

The ongoing depletion of global timber resources has increasingly directed attention toward bamboo as a viable and sustainable structural alternative. This study investigated the influence of epoxy resin coatings on the compressive performance of short laminated bamboo columns. Three treatment conditions were evaluated: untreated (control), epoxy resin-coated, and externally reinforced with steel plates. The test specimens, manufactured using Dendrocalamus asper, were subjected to axial compression by SNI 03-3959:1995. Before testing, the physical and mechanical properties of both bamboo and steel reinforcement materials were characterized. Experimental results indicated that epoxy coating enhanced the average compressive strength by 2.54%, whereas steel plate reinforcement yielded a more substantial increase of 9.94% relative to the control group. One-way ANOVA analysis confirmed that only the steel-reinforced group demonstrated a statistically significant improvement in compressive capacity ($p < 0.05$). The observed failure modes revealed that the untreated and epoxy-coated specimens were prone to surface cracking and adhesive delamination, whereas the steel-reinforced columns exhibited a more localized damage with reduced deformation. It was concluded that although epoxy resin provided a modest enhancement, applying steel reinforcement significantly improved the axial load-bearing capacity of laminated bamboo columns. These findings underscore the structural potential of hybrid bamboo composites for sustainable construction applications.

Keywords: *Laminated Bamboo Columns, Compressive Strength, Epoxy Resin Coating, Steel Plate Reinforcement, Sustainable Construction Materials*

INTRODUCTION

Rapid population growth has substantially increased the global demand for construction materials, particularly wood (De dan Cruz, 2021; Gandhi et al., 2022; Septia et al., 2022). This surge in demand has driven widespread deforestation, resulting in diminished wood availability and raising concerns over long-term environmental consequences (Dela et al., 2024). In response, bamboo has gained attention as a sustainable alternative because of its fast growth cycle and adaptability across diverse climatic conditions, ranging from arid to humid zones and from lowlands to mountainous terrains. Unlike hardwood species, which typically require more than 30 years to mature, bamboo can be harvested within 3.5 to 5 years (Darwis et al., 2024).

Bamboo is also economically attractive due to its easy cultivation under several soil and moisture conditions. Generally, it thrives in well-drained, non-waterlogged soils and is readily available in many developing regions. According to Das et al. (2025), high-quality bamboo suitable for construction can be harvested in significantly shorter cycles than conventional timber, making bamboo a viable renewable material for structural applications.

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When engineered into laminated columns, bamboo's rapid renewability and carbon uptake translate into a lightweight, locally sourced material that dramatically reduces transport volume. Life-cycle analyses show that replacing concrete frames with bamboo laminates can reduce embodied emissions by about 20%, a benefit that is magnified when columns are shipped flat-packed on smaller vehicles and managed via IoT-based routing and inventory systems. Such streamlined regional supply chains align perfectly with green logistics initiatives, curb last-mile fuel consumption, and equip operations teams with data-driven strategies for low-carbon construction.

Prior research has shown that wrapping laminated bamboo sheets with continuous BFRP sheets (Zhou et al., 2022) or fully encasing them in thick steel tubes (Wu et al., 2023) can boost compressive capacity, whereas Li et al. (2013) highlighted how the parent-culm location influences the strength and failure mode. However, no study has yet compared light, surface-level interventions, such as a thin epoxy barrier and discrete external steel plates—against an untreated baseline to determine (i) how much axial strength can be gained without the weight and material penalty of full jackets or tubes, and (ii) how these minimalist treatments redirect failure morphology. The present work fills this gap by systematically testing short laminated bamboo columns in three states, control, epoxy-coated, and steel-plate-reinforced—thereby delivering the first head-to-head dataset on their compressive behavior and offering design guidance for low-mass, field-applicable reinforcement strategies.

We evaluated three column types, control (no treatment), resin-coated, and steel-reinforced, to measure the axial load capacity and document distinct failure modes. By linking compressive performance to visible fracture patterns, we determine which treatment best enhances laminated bamboo's structural integrity, paving the way for tailored reinforcement approaches that respect bamboo's natural anisotropy.

LITERATURE REVIEW

To present this overview, we conducted a thorough review of peer-reviewed journals to capture the latest insights. Laminated bamboo columns stand out because they exhibit high structural performance with a low-carbon profile. Bamboo reaches maturity in just three to five years, absorbs significant CO_2 as it grows, and can be harvested without causing deforestation, making it a "green" alternative with far lower global-warming impact than concrete or steel (Li et al., 2015). When split, dried, and bonded into lamellas, bamboo achieves tensile strength and strength-to-weight ratios comparable to those of traditional timber but at a fraction of the mass of reinforced concrete, lightning foundation demands, streamlining off-site fabrication, and cutting transport emissions. The dimensional stability, ease of machining, and modular format also enable flat-pack delivery and quick assembly, which aligns perfectly with contemporary lightweight design and lean logistics. Altogether, these attributes—fast renewability, carbon sequestration, robust mechanics, and logistical efficiency—make laminated bamboo columns a scientifically validated choice for sustainable, low-embodied-carbon construction.

Structural role and generic failure modes of columns

The columns are the primary vertical load-bearing elements responsible for transferring both the gravity and lateral forces from the superstructure to the foundation. Recent experimental investigations on engineered bamboo have revealed a marked decline in the axial load resistance when the slenderness ratio (λ) exceeds approximately 80, which is consistent with the classical Euler buckling behavior observed in orthotropic bio-composites. Zhang et al. (2021) further identified a size-effect coefficient ranging from 0.64 to 0.67 for ultimate load, highlighting the importance of calibrating design parameters for full-scale laminated bamboo structures. These findings are consistent with those of Zhou et al. (2022), who reported that failure in short columns is primarily governed by glue-line shear, while global buckling becomes the dominant failure mechanism in slender members.

Engineered laminated-bamboo technology

The glucan concept has been further developed into engineered bamboo products such as laminated bamboo lumber (LBL), parallel bamboo strand lumber, and bamboo scriber. Compared to conventional sawn timber, LBL exhibits 15%–35% higher specific compressive strength and significantly reduced variability, owing to the reconstitution of the natural culm geometry into a quasi-isotropic laminated structure. Current design guidelines recommend limiting the slenderness ratio (λ) to ≤70 for unconfined LBL columns and up to ≤120 when sufficient external confinement is applied.

FRP-based confinement strategies

Early investigations employed Aramid Fiber Reinforced Polymer (AFRP) and Basalt Fiber Reinforced Polymer (BFRP) jackets to strengthen Laminated Bamboo Lumber (LBL) columns. However, the improvements in peak load capacity were modest (approximately 1–2%), primarily due to failure shifting toward the adhesive end zones. Wang et al., (2025) demonstrated that the application of a thin Glass Fiber Reinforced Polymer (GFRP) jacket can increase the ultimate load capacity by up to 25% and effectively delay buckling in columns with slenderness ratios (λ) as high as 150. Finite element simulations conducted in the same study successfully replicated the observed combined compression–buckling failure mode and confirmed the pivotal role of the wrap's hoop stiffness in enhancing structural stability.

In a parallel development, Cui et al. (2024) introduced a hybrid bamboo–phosphogypsum composite system incorporating hose-clamp-type hooping and internal fillers. Their approach demonstrated a synergistic improvement in the initial stiffness and ductility, highlighting an alternative confinement strategy for bio-composite columns.

Hybrid steel-bamboo composites

Long-term testing of steel–bamboo I-section composite columns has demonstrated that increasing the steel reinforcement ratio from 10% to 20% enhances the yield capacity by approximately 30% while maintaining creep deformations within the bounds predicted by the Burger viscoelastic model. These hybrid configurations also mitigate the brittle splitting failures frequently observed in untreated bamboo shell structures.

Conditioning of short laminated bamboo columns

When the axial load P is gradually increased, the column eventually reaches a state of neutral equilibrium at which it begins to deflect laterally. The magnitude of the axial load at this point is known as the critical load, Pcr. At this load level, the column can sustain small lateral deflections without any change in the axial force. Accordingly, the column remains in equilibrium in either a straight or slightly bent configuration (Botis et al., 2023).

Beyond this threshold, as the axial load increases further, the column enters an unstable equilibrium condition and becomes susceptible to collapse due to excessive lateral deflection or bending. In this state, even a minor disturbance can trigger significant sideways deflection, leading to sudden buckling failure. The theoretical behavior of an ideal column under axial loading can be summarized as follows:

a. If P < P_{cr}, then the column is in stable equilibrium in a straight position.
b. b. If P = P_{cr}, then the column is in neutral equilibrium in a straight position or slightly bent position.c. If P > P_{cr}, the column is in unstable equilibrium in a straight position and will bend at a slight disturbance.

The critical stress associated with this condition can be calculated by dividing the critical load by the cross-sectional area as follows:

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 EI}{AL^2}$$

Moisture content is the proportion of water contained in bamboo relative to its oven-dry weight. For Petung bamboo, this value is typically expressed as a percentage and is calculated using the following equation:

$$w = \frac{m_1 - m_2}{m_2} \times 100\%$$

Information:
w = up to air bamboo (%)
m_1 = mass of bamboo before drying (g)
m_2 = mass of bambu barrier oven (g)

Specific gravity is a key physical property used to predict bamboo performance, ranging from 0.4 to 0.8. The proportion of solid material in the bamboo cell walls is determined as the ratio of the oven-dry weight at 0% moisture content to the weight of the displaced water volume (Gelanew dan Demiss, 2023):

$$SG = \frac{Weight\ of\ Over\ Dry\ Bamboo}{Weight\ of\ Bamboo\ in\ Water}$$

Density is defined as the mass of bamboo per unit volume, measured either at a specific moisture content or in the oven-dry state:

$$\rho = \frac{mass}{volume}$$

The compressive strength represents the bamboo's capacity to withstand axial compressive loads, which varies based on the culm segment (node vs. internode). The compressive strength is calculated as

$$\sigma_{tk} = \frac{P_{max}}{A}$$

information:
σ_{tk} = compressive strength parallel to the fiber (MPa),
$P_{\_max}$ = maximum compressive force (N)
A = thickness × width = area of the stressed field (mm2) of the test piece.

Studies have shown that bamboo segments without nodes can exhibit a compressive strength 8%–45% higher than segments containing nodes (Onikeku et al., 2019). Tensile strength refers to the bamboo's resistance to axial tension and depends on the location along the culm. The tensile strength at the tip was approximately 12% lower than that at the base (Onikeku et al., 2019). Then, it is calculated as follows:

$$\sigma_{tr} = \frac{P_{max}}{A}$$

Information:

σ_{tr} = tensile strength of the parallel fiber (MPa),

P_{max} = maximum tensile force (N),

A = thickness × width = area of the field of interest (mm2) of the specimen.

RESEARCH METHOD

This study took place in the Civil Engineering Laboratory at Sultan Ageng Tirtayasa University using petune bamboo (Dendrocalamus asper) sourced from Pandeglang as the main structural material (Mustafa et al., 2021). To improve its durability and protect against decay, the bamboo was first treated with a sodium tetraborate (borax) solution (Liu, 2022). For external reinforcement, 2-mm steel plates were applied to selected columns (Wang et al., 2022), and epoxy resin served as the bonding agent during lamination to ensure that the layers adhered tightly. These materials and treatments were chosen to examine how different reinforcement strategies affect the compressive strength and failure patterns of laminated bamboo columns (Li et al., 2015).

Our experimental workflow consisted of six clear stages. In Stage 1, mature bamboo culms were harvested, dried, and conditioned until they reached a stable moisture level. The physical and mechanical properties of the lamellar selection were measured in Stage 2. In Stage 3, we verified the performance of the steel plates and epoxy resin, checking both material strength and bond quality. Stage 4 covered the fabrication of laminated billets, which were divided into three groups: unreinforced, epoxy-coated, and steel-plated, then cut into columns and fitted with end caps for even load distribution. During Stage 5, each column was instrumented and subjected to axial compression until failure, with the load, displacement, and strain recorded continuously. Finally, Stage 6 used statistical analysis—normalizing results by added mass—to compare strength, stiffness, and ductility across the treatment groups. A comprehensive account of these procedures is presented in the Results and Discussion section.

Physical and mechanical property testing

All laminated bamboo samples were subjected to rigorous screening against international quality standards, so we first measured key physical and mechanical properties: moisture content, density, and dimensional shrinkage. These metrics serve as proxies for material performance—lower moisture (ideally under 10 %), higher specific gravity, and minimal shrinkage usually translate into greater stiffness, strength, and dimensional stability under load (International Organization for Standardization, 2019).

Despite these benchmarks, several areas lack clear guidance. We still do not have systematic data on how laminated bamboo assemblies creep or swell over seasonal humidity cycles, particularly in hot, humid climates. There are no unified density-grading rules for mixed-lamella products, which can mask weaker lamellas, nor are there service-humidity shrinkage limits for bamboo reinforced with steel or FRP skins. Filling these voids will help to align certification protocols with the real-world demands of low-carbon construction.

Figure 1. Design of Bamboo Material for Physical and Mechanical Property Testing

Table 1. Number of Material Specimens for Physical and Mechanical Property Testing

Bamboo Part	Physical Property			Mechanical Property	
	Moisture Content	Density	Shrinkage	Compressive Strength	Tensile Strength of steel plate
Bottom	3	3	3	3	-
Middle	3	3	3	3	-
Tip/End	3	3	3	3	-
Total	9	9	9	9	3

Mechanical properties serve as essential indicators of bamboo's structural capacity, particularly in construction-related applications (International Organization for Standardization, 2019). In this study, mechanical tests were conducted to determine the compressive strength of the cylindrical bamboo specimens and the tensile strength of the steel reinforcement. Several factors are known to influence bamboo's physical characteristics, including culm age, longitudinal height position, culm diameter, wall thickness, and whether the applied load is on a nodal or internodal region (Sewar et al., 2024). To ensure representative sampling, three specimens were taken from each base, middle, and top section of the bamboo culm. Steel tensile tests were performed on three specimens with a constant thickness of 2 mm, following the ASTM E8 test standards (International ASTM, 2022). The schematic arrangement of the bamboo preparation used for testing is illustrated in Figure 1, while Table 1 presents the detailed specimen configuration.

Design of short laminated bamboo column test specimens

Compressive tests were performed on short laminated bamboo columns using the parallel-to-grain method by *Standar Nasional Indonesia* (1995). The primary objectives were to measure the axial compressive strength and document how each specimen failed under load. We divided the samples into three groups: (1) unreinforced controls, (2) columns fully coated with epoxy resin, and (3) columns reinforced externally with 2-mm steel plates at the top, middle, and bottom. During each test, we continuously recorded the load and displacement while photographing the specimens at regular intervals and at the moment of failure. After testing, we examined the fracture surfaces and deformation patterns—such as fiber buckling, lamella splitting, resin crushing, and plate detachment—to classify failure modes. This systematic approach enabled us to correlate treatment type with distinct failure characteristics and to evaluate how coatings or steel plates alter both strength and collapse behavior.

These treatments were designed to assess the effectiveness of surface coating and external reinforcement in enhancing axial performance. The epoxy-coated specimens were prepared by applying a uniform epoxy layer over the entire surface area, whereas the steel-reinforced specimens incorporated bonded steel plates at structurally critical locations using the same epoxy resin as an adhesive. The overall configuration of the test specimens is shown in Figure 2, and additional specimen details are provided in Table 2.

Figure 2. Design of Short Laminated Bamboo Column Test Specimens

Table 2. Number of Short Laminated Bamboo Column Test Specimens

Specimen	Treatment Type	Specimen Code	Number of specimens	Total
Short Colomn Laminated-Bamboo	Normal	KN-L	3	9
	Epoxy Resin	KE-L	3	
	Steel Plates for Reinforcement	KP-L	3	

FINDINGS AND DISCUSSION

Physical and Mechanical Property Testing Results

Table 3 presents the test results, which indicate that the average moisture content of the bamboo was 15.44%. The recommended range of bamboo moisture content is 8%–12%. Moisture content plays a critical role in the bonding process, as values that deviate significantly from this range, either excessively high or low, can impair adhesive performance and lead to bonding failure (International Organization for Standardization, 2019).

The average density of the bamboo specimens was found to be 0.77 g/cm^3, classifying it as heavy wood. Higher density is generally correlated with improved mechanical strength, making bamboo suitable for structural applications (Gao et al., 2022). Shrinkage tests conducted on the tip, middle, and base segments of the culm yielded an average value of 9.22%. This shrinkage is primarily attributed to the loss of water from the bamboo fiber structure, which becomes more pronounced as moisture evaporates (Kelkar et al., 2023).

The average compressive strength of the cylindrical bamboo specimens was 40.45 MPa. Based on its density classification, this value falls within Category III, which denotes wood suitable for heavy structural use, provided it is installed under a roof and not in direct contact with moisture or ground conditions (Ramage et al., 2017). Additionally, tensile testing of the steel reinforcement yielded an average maximum stress of 461.67 MPa, indicating adequate tensile performance for use as external reinforcement.

Table 3. Results of Physical and Mechanical Property Testing

Testing	Specimen			Average
	Bottom	Middle	Tip/End	
Moisture Content (%)	15,38	14,17	16,77	15,44
Density (g/cm3)	0,77	0,74	0,78	0,77
Shrinkage (%)	8,18	11,38	8,10	9,22
cylindrical Compressive Strength	43,75	41,47	36,12	40,45
Tensile Strength of steel plate (MPa)	460	465	460	461,67

The complete procedure for testing the physical and mechanical properties is illustrated in Figure 3, and the tensile strength test results for the steel are depicted in Figure 4. It is important to note that these findings differ from those of previous studies that reported lower compressive strength values in untreated bamboo under similar test conditions, suggesting that specimen conditioning and material origin play a significant role in determining performance characteristics.

Figure 3. Physical and Mechanical Property Testing Processes

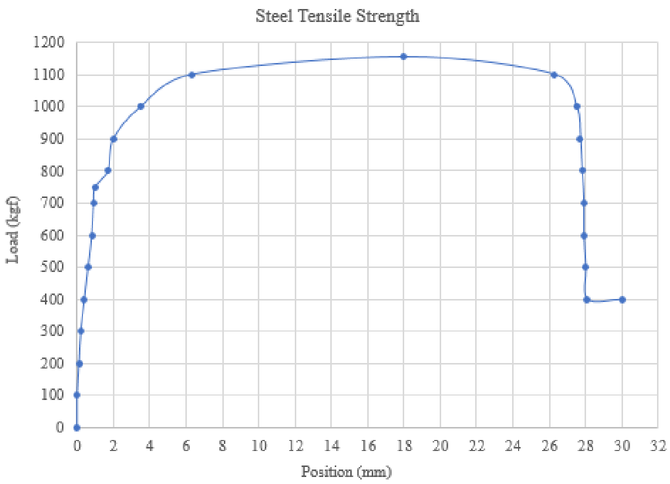

Figure 4. The Results of the Steel Tensile Strength

Results of Normal Short Laminated Bamboo (KN-L)

Table 4. Compressive Strength Results of Short Laminated Bamboo Column Specimens

Specimen Code	Compressive Strength (MPa)	Compressive Strength Average (MPa)	Percentage Increase in Compressive Strength (%)
KN-L 1	28.582		
KN-L 2	28.491	28.044	0
KN-L 3	27.059		
KE-L 1	28.751		
KE-L 2	28.593	28.774	2.54
KE-L 3	28.979		
KP-L 1	29.774		
KP-L 2	31.151	31.138	9.94
KP-L 3	32.490		

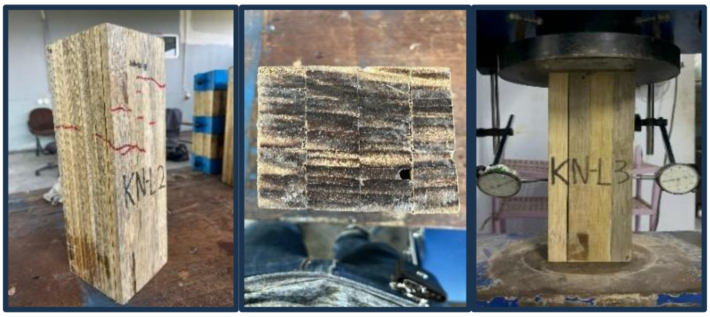

Figure 5. The damage pattern of KN-L

The compressive strength results of the KN-L specimens are presented in Table 4. The measured compressive strengths for specimens KN-L 1, KN-L 2, and KN-L 3 were 276.2 kN, 276.7 kN, and 261.2 kN, respectively, yielding an average compressive strength of 271.4 kN. The failure mode observed in the KN-L group was characterized by compressive crushing at the top end of the column, accompanied by shear failure across the upper cross-sectional region. These failures were induced by sustained axial loading, which led to delamination and adhesive failure between the bamboo strips, as well as localized material failure in the bamboo itself. Cracking was visibly concentrated at the top and mid-height regions of the columns. The observed damage pattern is illustrated in Figure 5.

The recorded deformations for KN-L 1, KN-L 2, and KN-L 3 were 8.4 mm, 8.6 mm, and 8.4 mm, respectively. The load–load-displacement behavior of the KN-L specimens is shown in Figure 6. The corresponding maximum compressive stresses were calculated as 28.582 MPa for KN-L 1, 28.491 MPa for KN-L 2, and 27.059 MPa for KN-L 3. The stress–strain relationship for the KN-L group is presented in Figure 7.

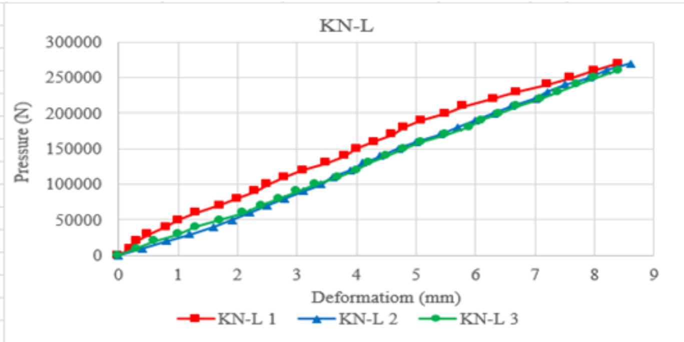

Figure 6. Pressure-Deformation Graph of KN-L

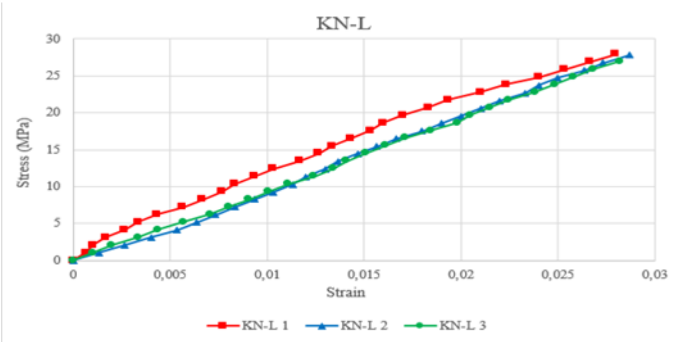

Figure 7. Stress-Strain Graph of KN-L

Results of Testing Short Laminated Bamboo Columns Coated with Epoxy Resin (KE-L)

The compressive strength results of the KE-L specimens are presented in Table 4. The compressive strength values recorded for KE-L 1, KE-L 2, and KE-L 3 were 279.2 kN, 282.0 kN, and 288.4 kN, respectively, resulting in an average compressive strength of 283.2 kN. The failure pattern observed in the KE-L group was primarily characterized by compressive failure, which manifested as minor surface cracking at the top ends of the columns. The failure morphology of the KE-L is illustrated in Figure 8.

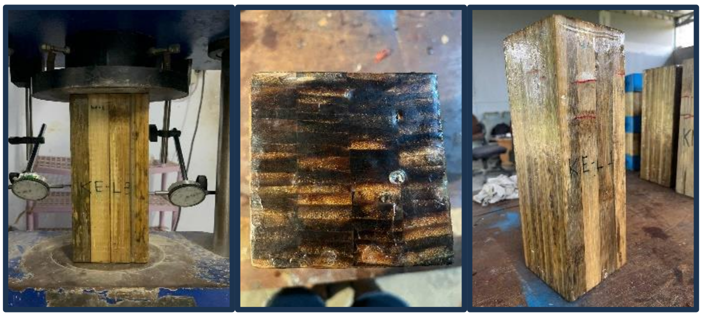

Figure 8. The damage pattern of the KE-L

The corresponding axial deformations for specimens KE-L 1, KE-L 2, and KE-L 3 were measured as 7.9, 7.5, and 7.3 mm, respectively. The load–load-displacement response of the KE-L specimens is shown in Figure 9. The maximum compressive stress values of the respective specimens were 28.751 MPa, 28.593 MPa, and 28.979 MPa. The stress–strain curve for the KE-L group is shown in Figure 10.

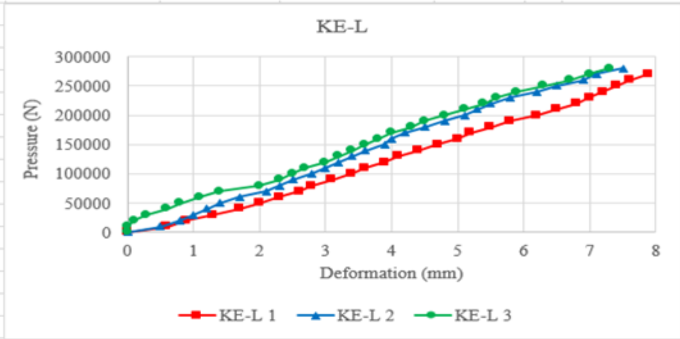

Figure 9. Pressure-Deformation Graph of KE-L

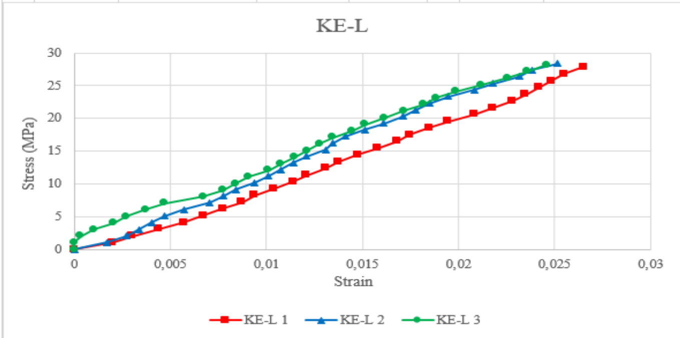

Figure 10. Stress-Strain Graph of KE-L

Short Laminated Bamboo Columns Reinforced with Steel Plates (KP-L)

The compressive strength results for the KP-L specimens are presented as follows: KP-L 1, KP-L 2, and KP-L 3 exhibited compressive strength values of 290.3 kN, 301.9 kN, and 312.6 kN, respectively, resulting in an average compressive strength of 301.6 kN. The dominant failure mode observed in the KP-L group was material failure in the bamboo, which manifested as cracking around the steel reinforcement plates. The failure pattern for KP-L is illustrated in Figure 11.

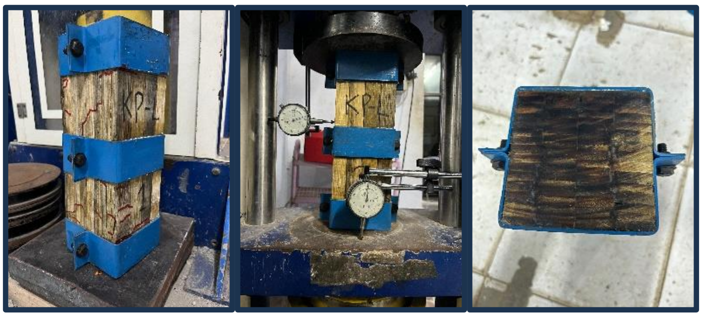

Figure 11. The damage pattern of KP-L

The axial deformations recorded for KP-L 1, KP-L 2, and KP-L 3 were 5.7, 5.3, and 5.2 mm, respectively, indicating reduced deformation relative to the untreated specimens. The load–load-displacement behavior for the KP-L group is presented in Figure 12. The calculated maximum compressive stresses for KP-L 1, KP-L 2, and KP-L 3 were 29.774 MPa, 31.151 MPa, and 32.490 MPa, respectively, as shown in the stress–strain diagram in Figure 13.

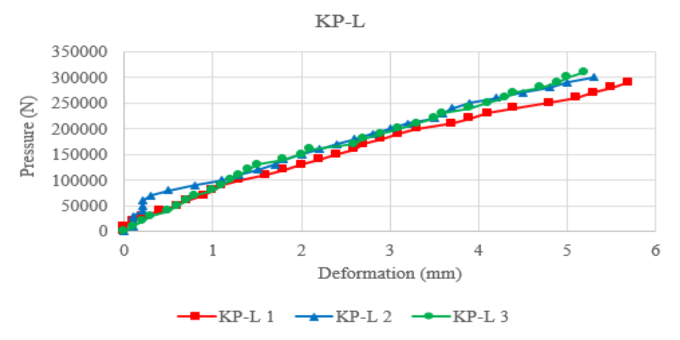

Figure 12. Pressure deformation of KP-L

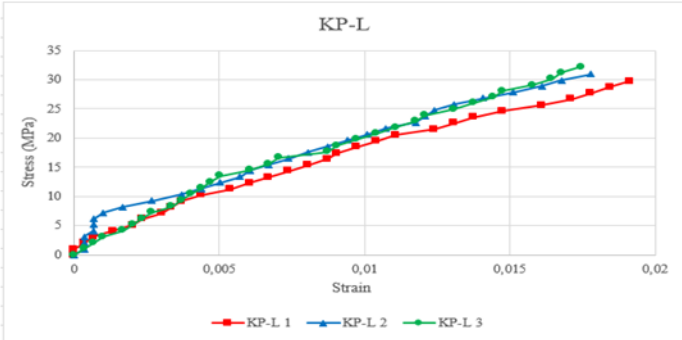

Figure 13. Stress-Strain of KP-L

A summary of the compressive strength test results for all short-laminated bamboo column groups is presented as follows: the average compressive strength was 28.044 MPa for KN-L (control), 28.774 MPa for KE-L (epoxy-coated), and 31.138 MPa for KP-L (steel-reinforced). It can be concluded that the application of an epoxy resin coating (KE-L) resulted in a 2.54% increase in compressive strength compared to the untreated control group (KN-L). In contrast, the inclusion of steel plate reinforcement (KP-L) led to a more significant improvement in compressive strength, increasing it by 9.94% relative to KN-L. A comparative graph of compressive strength enhancement among the treatment groups is presented in Figure 14.

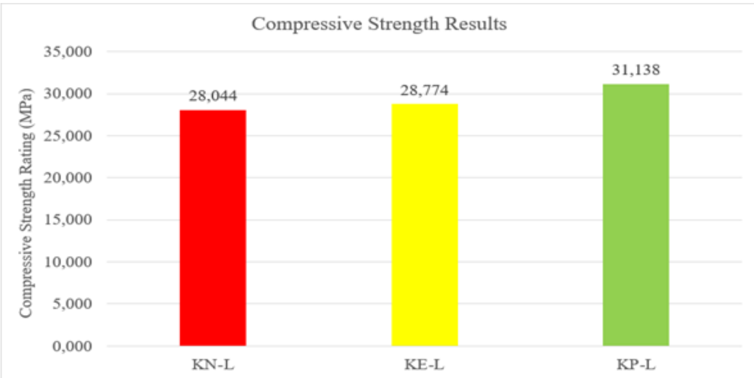

Figure 14. The results of the Compressive Strength Tests for the Short-Laminated Bamboo Columns

P-Critical Calculation Results

Euler's critical buckling load for the short-laminated bamboo columns was calculated by assuming effective end conditions based on joint-to-joint convergence. The computed values of the critical load Pcr are presented in Table 5. The results indicate that the highest critical load was recorded in specimen KE-L 3, with a value of 533,099.79 kg, while the lowest critical load was observed in specimen KN-L 1, with a critical load of 475,624.99 kg.

Table 5. Results of Calculation of P-Critical Values

No	Test Specimen Name	Dimension (mm²)	Height (mm)	Inertia (mm⁴)	Elasticity (N/mm²)	*P-Critical* (N)	*P-Critical* (kg)	*P-Critical* (kN)	*P-Critical* (Ton)
1	KNL-1	99,6 × 97,1	300,1	7584620,93	5610	4662990,13	475624,99	4727,35	482,19
2	KNL-2	99,1 × 98,0	300,1	7772677,27	5610	4778606,30	487417,84		
3	KNL-3	99,3 × 97,2	298	7603107,22	5610	4740467,72	483527,71		
4	KEL-1	98,5 × 98,6	298	7864398,55	5610	4903380,47	500144,81	5063,94	516,52
5	KEL-2	99,2 × 99,4	298	8118762,13	5610	5061973,83	516321,33		
6	KEL-3	99,3 × 100,2	297	8326426,05	5610	5226468,50	533099,79		
7	KPL-1	99,4 × 98,1	298	7811288,24	5610	4870266,68	496767,20	4789,22	488,50
8	KPL-2	99,3 × 97,6	298	7687024,84	5610	4792789,59	488864,54		
9	KPL-3	99,2 × 97,0	298	7545575,55	5610	4704597,25	479868,92		

Table 6 lists the compressive test load values for each specimen. All the tested specimens fell within the condition of stable equilibrium in a straight configuration. This observation is supported by the fact that the applied compressive load, P, for each specimen was lower than its respective critical load, Pcr, as determined from Euler's buckling criterion. Accordingly, specimen failure was attributed to material failure rather than instability or global buckling. This was further evidenced by the post-test failure patterns, which exhibited localized crushing and cracking consistent with axial material failure, confirming that $P<P_{cr}$ for all cases.

Table 6. Laminated Bamboo Short Column Test Results

No	Test Specimen Name	Dimension (mm²)	Height (mm)	Load (kg)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Average Load (Ton)
1	KNL-1	99,6 × 97,1	300,1	28164,11	28,58	28,04	27,67
2	KNL-2	99,1 × 98,0	300,1	28215,10	28,49		
3	KNL-3	99,3 × 97,2	298	26634,56	27,06		
4	KEL-1	98,5 × 98,6	298	28470,02	28,75	28,77	28,88

No	Test Specimen Name	Dimension (mm²)	Height (mm)	Load (kg)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Average Load (Ton)
5	KEL-2	99,2 × 99,4	298	28755,54	28,59		
6	KEL-3	99,3 × 100,2	297	29408,15	28,98		
7	KPL-1	99,4 × 98,1	298	29601,89	29,77		
8	KPL-2	99,3 × 97,6	298	30784,74	31,15	31,14	30,75
9	KPL-3	99,2 × 97,0	298	31875,82	32,49		

Comparison of Results using ANOVA

Analysis of Variance (ANOVA) is a parametric statistical method used to determine whether there are statistically significant differences between the means of three or more independent groups by analyzing their variances (Ghozali, 2011). In this study, the variance analysis was performed using MiniTab 19 software. A One-Way ANOVA test was used to assess the effect of different treatments on the compressive strength of short laminated bamboo columns. The term "one-way" refers to the analysis of a single independent factor. The results of the ANOVA test are summarized in Table 7.

Table 7. ANOVA Results

Source	DF	Adj SS	ADJ MS	F-Value	P-Value
Specimen	2	15.697	7.8484	9.02	0.016
Error	6	5.223	0.8706		
Total	8	20.920			

As shown in Table 7, the P-value obtained from the analysis was 0.016, which is less than the significance level $\alpha = 0.05$. Therefore, the null hypothesis (H_0), which assumes no difference between group means, is rejected, and the alternative hypothesis (H_1) is accepted. To further evaluate pairwise differences among the treatment groups, Fisher's Least Significant Difference (LSD) method was applied, and the results are presented in Table 8.

Table 8. Comparison Results Using the Fisher Method

Difference in Levels	Difference in Means	SE of the difference	95% CI	T-Value	Adjusted P-Value
KN-L – KE-L	-0,730	0,762	(-2,594 , 1,134)	-0,96	0,375
KP-L – KE-L:	2,364	0,762	(0,500 , 4,228)	3,10	0,021
KP-L – KN-L	3,094	0,762	(1,230 , 4,958)	4,06	0,007

The comparison between KN-L and KE-L yielded a P-value greater than α, indicating no statistically significant difference in compressive strength between these two groups. This suggests that the performance of epoxy-coated columns (KE-L) is statistically similar to that of the untreated control group (KN-L). In contrast, the comparison between KP-L and KE-L produced a P-value less than α, indicating a significant difference in performance. Based on the compressive strength values shown in Table 9, KP-L exhibited superior performance, suggesting that the addition of steel plate reinforcement significantly enhanced the compressive capacity relative to the epoxy-only treatment.

Table 9. Grouping Comparison

Specimen Name	N	Mean	Grouping
KP-L	3	31,138	A
KE-L	3	28,774	B
KN-L	3	28,044	B

Similarly, the comparison between KP-L and KN-L also resulted in a P-value below the α threshold, confirming a statistically significant difference between these two groups. Therefore, KP-L demonstrates better structural performance than both KE-L and KN-L. According to the quality classification based on SNI 7379-2013 (*Standar Nasional Indonesia*, 1995), the KN-L and KE-L groups are categorized under the wood strength class E14, while KP-L is classified as E15, further confirming the improved structural quality resulting from the steel plate reinforcement.

CONCLUSIONS

This study presents the first direct comparison of thin epoxy jackets and steel-plate appliqués as minimally invasive reinforcements for short laminated bamboo columns. We show that epoxy coatings promote diffuse crushing, while steel plates localize damage and significantly reduce deformation. Practically, epoxy increases load capacity by 2.54%, and steel plates by nearly 10% without causing splitting. These results offer practical guidance for engineers designing sustainable, low-carbon bamboo structures, especially for efficient reinforcement and on-site assembly in bamboo-rich areas.

LIMITATION and FURTHER RESEARCH

Based on the research findings, no significant difference was observed between the compressive strength of untreated (normal) columns and those reinforced with epoxy resin. To capitalize on our findings, managers should source mature, certified bamboo culms locally and inspect moisture and density to meet ISO 22157 standards; negotiate bulk agreements for pre-cut S235 steel plates and a proven low-viscosity epoxy to ensure consistent reinforcement quality; ship laminated billets flat-pack and implement just-in-time cross-dock logistics to halve transport volume and fuel use; standardize fabrication protocols and employ in-line bonding checks to guarantee repeatable performance gains; and establish a digital feedback loop, tracking in-service load capacity and deformation, to refine material specs, optimize order quantities, and continuously improve both structural performance and supply-chain efficiency.

Future research should move beyond short-column tests to explore slender, full-scale bamboo elements under combined axial, bending, and lateral loads, thereby uncovering buckling behavior, second-order effects, and post-buckling ductility essential for real structures. At the same time, long-term durability studies, incorporating cyclic moisture, UV, biological attack, and fire exposure, are needed to predict the service life and maintenance schedules for both unreinforced and reinforced laminated bamboo systems.

Complementary work on joint and connection design, especially modular bolted or bonded assemblies that leverage steel-plate stiffness enhancements, will support rapid, off-site prefabrication and seismic resilience. Finally, integrating experimental data into digital tools (finite-element and machine-learning models, BIM workflows, and blockchain-enabled supply chains) and performing cradle-to-grave life-cycle assessments will quantify true carbon savings, guide circular-economy strategies, and enable just-in-time logistics for low-embodied-carbon construction worldwide.

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