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AN EXPERIMENTAL STUDY ON COMPRESSIVE STRENGTH OF CONCRETE-FILLED BAMBOO COLUMNS: NOVEL DRILLING AND CASTING SYSTEM

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ABSTRACT: In tropical regions like Vietnam, the utilization of bamboo as a sustainable building material is on the rise, particularly for eco-conscious construction projects. This research investigated the reinforcement of bamboo culms filled with high-strength concrete, employing a novel drilling system to drill bamboo knots. Additionally, a specialized concrete-pouring and multi-level compression system was engineered to facilitate casting concrete into the narrow, elongated cavities of bamboo culms and enable testing of samples of varying lengths. A total of 56 experiments were conducted, revealing that longer samples exhibited elastic failure, whereas shorter samples succumbed to buckling failure. Notably, bamboo-concrete composite samples demonstrated a significantly higher ultimate load capacity compared to conventional concrete columns. The study also established a strong correlation between the slenderness ratio of the sample and its ultimate load, suggesting that engineers can efficiently estimate the ultimate bearing capacity based on the inherent characteristics of the bamboo culm.

Keywords: Bamboo, Compressive strength, Concrete-filled Bamboo, Slenderness ratio, Experimental Study

1. INTRODUCTION

The growing emphasis on sustainable construction practices, coupled with the increasing demand for eco-friendly building materials, has spurred investigations into alternative resources. Bamboo, a rapidly renewable material with favorable mechanical properties, has emerged as a promising candidate. In Vietnam and several Asian countries, bamboo has a long history of use in various construction applications, including scaffolding, formwork, roofing, small bridges, erosion control embankments, and piles. Its favorable mechanical properties have earned it the moniker "green steel bar" within the Vietnamese engineering community. As the demand for cost-effective and sustainable construction practices increases, bamboo presents itself as a viable alternative, offering the potential to stimulate the local economy while decreasing dependence on imported materials. Its potential applications extend beyond traditional uses, with recent research focusing on its incorporation into concrete structures.

The utilization of bamboo as a construction material, particularly as a composite element to enhance concrete's mechanical properties, is a subject of growing interest in the literature [1–9]. Two primary approaches to incorporating bamboo in construction have been explored:

Firstly, bamboo can be used as reinforcement in concrete beams: Although recognized as an environmentally friendly and cost-effective alternative to steel reinforcement, bamboo's poor bond performance with concrete presents a significant challenge to its widespread adoption [6,7,10–16]. This weak adhesion results in diminished flexural strength and less desirable failure mechanisms compared to steel-reinforced concrete beams [6,10,12,13]. To address this issue, various treatment methods for bamboo bars have been proposed, including grooving, wrapping with steel wire, and the application of adhesives like Sikadur 32 Gel or Bond Tite 266 [3,10]. These treatments aim to enhance the mechanical bond between bamboo and concrete, thereby improving the load-bearing capacity and ductility of the beams.

To improve the composite performance of bamboo as reinforcement and concrete, several alternatives have been considered. Ghavami investigated the use of bamboo as reinforcement in lightweight concrete beams, demonstrating a higher ultimate load compared to steel-reinforced beams [6]. Moreover, bamboo reinforcement resulted in a fourfold increase in ultimate capacity compared to unreinforced concrete beams. Terai and Minami observed similar behavior in axial compression tests comparing bamboo and steel-reinforced concrete beams [14]. Rahman et al., through flexural tests, reported that bamboo-reinforced beams exhibited a 2 to 2.5 times increase in load-carrying capacity compared to unreinforced beams of the same dimensions [17]. They also noted significantly higher maximum deflections in singly and doubly bamboo-reinforced beams compared to unreinforced beams.

Another drawback to using bamboo as reinforcement that was mentioned in previous research. The water absorption and the chemical decomposition of bamboo can be accelerated by the alkaline environment of concrete mortar [13,18]. The work of making bamboo bars accidentally loses the integrity of the bamboo tree, and as a result, reduces the global strength of bamboo trees and increases the decomposition of bamboo fiber.

Secondly, sealed bamboo tubes can be used as confinement for concrete: Analogous to the use of concrete-filled steel tubular columns, the application of bamboo tubes as confinement for concrete has also been investigated [1–7]. Studies have shown that bamboo tubes offer substantial confinement to concrete, leading to increased strength and ductility in the resulting composite columns [1,4]. Research has also examined the influence of various parameters on the behavior of concrete-filled bamboo columns, such as bamboo tube thickness, diameter, and the use of supplementary reinforcement [1–3,16]. Additionally, the combination of other materials, like steel tubes or bamboo slats, with bamboo tubes has been explored to further enhance confinement and overall structural performance [2,3].

The burgeoning ecotourism sector in Vietnam has created a tangible demand for sustainable accommodations, such as bamboo bungalows and mini-hotels, seamlessly integrated into the natural landscape. The innovative concept of infusing bamboo with concrete addresses this need by not only enhancing the structural strength but also leveraging the inherent flexural resilience of monolithic bamboo. Consequently, the treatment and maintenance requirements for bamboo in this configuration are significantly easier compared to its use as internal reinforcement within concrete structures.

Furthermore, the existing knowledge of bamboo-concrete columns remains limited. Júnior et al. experimentally observed that the ultimate load capacity of a bamboo concrete column was marginally lower than that of a column constructed solely from bamboo culms [19]. However, their study did not adequately address the techniques of core drilling and mortar pouring into the bamboo culm, which could have potentially compromised the ultimate load of the samples.

To address the need for further investigation and data collection on bamboo-concrete columns, driven by the increasing demand for environmentally friendly buildings, this research conducted a series of axial compression tests on bamboo-concrete column samples of various lengths and diameters. A core-drilling and multi-level axial testing system was specifically designed for this study. The experimental results were then compared with those of concrete samples having the same diameter.

In addition, the knowledge related to bamboo-concrete columns has not been thoroughly understood [19,20]. Only Júnior et al. (2010) experimentally found that the ultimate load capacity of a bamboo-concrete column was slightly lower than that of a column made only with bamboo culm [19]. In this study, however, methods for core drilling and pouring mortar into bamboo culm were not well considered, which could reduce the ultimate load of the sample. To meet the necessity of investigating and gathering more data on the bamboo-concrete column for the real demand for more environmental buildings, a series of axial compression tests on bamboo-concrete column samples with various lengths and diameters. A core-drilling and multi-level axial testing system was designed in the research. The testing results were compared with the concrete sample with the same diameter.

2. RESEARCH SIGNIFICANCE

Through experimentation, novel discoveries have been made regarding the synergistic behavior of bamboo-concrete composite materials. This research delved into innovative techniques for casting concrete into structural members characterized by small cross-sections, employing a testing apparatus capable of accommodating various sample lengths. The study successfully ascertained the compressive load-bearing capacity of the bamboo-concrete composite structure and established the relationship between bamboo diameter, length, and critical buckling force. Furthermore, a correlation between the critical force and the slenderness ratio of the bamboo-concrete composite structure was proposed. This research contributes valuable insights into the potential of bamboo-concrete composites as a sustainable and resilient building material, particularly relevant in regions where bamboo is abundant and readily available.

3. EXPERIMENTAL PROGRAM

3.1 Material Properties

The bamboo used in this study was sourced from Nghe An province, a major supplier of construction-grade bamboo in Vietnam. Straight bamboo culms with diameters ranging from 70mm to 100mm and inner diameters of 60mm to 80mm were selected. To enhance strength and minimize moisture-related effects, all bamboo underwent steaming at temperatures between 160°C and 180°C followed by continuous drying, as per established practices [21,22]. The Vietnam Academy for Water Resources (VAWR) laboratory determined the bamboo's strength properties, following ISO 22157-1 standard procedures on three test samples [23]. Bamboo, being a lightweight material with a unit weight of approximately 0.71 tons/m3, exhibited a Young's modulus ranging from 12.0 to 13.0 GPa, notably lower than concrete and steel. However, its ultimate compressive strength was comparable to concrete, reaching at least 22 MPa.

Table 1 Fundamental properties of three test groups

Parameter	Unit	Group 1	Group 2	Group 3
Unit weight	ton/m3	0.72	0.72	0.71
Flexural strength	MPa	51	54	52
Compressive strength	MPa	22	25	24
Tensile strength	MPa	32	34	34
Shear strength	MPa	4.5	4.7	4.7

The concrete used was provided by Hoang Vinh TRCC company, a provider of millet concrete solutions in Vietnam. Sand and stone particle distributions were optimized for a concrete strength grade of B45. The ability to fill concrete mortar into bamboo with an inner diameter of around 60mm was tested before sample fabrication. An additive was incorporated to increase mortar viscosity and accelerate curing time to approximately 7 days. Three cylindrical and cubic samples were prepared and tested to assess the concrete's strength grade.

3.2 Specimen Preparation

To enhance bamboo's strength and facilitate its use in construction applications such as piles and retaining walls, a core drilling system was designed (Fig. 1a) to enlarge bamboo knots for rebar insertion and concrete casting. This system addresses the challenges of inconsistent inner diameters and curved bamboo culms by incorporating a mechanism for adjusting the drill bit's direction and elevation. Additionally, specialized drill bits were developed for various purposes (Fig. 1b and 1c). A small, short drill bit (left) was used to create an initial pilot hole at the center of the knot, enabling rapid and precise positioning. Subsequently, a second set of drill bits, designed for gradual and continuous expansion with minimal damage to the bamboo body, was employed to enlarge the hole to a diameter corresponding to the bamboo's inner diameter. These second drill bits were produced in various diameters to accommodate different bamboo culms, and by matching the drill bit diameter to the inner diameter of the bamboo, a continuous hole could be created through the bamboo body while minimizing potential damage. Fig. 1(d) depicts a bamboo culm after knot drilling.

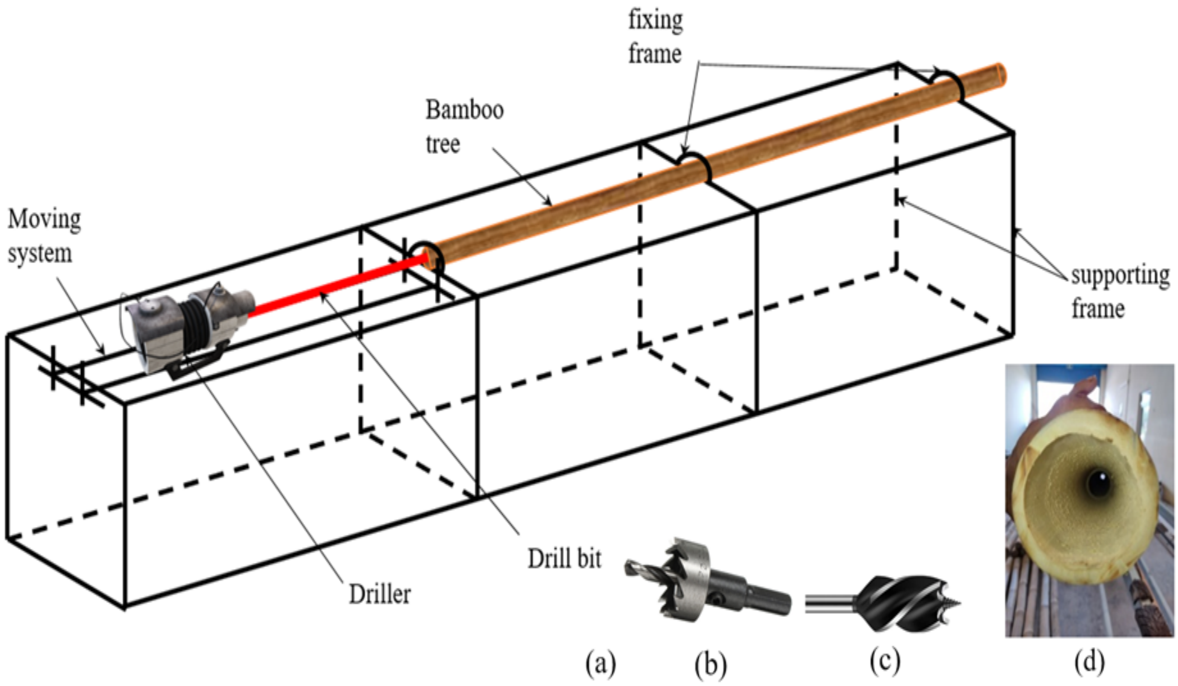


Fig. 1 (a): Core drilling setup; (b) and (c): Two type of drill bits; and (d): Bamboo culm after drilled.

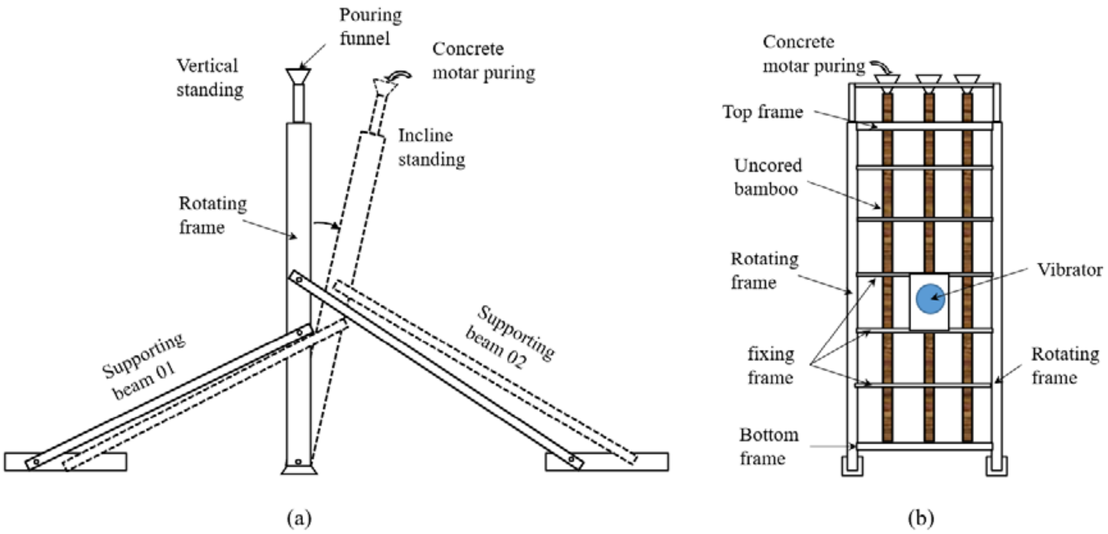


Fig. 2 Two systems for pouring concrete mortar into bamboo culms with a vibrator

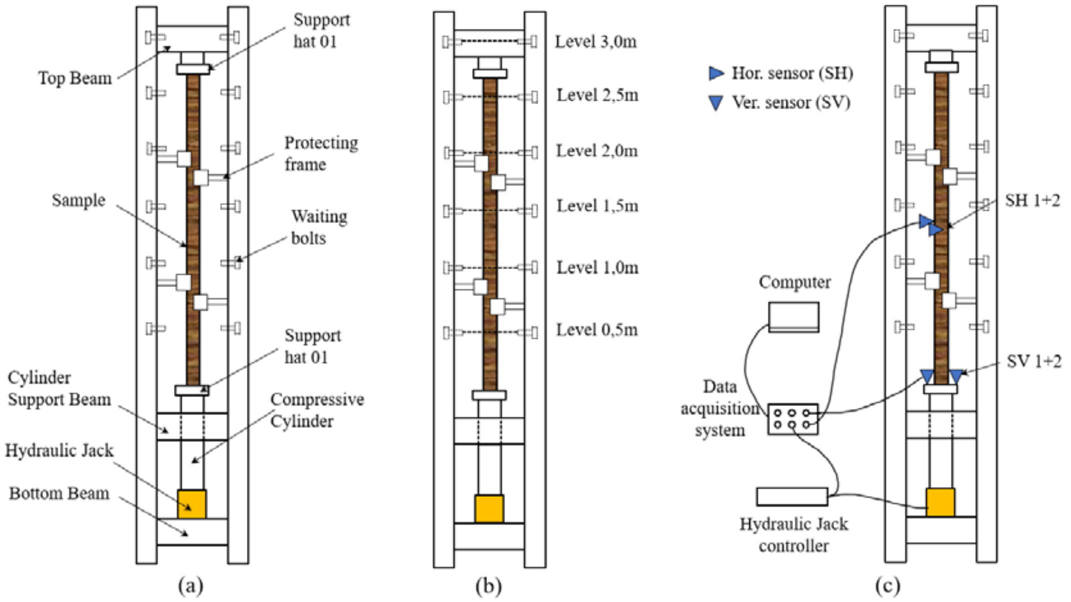


Fig. 3 Multi-level compressing test system [24]

The limited prevalence of bamboo concrete and/or reinforced concrete is partly due to the challenges associated with casting high-strength concrete into the long, narrow cavities of bamboo culms. To address this, a casting system was designed (Fig. 2) to facilitate the process. Bamboo culms were secured within the system using top and bottom frames and multiple fixing frames. Each frame had three holes designed to accommodate the core-removed bamboo culms. The fixing frames, consisting of two parts, were easily removable and secured with bolts. Each fixing frame also featured three half-circular holes to support the bamboo during the pouring process, aided by a vibrator. Rubber liners were used at the connection points between the bamboo and the frames to prevent damage during pouring and vibration. The amplitude and frequency of the vibration were adjustable and calibrated for optimal concrete mortar density. Additionally, the concrete mortar was designed with a slightly higher slump to ensure smooth flow into the narrow bamboo cavities. To prevent premature drying and enhance curing, all bamboo culms were soaked in water for approximately three days prior to concrete casting. The samples were then continuously moistened during the curing process, which lasted approximately 14 days before testing.

Table 2 Sample's information and experimental value of ultimate load (Qu)

Sample	Curvature (mm)	Number of knots	Length, L (mm)	Diameter (mm)	Slenderness ratio, λ	Bamboo thickness (mm)	Qu (kN)
BC1	1.0	2	500	78.0	25.6	8.0	165.6
BC2	1.0	1	500	79.0	25.3	8.0	165.6
BC3	2.0	2	500	85.5	23.4	9.0	208.0
BC4	2.0	2	500	88.0	22.7	7.0	208.0
BC5	1.0	2	500	87.0	23.0	9.0	208.0
BC6	2.0	1	500	100.0	20.0	13.0	247.5
BC7	1.0	2	500	96.0	20.8	8.0	247.5
BC8	5.0	3	1000	82.0	48.7	11.5	148.0
BC9	4.0	3	1000	79.0	50.6	7.5	148.0
BC10	3.0	4	1000	88.5	45.2	14.0	185.0
BC11	6.0	3	1000	89.0	44.9	9.0	185.0
BC12	5.0	3	1000	98.0	40.8	14.5	226.5
BC13	4.0	4	1000	97.0	41.2	11.0	226.5
BC14	5.0	4	1000	99.0	40.4	7.0	226.5
BC15	9.0	7	1500	87.0	66.3	12.0	97.9
BC16	7.0	4	1500	88.0	68.2	8.0	136.0
BC17	8.0	7	1500	89.0	67.4	12.5	136.0
BC18	8.0	5	1500	91.0	65.9	10.0	136.0
BC19	7.0	5	1500	104.5	57.4	18.0	179.5
BC20	9.0	8	1500	94.0	63.8	10.0	179.5
BC21	11.0	3	1500	98.0	61.2	10.0	179.5
BC22	14.0	7	2000	80.0	100.0	8.0	62.4
BC23	7.0	8	2000	86.0	93.0	11.0	62.4
BC24	15.0	7	2000	92.0	87.0	12.0	88.0
BC25	4.0	5	2000	89.0	89.9	8.0	88.0
BC26	18.0	7	2000	99.0	80.8	8.5	121.0
BC27	5.0	6	2000	100.0	80.0	11.0	121.0
BC28	2.0	5	2000	101.0	79.2	6.0	121.0
BC29	20.0	10	2500	79.0	126.6	10.0	42.7
BC30	20.0	10	2500	87.0	114.9	6.0	58.5
BC31	12.0	8	2500	85.0	117.6	7.0	58.5
BC32	10.0	7	2500	86.0	116.3	8.0	58.5
BC33	11.0	8	2501	89.0	112.4	9.5	58.5
BC34	18.0	9	2500	110.0	90.9	16.0	82.0
BC35	13.0	7	2500	92.0	108.7	10.0	82.0
BC36	15.0	6	2500	94.0	106.4	9.5	82.0
BC37	12.0	8	2500	92.0	108.7	10.0	82.0
BC38	13.0	9	2500	101.0	99.0	10.5	82.0
BC39	20.0	10	3000	87.0	129.0	12.0	31.3
BC40	11.0	10	3000	87.0	137.9	10.0	31.3
BC41	15.0	10	3000	92.0	130.4	9.0	41.5

Table 2 continued

BC42	20.0	9	3000	91.0	131.9	11.0	41.5
BC43	12.0	7	3000	91.0	131.9	8.0	41.5
BC44	19.0	11	3000	101.0	118.8	17.5	50.8
BC45	15.0	9	3000	97.0	123.7	9.0	50.8
BC46	13.0	9	3000	103.0	116.5	15.0	50.8
BC47	13.0	9	3000	100.0	120.0	14.0	50.8
BC48	10.0	8	3000	97.0	123.7	9.0	50.8

3.3 Test System

To facilitate compression testing of bamboo-concrete samples across a wide range of lengths (0.5m, 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m), a multi-level compression system was constructed, as depicted in Fig. 3 [24]. Four main vertical beams were connected by a bottom beam, a top beam, and a cylinder support beam using high-strength bolts. The top beam was designed to be adjustable in order to accommodate different sample lengths. A hydraulic jack, mounted on the bottom beam, applied compressive force to the bottom of the sample through a compression cylinder. To safeguard sensors and devices during testing, protective shackles were installed on the main beams. The position of these shackles could be adjusted based on sample length and sensor placement.

For displacement monitoring, four sensors were employed: two vertical sensors affixed to the bottom hat to track vertical sample displacement and two horizontal sensors attached to the bamboo culms. All sensors, boasting a measurement range of up to 70 mm to accommodate long samples, were calibrated to a high resolution of 0.001 mm. Data, including the force applied by the hydraulic jack, was recorded by a data acquisition system and transmitted to a remote computer. The entire system's displacement was calibrated by compressing a high-strength sample under varying loads.

3.4 Summary of Conducted Tests

Approximately 48 experiments were conducted, utilizing about 7 samples for each length between 0.5m and 1.5m, and 10 samples for both 2.5m and 3.0m lengths. The bamboo, as previously noted, was sourced randomly from Nghe-an province, Vietnam. Table 2 presents details of the bamboo culms, including inner and outer diameters, number of knots, and natural curvature. Outer diameters ranged from 70mm to 105mm, while inner diameters ranged from 56mm to 80mm. Notably, diameters were measured at the narrowest point of each culm, which could be a potential site of damage during sample preparation.

The slenderness ratio (λ) was also calculated from the length (L) and radius of gyration (i_o) of the sample following the equation:

$$\lambda = \mathrm{L}/\mathrm{i}_o \tag{1}$$

The slenderness ratio values in this study ranged from 20 to 141, exceeding the standardized limit for reinforced-concrete columns [25]. Additionally, the natural curvature values of all samples surpassed the standard eccentricity specified in Vietnamese concrete structure standards [26]. Fig. 4 (a) and (b) illustrate the relationship between natural curvature, length, and slenderness ratio of all samples, compared to the standard natural curvature value of approximately 6 mm.

While straightening bamboo could reduce natural curvature, this method may induce pre-stress and weaken the sample. Therefore, all trees and samples were used in their natural state. To evaluate the contribution of bamboo in compression, 21 concrete-only samples with similar inner diameters and lengths were created. However, due to high slenderness ratios, samples over 1.5m in length fractured during curing and handling (noted as B-S in the table).

Table 3 Load steps in compression test

Stages	Load	Remark
1	0-5% Qu	Skip in 5 min to remove system deformation
2	0 %	Skip in 5 min
3	20% Qu	Skip in 5 min
4	40% Qu	Skip in 5 min
5	60% Qu	Skip in 5 min
6	80% Qu	Skip in 5 min
7	90% Qu	Skip in 5 min
8	100% Qu	Skip in 20 min
9	110% Qu	Skip in 5 min
10	Increase 10% Qu until failure	Skip in 5 min

4. RESULTS AND DISCUSSIONS

4.1 Compressive Strength of Bamboo-Concrete Samples

Figure 5 illustrates typical failure modes for samples of 1.0m and 3.0m bamboo-concrete composites, as well as 1.5m concrete columns. Short bamboo-concrete samples exhibited brittle failure, with simultaneous destruction of both bamboo and concrete (Fig. 5(a)). In contrast, long bamboo-concrete samples demonstrated excessive bending, returning to their original shape upon unloading (Fig. 5(b)). Concrete columns showed a failure mode somewhat similar to short bamboo-concrete samples (Fig. 5(c)). These distinct failure types will be further analyzed in the context of the limiting slenderness ratio for bamboo-concrete composites.

Figure 6 illustrates typical compression test results for samples with lengths of 0.5m and 3.0m. The axial strain was calculated from vertical displacements measured by two vertical LVDTs, adjusted for system deformation through calibration, and two horizontal LVDTs. The deflection of the sample (y) at a position (z) was theoretically modeled as a sine function of the sample length (L) and a constant (C), adhering to Euler's rule:

$$y = C.\sin(\pi z/L) \qquad (2)$$

Utilizing the deflection measurements from the two horizontal LVDTs, the parameter C was estimated at each loading stage, allowing for the calculation of sample length and axial strain. The ultimate load of each sample was determined as the peak load in the load-deformation curves. Fig. 7(a) illustrates the relationship between ultimate load and sample length for bamboo-concrete samples. An upper and lower bound trendline reveals that longer samples generally experienced lower ultimate loads due to their higher slenderness ratios. Additionally, for a given length, larger samples tended to exhibit higher experimental loads. These findings underscore the significant influence of the slenderness ratio on the tested ultimate load of bamboo-concrete samples.

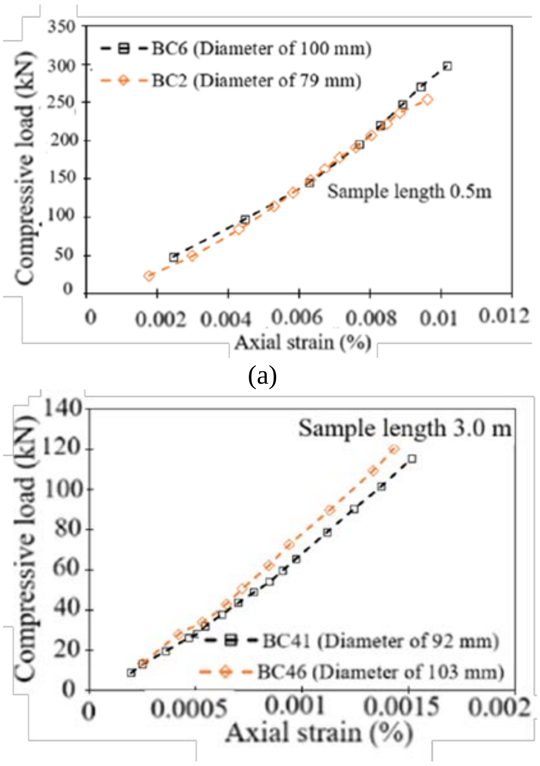
All samples demonstrated an ultimate load exceeding the estimated load. The over-estimated load (OEL), expressed as a percentage, was calculated as the difference between the tested ultimate load of the concrete bamboo sample (QCB) and the estimated ultimate load (Qu) of the samples, using the following formula:

$$OEL = \frac{Q_{CB} - Q_u}{Q_u} \cdot 100\% \qquad (3)$$


(a) (b) (c)

Fig. 5 Failing figure for (a) BC1 sample, (b) BC49 sample, and (c) C8 sample.

Fig. 7(b) illustrates the OEL for all samples. Almost all samples exhibited ultimate loads exceeding those estimated by the standard code, with some surpassing the estimated load by over 200% in samples longer than 2.0m, indicating a significant contribution from bamboo culms. Shorter samples, with lengths below 1.5m and high Qu values, showed lower OEL due to the reduced contribution of bamboo culms to their ultimate load.

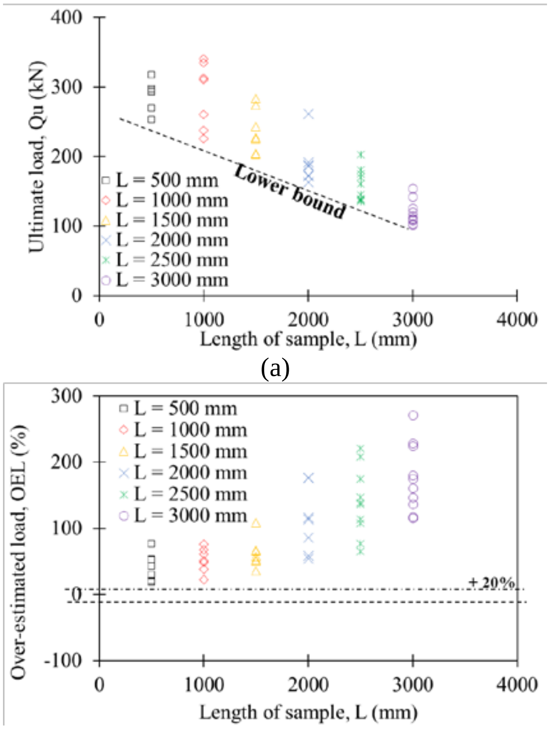


(a)

(b)

Fig. 6 Typical compressive test results for BC samples with length of (a) 0.5 m and (b) 3.0 m.

Table 4 presents results for concrete column samples. The over-concrete-load (OCL) value, estimated as the percentage difference between the ultimate load of the bamboo-concrete sample (QCB) and that of the concrete column sample (QC) with similar inner diameters, represents the contribution of bamboo in bamboo-concrete samples. The OCL value ranged from approximately 30% to 180% for samples shorter than 1.5m, while longer samples showed infinite values due to fracturing during curing and handling. For eight concrete column samples, the OCL value generally increased with sample length, suggesting that the contribution of bamboo culms to the ultimate load is more significant in longer samples



(a)

(b)

Fig. 7 (a) Ultimate load, Qu, and (b) Over-estimated load, OEL of BC samples

Table 4 Test results for concrete column samples

Sample	Length (mm)	Diameter (mm)	Slenderness ratio	Qu (kN)	QC (kN)	BC sample	QCB (kN)	OCL (%)
C1	500	60.0	33.3	104.0	132.7	BC1	293.3	121.0
C2	500	69.0	29.0	139.0	193.4	BC5	317.9	64.4
C3	500	80.0	25.0	172.0	226.5	BC7	295.3	30.4
C4	1000	58.0	69.0	75.0	96.0	BC8	237.5	147.4
C5	1000	68.5	58.4	112.0	167.7	BC12	312.5	86.3
C6	1000	76.0	52.6	147.0	175.0	BC13	340.7	94.7
C7	1500	65.5	91.6	44.6	81.2	BC17	227.3	179.9
C8	1500	78.0	76.9	99.0	121.5	BC20	283.2	133.1

4.2 Limited Slenderness Ratio

As illustrated in Fig. 7, it was evident that the slenderness ratio, determined by length and diameter, significantly influenced the compressive load capacity of the sample. Fig. 8 demonstrates a stronger correlation between ultimate load and slenderness ratio compared to the relationship with sample length shown in Fig. 7. Samples with higher slenderness ratios exhibited lower ultimate loads, and vice versa. A lower bound was established, delineating a safe region below this boundary. The function defining this lower bound, which also serves as the function for determining the limited slenderness ratio (λ) based on ultimate load, was experimentally derived as follows:

$$Q(CB) = -1.53 \cdot \lambda + 291.6 \qquad (4a)$$

In contrast to the limited slenderness ratio of a concrete column, which is approximately 90 as specified in [27], the concrete bamboo column demonstrated the capacity to withstand higher slenderness ratios without failure during curing and handling. Notably, even at a slenderness ratio of around 90, the concrete bamboo column achieved an ultimate load of approximately 160 kN, a value considered significant in structural engineering. Furthermore, equation [4.a] enables engineers to determine the slenderness ratio of a concrete bamboo column based on a desired compression load. For economic considerations, equation [4.b] could be employed, ensuring that approximately 90% of samples fall within a safe region, as indicated by the red-dashed line in Fig. 8.

$$Q(CB) = -1.57 \cdot \lambda + 307.0 \qquad (4.b)$$

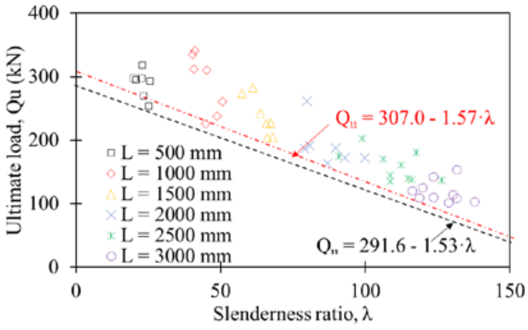


Fig. 8 Correlation between ultimate load, Qu, and slenderness ratio, λ, of BC samples

4.3 Elastic Limited Slenderness Ratio

While numerous studies have investigated the effectiveness of bamboo as reinforcement in concrete columns, research on concrete-filled bamboo with the bamboo acting as an external protective layer for the concrete is limited. To demonstrate the effectiveness of bamboo in this configuration, Fig. 9 compares the ultimate load of concrete bamboo and concrete column samples. Notably, without bamboo reinforcement, the ultimate load of the concrete column decreases significantly compared to the concrete bamboo column, particularly in samples with slenderness ratios exceeding 90, where concrete column samples failed during handling, consistent with the aforementioned limitations [27]. However, the concrete bamboo samples maintained relatively high ultimate loads even with slenderness ratios over 90 and exhibited elastic behavior, as shown in Fig. 5. To assess whether the samples behave elastically or plastically, the elastic limit slenderness ratio (λo) was estimated using the following equation:

$$\lambda_o = \sqrt{\frac{\pi^2 E}{\sigma_{le}}} \qquad (5)$$

where E is the modulus estimated by the slope of the axial stress-strain curve, and σle was the elastic-limited axial stress defined from the stress-strain curve of each sample.

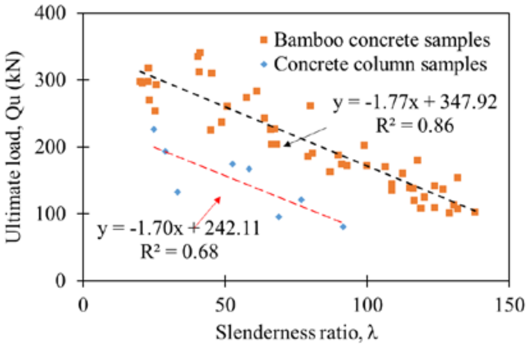


Fig. 9 Comparison of ultimate load between bamboo concrete samples and concrete column samples.

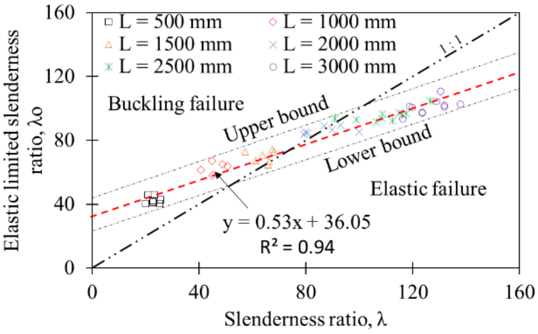


Fig. 10 Correlation between estimated elastic limited slenderness ratio and slenderness ratio of BC samples.

Figure 10 illustrates the correlation between the elastic limit slenderness ratio (λo) and the actual slenderness ratio (λ) for all samples. The 1:1 curve represents the point at which λo equals λ. The figure reveals that concrete bamboo samples exhibit elastic behavior when the slenderness ratio surpasses approximately 70. Furthermore, samples with lengths exceeding 1.5m demonstrated elastic behavior, which is distinctly different from the behavior of concrete-only samples.

5. CONCLUSIONS

In this study, the compressive strength of approximately 48 bamboo-concrete samples and 8 concrete column samples was investigated. A core-drilling, concrete-casting, and multi-level testing system was devised to address the challenges of pouring concrete into bamboo culms. Samples were fabricated with varying lengths from 0.5m to 3.0m, with several exhibiting high slenderness ratios, up to 140. The results of the compression tests on bamboo-concrete samples were analyzed and compared to those of concrete column samples.

Several key conclusions can be drawn from this study:

- The bamboo-concrete structure can be successfully created using a core-drilling and casting system to minimize damage to bamboo culms and improve the homogeneity of the concrete within.
- The test results demonstrate that shorter samples exhibit higher ultimate loads and vice versa. Notably, bamboo-concrete samples showed higher ultimate loads compared to estimated values based on Vietnamese standards, particularly for longer samples exceeding 2.0m in length. Longer samples generally exhibit higher over-estimated load values, highlighting the contribution of bamboo culms to the sample's ultimate load.
- Bamboo-concrete samples also demonstrated higher ultimate loads compared to concrete column samples with the same internal diameter. Concrete column samples longer than 1.5m failed during handling due to high slenderness ratios, while bamboo-concrete samples of the same length maintained high ultimate loads.
- Bamboo culms can increase the limiting slenderness ratio of a column structure up to 140, significantly exceeding that of concrete columns. The strong correlation between slenderness ratio and ultimate load in bamboo-concrete samples enables structural engineers to quickly determine the bearing capacity of such structures.
- Failure modes of the samples can be categorized as either buckling or elastic failure, distinguished by their slenderness ratios, as shown in Fig. 10.
- Due to the natural size limitations of bamboo, when applying this material to large structures, design considerations such as truss systems should be employed to maximize strength. The maximum member length should be limited to 3m based on recent experimental results. Further experimentation is recommended to refine this guideline.

Limitations: This study did not investigate the long-term durability of these structures. However, the primary focus was to evaluate the ultimate load capacity of this novel combination of materials in structural engineering. The longevity of bamboo can potentially be enhanced through coating methods, as described in research by Javadian et al. (2016). Additionally, the treatment process used in this study, including steaming and drying, may mitigate the deterioration of bamboo fibers.

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