

# Flexural Behavior of Bamboo Reinforced Concrete Beams Treated with Sikadur 32 F

**Abdourahim Jallow**

Pan African University Institute of Basic Sciences, Technology and Innovation, Hosted at Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000-00200, Nairobi, Kenya  
jallow.abdourahim@students.jkuat.ac.ke (corresponding author)

**Stanley Muse Shitote**

Department of Civil and Structural Engineering, Moi University, P.O. Box 3900-30100, Eldoret, Kenya  
shitote@hotmail.com

**Silvester Abuodha**

Department of Civil & Construction Engineering, University of Nairobi, Nairobi, Kenya  
sochieng@yahoo.com

**Isaac Fundi Sanewu**

Construction Management Department, Jomo Kenyatta University of Agriculture and Technology P.O. Box 62000-00200, Nairobi, Kenya  
fsanewu@gmail.com

Received: 17 February 2025 | Revised: 1 April 2025, 4 June 2025, 16 June 2025, 20 June 2025, and 24 June 2025 | Accepted: 27 June 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.10602>

## ABSTRACT

This experimental study investigates the flexural behavior of bamboo-reinforced concrete as a sustainable alternative to steel reinforcement. A series of tests, including compressive strength, ductility, and four-point bending, were conducted to assess the material's performance. The key parameters analyzed include the load-induced bending behavior, strain distribution, and failure capacity. The measured flexural stress of 37.71 N/mm<sup>2</sup> demonstrated effective tensile resistance and strong load transfer between bamboo and concrete. The bamboo-reinforced concrete exhibited adequate ductility, with an average displacement of 8.69 mm under load. The strain analysis revealed a conventional stress profile, with compression in the top fibers and tension in the bottom like steel-reinforced beams. The beam comparisons exhibited that increasing the depth improved the stiffness and load capacity but reduced the ductility. Overall, the findings support bamboo as a viable and eco-friendly reinforcement material, particularly where steel is cost-prohibitive. Nonetheless, further research is needed to enhance the bond strength and long-term durability for a broader application.

**Keywords-***bamboo reinforced concrete; flexural strength; bonding; ductility; deflection; sustainable construction*

## I. INTRODUCTION

Concrete is the most common construction material worldwide [1]. Its high compressive strength is offset by its relatively low tensile strength, which makes structures weak and requires reinforcement [2]. Steel is primarily used for strengthening, but its fabrication consumes a lot of energy and fossil fuels [3]. Additionally, producing steel releases a substantial amount of CO<sub>2</sub>, about 1.83 tons per unit [4]. Due to the environmental concerns, alternative, more eco-friendly construction materials have been explored and developed [5]. Bamboo has gained popularity in construction because of its durability, availability, and sustainability [6]. However, studies

have identified issues, such as poor adhesion in concrete reinforced with bamboo, especially high shrinkage [7]. Authors in [8] examined the adhesion between concrete and knitted bamboo bars and found that, although strong adhesion could be achieved, they remained susceptible to high tension failure caused by adhesive force and friction. Authors in [9] investigated the bonding stress between bamboo and concrete after applying Sikadur 32 gel epoxy coating and G.I. rolled wires. Furthermore, authors in [7] studied how adding pegs along bamboo reinforcement could increase the bonding strength, and found that using pegs resulted in higher load capacities for the beam structures. As explained in [10], factors influencing the bonding force include the adhesion between the

concrete components and reinforcement, gripping effects due to concrete shrinkage around the bars, friction resistance, and concrete quality. The friction between the bamboo surfaces and concrete, along with the mechanical interlock and coating adherence, significantly affect the bond in the final concrete. Authors in [11] used numerical analysis with petung-reinforced beams with varying strands and showed that increasing the strands improves the tensile and flexural strength. Authors in [12] examined the impact of replacing steel with bamboo at levels of 50% and 100% and found that although the 50% replacement resulted in 14% lower strength, it exhibited minimal deformation and less cracking. Authors in [13] conducted experimental research on the flexural behavior of concrete beams, focusing on the load-carrying capacity and ductility. Bamboo bars were used to partially replace steel reinforcement. The beams were categorized as follows: Prestressed Reinforced Concrete (PRS-BRC), Fiber Reinforced Concrete (FRS-BRC), Reinforced Cement Concrete (RCC), and Plain Cement Concrete (PCC). Each category represented different reinforcement configurations, such as compression bars, main bars, conventional steel reinforcement, and unreinforced concrete. Among these, the FRS-BRC beams showed a 3.29% higher ductility compared to the PRS-BRC beams. Similarly, authors in [14] analyzed the structural behavior of bamboo-reinforced concrete slabs with different reinforcement sizes under concentrated loads. They evaluated parameters, such as the load-deflection behavior, ultimate load capacity, stiffness, ductility, cracking patterns, and energy absorption. The results revealed that steel-reinforced slabs achieved about 82% of the strength of bamboo-reinforced slabs. Furthermore, bamboo-reinforced slabs demonstrated similar ductility to the steel-reinforced ones, indicating that bamboo can provide a comparable ductile performance in structural applications. Authors in [15] confirmed that bamboo fibers, across all dimensional scales, are effective reinforcement materials in both organic and inorganic matrices. This study focused on using plant fibers, including bamboo, to reinforce cement mortar and structural elements, such as beams, columns, and slabs. The findings emphasize bamboo's potential to replace steel in specific structural uses while offering environmental benefits. Although earlier research has compared bamboo reinforcement to steel and unreinforced concrete, the present study focuses on isolating and analyzing the flexural performance of bamboo-reinforced beams.

## II. MATERIALS AND METHODS

### A. Materials

#### 1) Material Acquisition

The type of cement used in this study was Ordinary Portland Cement (OPC), belonging to the CEM I class and with a strength of 42.5 N, acquired from Bamburi Cement Company. Other materials included fine aggregates and coarse aggregates, which were both sourced from a local reserve, water, bamboo, and epoxy bonding agent (Sikadur 32). The bamboo bars were obtained from a research facility, and the Sikadur 32 agent was purchased from Sika Kenya Limited. Figure 1 illustrates these materials.

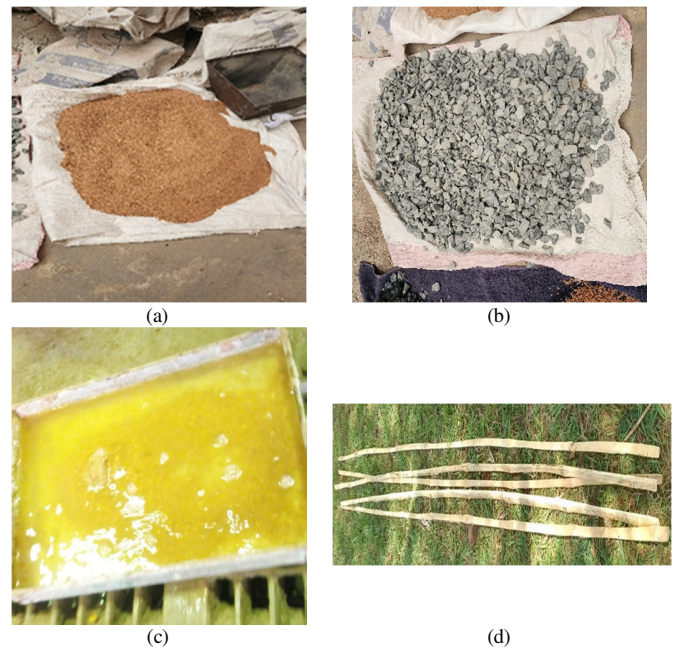


Fig. 1. Images of: (a) fine aggregates, (b) coarse aggregates, (c) sikadur 32, and (d) bamboo.

#### 2) Material Preparation

Before the experimental work began, the fine aggregates were sieved through a 4.75 mm mesh, while the coarse aggregates were passed through a 20 mm mesh. Both types of aggregates were thoroughly washed to remove silt and debris, then air-dried. Stirrups were bent to the required dimensions in preparation for enclosing the bamboo reinforcement. The bamboo bars were coated with the epoxy bonding agent Sikadur 32, following the designer's specifications, as shown in Figure 2 [18]. Proper mixing procedures are essential to ensure the desired performance characteristics of the concrete [17]. The epoxy mix was stirred thoroughly to eliminate any trapped air [22]. The mix design, including the ratios of cement, water, fine aggregates, and coarse aggregates, was determined through precise calculations.



Fig. 2. Coating bamboo bars using Sikadur 32.

B. Methods

1) Material Characterisation

Tests were conducted to evaluate the physical and mechanical properties of the concrete aggregates, as these characteristics are critical to ensuring material suitability and an efficient overall performance. Grading curves for both the fine and coarse aggregates were obtained through sieve analysis, in accordance with [28]. This process, illustrated in Figure 3(a) for coarse aggregates and Figure 3(b) for fine aggregates, provided essential data on the particle size distribution, ensuring a well-graded and densely packed concrete mix.

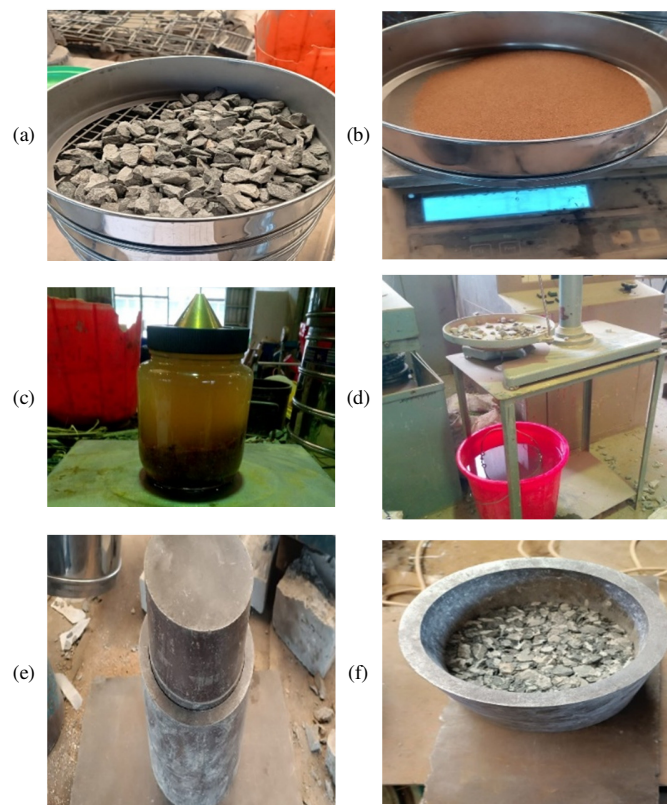


Fig. 3. (a) Particle size distribution of coarse aggregates, (b) particle size distribution of fine aggregates, (c) specific gravity of fine aggregates, (d) specific gravity of coarse aggregates, (e) ACV setup, and (f) aggregate after ACV setup.

To assess the strength of the coarse aggregates under sustained loading, the Aggregate Crushing Value (ACV) test was carried out following the BS 812-110 standards. The ACV test setup is shown in Figures 3(e) and 3(f). Water absorption tests for both the fine and coarse aggregates were performed according to [26], while their specific gravity was determined using the methods outlined in [25]. These properties influence the concrete's density and porosity, both of which are important for the mix design and long-term performance. The toughness of the coarse aggregates under sudden impact was evaluated using the Aggregate Impact Value (AIV) test. This test helps determine the aggregates' resistance to the wear and

mechanical stress. Figures 3(c) and 3(d) display the specific gravity testing procedures for both types of aggregates. The specific gravity indicates how dense the aggregates are relative to water and is a key factor in the mix design, as it affects the weight and stability of the final concrete product. The results from these tests were also used to calculate the water absorption capacity of the aggregates.

2) Material Characterization Results

a) Physical Properties

Sieve analysis was conducted on both the fine and coarse aggregates following the method outlined in [28]. This test provided valuable data on the particle size distribution and grading, which are essential for producing a well-compacted concrete mix. The gradation results showed that the coarse aggregates were evenly distributed, with most particles passing through the 25 mm sieve and fewer through the 2.36 mm sieve, as shown in Figure 4(b).

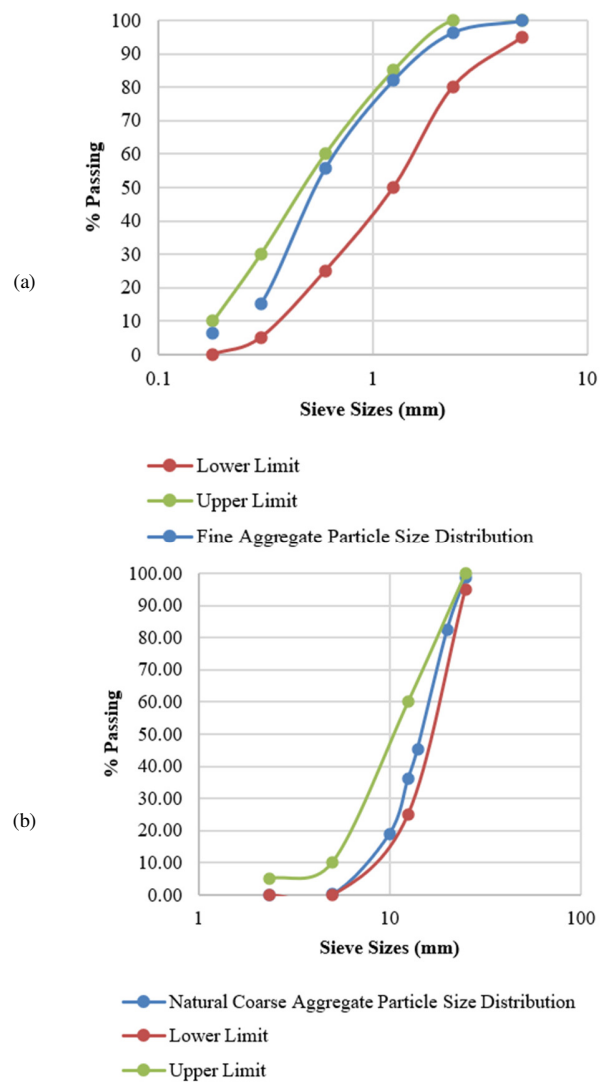


Fig. 4. Particle size distribution for: (a) fine aggregates and (b) coarse aggregates.

TABLE I. SPECIFIC GRAVITY OF FINE AND COARSE AGGREGATES

Properties	Fine aggregates	Coarse aggregates
Specific gravity (oven dry)	2.41	2.53
Specific gravity of SSD	2.48	2.58
Water absorption	2.78	2.09

This indicates a well-graded aggregate, which contributes to greater concrete strength. Similarly, the fine aggregates, as presented in Figure 4(a), were also well-graded and fell within the standard limits, promoting a better bonding between the cement paste and aggregates. As depicted in Table I, the specific gravity of the fine aggregates was 2.41 (oven dry) and 2.48 (saturated surface dry), while the coarse aggregates had slightly higher values of 2.53 and 2.58, respectively. These values fall within the typical range for natural aggregates (2.4–2.9), indicating that both types of aggregates possess adequate density and mass to support a strong and stable concrete mix. The water absorption was measured at 2.78% for the fine aggregates and 2.09% for the coarse aggregates. The higher absorption rate of the fine aggregates is expected due to their smaller particle size and greater surface area. These values are within acceptable limits, generally less than 3% for fine aggregates and 2.5% for coarse aggregates, suggesting a minimal risk of fluctuation in the water-cement ratio. These physical properties are critical to the performance of the concrete matrix. Since flexural failure is often initiated in the tension zone, using aggregates with stable and consistent physical characteristics helps create a concrete mix that better resists bending and cracking.

#### b) Mechanical Properties

The ACV of 17.70 and the AIV of 7.4, as shown in Table II, provide an understanding of the concrete's strength and toughness. Usually, the ACV values fall below 25% which implies that the aggregates used herein are of good quality and have sufficient strength to withstand the applied loads, without excessive crushing. Similarly, the AIV measures the toughness of the aggregates and their ability to resist sudden impact forces. AIV values below 20% are an indication of strong aggregates. The obtained AIV of 7.4 then implies that the aggregates have high toughness and high endurance for sustained dynamic loads. Regarding the flexural failure, using durable aggregates would ensure that concrete is more resistant to stress and that crack formation is delayed. This reduces the likelihood of sudden failure. Also, stronger aggregates will contribute to a higher compressive strength. This implies that the beam's resistance to the bending stress is enhanced. The results of the mechanical attributes of the aggregates are tabulated in Table II.

TABLE II. MECHANICAL PROPERTIES OF COARSE AGGREGATES

Properties	Coarse aggregates
ACV	17.7
AIV	7.4

### 3) Experimental Setup and Data Collection Procedure

#### a) Test on Fresh and Hardened Concrete

The concrete used in this study was classified as Grade 40 and was designed using the Department of Environment (DOE)

method. The final mix ratio was 1:1.55:3 for cement, fine aggregates, and coarse aggregates, with a water-cement ratio of 0.45.

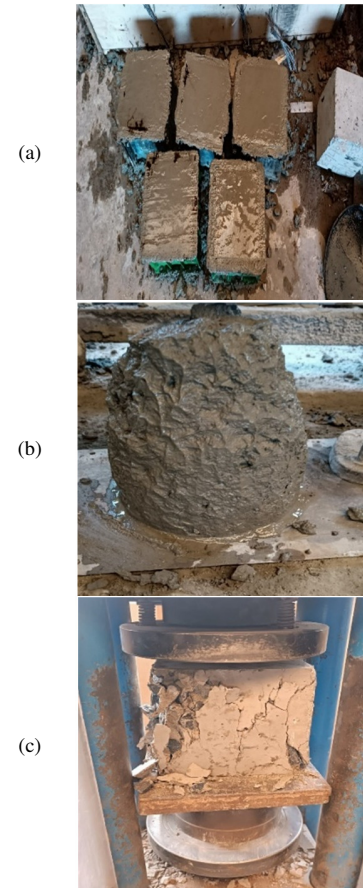


Fig. 5. Images of: (a) casting of cubes, (b) slump test, and (c) compressive strength test.

To assess the workability, a slump test was performed according to [32]. The concrete was placed into a slump cone in three layers, with each layer compacted using a tamping rod to eliminate the trapped air. After filling, the cone was carefully lifted, and the slump value was measured, as shown in Figure 5(b), to ensure proper consistency for placement. For the compressive strength testing, concrete cubes measuring 100 mm × 100 mm × 100 mm were cast, following the procedure illustrated in Figure 5(a) and [29]. The cubes were cured in water tanks and tested at 7 and 28 days. During testing, each specimen was placed in a Universal Testing Machine (UTM), and a load was applied until failure, as portrayed in Figure 5(c).

#### b) Test on the Bamboo

A splitting tensile strength test based on [27] was performed to analyze the bamboo's resistance to tensile loads, and the results were recorded. Bamboo strips of uniform cross-section were prepared and mounted vertically in a UTM using wedge grips, as shown in Figure 6. Care was taken to prevent the slippage and splitting at the gripping points by applying appropriate end treatments and using padded clamping. The

load was applied axially at a constant rate until failure. The load and elongation data were recorded to calculate the tensile strength and stress-strain response of the bamboo specimens.

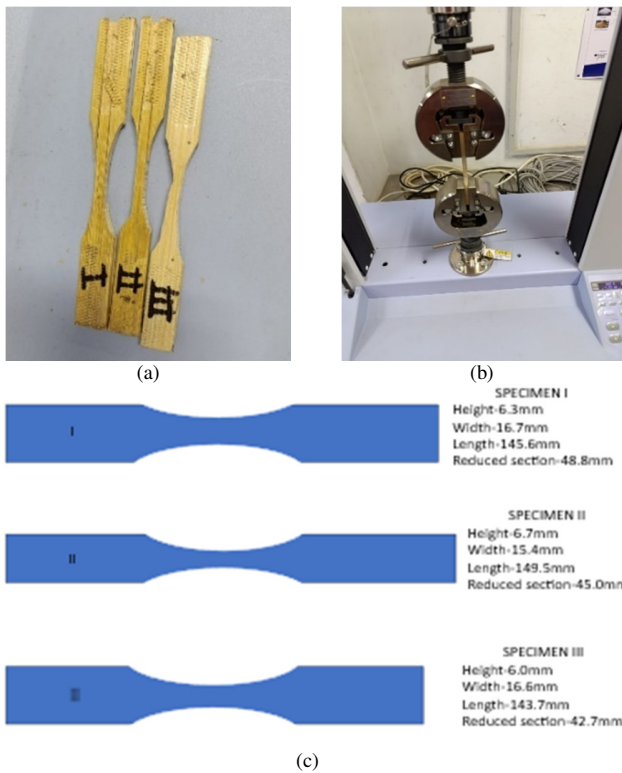


Fig. 6. Images of: (a) three bamboo specimens, (b) tensile test on a bamboo specimen, and (c) the measurements of bamboo specimens.

c) Test on Reinforced Concrete Beams

Two beam specimens, sized 1100 mm × 150 mm × 300 mm (B1) and 1100 mm × 300 mm × 300 mm (B2), were tested for flexural strength after 28 days of curing. A four-point bending test, conducted in [30, 31], was used to evaluate the beams' flexural performance, including their stiffness and overall structural behavior. As shown in Figure 7(a), each beam was simply supported at both ends, with a concentrated load applied at two points near the center. As the load increased, the beams began to deflect, and cracks developed in the tension zone. The loading continued until the beams reached the ultimate failure, allowing for a full assessment of stiffness and ductility. To capture the real-time structural responses, Linear Variable Differential Transformers (LVDTs) were placed at the midspan to measure the deflection, while strain gauges were attached to the beam surfaces to monitor the strain distribution in both compression and tension zones, as illustrated in Figure 7(b). These instruments provided the data used to develop the load-deflection and load-strain curves, offering insights into how efficiently the bamboo reinforcement transferred the loads within the concrete matrix. Additionally, the test results revealed patterns of failure, crack propagation, and strain distribution, helping to identify the causes of flexural failure, such as bamboo slippage and limitations in ductility, as discussed in [23].

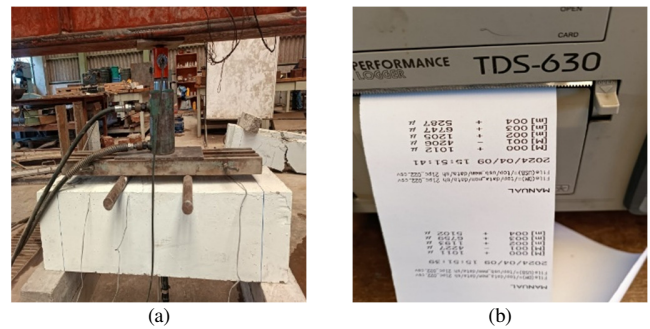


Fig. 7. Images of: (a) a concrete beam set up for flexural test and (b) operation of the LVDT.

III. RESULTS AND DISCUSSION

A. Mechanical Properties of Hardened Concrete

1) Compressive Strength Test Results

The evaluation of the concrete crushing resistance was performed through a compressive strength test. According to [19], the flexural behavior depends in part on the relationship between the tensile capacity of reinforcement and the compressive strength of the concrete mix. The compressive strength results indicate how well the bamboo-reinforced concrete can withstand axial loads. From the results demonstrated in Table III, it was found that the average compressive load was 803.121 N. Furthermore, the compressive strength test scored an average of 35.695 N/mm<sup>2</sup>. The average strength suggests that it offers moderate resistance, which is important for compression zones in structures like beams. However, there were some noticeable differences between the specimens. For instance, specimen C2 demonstrated a much lower compressive strength (30.656 N/mm<sup>2</sup>) compared to specimens C1 (40.943 N/mm<sup>2</sup>) and C3 (35.695 N/mm<sup>2</sup>). This variability is likely due to inconsistencies in the concrete mix, compaction, or curing conditions.

TABLE III. COMPRESSIVE STRENGTH CUBE TEST RESULTS

Sample	Compressive load (N)	Compressive strength (N/mm <sup>2</sup> )
C1	921.209	40.943
C2	689.753	30.656
C3	798.402	35.485
Avg	803.121	35.695

2) Tensile Strength Test Results

From the results presented in Table IV, it can be shown that the bamboo exhibits a high tensile strength, which is comparable to the lower range of steel [20]. The tensile behavior of the bamboo reinforcement was assessed through direct tensile tests on three specimens with slightly varying geometries, as shown in Figure 6(a). Each specimen had a reduced gauge section and a similar overall length, but with variations in width, thickness, and tapering shape, as illustrated in the accompanying sketches in Figure 6(c). Despite the geometric differences, Specimen I, with the widest reduced section of 48.8 mm, recorded the highest load, 4002.3 N, and a tensile strength of 213.48 MPa. Specimen II, which had the

narrowest reduced section of 45 mm and slightly more material tapering, showed a slightly lower strength at 212.4 MPa. Specimen III was the thinnest overall but had a slightly smaller gauge width of 42.7 mm, producing a similar failure load and the highest tensile strength of 214.14 MPa. These consistent results across the specimens, despite the minor dimensional variations, highlight the reliability and uniform strength behavior of bamboo under tension. The relatively low variability indicates that the preparation method and material integrity were stable across all samples. The high tensile strength values reflect the contribution of bamboo as a reinforcing material in resisting the tensile forces effectively. The average yield stress of 213.336 N/mm<sup>2</sup> demonstrates that the bamboo can sustain tensile loads, which ultimately keeps the flexural members strong and stable. The displacement values are a measure of how the bamboo deforms under tensile loading. The higher displacements in specimens I and II suggest that the material has some ductility, which implies it can bend considerably before it finally breaks. Specimen III exhibited a noticeably lower displacement at failure compared to the other specimens. This reduced deformation is likely due to its smaller cross-sectional area and narrow-gauge width, which resulted in a higher localized stresses and a more brittle failure response. The thinner profile also limited its ability to elongate under axial loading. Although Specimen III achieved the highest tensile strength, its lower ductility suggests a stiffer behavior, potentially caused by internal structural variations or the early formation of microcracks under stress. In a flexural member, the tension zone experiences tensile stresses, and the reinforcement must effectively resist these forces to control cracking and prevent failure [21].

The test results indicate that the bamboo provides both sufficient tensile strength and ductility, allowing bamboo-reinforced concrete to resist bending moments efficiently. This delays the crack initiation and propagation. Moreover, the bond between the bamboo and the surrounding concrete matrix helps maintain structural integrity under flexural loading. The average tensile strength across the tested bamboo specimens was 213.336 N/mm<sup>2</sup>. This splitting tensile strength test applies force over a narrow area, causing splitting along the specimen. As such, the test does not account for a crack-bridging behavior. According to [22], concrete's tensile strength is generally estimated to be about 10% of its compressive strength, an assumption supported by the results of this study. The tensile strength test also plays a critical role in estimating the maximum pull-out load, which is essential for evaluating the bond stress and tensile stress between the bamboo and concrete [23]. Interestingly, the yield strength of bamboo was found to be the same as its ultimate strength, suggesting that bamboo exhibits brittle failure, unlike steel, which has a distinct yield plateau. This indicates that twisted bamboo specimens, when pulled from concrete, are likely to fail in tension. Due to bamboo's strong adhesive interaction with concrete, especially when twisted, it is difficult to be extracted once embedded. This strong bond likely results from the combined effects of the mechanical interlock, surface friction, and chemical adhesion between the concrete and the bamboo reinforcement [24].

TABLE IV. TENSILE STRENGTH TEST RESULTS

Sample	Tensile load (N)	Displacement (mm)	Fy (N/mm <sup>2</sup> )	Fu (N/mm <sup>2</sup> )
I	8278.94	10.0864	258.717	258.717
II	7652.80	9.69747	239.150	239.150
III	4548.54	4.66017	142.142	142.142
Avg	6826.76	8.14801	213.336	213.336

B. Flexural Capacity of the Beam

The four-point bending test results provide insights into the flexural capacity of bamboo-reinforced concrete beams, which helps understand the performance of such systems under bending forces. The average flexural stress attained was 37.30725 N/mm<sup>2</sup> corresponding to an average maximum load of 28.7211 kN, as illustrated in Table V.

TABLE V. 4-POINT BEND TEST RESULTS

Sample	Ultimate load (kN)	Displacement (mm)	Flexural stress (N/mm <sup>2</sup> )
B1	31.7208	26.37468	41.3031
B2	25.7214	25.07832	33.4914
Avg	28.7211	25.7265	37.30725

Load Cell(KN) vs LVDT(mm)

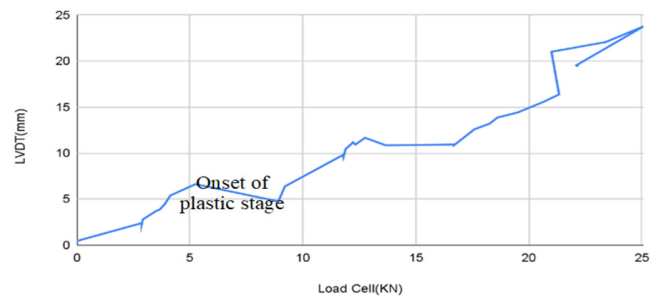


Fig. 8. Load versus deflection graph for 1100 mm × 150 mm × 300 mm beam (B1).

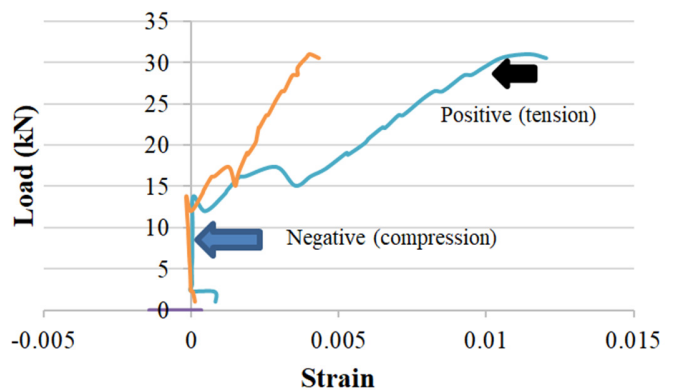


Fig. 9. Load versus strain graph for 1100 mm × 150 mm × 300 mm beam (B1).

The flexural stress attained given the concrete class used (40MPa) is important, as it asserts that the bamboo reinforcement enables the concrete to effectively resist the tensile forces induced by bending, thereby compensating for the inherent weakness of concrete in tension.

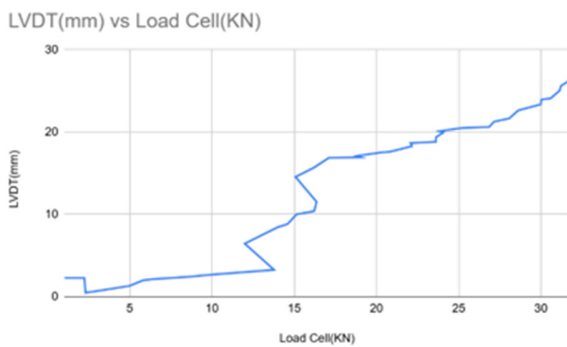


Fig. 10. Load versus deflection graph for 1100 mm × 300 mm × 300 mm beam (B2).

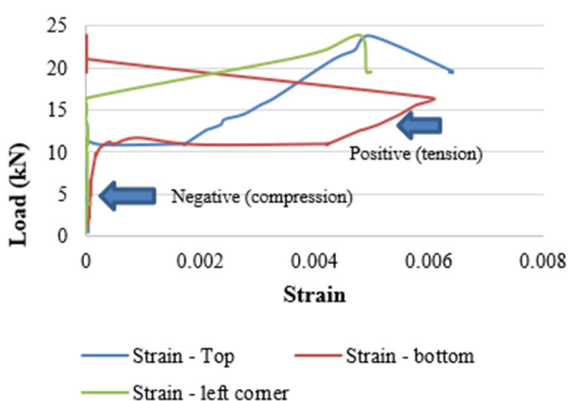


Fig. 11. Load versus strain graph for 1100 mm × 300 mm × 300 mm beam (B2).



Fig. 12. Crack development in bamboo-reinforced concrete beam (B2) under four-point bending.

The average flexural stress observed in this study is near the expected upper limit for bamboo-reinforced systems, demonstrating bamboo's effectiveness as a tensile reinforcement material. With its high tensile strength and flexibility, bamboo presents a practical alternative to steel, especially in regions where steel is expensive or difficult to obtain. The consistent performance across the three beam specimens highlights bamboo's potential as a sustainable, low-cost solution for reinforcing concrete in environmentally friendly constructions. The flexural stress values ranged from 33.49 N/mm<sup>2</sup> to 41.30 N/mm<sup>2</sup>, showing minimal variation. This consistency indicates a strong and uniform bonding between the bamboo and concrete, which is crucial for efficient load

transfer and overall structural performance. As presented in Figure 12, the failure mode in the bamboo-reinforced beams involved vertical and diagonal cracks forming in the tension zone. These cracks extended upward as the load increased, which is consistent with the typical flexural failure behavior. The image also suggests that debonding between bamboo and concrete may have occurred, resulting in localized stress concentrations and a possible reinforcement pull-out. The load-deflection curve for the 1100 mm × 150 mm × 300 mm beam, as depicted in Figure 8, illustrates the beam's response under increasing load. Initially, the curve is linear, indicating elastic behavior where both bamboo and concrete share the load without significant damage. As loading continues, the deflection increases rapidly, marking the onset of cracking and transition into the plastic phase. During this stage, bamboo takes on a greater share of the tensile stress. The peak of the curve represents the beam's ultimate flexural capacity beyond which failure occurs due to severe cracking or breakdown of the bamboo-concrete bond.

Figure 9 shows the load-strain graph for the same beam; it gives more details about how the strain is distributed at different points. The strain readings from the top, bottom, and left corner help show how different areas of the beam respond to stress. The top strain values are negative, which makes sense since the upper part of the beam is under compression, as expected in flexural members. Conversely, the bottom strain is positive, showing tensile strain as the beam bends downward under sustained load. The strain at the left corner provides an insight into how strain varies across the width of the beam. The strain distribution suggests that the beam undergoes a typical flexural response, where the neutral axis separates the compression and tension zones. The magnitude of strain at the bottom exceeds that at the top, further confirming that the bamboo reinforcement actively resists the tensile forces, minimizing and preventing brittle failure of the concrete. The smooth progression in strain with load is also evidence of a stable bond between the bamboo reinforcement and the concrete. As can be seen in Figure 10, the mechanical response shown by the load-deflection graph for the 1100 mm × 300 mm × 300 mm beam is different from the other beams, and this could be attributed to the increased depth of the beam. The larger beam section is subjected to higher stiffness, as observed in the graph where the initial gradient is steeper compared to the smaller beam. This implies that for the same applied load, the 1100 mm × 300 mm × 300 mm beam experiences less deflection, affirming that larger beams have a higher resistance capacity to bending. Compared to the smaller beam, the graph shows an initial elastic phase, followed by a non-linear behavior as cracking develops and flexural failure approaches. However, the 1100 mm × 300 mm × 300 mm beam deflection at ultimate load is lower, indicating that while it has a higher load-carrying capacity, its ductility is less than that of the 1100 mm × 150 mm × 300 mm beam. This behavior is typical in larger beams, where a reduction in flexibility stems from an increase in stiffness. A similar strain pattern may be observed for the 1100 mm × 300 mm × 300 mm beam load-strain graph in Figure 11, although with a noticeable reduction in overall strain values compared to the smaller beam. The reduced strain levels imply that the larger beam experiences lower unit

deformation under the same load, validating the theory that increasing the beam's cross-sectional area improves its resistance to bending. The top strain remains in compression while the bottom strain remains in tension, asserting that the neutral axis shifts as the load increases. Furthermore, the left corner strain is vital in the understanding of the lateral strain distribution. It confirms that while the strain levels are lower in the larger beam section, the overall pattern aligns consistently with the primary flexural behavior.

#### IV. CONCLUSIONS

Considering the growing interest in sustainable construction materials, this study explored the viability of bamboo as an alternative reinforcement to steel in concrete beams, focusing on flexural performance. With bamboo being a renewable, lightweight, and locally available material, it presents a compelling case for use in developing regions, where cost and environmental impact are key considerations. To assess its structural suitability, bamboo-reinforced concrete beams were tested using four-point bending setups. The study evaluated the flexural stress, load-deflection behavior, load-strain responses, the effect of beam geometry, and bonding characteristics between the bamboo and concrete. These tests were designed to reveal whether bamboo could effectively compensate for the tensile weakness of concrete while maintaining a safe and predictable behavior under load. The results yielded several important findings:

- Bamboo-reinforced beams attained an average flexural stress of 37.31 N/mm<sup>2</sup>, demonstrating significant tensile contribution.
- The beams showed adequate ductility, with an average displacement of 25.73 mm before failure.
- Strain distribution conformed to the classical flexural theory, with a well-defined neutral axis during loading.
- Larger beam sections provided greater load resistance but exhibited reduced ductility, emphasizing the role of cross-sectional size in performance.
- Surface treatments, like epoxy and sand coatings markedly improved the bond strength between bamboo and concrete.

However, performance variability was observed due to natural inconsistencies in bamboo and placement precision.

This study contributes new insights by providing quantitative evidence of bamboo's effectiveness as a flexural reinforcement material. It also offers a detailed analysis of how the beam geometry and surface treatment techniques influence performance. Unlike previous studies that primarily focused on bamboo's behavior under compressive or axial loads, this research emphasizes its performance under bending, an essential aspect of real-world structural applications. The findings highlight bamboo's potential as a low-cost, sustainable alternative to steel reinforcement, especially in regions where steel is economically or logistically unfeasible. To fully realize bamboo's potential in structural applications, further research is needed to standardize the treatment methods and enhance the consistency of its mechanical properties.

#### REFERENCES

- [1] T. F. Awolusi, O. J. Aladegboye, O. E. Babalola, E. K. Ayo, M. Azab, and A. F. Deifalla, "Optimizing the Flexural Behavior of Bamboo Reinforced Concrete Beams Containing Cassava Peel Ash using Response Surface Methodology," *Civil Engineering Journal*, vol. 9, no. 8, pp. 1971–1990, Aug. 2023, <https://doi.org/10.28991/CEJ-2023-09-08-011>.
- [2] M. Afzal, Y. Liu, J. C. P. Cheng, and V. J. L. Gan, "Reinforced concrete structural design optimization: A critical review," *Journal of Cleaner Production*, vol. 260, Jul. 2020, Art. no. 120623, <https://doi.org/10.1016/j.jclepro.2020.120623>.
- [3] M. Maier, A. Javadian, N. Saedi, C. Unluer, H. K. Taylor, and C. P. Ostertag, "Mechanical Properties and Flexural Behavior of Sustainable Bamboo Fiber-Reinforced Mortar," *Applied Sciences*, vol. 10, no. 18, Jan. 2020, Art. no. 6587, <https://doi.org/10.3390/app10186587>.
- [4] P. R. Mali and D. Datta, "Experimental evaluation of bamboo reinforced concrete beams," *Journal of Building Engineering*, vol. 28, Mar. 2020, Art. no. 101071, <https://doi.org/10.1016/j.jobe.2019.101071>.
- [5] S. Lumar *et al.*, "Sustainable and Renewable Bio-Based Natural Fibres and Its Application for 3D Printed Concrete: A Review," *Sustainability*, vol. 12, no. 24, Jan. 2020, Art. no. 10485, <https://doi.org/10.3390/su122410485>.
- [6] A. Daultebek, H. Li, Z. Xiong, and R. Lorenzo, "A review of mechanical behavior of structural laminated bamboo lumber," *Sustainable Structures*, vol. 1, no. 1, 2021, <https://doi.org/10.54113/j.sust.2021.000004>.
- [7] D. Nuralinah, A. Pujiraharjo, R. M. Simatupang, and M. Veronica, "Flexural Behavior of Bamboo-Reinforced Concrete Beam under Variation Condition," *Civil Engineering and Architecture*, vol. 12, no. 3, pp. 1904–1914, May 2024, <https://doi.org/10.13189/cea.2024.120346>.
- [8] D. Nuralinah, "The pull-out test on knit bamboo reinforcement embedded into concrete beam," *MATEC Web of Conferences*, vol. 258, 2019, Art. no. 01007, <https://doi.org/10.1051/mateconf/201925801007>.
- [9] A. Dixit and V. Puri, "Bamboo Bonding in Concrete: A Critical Research," *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 11S, pp. 323–334, Oct. 2019, <https://doi.org/10.35940/ijitee.K1061.09811S19>.
- [10] M. A. Mujalli, S. Dirar, E. Mushtaha, A. Hussien, and A. Maksoud, "Evaluation of the Tensile Characteristics and Bond Behaviour of Steel Fibre-Reinforced Concrete: An Overview," *Fibers*, vol. 10, no. 12, Dec. 2022, Art. no. 104, <https://doi.org/10.3390/fib10120104>.
- [11] Basyaruddin, A. S. Suprayitno, and A. Jatmoko, "The effect twisted petung bamboo variations as reinforcement on concrete beam," *Journal of Physics: Conference Series*, vol. 1726, no. 1, Jan. 2021, Art. no. 012009, <https://doi.org/10.1088/1742-6596/1726/1/012009>.
- [12] P. O. Awoyera, S. Karthik, P. R. M. Rao, and R. Gobinath, "Experimental and numerical analysis of large-scale bamboo-reinforced concrete beams containing crushed sand," *Innovative Infrastructure Solutions*, vol. 4, no. 1, Jul. 2019, Art. no. 41, <https://doi.org/10.1007/s41062-019-0228-x>.
- [13] B. Govindan, V. Ramasamy, B. Panneerselvam, and D. Rajan, "Performance assessment on bamboo reinforced concrete beams," *Innovative Infrastructure Solutions*, vol. 7, no. 1, Oct. 2021, Art. no. 16, <https://doi.org/10.1007/s41062-021-00616-8>.
- [14] Y. Haryanto, N. G. Wariyatno, H. T. Hu, A. L. Han, and B. A. Hidayat, "(Kajian ke atas Sifat Struktur Slab Konkrit diperkuat Buluh di bawah Beban Tertumpu)," *Sains Malaysiana*, vol. 50, no. 1, pp. 227–238, Jan. 2021, <https://doi.org/10.17576/jsm-2021-5001-22>.
- [15] V. C. Correia, S. F. Santos, G. H. D. Tonoli, and H. Savastano, "7 - Characterization of vegetable fibers and their application in cementitious composites," in *Nonconventional and Vernacular Construction Materials (Second Edition)*, K. A. Harries and B. Sharma, Eds. Woodhead Publishing, 2020, pp. 141–167.
- [16] Y. Takva, C. Takva, and F. Goksen, "A Contemporary House Proposal: Structural Analysis of Wood and Steel Bungalows," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 11032–11035, Jun. 2023, <https://doi.org/10.48084/etasr.5896>.

- [17] C. Zhang *et al.*, "Mix design concepts for 3D printable concrete: A review," *Cement and Concrete Composites*, vol. 122, Sep. 2021, Art. no. 104155, <https://doi.org/10.1016/j.cemconcomp.2021.104155>.
- [18] M. Kaur, H. Chawla, and N. Kwatra, "Effect of GO-modified epoxy on the bond behavior of old-new concrete and comparison with different surface preparation techniques," *Construction and Building Materials*, vol. 396, Sep. 2023, Art. no. 132369, <https://doi.org/10.1016/j.conbuildmat.2023.132369>.
- [19] J. J. Xu, W. W. Xiong, B. Shan, J. Wen, and Y. Xiao, "Bending stiffness of bamboo-concrete composite (BCC) beams under short-term loads," *Journal of Building Engineering*, vol. 60, Nov. 2022, Art. no. 105170, <https://doi.org/10.1016/j.jobbe.2022.105170>.
- [20] B. Mondal, D. Maity, and P. K. Patra, "Tensile characterisation of bamboo strips for potential use in reinforced concrete members: experimental and numerical study," *Materials and Structures*, vol. 53, no. 5, Oct. 2020, Art. no. 128, <https://doi.org/10.1617/s11527-020-01563-z>.
- [21] J. Slaitas, J. Valivonis, and L. Rimkus, "Evaluation of stress-strain state of FRP strengthened RC elements in bending. Fracture mechanics approach," *Composite Structures*, vol. 233, Feb. 2020, Art. no. 111712, <https://doi.org/10.1016/j.compstruct.2019.111712>.
- [22] O. Mohamed, W. A. Hawat, and O. Najm, "Compressive Strength, Splitting Tensile Strength, and Chloride Penetration Resistance of Concrete with Supplementary Cementitious Materials," *IOP Conference Series: Materials Science and Engineering*, vol. 960, no. 4, Sep. 2020, Art. no. 042078, <https://doi.org/10.1088/1757-899X/960/4/042078>.
- [23] A. Qasem, Y. S. Sallam, H. Hossam Eldien, and B. H. Ahangarn, "Bond-slip behavior between ultra-high-performance concrete and carbon fiber reinforced polymer bars using a pull-out test and numerical modelling," *Construction and Building Materials*, vol. 260, Nov. 2020, Art. no. 119857, <https://doi.org/10.1016/j.conbuildmat.2020.119857>.
- [24] Y. Liu, H. Li, Z. Feng, L. Ge, R. Li, and S. Liu, "Study on the interfacial bonding properties between alkali-treated bamboo fibers and high-performance seawater sea-sand concrete," *Construction and Building Materials*, vol. 426, May 2024, Art. no. 136190, <https://doi.org/10.1016/j.conbuildmat.2024.136190>.
- [25] *ASTM C127-24 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. USA: ASTM International, 2024.
- [26] *ASTM C128-22 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. USA: ASTM International, 2022.
- [27] *ASTM C496/C496M-17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. USA: ASTM International, 2017.
- [28] *ASTM C136-06 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. USA: ASTM International, 2015.
- [29] *ASTM C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. USA: ASTM International, 2023.
- [30] *ASTM C78-09 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. USA: ASTM International, 2010.
- [31] *ASTM C293/C293M-16 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading) (Withdrawn 2025)*. USA: ASTM International, 2025.
- [32] *ASTM C143/C143M-12 Standard Test Method for Slump of Hydraulic-Cement Concrete*. USA: ASTM International, 2015.