SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I4P112

Volume 12 Issue 4, 119-127, April 2025
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Original Article

Flexural Failure of Bamboo Reinforced Concrete Beams

Abdourahim Jallow[1], Stanley Muse Shitote[2], Silvester Abuodha[3], Isaac Fundi Sanewu[4]

[1]*Pan African University Institute of Basic Sciences Technolgy and Innovation, Hosted at Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya.*
[2]*Department of Civil and Structural Engineering, Moi University, Eldoret, Kenya.*
[3]*Department of Civil & Construction Engineering, University of Nairobi, Nairobi, Kenya.*
[4]*Construction Management Department, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya.*

[1]*Corresponding Author : jallow.abdourahim@students.jkuat.ac.ke*

Received: 09 February 2025 Revised: 11 March 2025 Accepted: 12 April 2025 Published: 30 April 2025

Abstract - *Flexural failure is a critical concern in bamboo-reinforced concrete, where bending forces cause tensile cracks to develop and propagate, ultimately leading to structural collapse. This research investigates the failure in terms of flexure of bamboo-reinforced concrete beams through experimental analysis, including compressive and tensile strength tests, three-point bending tests, and load-deflection and load-strain relationships. The results show that the beams achieved an average flexural stress of 37.7099 N/mm², with maximum displacements before failure ranging from 7.43017 mm to 9.42547 mm. Load-deflection analysis showed that the 1100 × 300 × 300 mm beams exhibited greater stiffness and lower deflection compared to the 1100 × 150 × 300 mm beams, reinforcing the role of beam size in flexural performance. Strain measurements confirmed that compression occurred at the top of the beams, while tension at the bottom led to crack initiation and eventual failure as the loads applied exceeded the material's capacity. The findings highlight the suitability of bamboo as an alternative material for reinforcement while emphasizing the importance of material strength, strain distribution, and bond efficiency in resisting flexural stresses and delaying failure.*

Keywords - *Bamboo reinforced concrete, Bonding, Deflection, Flexural failure, Stiffness.*

1. Introduction

Concrete is the most common construction material globally [1]. With a high compressive strength, its weakness in tension makes its structure unsound and must, therefore, be strengthened [2]. Steel is most commonly utilized for its strengthening, and its fabrication involves high-energy and high-fossil-fuel use [3]. Furthermore, its production emits a significant amount of CO_2, approximately 1.83 tons for one produced [4]. Due to such environment-related concerns, alternative, less environmentally friendly substitutes for conventional construction materials have been researched and developed [5].

A lot of studies have gone into investigating the flexural failure of bamboo-reinforced concrete. It was established that the bonding strength increases as the cross-sectional area of the bamboo reinforcement enlarges, which results in a higher capacity of the beam to carry loads [6]. BVCB and BHCB beams achieved 63% and 33% load-carrying capacity, respectively, and BVCB was twice the size of BHCB. Experiments conducted by [7] carried out experimental work on flexural behavior to observe failure. The ultimate load from the FRS-BRC beam and its crack load was near the RCC control beam, 2.81% and 3.17% lower compared to the control beam. [8] used the proportions 0%,25%,50%,60%,75% and 100% to replace steel with bamboo. The failure modes of the beams were similar and occurred at loads (70,100,95,85,80,65 and 70) kN, respectively. More cracks were seen in the bottom portion of the beam after increasing the load, and cracks due to flexural bending were observed at different loading points thereafter. [9] contributed to the understanding of the flexural performance of bamboo concrete by finding out that Assembled Bamboo-Lightweight Concrete Composite (ABLCC) beams had better flexural stiffness, about (2.18-3.47) times that of Bamboo Beams and Higher Than Cast-In-Place (PBLCC) by 1.09 times. [10] researched the failure trend of bamboo and its flexural strength exhibited by cement stabilized and unstabilized rammed earth wallette. Initial crack was observed at 7.5kN load application, and the ultimate failure load was observed at the load of 10.67 kN for the VBFRCSRE sample and 11.5kN and at 17.17Kn for the HBFRCSRE sample; the results showed that higher flexural strength is provided by bamboo placed within rammed earth wallets and this reduces unexpected failure and reduces the possibility of compacted layers separating from each other upon failure [10].

The flexural failure of bamboo-concrete beams, as observed by [11], was such that slight cracks were seen at the bamboo-concrete interface at the time the value of load was below 60% of the ultimate load. The interface slip at this stage was very small, and as the load approached 70% of the ultimate load, the inclined cracks were extended from the central part of the concrete downwards. [12] studied flexural properties of bamboo fibers which had been filled with the cement-based type of composites and learnt that since fiber content in small amounts is not sufficient for uniform distribution within the cement matrix, then during flexural tests, cracks will start form in areas where fibers are not present which causes failure of the specimen under less load. Furthermore, adding about 16% by weight of bamboo fiber to the mix would cause a reduction of about 8.9% in maximum flexural strength. Bamboo presents significant ecological advantages, particularly in carbon sequestration, soil conservation, and biodiversity support. However, challenges such as monoculture expansion and sustainability concerns require further investigation. Future research should focus on sustainable management, climate policy integration, ecological impacts, and innovative uses to maximize bamboo's benefits while mitigating risks.

[13] We carried out experimental research on strengthening reinforced concrete openings by bamboo fibres. Regarding failure, they established that several vertical cracks occur in the unstrengthened specimen. The cracks first appeared at the centre before propagating towards the beam's neutral axis. Where circular openings were present at the shear spans, diagonal cracks originated from the bottom chord before extending diagonally to the support. [14] We did a demonstration of the poor structural performance of concrete members reinforced using bamboo whey; they found out that poor placement of concrete, as done on one of the beams (Beam BE), caused a behavior of initial cracking, which resulted in an initial stiff behavior and no ultimate cracking load. For beam S, failure occurred at the 27.5 kN load, causing the loss of bond capacity as well as the development of a flexural shear crack.

[15] We researched the flexural behavior of fully scaled laminated bamboo concrete beams containing recycled concrete aggregates. From the findings, a shear slip (horizontally laminated) at the bottom of the notched glubam and concrete cracks in a diagonal direction occurs during flexural failure. According to [16] research on retrofitting of RC slabs using bamboo fibre for structural use, they observed that a mean load of 42.45 kN caused an early crack in the control slabs, which was higher by 67.79% as compared to the slabs that had not been retrofitted. [17] We found out that HSC-SBRF beams experienced flexural failure since fractures were observed in the flexural areas, but none were seen in the foothold zone. The early fracture load in these samples occurred at 32.36 kN, causing a deformation of 3.03mm. In comparing the flexural ductility of bamboo and that of wood, [18] observed that the failure strain of wood was 2.52%, whereas failure occurred at the strain of 5.52% in the case of bamboo. It was also observed that the modulus of the rapture of bamboo was more than that of wood upto 1.72 times, and its modulus of elasticity was 0.84 times compared to teakwood.

Flexural failure on bamboo has been studied by mixing the concrete with different materials, such as sea sand, as done by [19]. [20] We proved that flexural capacity, which dictates flexural failure, is improved by up to 81.88% bamboo sheet reinforcement, making an allowance for a 10% error.

In reviewing failure in beams, the position and orientation of cracks are also important. According to [21], vertical cracks started appearing in the beam's zone of tension when the load was applied. This occurred at about 4 kN – 6 kN. Apart from the formation of cracks, flexural failure may also be evidenced by the debonding of the reinforced fibres from concrete, as supported by [22].

2. Materials and Methods

2.1. Materials

2.1.1. Material Acquisition

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


(a)


(b)


(c)

(d)

Fig. 1 Pictorial representation of (a) Fine aggregates, (b) Coarse aggregates, (c) Sikadur 32, and (d) Bamboo.

2.1.2. Material Preparation

The fine aggregates were subjected to sieving through a 4.75mm sieve, whereas the coarse aggregates were passed through a 20 mm mesh before the experimental work began. The aggregates were thoroughly washed and air dried afterwards to reduce silt content and other debris. The stirrups were also bent to the appropriate dimensions awaiting to enclose the bamboo bars. The epoxy bonding agent, Sikadur 32, was used to coat the bamboo culms in accordance with the designer's specifications. Stirring of the agent mix was done appropriately to remove any entrapped air [23].

Fig. 2 Coating bamboo bars using Sikadur 32

2.2. Methods

2.2.1. Material Characterisation

Tests were performed to examine both the physical and mechanical characteristics of concrete aggregates because they guarantee suitable materials and performance outcomes. Fine and coarse aggregates underwent sieve testing according to the ASTM C136 method for analysis. The test was conducted to provide information about the size distribution and grading characteristics needed to produce a densely packed mixture.

The strength assessment of coarse aggregates under continuous load impact occurred through the Aggregate Crushing Value (ACV) test, which followed BS 812-110 standards. The fine and coarse aggregates were analyzed for water absorption following ASTM C128 standards while their specific gravity was tested using ASTM C127. The test results contributed to concrete density determination and porosity measurement, which shaped the mix design for future performance assessment. The Aggregate Impact Value (AIV) test was done to check how tough the coarse aggregates were when subjected to sudden impact. This helps gauge their resistance to wear and tear. The specific gravity of both coarse and fine aggregate tests followed the ASTM C127 and ASTM C128 to see how dense they were compared to water. This is important for mix design since it affects concrete's overall weight and stability. Using these results, the water absorption was calculated.

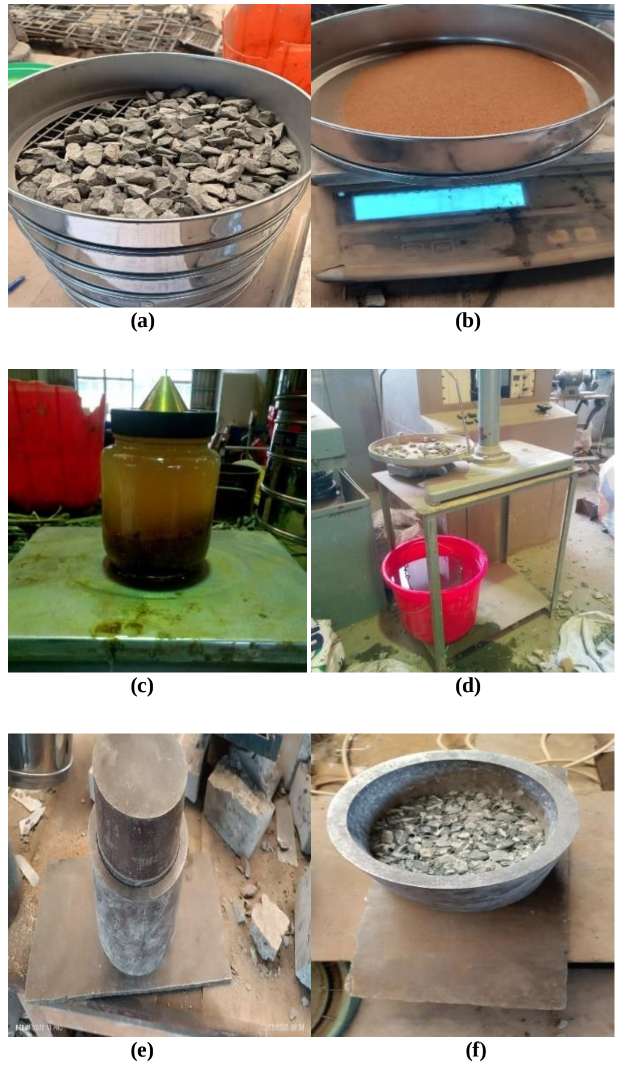


Fig. 3 Tests conducted on fine and coarse aggregates: (a) Particle size distribution of coarse aggregates, (b) Particle size distribution of fine aggregates, (c) Specific gravity of fine aggregates, (d) Specific gravity of coarse aggregates, (e) and (f) ACV setup

2.2.2. Experimental Setup and Data Collection Procedure Tests on Fresh and Hardened Concrete

The concrete used in this research was class 40 and was designed according to the DOE Department of Environment method. The ratio achieved for the mix proportions was 1:1.55:3 for cement, fine aggregate, and coarse aggregate, with a water-cement ratio of 0.45.

The workability of the fresh concrete was obtained from the slump test following the ASTM C143, the purpose of which was to determine the right consistency for placement. The concrete was filled in a slump cone in three successive layers, and compaction was done carefully using a tamping rod in addition to each layer to remove any trapped air. Once filled, the cone was lifted, and the slump value was measured.

Cubes of dimension 100 × 100 × 100 mm were subjected to compressive strength test in line with the ASTM C39 procedure. The cubes were placed in a curing tank and tested at 7 and 28 days. During testing, the cubes were placed in a Universal Testing Machine (UTM) and load was applied until failure. Additionally, a splitting tensile strength test following ASTM C496 was performed to analyse the concrete's resistance to tensile loads, and the results were recorded.

(a) **(b)**

(c)

Fig. 4 Pictorial representation of: (a) Casting of cubes, (b) Slump test, and (c) Compressive strength test

Tests on Reinforced Concrete Beams

Beams of sizes 1100 × 150 × 300 mm and 1100 × 300 × 300 mm were subjected to flexural strength tests after 28 days. The three-point bending test was used to evaluate flexural performance and was conducted according to ASTM C78 and ASTM C293. This provided important information on the beam's stiffness and overall structural behavior.

In the test setup, both extremes of each beam were simply supported, with a concentrated load applied at the center. On increasing the load, deflection occurred on the beam, and cracks started to form in the zone of tension. The test was continued until ultimate failure to allow for the measurement of stiffness and ductility.

LVDTs (Linear Variable Differential Transformers) and strain gauges were used to capture the beam's structural response in real-time. LVDTs were used to gauge the deflection, while strain gauges monitored how different beam sections responded to the applied loads. From this, relationships between load-deflection and load-strain were developed. The relationships helped to understand how efficiently loads are transferred between the bamboo and concrete. These tests and relationships provided direct evidence of failure through crack patterns, modes of failure, and distribution of strain, as well as an understanding of causes of flexural failure, as researched by [24], such as bamboo slipping and failure in ductility. Some of the illustrations of the tests are shown below.

(a) **(b)**

Fig. 5 Pictorial Representation of, (a) Concrete beam set up for the flexural test, and (b) Operation of the LVDT

3. Results and Discussion

3.1. Characterization of Constituent Materials

3.1.1. Fine and Coarse Aggregates

Physical Properties

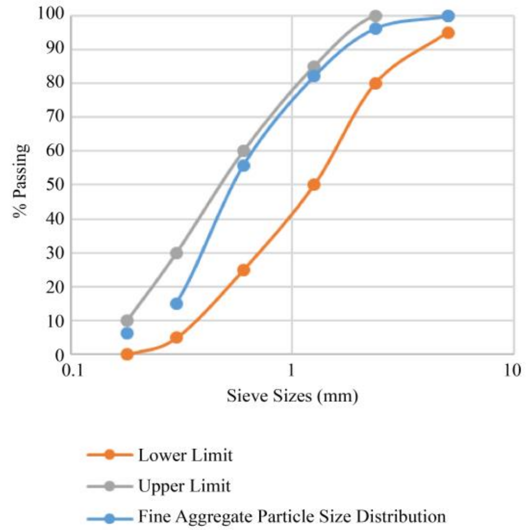
Fine and coarse aggregates underwent sieve testing according to the ASTM C136 method for analysis and yielded the following results. The test method revealed meaningful information about the size distribution and grading characteristics needed to produce a densely packed mixture. The gradation of the coarse aggregates shows an even distribution, with most particles passing the upper sieves (25 mm) and fewer in the lower sieves (2.36 mm).

This indicates a well-graded coarse aggregate that imparts higher strength to concrete. Similarly, the outcome indicates a well-graded fine aggregate that falls within the specified limits. The well-graded nature of the fine aggregates will ensure that the cement paste-to-aggregate bond is improved.

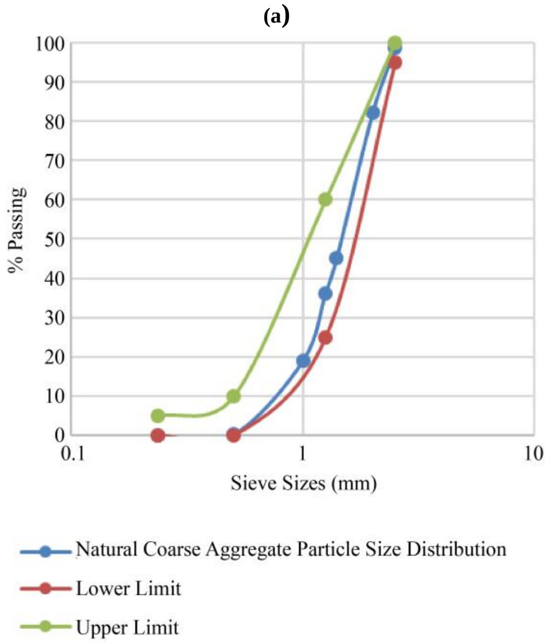
As captured in Table 1, the specific gravity of the fine aggregates was recorded as 2.41 (oven dry) and 2.48 (SSD), while that of the coarse aggregates was slightly higher at 2.53 (oven dry) and 2.58 (SSD). Typically, the specific gravity of natural aggregates falls within the range of 2.4 to 2.9, meaning the values obtained are within acceptable limits. This suggests the aggregates have sufficient density and mass to contribute to a strong and stable concrete mix.

The water absorption values were obtained as 2.78% for fine aggregates and 2.09% for coarse aggregates. Fine aggregates tend to absorb more water due to their smaller particle size and larger surface area, which is reflected in the results. Generally, water absorption for fine aggregates is usually below 3%, and for coarse aggregates, it is mostly below 2.5%. The results confirm that these values are within acceptable limits and that there is less likely to be a lot of fluctuations in the water-cement ratio.

The results are significant to the overall behavior of the concrete matrix in that since flexural failure often starts in the tension zone, it is, therefore, important to use aggregates with stable and physical properties to help create a mix that resists bending more effectively.



(a)



(b)

Fig. 6 Particle size distribution for, (a) Fine aggregates, and (b) Coarse aggregates

Table 1. Specific gravity of fine and coarse aggregates

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

Mechanical Properties

The Aggregate Crushing Value (ACV) of 17.70 and the Aggregate Impact Value (AIV) of 7.4 give 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 applied loads without excessive crushing.

Similarly, the AIV measures the aggregates' toughness and ability to resist sudden impact forces. AIV values of 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.

With regards to 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 bending stress is enhanced. The results of the mechanical attributes of the aggregates are tabulated below.

Table 2. Mechanical properties of coarse aggregates

Properties	Coarse Aggregates
ACV	17.70
AIV	7.4

3.1. Mechanical Properties of Hardened Concrete

3.1.1. Compressive Strength

The compressive strength results vary from one specimen to another, as shown in Table 3, with values ranging from 3.23165 N/mm² to 21.3781 N/mm² and an average of 14.5456 N/mm².

This kind of inconsistency may result from variations in curing conditions or differences in compaction during casting. Compression strength has to be considered in the study of flexural failure since the top portion of a flexural member (beam) is subjected to compression.

If the concrete in the top portion is too weak, it may crush before the action tensile reinforcement fully engages, leading to a sudden failure. Overall, these results suggest that the aggregates used in this research work are of good quality and suitable for structural application, especially in bamboo-reinforced concrete beams where both compressive and tensile forces influence flexural failure modes.

Table 3. Compressive strength test results

Sample	Compressive Load (N)	Displacement (mm)	Compressive Strength (N/mm2)
1-1	2052.29	11.0998	21.3781
1-2	310.238	7.34390	3.23165
1-3	1826.60	8.91987	19.0271
Average	1396.38	9.12119	14.5456

Tensile Strength Results

The tensile splitting strength results are such that ultimate strengths range from 142.142 N/mm² to 258.717 N/mm² and an average of 213.336 N/mm². A possible reason for the variation in these results could be internal microcracking, which occurs as a concrete cure. It is likely that some specimens have more micro-cracks due to uneven drying. These variations further highlight why reinforcement of the concrete is important. Tensile stresses occur bottomward of the beam and it is evidenced through early formation of cracks. Reinforcement using bamboo helps to bridge these cracks and delay failure depending on how well the reinforcement will interact with the concrete. The variations in tensile strength emphasize the importance of achieving a uniform and well-bonded concrete mix so that the behavior of any flexural member under load may be predicted accurately.

Table 4. Tensile strength test results

Sample	Tensile Load (N)	Displacement (mm)	Fy (N/mm2)	Fu (N/mm2)
1-1	8278.94	10.0864	258.717	258.717
1-2	7652.80	9.69747	239.150	239.150
1-3	4548.54	4.66017	142.142	142.142
Average	6826.76	8.14801	213.336	213.336

3.2. Flexural Failure

Table 5. 3-Point bend test results

Sample	Maximum Displacement Force (N)	Displacement (mm)	Flexural Stress (N/mm2)
1-1	317.208	9.42547	41.3031
1-2	257.214	7.43017	33.4914
1-3	294.415	9.22617	38.3353
Average	289.612	8.69394	37.7099

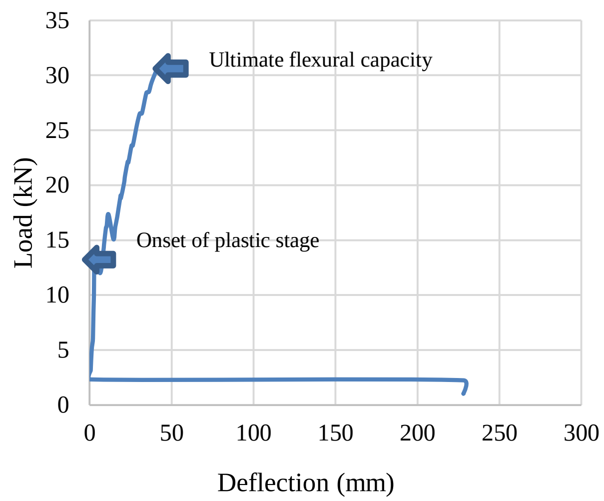


Fig. 7 Load vs deflection graph for 150 × 300 beam

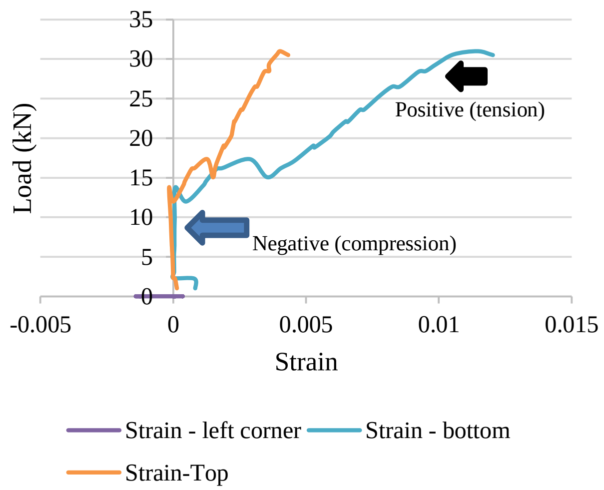


Fig. 8 Load vs strain graph for 150 × 300 beam

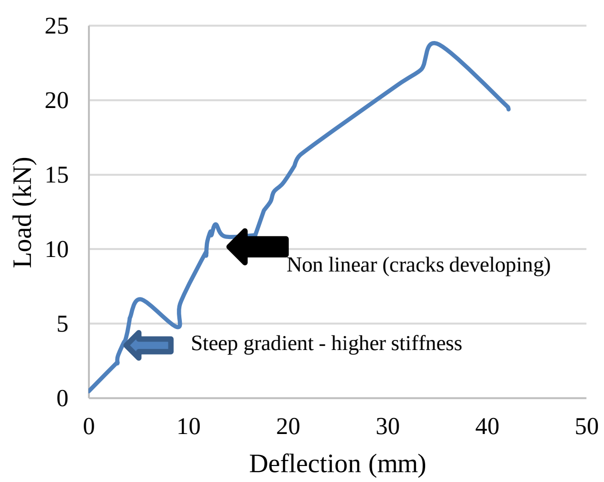


Fig. 9 Load vs deflection graph for 300 × 300 beam

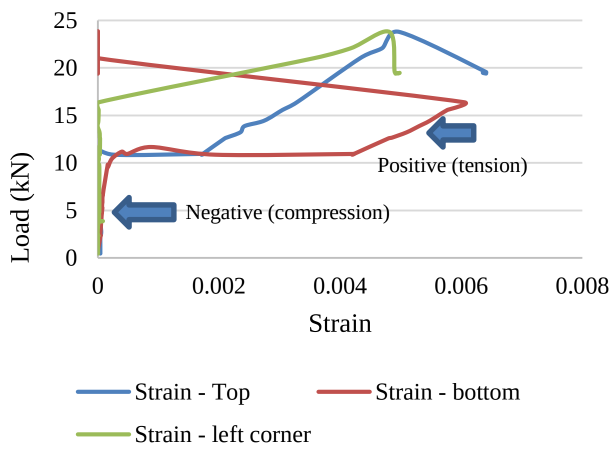


Fig. 10 Load vs strain graph for 300 × 300 beam

The three-point bend test results give an understanding of the capacity of the beams to resist bending before failure. The specimens recorded an average maximum force of 289.612 N, with individual values ranging from 257.214 N to 317.208 N. Correspondingly, the displacement values ranged from 7.43017 mm to 9.42547 mm, with an average of 8.69394 mm. These values indicate how much deformation was imposed on the beams due to loading before reaching their failure point. The flexural stress, a measure of the beam's resistance to bending, averaged 37.7099 N/mm², with the highest recorded stress at 41.3031 N/mm². These results confirm that the bamboo-reinforced beams have sufficient capacity to withstand flexural forces. The variations in the results may suggest differences due to bonding efficiency across the beam sizes.

The load-deflection graphs show the beam response to applied loads. The 150 × 300 mm beam displayed a clear transition from an initial linear phase, where the beam behaved elastically, to a non-linear phase. This pointed to the development of cracks and the progression into plastic deformation. The ultimate flexural capacity reached the graph's peak, beyond which the beam could no longer withstand additional loading. The 1100 × 300 × 300 mm beam displayed similar behavior, the difference being the noticeably steeper initial gradient. This implies higher stiffness because of the increased cross-sectional area. The implication is that the larger beam will experience less deflection when you apply the same load, supporting the idea that depth plays a crucial role in flexural performance. As seen, deflection increased rapidly beyond the elastic limit, meaning that whereas the bamboo reinforcement accounts for some capacity of ductile behavior, the flexural strength of the beam is what enabled it to resist failure. The cracks present in the tension zone weaken the beam over time, leading to failure as the load exceeds the resistance capacity [25].

The strain readings at the top, bottom, and left corner align with previous research since compression occurs on top and tension bottomward. In the 1100 × 150 × 300 mm beam, the transition from elastic to plastic deformation can be seen as strain values increase, particularly in the bottom section where tensile forces are most significant. The left corner strain provides information on how strain is distributed across the beam's width. The larger 300 × 300 mm beam was similar but with lower strain values due to its increased stiffness. The negative strain at the top highlights compression, while the positive strain at the bottom confirms the tensile forces that cause crack formation. As the strain increased beyond the elastic range, failure occurred. The strain distribution is consistent with flexural failure mechanics, whereby cracks develop due to the inability of the tension zone to withstand increasing stress.

4. Conclusion

Flexural failure in bamboo-reinforced concrete occurs as a result of tensile stresses in the bottom region exceeding the material's capacity, causing the development and spreading of cracks.

Flexural Stress of Bamboo: Typically ranges between 50–150 MPa, depending on species, moisture content, and testing conditions. Bamboo has a relatively high strength-to-weight ratio.

Flexural Stress of Steel: Usually above 250 MPa for mild steel and much higher for structural steel (e.g., 400–550 MPa). Steel is isotropic, meaning its strength is uniform in all directions, unlike bamboo, which is anisotropic and varies based on fiber alignment.

The experimental results highlight how factors such as beam size, material properties, and strain distribution influence the failure process. The following conclusions were drawn:

- Cracks first appeared at the bottom of the beam and extended upward as loading increased. Maximum displacement before failure ranged from 7.43017 mm to 9.42547 mm, with an average of 8.69394 mm, showing how much deformation occurred before structural failure.
- The load-deflection curves showed that the 1100× 300 × 300 mm beam had higher stiffness than the 1100 × 150 × 300 mm beam, experiencing lower deflection for the same applied load. However, both beams exhibited similar non-linear behavior as cracks developed, indicating the onset of failure.
- Strain analysis confirmed that compression occurred at the top while tension built up at the bottom, causing crack formation. The top strain had a negative value range, while the bottom strain was all positive, with strain values ranging from -0.005 to 0.015 for the 1100 × 150 × 300 mm beam and 0 to 0.008 for the 1100× 300 × 300 mm beam.
- The bamboo reinforcement delayed failure but did not entirely prevent it. The bond strength of bamboo and concrete matrix influenced the failure process, with the

beams failing once the tensile strain exceeded the material's limit.

- Variability in compressive and tensile strength among specimens suggested that material inconsistencies and curing conditions influenced structural performance. The strength in compression ranged from 3.23165 N/mm² to 21.3781 N/mm², while the tensile strength ranged from 142.142 N/mm² to 258.717 N/mm², affecting how and when the flexural failure occurred.

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