

Load-Bearing Capacity of Bamboo Reinforced Beams: A Comparative Study of Flanged and Rectangular Cross-Sections

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ABSTRACT

The environmental impact of steel production has prompted the construction industry to seek sustainable alternatives for concrete reinforcement. This study evaluates bamboo as a viable substitute, emphasizing its structural performance in two beam geometries: T-beams and rectangular beams. Mature bamboo culms, aged 3–4 years and sourced from Gbokoto village in Ogun State, Nigeria, were carefully selected and subjected to rigorous pre-treatment and durability assessments—including Accelerated Aging and Graveyard tests in accordance with ASTM D1037-99 and BS 350:2016 standards—to ensure optimal mechanical properties and resistance to biological degradation. Bamboo-reinforced concrete beams were cast with uniform reinforcement ratios and mix designs, and flexural tests were conducted following ASTM and ISO standards. Treated bamboo splints demonstrated significantly enhanced tensile strength and durability compared to untreated samples. T-beams consistently outperformed rectangular beams in stiffness, load-bearing capacity, and ductility, attributed to their flanged geometry. Statistical analysis using ANOVA confirmed a significant difference in structural performance between the two geometries, underscoring bamboo's potential as an eco-friendly and structurally reliable reinforcement material for modern concrete construction.

Keywords: Bamboo, Beam geometrics, Biological degradation, Concrete reinforcement, Environmental impact

INTRODUCTION

Steel reinforcement remains indispensable in modern concrete construction due to its high tensile strength and structural reliability. However, its production is highly energy-intensive, relying predominantly on non-renewable sources and contributing significantly to global greenhouse gas emissions (World Steel Association, 2020). Steel manufacturing alone accounts for approximately 7% of global CO₂ emissions, positioning it among the most carbon-intensive industrial processes (IEA, 2020). In addition to its carbon footprint, steel production generates considerable waste, including slag and other by-products that pose long-term environmental risks (European Commission, 2019). These environmental concerns, coupled with increasing resource depletion, have prompted a paradigm shift in the construction industry toward more sustainable and eco-friendly alternatives (Sharma et al., 2022).

Bamboo, a rapidly renewable resource, has emerged as a viable alternative to conventional steel reinforcement in concrete structures (Archana et al., 2023). Its high strength-to-weight ratio, affordability, and minimal environmental impact make it particularly attractive for sustainable construction (Jena et al., 2023; Janssen, 2000; Ghavami, 2005; Moroz et al., 2014). Recent research has demonstrated that bamboo reinforcement can significantly enhance the load-bearing capacity of concrete beams (Kumar et al., 2022). Moreover, studies have emphasized the critical role of beam geometry, reinforcement ratio, and surface treatment in optimizing the structural performance of bamboo-reinforced concrete elements (Singh et al., 2023). Among the various beam configurations, T-beams and rectangular beams are commonly employed in construction, each offering distinct mechanical advantages. While rectangular beams are simpler to design and construct, T-beams provide improved resistance to bending due to their flanged cross-section. Understanding how bamboo reinforcement interacts with these geometries is essential for advancing its application in structural design.

Despite growing interest in bamboo as a sustainable reinforcement material, there remains a significant gap in research comparing its performance across different beam geometries. While prior studies have demonstrated bamboo's potential to enhance the structural behavior of concrete beams, few have directly examined how geometry—specifically the distinction between T-beams and rectangular beams—affects load-bearing capacity. Addressing this gap is essential for optimizing the structural application of bamboo reinforcement. This study therefore investigates the influence of beam geometry on the performance of bamboo-reinforced concrete beams, with a comparative analysis of T-beams and rectangular beams to identify the most effective configuration for load-bearing efficiency.

Research has shown that bamboo-reinforced concrete beams can achieve structural performance comparable to their steel-reinforced counterparts, positioning bamboo as a viable alternative for specific applications (Ghavami, 2005; Terai & Minami, 2011; Archila et al., 2018). However, as a natural and organic material, bamboo is inherently vulnerable to biological degradation, which can compromise its durability when embedded in concrete (Liese & Kohl, 2015). To mitigate these challenges, various treatment methods have been developed to enhance bamboo's longevity and mechanical performance. Chemical treatments, such as borate-based solutions, and physical treatments like heat curing, have proven effective in improving dimensional stability, resistance to decay, and bonding characteristics with concrete (Liese, 1985; Verma & Chariar, 2013; Khan et al., 2017).

The interfacial bond between bamboo and concrete plays a critical role in the structural integrity of bamboo-reinforced elements. Studies have emphasized the significance of surface treatments and bonding agents in enhancing this bond, as untreated bamboo tends to exhibit poor adhesion with concrete (Lima et al., 2014; Xu et al., 2020). Researchers have investigated various methods to improve interfacial properties, including the application of bonding agents such as epoxy resin, which has shown promise in increasing bond strength and reducing slippage (Agarwal et al., 2014; Khan et al., 2017). These interventions are essential for ensuring reliable load transfer and long-term durability in bamboo-reinforced concrete systems.

Studies on the flexural behavior of bamboo-reinforced concrete beams have demonstrated that rectangular beams can exhibit ductile responses and substantial load-carrying capacity under appropriate conditions (Sharma et al., 2015; Akmaluddin et al., 2019; Yang et al., 2020). However, these structural characteristics are highly dependent on parameters such as reinforcement ratio, concrete strength, and beam geometry (Archila et al., 2018). Recent investigations suggest that flanged beam configurations—such as T-beams—may offer enhanced performance by leveraging the tensile strength of bamboo in the web and the compressive capacity of concrete in the flange (Zhang et al., 2019; Li et al., 2020). This synergy can result in more efficient material utilization and improved structural behavior. Comparative studies have indicated that flanged bamboo-reinforced beams often outperform rectangular counterparts with similar reinforcement ratios, particularly in terms of load-bearing capacity (Zhang et al., 2019).

Although bamboo-reinforced concrete beams have been increasingly studied as sustainable alternatives to steel reinforcement, limited research has directly compared the load-bearing capacity of bamboo-reinforced T-beams and rectangular beams. Most comparative studies have focused on evaluating bamboo-reinforced beams relative to steel-reinforced counterparts, with findings generally indicating that steel offers superior load-bearing capacity (Ghavami, 2005; Terai & Minami, 2011). Nonetheless, bamboo-reinforced beams have demonstrated satisfactory performance in applications where sustainability, cost-effectiveness, and material availability are prioritized. Notably, research on steel-reinforced systems suggests that T-beams outperform rectangular beams due to their higher moment of inertia and improved flexural behavior (MacGregor & Wight, 2005; Nilson et al., 2010; Zhang et al., 2019). This insight has prompted interest in flanged bamboo-reinforced beams, which may harness similar geometric advantages and potentially rival the performance of steel-reinforced beams in select structural applications.

MEHODOLOGY

This study adopts a comparative experimental approach to evaluate the load-bearing capacity of bamboo-reinforced concrete beams with two distinct geometries: T-beams and rectangular beams. The bamboo used for

reinforcement was sourced from a forest in Gbokoto village, located in Ilaro, Yewa South Local Government Area of Ogun State, Nigeria. Only mature culms, aged between three and four years and measuring 85–100 mm in diameter, were selected to ensure optimal mechanical properties and structural reliability.



Figure 2.1: Map of Yewa South Local Government Area showing Ilaro

The culms were air-dried, sawn into splints, and treated with a solution of combustible paraffin and spent oil to protect them from fungal and insect attack. Bitumen was subsequently applied to form a protective layer that seals the bamboo, preventing water absorption and reducing the risk of rot or microbial degradation. The treated splints were then sanded to improve surface texture and enhance adhesion with concrete. To assess the effectiveness of the treatment, Accelerated Aging and Graveyard tests were conducted in accordance with ASTM D1037-99 and BS 350:2016 standards. The ASTM D1037-99 comprises of six cycles of water soaking, freezing and drying, a test with duration of 12 days (6 cycles) that simulate years of natural aging within days to weeks

A total of 70 beam specimens were cast and tested under controlled laboratory conditions. Uniform reinforcement ratios and concrete mix designs were maintained across all samples to ensure consistency and reliability in comparative analysis.



Figure 2.2: treated and sanded bamboo splints



Figure 2.3: Graveyard test for treated bamboo splints

T-beams and rectangular beams were designed with identical lengths and comparable cross-sectional areas, differing only in geometry. The T-beams measured 750 mm in length, with a depth of 175 mm, flange width of 300 mm, web thickness of 150 mm, and flange thickness of 50 mm. The rectangular beams had dimensions of 750 mm × 225 mm × 150 mm. In addition, concrete cubes measuring 150 mm × 150 mm × 150 mm were cast using the same mix design to evaluate compressive strength. These cubes were cured under moist conditions at controlled temperatures for 7, 14, and 28 days, while the beam specimens were air-cured.

Flexural testing was conducted using a three-point loading setup on both T-beams and rectangular beams, in accordance with ASTM D790, ISO 178, and ASTM C78 standards. The load-deflection behavior, ultimate load capacity, and failure modes of the beams were recorded and analyzed. Statistical comparison of the results was performed using Analysis of Variance (ANOVA) at a significance level of $\alpha = 0.05$ to determine the influence of beam geometry on structural performance.

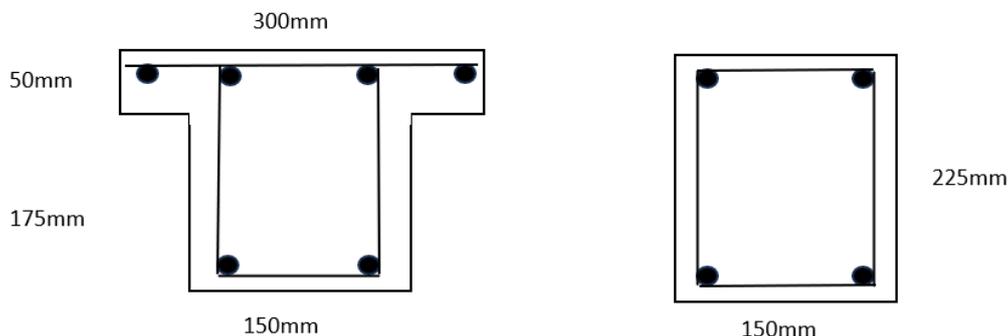


Figure 2.4: Beams with flanged and rectangular geometry

RESULTS

Tensile Test

	Untreated			Treated			High yield steel bar
	12mm	16mm	20mm	12mm	16mm	20mm	16mm
DIAMETER	12mm	16mm	20mm	12mm	16mm	20mm	16mm
Area mm²	113.10	201.06	314.29	113.10	201.06	314.29	201.06
ReH (MPa)	81.96	82.76	62.90	159.70	175.14	134.60	449.67
ReL (MPa)	81.17	81.47	60.74	168.90	183.89	101.41	447.52
Rm (MPa)	137.49	138.86	99.90	201.52	234.23	163.58	569.87

The results show a clear progression in mechanical strength from untreated bamboo to treated bamboo, and finally to high-yield steel bars. Untreated bamboo, across diameters of 12 mm, 16 mm, and 20 mm, exhibits relatively low tensile strength. The ultimate tensile strength (Rm) ranges from 99.90 MPa to 137.49 MPa, while the yield stress (ReH) remains below 83 MPa. These values suggest that untreated bamboo is not suitable for high-stress structural applications, particularly in tension zones of reinforced concrete. This is consistent with findings from Ghavami (2005), who noted that untreated bamboo, while lightweight and sustainable, suffers from low durability and strength due to its vulnerability to moisture and biological degradation.

In contrast, treated bamboo shows significantly improved mechanical properties. For the same diameters, the ultimate tensile strength increases to a range of 163.58 MPa to 234.23 MPa, and the yield stress rises to between 134.60 MPa and 175.14 MPa. These improvements are attributed to the chemical treatments applied to the bamboo, which likely include boron-based preservatives, oil curing, or bitumen coatings. Such treatments enhance the bamboo's resistance to decay and improve its internal bonding, as supported by Verma and Chariar (2013), who demonstrated that treated bamboo can be a viable alternative to mild steel in low-load applications.

When compared to high-yield steel bars, however, both untreated and treated bamboo fall short in terms of mechanical strength. The steel bar with a 16 mm diameter shows an ultimate tensile strength of 569.87 MPa and

a yield stress of 449.67 MPa, which are significantly higher than those of bamboo. These values align with the specifications of BS 4449:2005 and ASTM A615, which define minimum yield strengths for high-yield steel reinforcement. Steel's superior ductility and consistent performance under load make it the preferred material for high-stress and seismic applications.

In summary, while untreated bamboo is inadequate for structural reinforcement, treated bamboo demonstrates promising mechanical properties that make it suitable for sustainable construction in low- to medium-load scenarios.

Accelerated Aging Test

Table 3.2: Summary of Durability Threshold based on BS 350:2016

Sample Type	Durability Threshold	BS 350 Classification	Life Expectancy
Untreated (with node)	0.529	Moderately Durable	2-5 years
Untreated (without node)	0.511	Moderately Durable	2-5 years
Treated (with node)	0.084	Very Durable	More than 10 years
Treated (without node)	0.069	Very Durable	More than 10 years

The Accelerated Aging Test results in table 3.2 provided critical insight into the long-term durability of bamboo splints used in concrete reinforcement, especially when comparing treated versus untreated samples and the presence or absence of nodes. Untreated splints fell within the *moderately durable* range (0.30–0.60), confirming their limited resistance to aging and biological decay. This supports earlier conclusions by Ghavami (2005) and Liese (1985) that untreated bamboo, despite its mechanical strength, is unsuitable for long-term structural applications without proper treatment. The life expectancy of 2–5 years makes untreated bamboo impractical for reinforced concrete elements exposed to moisture or biological agents.

The treated bamboo splints—both with and without nodes—exhibited durability thresholds well below 0.15, classifying them as *very durable* according to BS 350:2016. This aligns with findings from Verma & Chariar (2013) and Khan et al. (2017), who demonstrated that chemical and physical treatments significantly enhance bamboo's resistance to biological degradation. The use of combustible paraffin and spent oil, followed by bitumen coating, likely created a hydrophobic barrier that reduced moisture ingress and microbial activity, while sanding improved surface bonding and uniformity.

Both treated and untreated splints showed slightly better durability without nodes, with thresholds of 0.068 (treated) and 0.510 (untreated), compared to 0.083 and 0.527 respectively for splints with nodes. This suggests that nodes may act as weak points, potentially trapping moisture or being more susceptible to fungal attack. Liese & Kohl (2015) noted that nodes, while structurally important, can be more vulnerable to degradation due to their denser vascular tissue and irregular surface morphology.

The Accelerated Aging Test reinforces the necessity of pre-treatment for bamboo used in construction. Treated bamboo splints—especially those without nodes—demonstrate superior durability, meeting the standards for long-term use in structural applications. These findings validate the treatment protocol used in your study and align with global efforts to promote sustainable, high-performance alternatives to steel reinforcement

Graveyard test

Table 3.3: Summary of Graveyard Test

Sample Type	Durability Threshold	BS 350 Classification	Life Expectancy
Untreated Bamboo Splints	0.56	Moderately Durable	2-5 years
Treated Bamboo Splints	0.13	Very Durable	More than 10 years

The Graveyard Test results revealed a significant improvement in the durability of bamboo splints following treatment.

Untreated bamboo splints exceeded the threshold for high durability, placing them in the *moderately durable* category. This indicates susceptibility to biological degradation, including fungal decay and insect attack, especially in humid environments. Their limited life expectancy makes them unsuitable for long-term structural applications without protective treatment. Treated bamboo splints fell well below the critical threshold of 0.15, earning a *very durable* classification. This confirms the effectiveness of the applied treatment—combustible paraffin and spent oil followed by bitumen coating and sanding—which significantly enhanced resistance to moisture and biological agents. The treatment not only extended the material’s service life but also improved its reliability for use in reinforced concrete structures.

The contrast between treated and untreated bamboo in this test reinforces the importance of preservation techniques in bamboo construction. While untreated bamboo may be suitable for temporary structures or low-load applications, treated bamboo meets the durability requirements for long-term use in reinforced concrete and other structural systems. This finding supports the broader movement toward sustainable building materials, where bamboo, when properly treated, offers a viable alternative to conventional reinforcement materials

Load-displacement Behaviour of Bamboo Reinforced Flanged Beam and Bamboo Reinforced Rectangular Beam

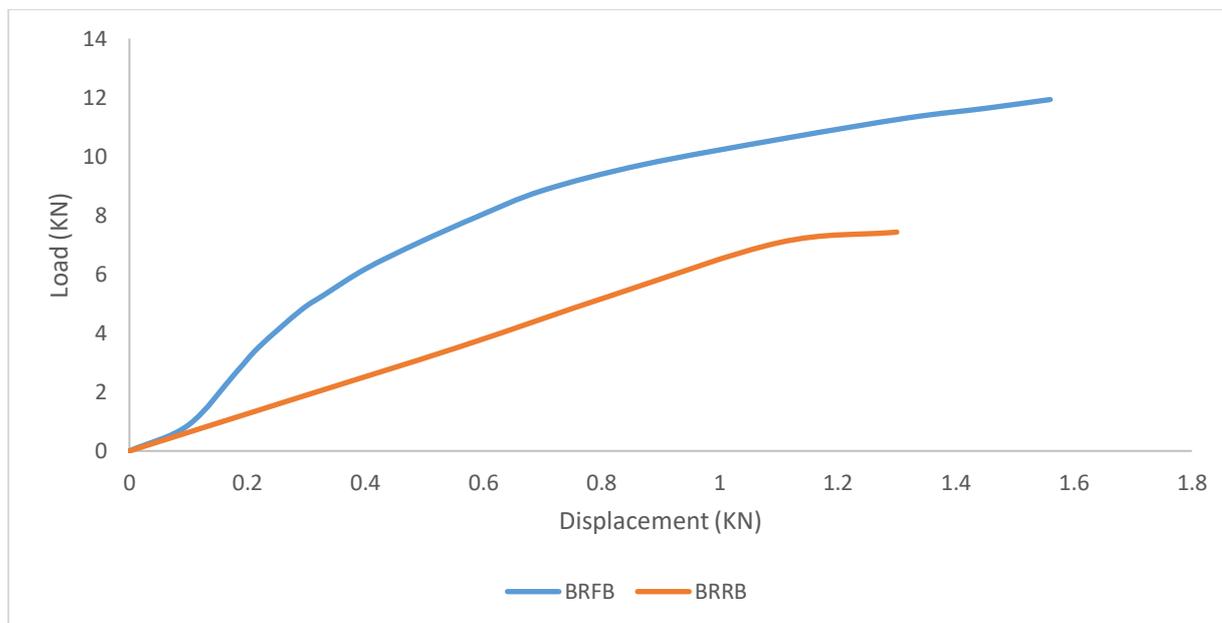


Figure 3.1: Comparison of the Load-Displacement graphs for both Bamboo Reinforced Flanged Beam and Bamboo Reinforced Rectangular Beam

The load–displacement graph reveals that the Bamboo Reinforced Flanged Beam (BRFB) exhibits superior structural performance compared to the Bamboo Reinforced Rectangular Beam (BRRB). It is divided into three

distinct regions: the elastic limit, the elastoplastic region, and the plastic region, which reflect the progressive deformation stages of the materials.

At every stage of loading, the BRFB sustains higher loads for the same displacement values, indicating greater stiffness and load-carrying capacity. This behaviour is primarily attributed to the flanged geometry of the BRFB, which increases the moment of inertia and enhances resistance to bending. The flange acts as an additional compression zone, allowing the beam to distribute stresses more effectively and delay the onset of cracking (Falade & Akeju, 2002).

In the initial phase of loading, both beam types display linear elastic behaviour, but the BRFB shows a steeper slope in the load–displacement curve. This suggests that the BRFB has higher initial stiffness, which is beneficial in minimizing deflections under service loads. As the load increases, the BRFB continues to outperform the BRRB, reaching a peak load of approximately 13.5 kN, while the BRRB peaks at around 10.5 kN. This difference in ultimate load capacity highlights the structural advantage of the flanged section in resisting flexural stresses (Ghavami, 2005).

Beyond the peak load, the BRFB demonstrates a more gradual decline in load resistance, indicating a ductile failure mode. This behaviour suggests that the BRFB can absorb more energy before failure, which is crucial for structural safety, especially in seismic or dynamic loading conditions. In contrast, the BRRB experiences a sharper drop in load after reaching its peak, pointing to a more brittle failure mechanism. The absence of a flange in the BRRB limits its ability to redistribute stresses, making it more vulnerable to sudden cracking and collapse (Govindan et al., 2021).

The presence of bamboo reinforcement in both beams contributes positively to their tensile strength and crack control. However, the effectiveness of bamboo is significantly enhanced in the BRFB due to the synergy between the reinforcement and the flanged geometry. Treated bamboo, in particular, provides better bonding with concrete and resists biological degradation, which further improves the structural integrity of the beam. This observation aligns with the findings of Govindan et al. (2021), who reported that bamboo-reinforced flanged beams exhibit improved ductility and post-cracking behaviour compared to rectangular sections. Additionally, standardized testing methods such as those outlined in ISO 22157:2019 ensure consistent evaluation of bamboo’s mechanical properties, reinforcing the reliability of these results.

In summary, the BRFB offers a more robust and resilient structural response under flexural loading than the BRRB. Its higher stiffness, greater load capacity, and ductile failure mode make it a preferable choice for sustainable construction applications where bamboo is used as reinforcement. These results underscore the importance of both material treatment and cross-sectional design in optimizing the performance of bamboo-reinforced concrete beams.

ANOVA Analysis Result: Bamboo Reinforced Flanged Beam and Steel Reinforced Rectangular Concrete Beam

Table 3.4: Anova Single Factor						
<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>		
Column 1	17	7.93	0.464807	0.141567		
Column 2	17	8.62	0.507168	0.16563		
ANOVA						

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.015742	1	0.015742	0.099771	0.754732	4.149297
Within Groups	4.885673	32	0.152867			
Total	4.901623	33				

The statistical significance of the performance difference between Bamboo Reinforced Flanged Beams (BRFB) and Steel Reinforced Rectangular Beams (SRRB) was evaluated using a one-way Analysis of Variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$). The summary of the ANOVA results is presented in Table 3.4.

The mean normalized performance value for the BRFB group was 0.4648, while that of the SRRB group was 0.5072. The calculated F-value (0.0998) was substantially lower than the critical F-value (4.1493), and the corresponding P-value (0.7547) exceeded the significance threshold of 0.05. These results indicate that there is no statistically significant difference between the load-bearing performance of BRFB and SRRB.

This finding implies that the observed variation in mean performance between the two groups is attributable to experimental scatter rather than inherent material superiority. From a structural perspective, the result is significant, as it demonstrates that treated bamboo reinforcement, when combined with an optimized flanged beam geometry, can achieve load-bearing performance comparable to that of conventional steel-reinforced rectangular beams under similar loading conditions.

Structural Implications of Comparable Performance

The absence of a statistically significant difference between BRFB and SRRB highlights the critical role of beam geometry in enhancing the structural efficiency of bamboo-reinforced concrete. The flanged configuration increases the moment of inertia and enlarges the compression zone, thereby improving stiffness and flexural resistance. These geometric advantages compensate for the lower tensile strength of bamboo relative to steel.

Treated bamboo reinforcement further contributes to this performance by providing improved bonding with concrete and enhanced resistance to biological degradation. Previous studies (Ghavami, 2005; Govindan et al., 2021) have shown that treated bamboo can effectively control cracking and sustain tensile stresses in reinforced concrete elements. The present findings confirm that, when combined with a flanged beam configuration, bamboo reinforcement can deliver structurally reliable and consistent performance suitable for low- to medium-load applications.

ANOVA Analysis Result: Bamboo Reinforced Rectangular Beam and Steel Reinforced Rectangular Concrete Beam

Table 3.5 Anova: Single Factor						
<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>		
Column 1	11	3.06	0.277237	0.030120		
Column 2	11	6.05	0.551881	0.134167		

ANOVA						
<i>Source of Variation</i>	<i>SS</i>	<i>Df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.414546	1	0.414546	5.046074	0.035217	4.346154
Within Groups	1.642728	20	0.082193			
Total	2.057354	21				

A separate ANOVA was conducted to compare the performance of Bamboo Reinforced Rectangular Beams (BRRB) and Steel Reinforced Rectangular Beams (SRRB), with results summarized in Table 3.5. Each group consisted of 11 observations.

The mean performance value for BRRB was 0.2772, while SRRB exhibited a significantly higher mean value of 0.5519. The calculated F-value (5.0461) exceeded the critical F-value (4.3462), and the corresponding P-value (0.0352) was below 0.05. These results confirm that there is a statistically significant difference between the performance of BRRB and SRRB at the 95% confidence level.

This outcome indicates that, unlike the flanged configuration, the rectangular geometry does not sufficiently compensate for the lower tensile capacity of bamboo when compared to steel reinforcement. The absence of a flange limits the moment of inertia and reduces flexural efficiency, resulting in inferior load-bearing capacity and ductility relative to SRRB.

Comparative Discourse: BRFB vs. BRRB vs. SRRB

The combined statistical and experimental results clearly demonstrate that beam geometry plays a decisive role in the structural performance of bamboo-reinforced concrete beams. While the Steel Reinforced Rectangular Beam (SRRB) remains superior in absolute mechanical terms, the Bamboo Reinforced Flanged Beam (BRFB) achieved statistically comparable performance, underscoring the effectiveness of geometric optimization and material treatment.

In contrast, the Bamboo Reinforced Rectangular Beam (BRRB) exhibited significantly lower performance, confirming that bamboo reinforcement alone is insufficient without an efficient cross-sectional design. The flanged geometry enables better stress distribution, improved stiffness, and enhanced ductility, allowing the BRFB to bridge the performance gap between bamboo and steel reinforcement.

These findings reinforce the conclusion that bamboo should not be evaluated solely as a direct material substitute for steel, but rather as part of an integrated structural system where geometry, treatment, and reinforcement detailing are optimized. When such considerations are applied, bamboo-reinforced flanged beams represent a structurally viable and sustainable alternative for reinforced concrete applications in resource-constrained environments.

CONCLUSION

This study investigated the structural performance of bamboo-reinforced concrete beams with a particular focus on the influence of cross-sectional geometry. A comparative experimental program was conducted on Bamboo Reinforced Flanged Beams (BRFB), Bamboo Reinforced Rectangular Beams (BRRB), and Steel Reinforced Rectangular Beams (SRRB), incorporating mechanical testing, durability assessment, load–displacement analysis, and statistical evaluation using Analysis of Variance (ANOVA).

The results demonstrate that bamboo, when properly treated and used within an optimized flanged beam configuration, can deliver load-bearing performance comparable to conventional steel-reinforced rectangular

beams. The ANOVA analysis revealed no statistically significant difference between the performance of BRFB and SRRB at the 95% confidence level, underscoring the structural efficiency of the flanged geometry in compensating for the lower tensile strength of bamboo relative to steel. This finding represents a critical outcome of the study, as it challenges the conventional assumption that steel reinforcement is categorically superior in all reinforced concrete applications.

In contrast, bamboo-reinforced rectangular beams exhibited significantly lower load-bearing capacity compared to steel-reinforced rectangular beams. The statistically significant difference observed between BRRB and SRRB confirms that beam geometry plays a decisive role in the effectiveness of bamboo as a reinforcement material. The absence of a flange in rectangular beams limits moment of inertia, stress redistribution, and ductility, thereby reducing structural efficiency even when treated bamboo reinforcement is used.

The superior performance of the bamboo-reinforced flanged beams is attributed to the combined effects of geometric optimization and material treatment. The flanged section increases flexural stiffness and provides a wider compression zone, while the applied bamboo treatments enhanced durability, bonding with concrete, and resistance to biological degradation. Together, these factors contributed to improved crack control, higher load capacity, and more stable post-peak behavior in BRFB specimens.

From a sustainability perspective, the findings reinforce bamboo's potential as a viable, low-carbon alternative to steel reinforcement in low- to medium-load structural applications. Given bamboo's rapid renewability, low embodied energy, and widespread availability in developing regions, its successful application in flanged beam configurations presents a compelling opportunity for sustainable infrastructure development, particularly in resource-constrained environments.

This study establishes that the performance of bamboo-reinforced concrete systems depends not only on material properties but also critically on structural design. Treated bamboo, when integrated into flanged beam geometries, can achieve reliable and statistically comparable performance to steel-reinforced systems. Future research should extend this work to full-scale structural elements, long-term durability under aggressive exposure conditions, and design optimization frameworks to facilitate the broader adoption of bamboo-reinforced flanged beams in engineering practice.

Contribution to the Body of Knowledge

This research contributes to the body of knowledge in several distinct ways:

1. It establishes that treated bamboo, when used in flanged beam configurations, can deliver reliable and consistent structural performance, challenging the dominance of steel in low- to medium-load applications.
2. The study highlights the synergistic effect of cross-sectional design and bamboo treatment, demonstrating that geometry plays a pivotal role in unlocking bamboo's structural potential.
3. By incorporating ANOVA analysis, the research introduces a quantitative framework for assessing the consistency and significance of bamboo's performance, which is often overlooked in material substitution studies.
4. It reinforces bamboo's viability as a sustainable alternative in reinforced concrete, especially in regions where steel is economically or logistically inaccessible, aligning with global goals for green construction.

In conclusion, this study not only bridges a critical research gap but also lays the groundwork for future innovations in bamboo-reinforced structural systems. It invites engineers, researchers, and policymakers to reconsider bamboo—not as a compromise, but as a credible and sustainable reinforcement material when thoughtfully designed and treated.

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