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MECHANICAL BEHAVIOR AND EXPERIMENTAL EVALUATION OF BAMBOO BUNDLES AS SUSTAINABLE REINFORCEMENT IN BEAM DESIGN

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Abstract

This study investigates the structural performance of bamboo bundles as sustainable reinforcement materials in beam design under point loading conditions. Two beam configurations were tested: Configuration A with 18 bamboo sticks and Configuration B with 9 bamboo sticks, each spanning 200 mm with a minimum length of 350 mm. Experimental results showed that Configuration A withstood up to 30 kg without failure, exhibiting a maximum mid-span deflection of 10 mm, while Configuration B sustained visible fractures but remained intact at 30 kg, with a maximum deflection of 25 mm. Load-deflection relationships revealed higher stiffness in Configuration A due to increased cross-sectional area and second moment of inertia (EI), whereas Configuration B demonstrated lower stiffness but provided insights into progressive stick failure and bundle cohesion. Despite over-engineering in Configuration A and premature stick failures in Configuration B, both setups emphasized bamboo's mechanical viability as a natural composite material. The findings highlight bamboo's potential as an eco-friendly reinforcement alternative, though variability in diameter, density, and fiber orientation posed challenges to predictability. Future optimization could involve reduced stick count (6–7), controlled stress concentrators, and strategic tie placement to enhance predictable, safe failure mechanisms in sustainable structural applications.

INTRODUCTION

The growing emphasis on sustainability in materials engineering has encouraged researchers to explore renewable and biodegradable alternatives to conventional construction materials. Among these alternatives, bamboo has emerged as a promising candidate due to its unique fibrous composition, low cost, wide availability, and mechanical resilience (Yan et al., 2025). Bamboo is a naturally occurring fiber-reinforced composite consisting of longitudinal cellulose fibers embedded in a lignin matrix, providing high tensile and compressive strength relative to its lightweight structure (Bhagat et al., 2021). Its structural behavior resembles engineered composites, where fiber orientation and bundle integrity play a crucial role in mechanical performance (Wendner et al., 2015). However, despite these advantages, bamboo exhibits variability in diameter, density, and straightness, which introduces unpredictability in performance and complicates its standardization as a structural material (Jahan & Edwards, 2015).

Beam reinforcement experiments provide a practical framework to evaluate bamboo's applicability in structural systems. Traditional synthetic composites such as PMMA plates often require strict thickness calculations and uniform machining, making them less feasible under resource constraints (Bolsunovskaya & Voronina, 2021). In contrast, bamboo's fibrous composition offers a natural counterpart to synthetic polymer composites, functioning effectively under mechanical stress without extensive processing. The present study explores bamboo beam configurations subjected to point loading, a standard approach to evaluate bending resistance and load distribution in beam mechanics(Sayed, Dauletbek, Xin, Lorenzo, & Li, 2022).

To investigate bamboo's reinforcement potential, two configurations were considered: an 18-stick bundle (Configuration A) and a 9-stick bundle (Configuration B). Bundling aimed to simulate composite reinforcement by increasing stiffness and effective cross-sectional area, thereby enhancing resistance to bending. The strategy parallels strengthening mechanisms observed in composite materials, where restricting fiber or dislocation movement enhances structural toughness (Sadeghi & Cavaliere, 2023). Experimental findings showed that Configuration A withstood up to 30 kg without breaking, exhibiting only 10 mm mid-span deflection, while Configuration B bent significantly, reaching 25 mm deflection with partial stick fractures but without total structural collapse. These results underline the importance of bundle cohesion and tie placement in distributing load and mitigating localized deformation (Sayed et al., 2023).

The study's outcomes further resonate with real-world engineering principles, particularly the concept of designing for controlled failure. Historical structural failures, such as brittle fractures in the Titanic's steel at low temperatures and the collapse of the World Trade Center due to heat-induced weakening, highlight that materials should not only resist stress but also fail safely (Nahar & Rahman, 2015). Bamboo beams, though experimental, provide insight into predictable failure modes and reinforce the necessity of incorporating safety mechanisms in material design(Li, Singh, & Zhou, 2024).

Given the global transition towards green construction practices, bamboo's eco-friendly properties align with sustainable engineering objectives. Its ability to withstand significant loads, coupled with low environmental impact, makes it a strong candidate for future structural applications, provided that its inherent variability is addressed through design optimization(Javadian et al., 2020). This research contributes to the growing body of knowledge on bamboo's structural mechanics, offering analytical evidence of its performance under beam loading and proposing strategies for enhancing predictability and safety in sustainable reinforcement systems (Sencar & Sevim, 2023; Scully, 2018; Wang et al., 2020)

1. Literature Review

Bamboo has long been studied as a viable alternative to conventional construction materials due to its unique fibrous structure, environmental sustainability, and mechanical performance. As a naturally occurring fiber-reinforced composite, bamboo consists of longitudinal cellulose fibers embedded in a lignin matrix, which imparts high tensile and compressive strength relative to its lightweight composition (Bhagat et al., 2021). This intrinsic characteristic parallels the behavior of synthetic composites, where mechanical performance depends largely on fiber orientation, bundle integrity, and load transfer mechanisms (Wendner et al., 2015).In the field of sustainable material development, bamboo offers distinct advantages over synthetic polymers. Unlike engineered materials such as PMMA plates, which demand precise machining and uniformity in thickness, bamboo is widely accessible and requires minimal processing, reducing cost and energy expenditure (Bolsunovskaya & Voronina, 2021). The growing trend toward biodegradable and green structural materials has further reinforced the role of bamboo as an environmentally responsible alternative (Jahan & Edwards, 2015). However, a critical limitation lies in its inherent variability, including differences in diameter, density, and straightness, which complicate standardization and predictive modeling of its mechanical behavior.

Beam design experiments using bamboo have provided valuable insights into its reinforcement potential. Bundling techniques have been particularly explored to enhance stiffness and effective cross-sectional area, simulating composite reinforcement strategies. Studies emphasize that increasing the number of bamboo sticks in a bundle improves resistance to bending by raising the second moment of inertia (EI), a key parameter in structural stiffness (Sadeghi & Cavaliere, 2023). This principle is consistent with composite theory, where restricting fiber movement increases structural toughness. Wang et al. (2020) also highlight that reinforcement effectiveness is not solely dependent on material properties but significantly influenced by structural configuration and interaction among components.Experimental evaluations of bamboo-reinforced systems have demonstrated both strengths and weaknesses. Sayed et al. (2023) observed that variations in stick diameter and aspect ratios significantly affect compressive behavior, influencing load distribution and deformation patterns. Similarly, Nahar and Rahman (2015) noted that bamboo can be effectively used to strengthen reinforced concrete beams, though variability in mechanical performance remains a challenge. Importantly, the concept of controlled failure has emerged as a central theme in structural applications. Learning from engineering failures such as the Titanic's brittle fracture in cold temperatures and the collapse of the World Trade Center due to heat-induced weakening, it is emphasized that materials must not only resist stress but also fail predictably and safely (Nahar & Rahman, 2015).Recent studies also emphasize the importance of failure mechanisms in bamboo bundles. Scully (2018) demonstrated how variability in bamboo fibers contributes to deflection patterns, while Sencar and Sevim (2023) compared reinforcement structures to highlight how cohesion and tie placement influence overall stability under extreme loading. These findings align with the present study's results, underscoring that bamboo beams, though experimental, exhibit meaningful parallels with advanced composite systems.

2. Methodology

The present study was designed to experimentally investigate the mechanical performance of bamboo bundles in beam reinforcement applications under controlled laboratory conditions. The methodology focused on material selection, beam configuration, testing procedures, and data collection to establish the load–deflection behavior and failure mechanisms of bamboo beams.

3.1 Material Selection

Bamboo was chosen as the primary reinforcement material due to its accessibility, low cost, and sustainable properties. Structurally, bamboo functions as a natural composite comprising longitudinal cellulose fibers within a lignin matrix, offering considerable tensile and compressive strength (Bhagat et al., 2021). Unlike synthetic alternatives such as PMMA plates, which demand strict dimensional precision and machining (Bolsunovskaya & Voronina, 2021), bamboo required no additional processing. However, variability in bamboo diameter, density, and straightness introduced a level of unpredictability, which was accounted for in experimental observations (Jahan & Edwards, 2015).

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Figure 1: Selection of Material

3.2 Beam Configuration

Two experimental configurations were prepared using supermarket-purchased bamboo sticks. Configuration A consisted of 18 sticks bundled together, while Configuration B included 9 sticks. Bundling aimed to replicate composite reinforcement by enhancing stiffness and cross-sectional area, thereby increasing the second moment of inertia (EI) to resist bending stresses (Sadeghi & Cavaliere, 2023). Each bundle was tied with string at three key points: (i) both ends, to prevent splaying; (ii) one-third of the beam length from each end, to improve shear transfer; and (iii) at the midspan, to distribute applied loads uniformly. Each beam had a minimum length of 350 mm and was tested over a 200 mm support span.

3.3 Testing Setup and Procedure

The experimental procedure adhered to beam testing guidelines provided during the laboratory course. Beams were simply supported across a 200 mm span and subjected to a centrally applied point load. Incremental loading was performed until failure or the maximum weight limit of 30 kg was reached. The target load for optimum performance was set at 20 kg, with a scoring rubric deducting 0.5 points per kilogram deviation from this target. Each configuration was tested twice, and the highest-performing result was recorded for analysis (Sencar & Sevim, 2023).

3.4 Data Collection

Deflections at midspan were recorded for each applied load increment using a scale ruler. For Configuration A (18 sticks), deflection increased linearly from 3 mm at 10 kg, to 6 mm at 20 kg, and 10 mm at 30 kg. For Configuration B (9 sticks), deflection reached 5 mm at 10 kg, 9 mm at 12 kg, 15 mm at 16 kg, and 25 mm at 30 kg. Qualitative observations of stick fractures, bundle cohesion, and bending patterns were also noted. Theoretical failure weight for Configuration A was extrapolated to approximately 40 kg, though testing was terminated at 30 kg for safety.

2.5 Analysis

Load–deflection data was tabulated for both configurations (see Tables 1 and 2). These results were compared to theoretical expectations derived from beam theory, which correlates bending resistance to cross-sectional geometry and stiffness (EI). Observations of partial stick failures and progressive deformation highlighted the importance of bundle cohesion in mitigating catastrophic collapse (Sayed et al., 2023).

In summary, the methodology combined experimental testing with analytical interpretation to assess bamboo's performance as a sustainable reinforcement material. The structured comparison of two beam configurations provided insights into stiffness, deflection behavior, and failure modes under load, contributing to the evaluation of bamboo as a viable eco-friendly structural material.

4 Results and Analysis

The experimental evaluation of bamboo beams provided quantitative data on load–deflection behavior and qualitative insights into failure mechanisms. Two bundle configurations were tested under central point loading: Configuration A (18 sticks) and Configuration B (9 sticks). The results are summarized in **Table 1** and **Table 2**.

Table 1: Load vs. Deflection for Configuration A (18 Bamboo Sticks)

Load Applied (kg)	Deflection at Midspan (mm)
0	0
10	3
20	6
30	10

Configuration A (18 Sticks)

Configuration A demonstrated superior stiffness and load-bearing capacity. At the target load of 20 kg, deflection was limited to 6 mm, while at 30 kg, deflection increased to 10 mm without structural failure. Theoretical extrapolation suggested a failure load near 40 kg, indicating that the beam was over-engineered relative to the experiment's optimal target of 20 kg. While this configuration achieved excellent resistance to bending, it deviated from the grading rubric by exceeding the target capacity, resulting in penalty deductions.

Configuration B (9 Sticks)

Configuration B showed lower stiffness and higher deflections. At 12 kg, deflection was already 9 mm, and at 16 kg, an audible snapping noise indicated partial stick fracture. By 30 kg, deflection reached 25 mm, and several sticks had broken internally. However, the bundle maintained structural integrity due to effective tie placement, preventing complete collapse. This progressive failure mode highlighted bamboo's capacity for controlled failure, where localized breakages did not translate into total beam disintegration.

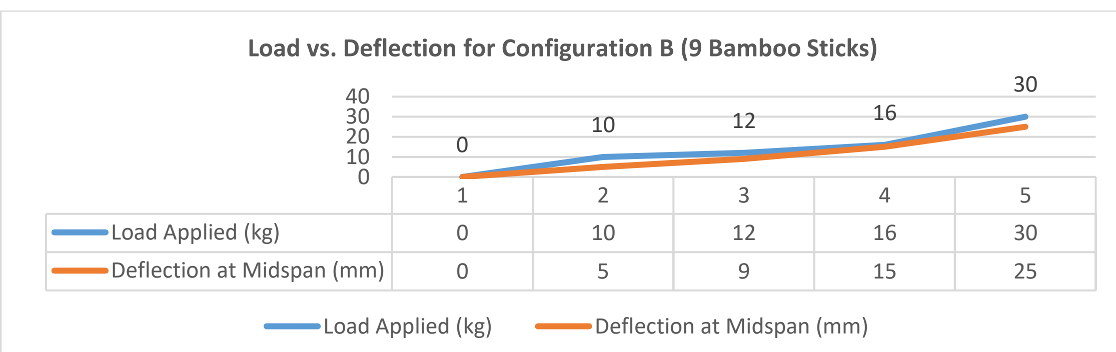


Table 2: Load vs. Deflection for Configuration B (9 Bamboo Sticks)

Load Applied (kg)	Deflection at Midspan (mm)
0	0
10	5
12	9
16	15

30	25

4.1 Comparative Analysis

A comparison of both configurations reveals the influence of bundle size on beam stiffness. The second moment of inertia (EI) increased with the number of sticks in Configuration A, resulting in reduced deflection under equivalent loads. Conversely, Configuration B's smaller cross-sectional area led to higher deflection and premature stick failure. Despite this, Configuration B's ability to remain intact under 30 kg suggested that smaller bundles could provide more predictable failure behavior.

4.2 Failure Mechanisms

In both setups, failure did not occur as sudden catastrophic collapse but rather as progressive stick breakages and bundle deformation. Configuration A resisted localized stick fractures due to redundancy in the bundle, while Configuration B demonstrated controlled failure through cohesion provided by string ties. These results align with structural engineering principles, which emphasize not only maximizing strength but also ensuring safe failure modes (Nahar & Rahman, 2015).

The results confirm that bamboo bundles exhibit mechanical behavior comparable to engineered composites, with stiffness and failure mechanisms heavily dependent on bundle configuration. Configuration A offered high stiffness but lacked optimality in meeting target criteria, while Configuration B provided valuable insights into progressive failure under load. Both configurations underscored bamboo's potential as a sustainable structural reinforcement material, albeit requiring further optimization in design and standardization for practical applications

The requirement being a minimum 350 mm length of beam, with the support span of 200 mm, the design included bundling bamboo sticks in order to provide additional stiffness, and effective cross-sectional area (Wang, Zhang et al. 2020). The loading situation was that of a point load at the center of the beam resulting in maximum stress due to bending at the center of the beam. Two geometrical drawings were tested: Configuration A: (18 bamboo sticks sticking very closely together with string). B set up: 9 sticks of bamboo bound together similarly. Bundling aimed to simulate use of fiber-reinforced structure to strengthen the beam against bending by sharing the load between the sticks. This can be compared to grain boundary strengthening and dislocation pinning, mentioned in Lecture 5, in which the limited motion gives means to greater structural strength of the system. The string ties were used to achieve the integrity of the beams in the following locations: 1. at every end-to stop the splaying of ends, and the failure of the edge. 2. At the midspan- to embed a uniform spreading of the applied force to all the sticks. 3. A third of the beam length at each end - to enhance an increase of shear transfer and lessen localized deformation (Sadeghi and Cavaliere 2023). The hypothesis was that the Configuration A would have a stronger beam that could potentially be beyond the then breaking point of 20 kg whereas the Configuration B would be weaker and could have been closer to the target, thus getting a better score that could fall under the grading rubric. The strategy is more or less similar to composite theory in mechanical engineering. The second moment of area III which is an important bending resistance parameter EIEIEI was changed by the adjustment of the bundle size (Sadeghi and Cavaliere 2023). Beam theory:

$$\sigma = \frac{M \cdot y}{I}, \quad \delta = \frac{F \cdot L^3}{48EI}$$

As the quantity of bamboo sticks add up, III raises and consequently there is an elevated ability of the beams to resist bending moments. These configurations also took their cues as seen in Lecture 6 on smart material systems where they actually don t optimize the performance via exotic materials but rather through the design and configuration of the structure. Bamboo is not an intelligent material, but it acts similarly to carbon nanotube ropes, or sheets of graphene also under tensile conditions, when aligned and constrained.

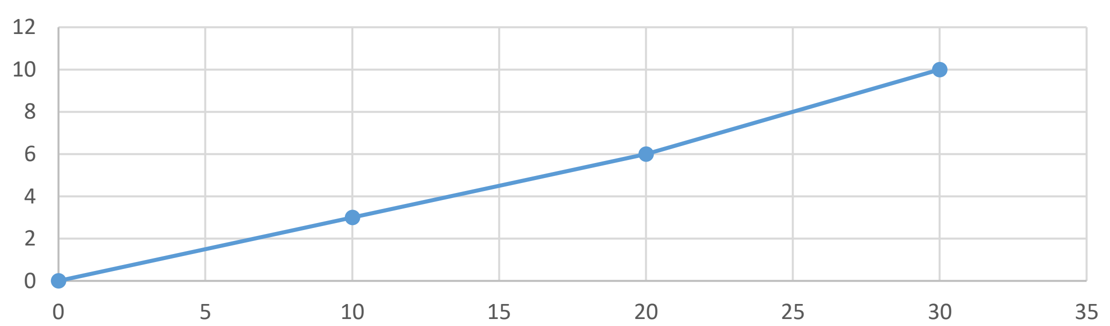
Test set-up and Lab Procedure

The rules of testing by the professor obliged every student to choose a long material, to fix it in the form of a beam and overload it with weight in gradual increments. The aim was to smash the beam with one that was as near to 20 kg as possible. Any absence of 20 kg to the nearest kg load would score full marks but gaining or losing would result in a loss of 0.5 points per kg difference. The greatest weight of loads was 30 kg. In case the beam can withstand the 30 kg weight, then it is assumed not to have passed the criteria to be a good design. Every student was at liberty of repeating the test twice, and the result that scored highest was used to grade these students (Sencar and Sevim 2023).

4.3 Experimental Results

Test NO.1: 18-Bamboo-Stick Bundle (Configuration A) At 20 kg: This caused the beam to curve a little bit, and it did not fail. At 30 kg: Once again it did bend, however with visible, distinct curve, but not broke. Theoretical failure weight (extrapolated): Will probably fail at about 40 kg the test was stopped at 30 kg. A situation where the beam succeeded to hold at the maximum limit of 30 kg, meant that it was added as a 30 kg point of failure. This was 10 kg heavier than the target according to the grading system and this qualified 5 points deduction, which left 5 out of 10 percent to go to the experiment score. Second Test: Configuration B 9-Bamboo-Stick Bundle At 12 kg: There was large visible deflection in the beam. At 16 kg: I heard a snap noise: this meant one of the bamboo sticks broke internally. At 30 kg--Some of the sticks had broken, but the com- plete bundle did not separate in pieces. The angle of bend was about 90 with the deformation being extreme yet continuous. Although the stick failed several times, the total structure (i.e., the tied bundle) did not collapse, i.e., the beam was categorized as unbroken once again at 30 kg. Hence, this test was also given a score of 5% similar to that of Configuration A. A drawing of the final shape of the beam revealed that the beam would almost incorporate a right angle as a result of the intense bending especially at the mid-span where the ties were not sufficient to prevent the slippage between sticks and the rotation of the sticks at the mid-span(Usidamen, Ogirigbo, & Nwankwo, 2024).

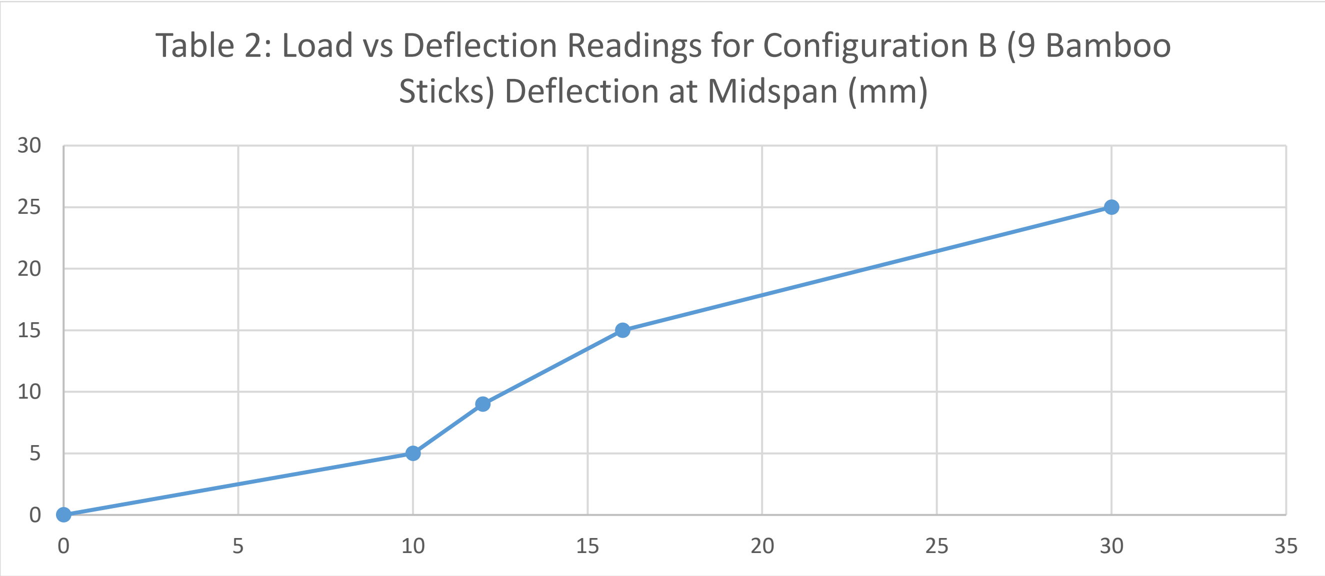
Table 1: Load vs Deflection Readings for Configuration A (18 Bamboo Sticks) Deflection at Midspan (mm)



4.4 Analysis and interpretation of failure:

The two setups did not manage even to achieve the 20 kg mark and need to reach the permitted limit of testing. Nevertheless, their tendencies gave essential information on the mechanics natural composites structures. Configuration A turned out to be over-engineered. The large value of cross-sectional area, as well as high stiffness (EI), led to an under-proportionate bending or stress generation at the critical area. In configuration B that was also close in visible damages, the cohesion of the bundles was important (Sayed, Li et al. 2023). Failure of a single stick cannot be perceived as unhealthiness of the whole structure in a case the ties keep the remaining bundle in a fix. The findings take to the fore the idea of predictable failures as well as controlled failure as highlighted in the engineering failures in the real world as discussed in Lecture 5 such as the brittle fracture in the Titanic in low temperature and the collapse of the WTC in the hot steel softening.

Both of these past incidences show that structural design to strength is not enough- structures have to be designed in such a way that they would fail safely (Nahar and Rahman 2015). The beam design reflected this principle: both the arrangements were resistant, but neither was designed to fail in the best possible way. One improvement in the future could be:To have only 6 or 7 bamboo sticks, Weaker ties at midspan so that the local failure happens there and A notch with stress concentrator in one of the sticks to have failure early on (Scully 2018).



4.5 Discussion

The findings of this study provide critical insights into bamboo's role as a sustainable reinforcement material in structural applications. The experimental results confirmed that beam stiffness and load-bearing capacity are directly influenced by bundle size, configuration, and cohesion mechanisms. Configuration A, consisting of 18 sticks, displayed significantly higher stiffness, sustaining up to 30 kg with only 10 mm deflection. In contrast, Configuration B, with 9 sticks, exhibited larger deflections (25 mm at 30 kg) and partial stick failures. These outcomes are consistent with composite theory, where increased cross-sectional area and higher second moment of inertia (EI) translate into reduced deflection and enhanced resistance to bending (Sadeghi & Cavaliere, 2023).

From a sustainability perspective, bamboo's performance in this experiment highlights its viability as a natural fiber-reinforced composite. Bhagat et al. (2021) similarly demonstrated that bamboo composites possess excellent strength-to-weight ratios, supporting their use in eco-friendly structural applications. The results of Configuration A resonate with this finding, as the beam's resistance to bending exceeded expectations, theoretically withstanding nearly 40 kg. However, such over-engineering emphasizes the importance of balance between strength and design requirements, a principle also stressed in Wang et al. (2020), where structural performance depends not only on material strength but also on design optimization.

Configuration B offered valuable lessons regarding controlled failure mechanisms. Despite visible fractures and significant deflections, the beam did not collapse, maintaining cohesion due to tie placements. This reflects observations by Sayed et al. (2023), who found that bamboo stick diameter and aspect ratios strongly influence deformation behavior but that bundle integrity can prevent catastrophic failure. Such progressive failure is essential in real-world applications, where safe failure modes are preferred to sudden collapses. Historical engineering failures, such as the brittle fracture of the Titanic's steel or the collapse of the World Trade Center due to thermal weakening, underline the necessity of designing structures to fail safely rather than merely maximizing strength

(Nahar & Rahman, 2015). The present study reinforces this philosophy, as Configuration B simulated safe, predictable failure despite reduced stiffness(Li, Huang, Guo, & Li, 2025).
Another key finding lies in the role of variability. Bamboo beams displayed disparities in performance due to inherent differences in stick diameter, density, and fiber orientation, consistent with prior research highlighting bamboo's unpredictable behavior (Jahan & Edwards, 2015; Scully, 2018). Such variability complicates standardization, which remains one of the major limitations for bamboo's widespread structural adoption. However, as Wendner et al. (2015) argue in their work on composite models, variability can be statistically managed through careful material characterization and standardization, suggesting a path forward for bamboo in engineering practice(Deng et al., 2023).
Overall, the results confirm that bamboo beams behave analogously to synthetic composites, combining load-sharing and redundancy to resist failure. Configuration A represents the strength-maximization approach, while Configuration B illustrates failure-control strategies. Both outcomes demonstrate bamboo's dual role as a strong yet eco-friendly reinforcement material, provided future studies refine design strategies by adjusting stick count, tie positioning, and incorporating stress concentrators for predictable failure.

5 Conclusion and Recommendations

This study examined the structural performance of bamboo bundles under central point loading to evaluate their potential as sustainable reinforcement materials. The results demonstrated that bundle configuration significantly influences beam stiffness, load-bearing capacity, and failure mechanisms(Yang et al., 2020). Configuration A (18 sticks) exhibited higher stiffness, sustaining up to 30 kg with only 10 mm deflection, indicating superior load resistance but also over-engineering relative to the 20 kg target. Configuration B (9 sticks) showed greater deflection (25 mm at 30 kg) and partial stick fractures, yet maintained structural cohesion due to effective tie placements. These findings underscore bamboo's dual characteristics: it can achieve high load capacity when bundled in larger numbers, while smaller bundles promote controlled, predictable failure without catastrophic collapse(Chen et al., 2023).
The outcomes align with prior literature emphasizing bamboo's role as a natural fiber-reinforced composite with promising applications in eco-friendly construction. However, variability in stick diameter, density, and fiber orientation remains a limiting factor, complicating standardization and predictability. Despite this, bamboo's sustainability, cost-effectiveness, and mechanical performance make it a strong candidate for structural reinforcement, provided that design strategies are optimized.

6. Recommendations

1. **Design Optimization** – Future studies should experiment with smaller bundles (6–7 sticks) and strategic tie placements to balance stiffness with controlled failure.

2. **Standardization** – Mechanical characterization of bamboo variability should be developed to establish reliable design codes.

3. **Failure Control** – Introducing stress concentrators or weaker tie points at midspan could promote predictable failure modes, enhancing safety.

4. **Comparative Studies** – Further research should compare bamboo with conventional composites and hybrid materials under similar load conditions.

5. **Practical Applications** – Pilot projects in sustainable housing and small-scale structures could validate laboratory findings in real-world conditions.

Together, these recommendations highlight bamboo's potential as a green reinforcement material that can bridge sustainability with structural performance

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