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Non-linear finite element analysis of bamboo reinforced concrete beams: Evaluating structural performance

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This study has evaluated the structural performance of Bamboo Reinforced Concrete (BRC) beams through a detailed Finite Element Method (FEM) analysis, utilizing different species of bamboo as reinforcement. The material properties, including density and Young's modulus of bamboo, have been established, showing significant variability across species. The '*Bullet*' bamboo has observed to have the highest Young's modulus, indicating potential for high stiffness applications, while '*Kanaat*' bamboo has displayed properties conducive to applications requiring flexibility and energy absorption under dynamic loading. FEM simulations have revealed that '*Bullet*' bamboo reinforced beams could withstand higher stresses in both tensile and compressive zones, suggesting a strong resistance to bending and making it an excellent candidate for structural elements. Conversely, '*Kanaat*' bamboo has exhibited a more even stress distribution, desirable in scenarios where a flexible response is beneficial. The stress and strain profiles for different bamboo reinforcements under loading conditions have been analysed, along with the stress distribution, along the beam's length and across its depth. The study has affirmed the potential of bamboo as a sustainable reinforcement material for concrete structures, with the choice of species playing a pivotal role in determining the beam's mechanical behaviour.

Keywords: Bamboo reinforced concrete (BRC), Finite element method (FEM) analysis, Structural performance, Sustainable construction materials

1 Introduction

In recent years, the push for sustainable construction materials has been at the forefront of engineering and architectural innovation. With the construction industry facing increasing environmental pressures, there is a growing need for alternative materials that can reduce carbon footprints and promote ecological balance. Bamboo, with its rapid growth, excellent mechanical properties, and carbon sequestration ability, has emerged as a promising reinforcement material in concrete structures. This study delves into the mechanical behaviour and performance of Bamboo Reinforced Concrete (BRC) beams by conducting a comprehensive non-linear Finite Element Method (FEM) analysis. Traditional steel reinforcement presents sustainability challenges, such as high energy consumption and significant carbon emissions during production. Bamboo, on the other hand, is abundantly available in many parts of the world and has a tensile strength comparable to that of steel, presenting a compelling case for its use in reinforcement applications. Non-linear FEM analysis offers an in-depth understanding of the complete stress-strain behaviour, including the post-yield response of materials, which is crucial for predicting the failure modes and overall safety of bamboo-reinforced structures. Figure 1 reveals a marked increase in research on Bamboo Reinforced Concrete beams, reflecting heightened interest and recognition of bamboo's potential in sustainable construction. This uptrend in scholarly publications, particularly over the

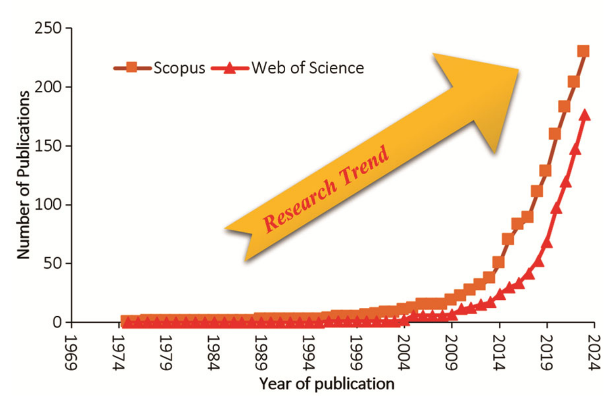

Fig. 1 — Trend analysis of research publications on bamboo reinforced concrete beams in Scopus and Web of Science databases.

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last two decades, underscores a broader commitment within the scientific community to explore and validate eco-friendly materials. The trend also validates the current study's relevance, contributing to a growing body of knowledge that supports the adoption of sustainable practices in structural engineering.

1.1 Background

The background of the study into the use of bamboo as reinforcement in concrete structures is both rich and varied, with historical records tracing back to the early 20th century in Southeast Asia. The early experimental explorations of bamboo-reinforced concrete were notably carried out across various global institutions, with seminal works by researchers such as Germany[1], alongside studies in Italy[2], the United States byGlenn[3], Smith and Saucier[4], and in Colombia[5]. These foundational studies predominantly utilized whole-culm bamboo bars or semi-round strips known as splints. Significant interest in the field was sparked by the US Navy's post-World War II initiative to facilitate rapid reconstruction in Southeast Asia, leading to Glenn's influential research financed by the US War Production Board[3,6]. Glenn's comprehensive mechanical tests and the subsequent construction of experimental buildings laid down early design and construction principles for bamboo reinforcement in concrete. However, Glenn also identified challenges, such as the propensity for high deflection, the brittleness under load, and bonding issues due to bamboo's tendency to crack and swell. To mitigate some of these issues, Glenn recommended specific bamboo tensile stresses based on maximum stress values observed during testing.

Subsequent to Glenn's work, notable 'design methodologies' were reported. Brink and Rush [7] advocated an allowable stress design approach for bamboo-reinforced concrete that paralleled the contemporary ACI 318[8] standards for steel reinforcement. They suggested specific bamboo tensile stresses and moduli of elasticity for bamboo as a tensile reinforcement. Geymayer and Cox[9]proposed a hybrid design approach, considering bamboo reinforcement as an additive to an unreinforced concrete member, recommending design stresses and moduli for bamboo used in both tension and flexural reinforcement, while paying heed to the unique bond behaviour of bamboo in concrete.

Regardless of the design approach, bond capacity emerged as a critical design limitation. For instance, bamboo reinforcing bars could develop a limited range of force when compared to steel, demonstrating the necessity for bond-enhancing measures. Research confirms that optimal longitudinal bamboo reinforcement ratios lie between 3 and 5%, substantially increasing the capacity of unreinforced concrete beams. The application of bituminous paint and wire wrapping on bamboo splints has been recommended to improve bond strength, as suggested by Ghavami [10].Further reinforcing the importance of bond treatment, Ghavami[11], Agarwal *et al.*[12], and Sevalia *et al.*[13] demonstrated that untreated bamboo splints offer negligible improvements over unreinforced concrete.

Conversely, beams with enhanced bond and appropriate reinforcement ratios exhibited significantly improved capacities[14]. Exploratory studies on axially loaded members such as concrete columns reinforced with bamboo also indicated potential for bamboo reinforcement to comply with building regulations and match the behaviour of steel reinforcement in certain conditions, although reliance on bond strength was less of a concern in these applications due to the specimen geometries[15,16].The historical context and previous research lay a solid foundation for the current study, demonstrating the evolving understanding of bamboo's capabilities and limitations as a reinforcement material in concrete structures. The durability of bamboo as a reinforcing material in concrete structures is a paramount consideration, intertwined with its natural composition of cellulose, hemicellulose, and ligni[17]. These components undergo chemical changes with the bamboo's age and after harvesting, initiating a decay process that Li *et al.*[18] and Hisham *et al.*[19] have found to correlate significantly with changes in chemical composition, age, and density.

Despite the paucity of studies specifically addressing bamboo's durability within concrete, extensive literature on the durability treatment of biomass in cementitious materials exists, with pioneering studies by Gram[20] and comprehensive reviews by Vo and Navard[21] and Pacheco-Torgal and Jalali[22]. These reviews, crucial to our understanding, focus on the durability issues pertinent to bamboo-reinforced concrete[23]. The highly alkaline environment of Portland cement concrete, which benefits steel by preventing corrosion, poses a risk to bamboo reinforcement. Alkali treatments known to break down the cell structure of lignocellulosic materials could result in significant degradation of bamboo embedded in concrete[24]. Reports by Hosoda[25] show alarming losses in tensile capacity of bamboo after prolonged exposure to high alkalinity, an environment not uncommon in hydrated cement and tropical climates. This vulnerability to high alkalinity is compounded by bamboo's natural proclivity for water absorption, leading to volumetric changes, and the material's susceptibility to biological attack. The latter, inclusive of insect infestation and fungal rot, is exacerbated by bamboo's thin-walled structure, high starch content, and lack of natural decay-resistant compounds. Protection strategies against such biological threats, such as chemical treatments and maintaining dry conditions, are a necessity, as noted in various studies[26–28].

Embedded in concrete, bamboo faces the risk of decay from moisture ingress, with the material's inherent porosity facilitating capillary action and moisture retention, particularly when cracks are present. While surface treatments may offer some degree of protection, they are generally insufficient in safeguarding against rot in timber and, by extension, bamboo[29]. These concerns highlight the complexity of using bamboo as a concrete reinforcement material and underscore the importance of comprehensive protective measures to ensure the durability and integrity of bamboo-reinforced concrete structures[30,31]. This background forms the basis for the current study, which aims to further our understanding of bamboo's suitability as a sustainable and durable reinforcement material, paving the way for its potential inclusion in concrete construction.

1.2 Importance of this study

The significance of this study extends beyond the technical analysis of Bamboo Reinforced Concrete (BRC) beams; it directly contributes to the achievement of multiple Sustainable Development Goals (SDGs) (Fig. 2). By integrating innovative approaches within the field of construction, this research aligns with SDG 9, as it seeks to bolster resilient infrastructure and foster sustainable industrialization through material innovation. The focus on bamboo as a building material underpins the commitment to SDG 11, advocating for sustainable cities and communities through the development of environmentally friendly infrastructure. Additionally, the study echoes the ethos of SDG 12 by promoting responsible consumption and production patterns, emphasizing the efficient use of resources and advocating for the sustainable management of natural materials. The potential reduction in greenhouse gas emissions, by substituting traditional construction materials with bamboo, illustrates a proactive step towards SDG 13, contributing to the global efforts in climate action. Lastly, the study underscores the role of bamboo in land restoration and biodiversity conservation, which is pivotal to SDG 15. Bamboo's cultivation and use do not necessitate the destruction of forests, thus preserving ecological balance and promoting life on land. Incorporating these SDGs, the study not only investigates the structural performance of BRC beams but also emphasizes the broader impact of engineering practices on environmental sustainability and societal well-being. It highlights the crucial role of research in the transition towards more sustainable construction practices, underlining the profound importance of this study in the context of global development goals.

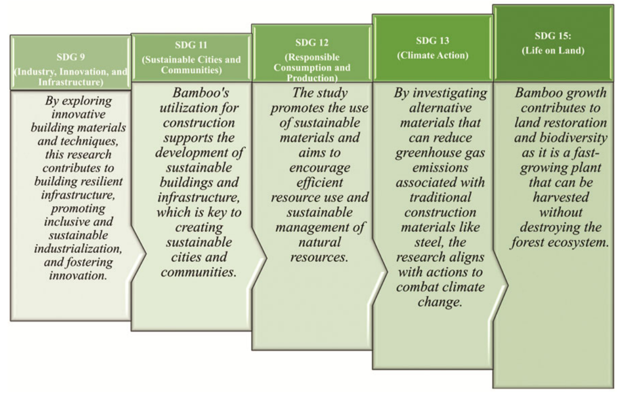

Fig. 2 — Alignment of the study's Objectives with sustainable development goals (SDGs)[32].

Figure 3 presents a co-occurrence network of key terms derived from the Scopus database, showcasing the thematic interconnections in the research landscape of bamboo reinforced concrete beams. Central to the network is the term "bamboo reinforced concrete," which is strongly linked to "fibre reinforced plastics," "microstructure," "mechanical testing," and "bamboo fibres," among others. This indicates a multifaceted research approach, encompassing material science, structural engineering, and sustainability studies. The prominence of terms such as "experimental study," "natural fibre," "composites," and "concrete construction" highlights the practical and experimental focus of current research. It also suggests a trend

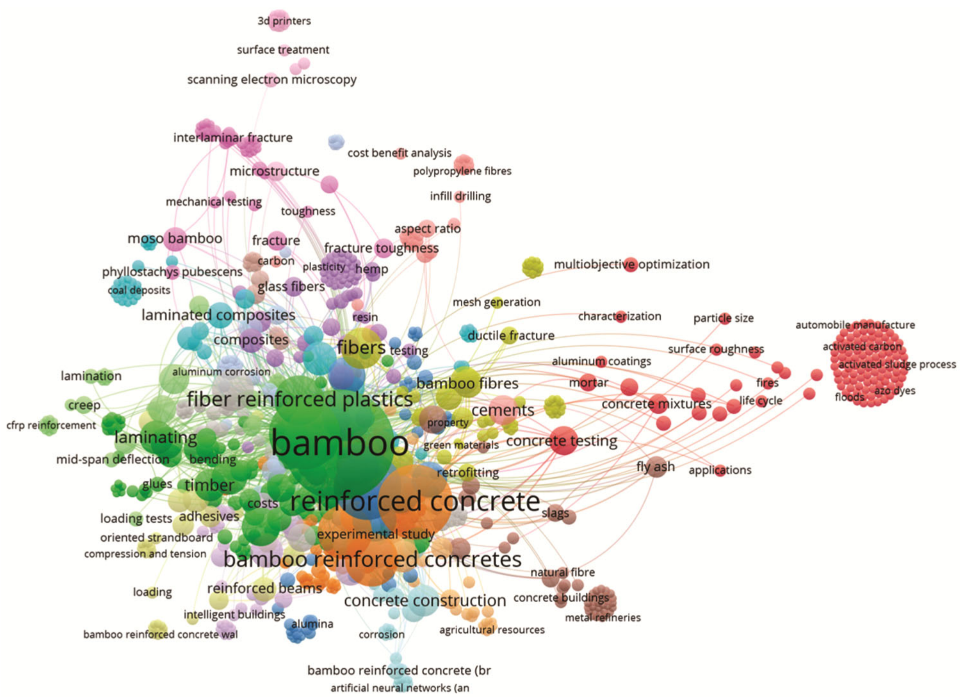

Fig. 3 — Co-occurrence network of terms related to bamboo reinforced concrete beams from Scopus database analysis.

towards exploring bamboo not just as an isolated material, but as a critical component within composite materials, investigating its interaction with concrete and its performance in construction settings. Furthermore, the co-occurrence of "bamboo reinforced concrete" with "green materials" and "sustainable resources" underlines the ecological aspect of this research, with an evident aim to address global sustainability challenges. The network also suggests emerging trends in the field, such as the consideration of "cost-benefit analysis" and "life cycle," which are essential for assessing the long-term economic and environmental viability of construction materials. This network visualization provides a comprehensive overview of the thematic structure and evolution of bamboo reinforced concrete research, underscoring the study's relevance in addressing current trends and contributing to the broader field of sustainable construction materials.

1.3 Objective of this study

The study's primary objective is to perform a non-linear Finite Element Analysis of Bamboo Reinforced Concrete beams to assess their structural efficacy and sustainability. This encompasses a detailed examination of bamboo's material properties and behaviour under stress, exploration of its environmental advantages.

2 Materials and Methods

2.1 General description of FEA

In this study, the Finite Element Analysis was conducted using the Abaqus software to evaluate the structural behaviour of bamboo-reinforced concrete beams under loading. The model represents a cantilever beam with dimensions of 230 mm in width, 300 mm in height, and 2600 mm in length, subject to a load applied at the free end as shown in Fig. 4. The beam was reinforced longitudinally with bamboo bars derived from five different species (Bullet, Deluxe, Choti-Khunti, Kanaat). The reinforcement layout included four bamboo bars, each with cross-sectional dimensions of 10.5 mm by 22 mm and a length of 2550 mm. Three of these bars were positioned along the bottom of the beam with a centre-to-centre spacing of 119.3 mm, optimizing structural integrity and load distribution. The top reinforcement featured two bars, strategically placed at a centre-to-centre spacing of 239.5 mm, providing additional tensile strength against the bending load. A uniform concrete cover of 50 mm was maintained on all sides to protect the reinforcement and ensure durability. The concrete used in the beam was of M20 grade, characterized by its high compressive strength and suitability for structural applications. The beam was modelled using the Static General Model in Abaqus, which is well-suited for analysing the static response of structures under applied loads.

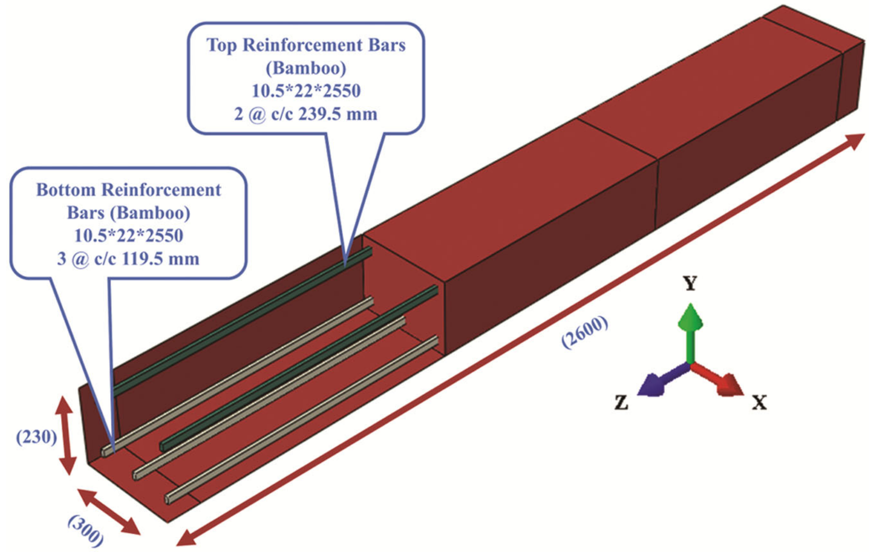

Fig. 4 — Schematic assembly of a bamboo reinforced beam model.

Table 1 — Material properties of bamboo species and M20 grade concrete for FEM analysis.

Part	Component	Density (kg/m^3)	Density (Tonne/mm^3)	Poisson's Ratio	Young's Modulus (Mpa)
Bullet	Bambusa bambos[33]	746.26	$7.463*10^{-10}$	0.334	3851.79
Deluxe	Bambusa polyporpha[33]	689.75	$6.898*10^{-10}$	0.334	3579.6
Choti – Khunti	Bambusa vulgaris [33]	868.85	$8.689*10^{-10}$	0.334	735.853
Kanaat	Gigantochloa Rostrata [33]	649.37	$6.494*10^{-10}$	0.334	288.289
Concrete	M20	2500	$2.50*10^{-9}$	0.18	22107.9

Table 2 — Mesh characteristics of concrete and bamboo reinforcement in FEM analysis.

Part Component	Type of Element	Number of Nodes	Number of Elements
Concrete	Linear Hexahedral (C3D8R)	58464	51900
Reinforcement Bars (Bamboo)	Linear Hexahedral (C3D8R)	1182	392

2.2 Material properties

In the FEM analysis, the mechanical properties of the bamboo species and M20 concrete are pivotal for predicting the behaviour of reinforced beams under load as described in Table 1. The densities of the bamboo species are markedly lower than that of concrete, suggesting lighter construction without compromising strength, essential for sustainable building practices. The Young's Modulus across the bamboo species varies widely, with Bambusa bambos (*Bullet*) being the stiffest, potentially contributing to higher rigidity in the composite beam. In contrast, Gigantochloa rostrata (*Kanaat*) exhibits the lowest stiffness, which could allow for more flexibility in the beam's response to stress (as shown in Table 1). The uniform Poisson's ratio among the bamboo species suggests similar lateral strain behaviour under axial loading. These variations in material properties are critical in assessing the suitability of each bamboo species for specific structural applications within concrete reinforcement. The Poisson's Ratio, consistent across the bamboo species, suggests a similar transverse to longitudinal strain response under stress, which does not significantly influence the deflection behaviour in this context. These material property variances are crucial for determining the selection of bamboo species for specific structural requirements and inform the design and utilization of bamboo as a sustainable alternative reinforcement in concrete structures

2.3 Mesh assignment

The finite element meshing parameters for the concrete matrix and bamboo reinforcement bars are detailed in Table 2. In the Abaqus model, the concrete component is discretized using 51,900 linear hexahedral (C3D8R) elements with a 15mm element size, providing a balance between computational efficiency and result accuracy. The reinforcement bars, modelled with a slightly smaller 13mm element size to capture the more complex behaviour of the bamboo within the concrete matrix, are constituted by 392 linear hexahedral (C3D8R) elements. A mesh sensitivity analysis was performed to ensure that the selected mesh sizes accurately capture the stress distribution and deformation without unnecessary computational overhead. The chosen mesh density for both materials reflect a refined approach necessary for analysing the nuances in the structural response of bamboo-reinforced concrete beams, critical for validating the effectiveness of bamboo as a reinforcing material.

2.4 Loading and boundary condition

Figure 5 presents the finite element model of the cantilever beam as configured in the Abaqus software, illustrating the applied loading and boundary conditions. The beam undergoes a displacement load of 50mm in the Y-direction at the free end, simulating a realistic bending scenario that the beam might encounter in service. This type of loading is crucial for understanding the deflection characteristics and the flexural response of the bamboo-reinforced concrete beam. The opposite end of the beam is subjected to fixed support conditions, which are mathematically denoted as Ux=Uy=Uz=UR1= UR2=UR3=0. This constraint effectively immobilizes the end of the beam in all translational and rotational degrees of freedom, replicating a perfectly clamped scenario typical in cantilever structures. This boundary condition is vital for the accurate assessment of the beam's behaviour under load since it influences the stress distribution and the natural frequencies of the system. The fidelity of the FEM analysis heavily depends on the accurate representation of these loading and support conditions. They are chosen to mimic the real-world constraints and forces that the bamboo-reinforced concrete beam would experience, ensuring that the simulation results are both relevant and applicable to practical design considerations.

3 Results and Discussion

3.1 Stress and strain generation profile

The displacement contours highlight the deformation gradient along the length of the beam as shown in Fig. 6. The maximum displacement occurs at the free end, as expected in a cantilever system, gradually decreasing towards the fixed support. The Von Mises stress profile (Fig. 7) reveals critical stress concentrations and the overall stress flow through the beam. The stress values are within the material’s elastic range, indicating that the bamboo reinforcement and concrete matrix are performing as intended under the applied load. The lower stress levels near the fixed support transition to higher levels towards the loaded end, suggesting a higher demand on the material’s mechanical properties in these regions.

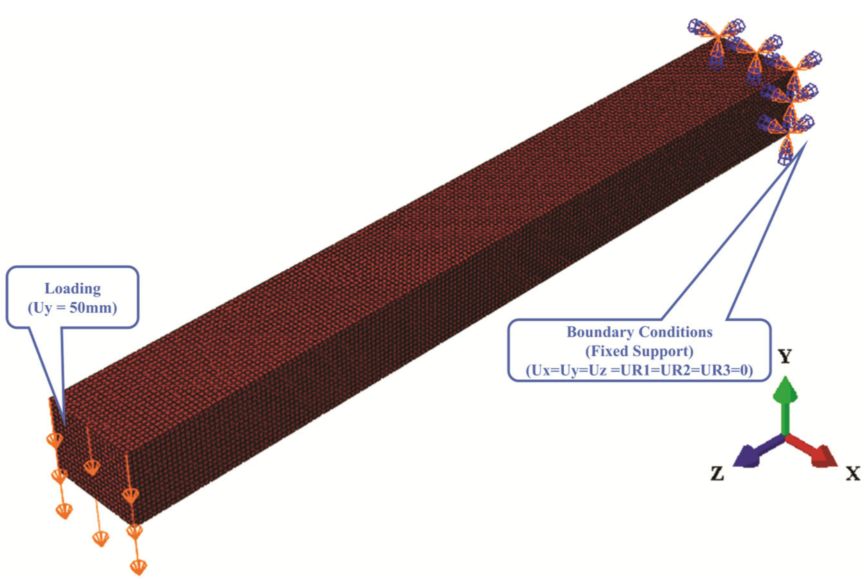

Fig. 5 — Finite element model of a cantilever beam showing loading and boundary conditions.

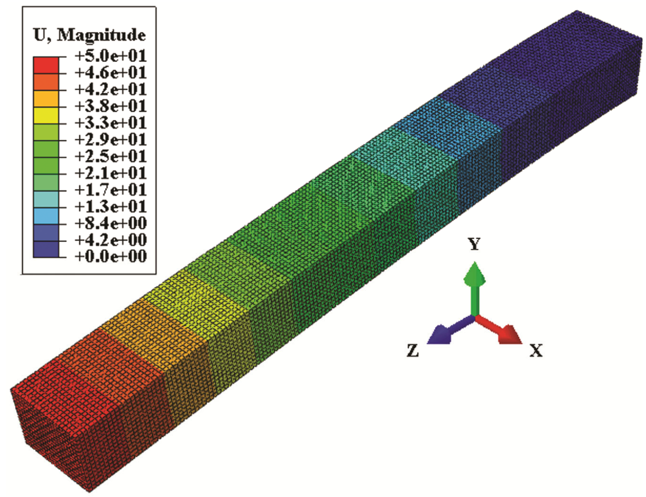

Fig. 6 — Displacement contours of the cantilever beam under applied loading.

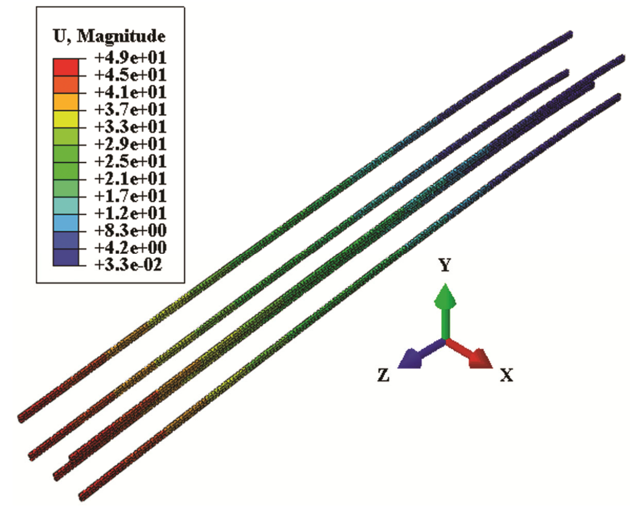

Fig. 8 — Displacement distribution in bamboo reinforcements of a cantilever beam.

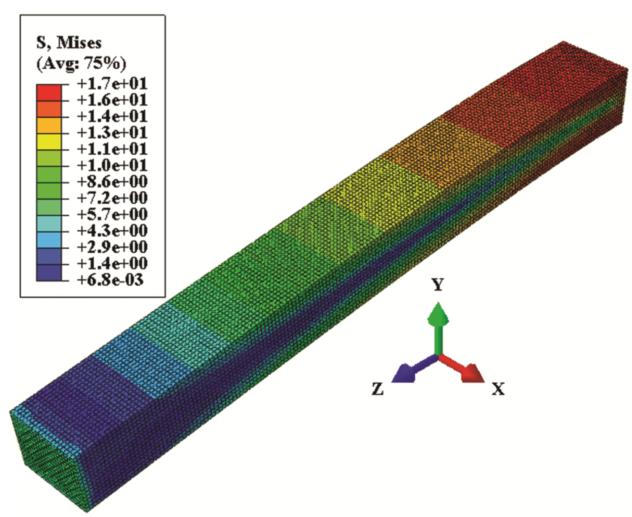

Fig. 7 — Von Mises stress distribution in the cantilever beam.

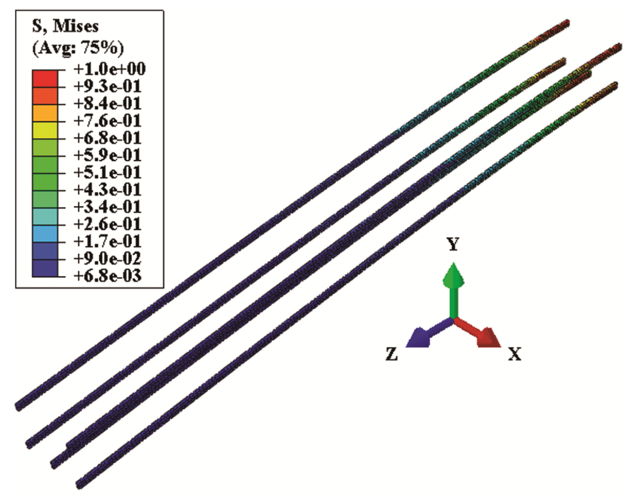

Fig. 9 — Stress distribution in bamboo reinforcements under loading.

Figure 8 illustrates the displacement distribution in the bamboo reinforcements within the cantilever beam. The gradients show varying displacement across the bars, providing insight into the flexural response and reinforcement efficiency. Figure 9 captures the Von Mises stress distribution in the bamboo reinforcements. The stress patterns reveal how the reinforcements share the applied load, crucial for evaluating their performance and optimizing reinforcement design. These figures highlight the compatibility of bamboo as a reinforcement material, offering a sustainable alternative in structural applications.

3.2 Load versus deflection and stress-strain curve

In the Load vs. Deflection analysis of Bamboo Reinforced Concrete (BRC) beams, the material properties outlined in the table are integral to understanding the behavioural differences between the various bamboo species under load as shown in Fig. 10. 'Bullet' bamboo, with its highest Young's Modulus among the tested species at 3851.79 MPa, demonstrates superior stiffness, which correlates with its increased reaction force at the support for a given deflection. This property implies that 'Bullet' bamboo can sustain greater loads before undergoing the same degree of deformation as the other species, making it an ideal candidate for applications requiring high stiffness and load-bearing capacity. On the other hand, 'Kanaat' exhibits the least reaction force at the support, which is reflective of its lower Young's Modulus (288.289 MPa), indicating a more flexible nature within the BRC beam under loading conditions.

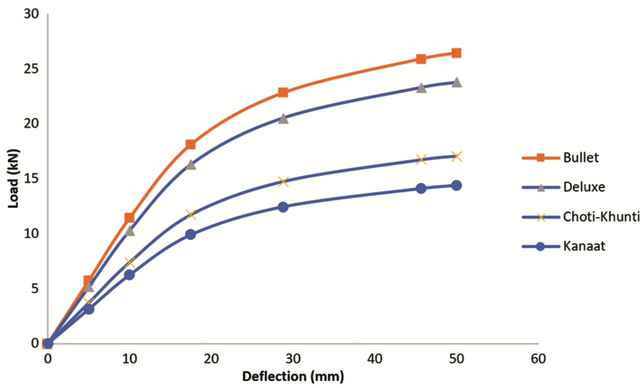

Fig. 10 — Load versus Deflection curves for bamboo reinforced concrete (BRC) beams with various bamboo species.

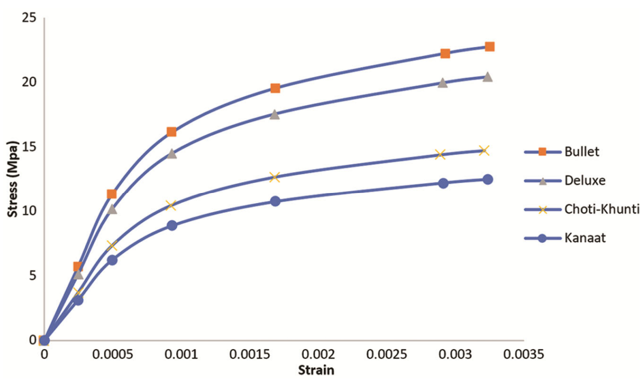

Fig. 11 — Stress-Strain Curves for Elements Adjacent to the Support in BRC Beams.

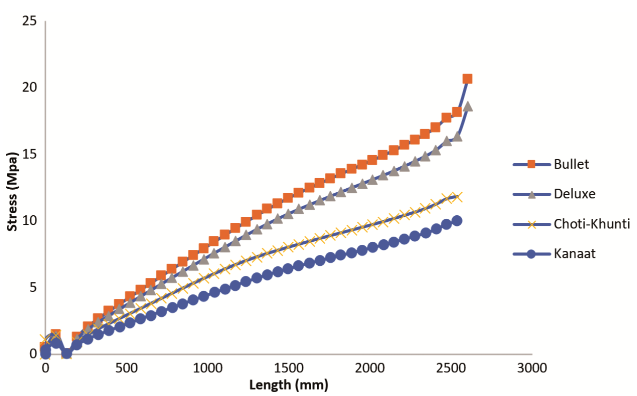

Fig. 12 — The stress distribution along the length of bamboo reinforced concrete (BRC) beams.

Despite having a lower modulus, 'Kanaat' may absorb energy more efficiently, which could be beneficial for applications where a certain degree of flexibility is advantageous. 'Deluxe' and 'Choti-Khunti' provide intermediate values in terms of stiffness and reaction forces, positioning them as versatile options depending on the required balance between stiffness and flexibility in the BRC beam design.

3.3 Stress-strain curve

The stress-strain profiles (Fig. 11) of concrete elements near the support, as depicted in the graph, show the elastic behaviour of the concrete when reinforced with different species of bamboo. The graph indicates that the 'Bullet' species reinforced concrete exhibits a higher stress at a corresponding strain in comparison to the other species, suggesting that the stiffness of the 'Bullet' bamboo contributes significantly to the overall stiffness of the concrete element. This is in line with the higher Young's modulus of 'Bullet' bamboo, which translates into a higher resistance to deformation in the composite material. 'Deluxe' and 'Choti-Khunti' species show a similar trend, with stress values increasing at a moderate rate with strain, denoting an expected elastic response before reaching the yield point. These species provide a balanced stress-strain behaviour that could be advantageous for structural elements requiring both strength and some ductility. The 'Kanaat' species reinforced concrete demonstrates the lowest stress for a given strain, which may be attributable to the lower Young's modulus of the 'Kanaat' bamboo, resulting in a more flexible response under loading conditions. This flexibility could potentially allow for greater energy absorption before failure, which might be desirable in seismic or dynamically loaded applications.

3.4 Stress generation along the length of BRC beam

The 'Bullet' bamboo reinforced beam demonstrates the highest stress values near the support, gradually increasing along the length of the beam as shown in Fig. 12. This could be attributed to the 'Bullet' bamboo's higher Young's modulus, indicating a stiffer and more resistant reinforcement, which tends to attract more stress in the system. As a result, 'Bullet' bamboo might be better suited for applications where high-stress resistance close to supports is critical.

The 'Deluxe' and 'Choti-Khunti' species show a moderate increase in stress along the beam's length. Their stress profiles suggest that these species provide a balanced distribution of stress, which may help to avoid stress concentrations that could lead to premature failure. 'Kanaat' bamboo, with the lowest stress increase, indicates a more flexible response along the beam's length. This behaviour may allow for a more uniform stress distribution, which can be beneficial in applications where the loading conditions are dynamic or variable. The stress gradients across all bamboo species highlight the importance of considering the distribution of stress in the design of BRC beams. The choice of bamboo species as reinforcement has a significant impact on the stress distribution along the beam, affecting the beam's overall performance and the design of the reinforced concrete structure.

3.5 Stress Strain generation in bamboo reinforcement

The stress-strain responses of bamboo reinforcements in both tensile and compressive zones of BRC beams provide a comprehensive understanding of the material's behaviour under different stress states (Fig. 13 & Fig. 14). In the tensile zone, 'Bullet' bamboo exhibits a higher stress for a given strain compared to other species, reaching the highest stress levels before plateauing. This indicates a robust tensile strength, suggesting that 'Bullet' bamboo is capable of carrying higher tensile loads, which is beneficial for regions in a beam where tensile forces are predominant. For 'Deluxe' and 'Choti-Khunti', the stress increases more gradually, indicating a less stiff response in tension, which could be favourable for applications where some degree of flexibility and ductility is required. 'Kanaat' shows the lowest stress response in tension, suggesting it might be better suited for applications where lower tensile forces are expected or where a higher strain capacity is needed before reaching critical stress levels. In the compressive zone, a similar trend is observed with 'Bullet' demonstrating a higher stress resistance. This could imply that 'Bullet' bamboo is also effective in withstanding compressive forces, making it a versatile reinforcement option for various loading conditions. The stress-strain curves are essential for identifying the suitability of each bamboo species for specific roles within BRC beams. The variations in stress at similar strain levels across the species underscore the importance of selecting the right type of bamboo based on the expected stress conditions in both tensile and compressive zones of structural elements.

3.6 Stress generation along the depth of BRC beam

The depicted stress gradient provides a visual representation of the neutral axis shift and the transition from tensile to compressive stress across the beam's depth as shown in Fig. 15. 'Bullet' bamboo shows the highest tensile stress at the upper regions of the beam, which rapidly transitions through the neutral axis and then into compressive stress. This

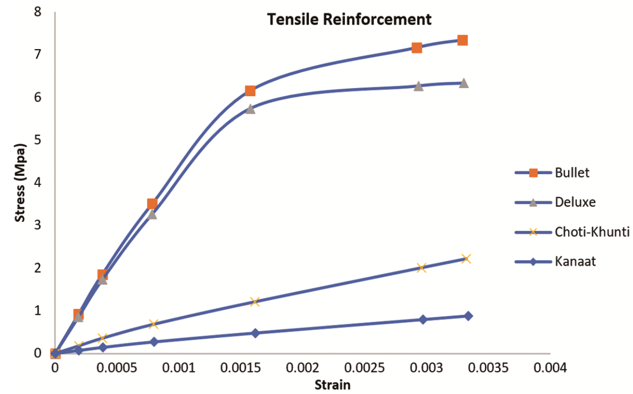

Fig. 13 — Stress-strain response of bamboo reinforcements in the tensile zone of BRC beam.

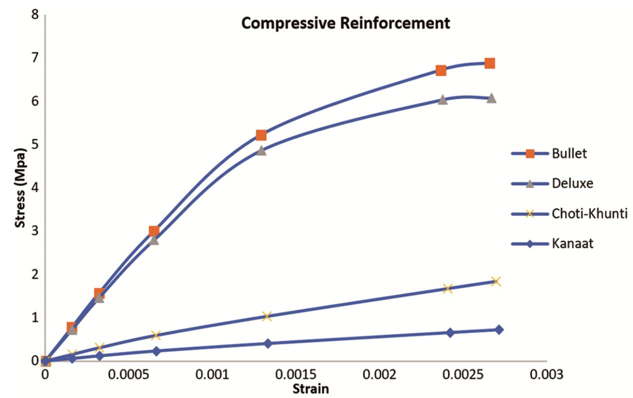

Fig. 14 — Stress-strain response of bamboo reinforcements in the compressive zone of BRC beams.

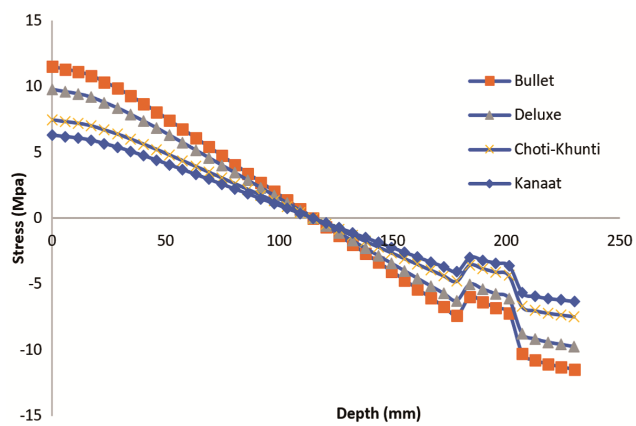

Fig. 15 — Stress gradient across the depth of BRC beams reinforced with various bamboo species.

indicates a strong resistance to bending and suggests a high modulus of elasticity, contributing to a steeper gradient. 'Kanaat', with the lowest gradient slope, indicates a more evenly distributed stress across the depth, pointing towards a reinforcement that allows for a more uniform stress distribution under bending loads. This might be particularly advantageous in scenarios where a beam is subjected to dynamic or reversing loading conditions. 'Deluxe' and 'Choti-Khunti' show intermediate stress gradients, suggesting balanced properties suitable for general-purpose structural applications.

The graph underscores the significance of the choice of bamboo species in determining the stress distribution in BRC beams. It is essential for optimizing beam design, especially in terms of the depth of the tensile and compressive reinforcement zones, to harness the full potential of bamboo as a sustainable construction material.

4 Conclusion

The comprehensive Finite Element Method analysis of Bamboo Reinforced Concrete (BRC) beams across various bamboo species has yielded significant insights into the structural performance and potential applications of these sustainable materials in construction. The conclusion of the study on the Finite Element Method analysis of Bamboo Reinforced Concrete (BRC) beams with different bamboo species can be summarized in the following key points:

a. The study demonstrated that the inherent material properties of the bamboo species, particularly Young's modulus and density, critically influence the structural behaviour of BRC beams.

b. 'Bullet' bamboo, with the highest Young's modulus among the species studied, exhibited the greatest resistance to deformation, suggesting it as a suitable option for structural applications requiring high stiffness.

c. In contrast, 'Kanaat' bamboo presented a more flexible response, which may be beneficial in structures subjected to dynamic or fluctuating loads, due to its lower stiffness.

d. The stress-strain profiles indicated that 'Bullet' bamboo can sustain higher stresses in both tensile and compressive zones, which points to its robustness as a reinforcement material.

e. There was a distinct variation in stress distribution along the beam's length and across its depth, with 'Bullet' bamboo reinforced beams showing steeper gradients, indicating strong resistance to bending near supports.

In conclusion, all bamboo species maintained structural integrity up to moderate stress levels, reinforcing the potential of bamboo as a sustainable and effective reinforcement material in concrete structures. The study highlighted the importance of selecting the appropriate bamboo species for different structural requirements, influencing the design and performance of BRC beams in sustainable construction.

Acknowledgement

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