



ORIGINAL RESEARCH ARTICLE

FINITE ELEMENT MODELING AND PERFORMANCE EVALUATION OF BAMBOO REINFORCED CONCRETE BEAMS AND COLUMNS

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ABSTRACT

The rising cost and environmental impact of steel reinforcement pose significant challenges to the construction industry. Bamboo, with its favourable mechanical properties and sustainability benefits, offers a promising alternative for reinforced concrete structures. However, accurately predicting its behaviour within concrete requires advanced modelling techniques. This study evaluates the structural performance of bamboo-reinforced concrete (BRC) beams and columns using Finite Element Analysis (FEA) in ABAQUS, validated against experimental data. Three beam configurations and five column configurations, featuring varying bamboo diameters and strip arrangements, were analysed using concrete grades M20 and M25. The results revealed a strong correlation between numerical and experimental outcomes, with correlation coefficients (R^2) ranging from 0.985 to 0.999. Experimentally, ultimate failure loads for beams ranged from 2.3 kN to 19.06 kN, while numerical predictions ranged from 2.89 kN to 18.0 kN. For columns, experimental failure loads varied between 127 kN and 357 kN, with numerical estimates deviating by less than 12%. A notable discrepancy of 26% was observed for Beam 3, primarily due to the weak bond between bamboo and concrete; a key limitation highlighted in this study. Overall, the findings demonstrate that finite element modelling can reliably predict the structural behaviour of BRC elements, particularly in lightly loaded applications. The study underscores the critical influence of reinforcement type and arrangement on failure loads and deflections.

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1.0 Introduction

Reinforced concrete is a structural material that overshadow other materials in the global construction due to the availability of its ingredients and simple skills requirement. The composite action of concrete and steel combines low cost, compressive strength and steel with high tensile strength and ductility (Bosunia, 2005). Steel reinforcement is placed in concrete structure to resist all tensile stresses, making it critical in overcoming weakness of concrete in tension and brittle failure (Basu et al., 2004). Additionally, the ductility of steel will make the concrete structure to undergo deformations and absorb energy before failure. This will provide warning signs and ensure safety especially under dynamic loads.

The construction industry faces challenges due to the rise in the price of construction materials, especially steel. This necessitates identifying a sustainable and cost-effective alternatives material (Atanda, 2015; Gana & Theophilus, 2016). After a number of researches, bamboo was found to be capable of being renewed and is an eco-friendly material that can provide a solution in areas where it's available, such as middle belt and southern parts of Nigeria (Gana & Theophilus, 2016). There is a high presence of bamboo ($\geq 10\%$ of vegetation) in Ogun, Rivers and Cross River states, while in states like Kano and Borno there is a limited presence ($< 3\%$) The bamboo material has an average culm height of 2.7 to 4.4 cm while its diameter ranges from 3.2 to 9.1 cm (Atanda, 2015). In addition, it's challenging to apply the findings of experimental analysis to real designs due to variations of bamboo's mechanical properties and its weak bonding with concrete (Archila et al., 2018). As

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a result of these challenges, the need to use modern techniques like numerical modeling to study and analyse the structural performance of bamboo as reinforcement in building structural elements. This study investigated the structural behaviour of bamboo reinforced concrete beams and columns subjected to bending and compressive loads, making use of numerical modeling with ABAQUS software and the results obtained were validated through experimental results obtained from previous research (Sethia & Baradiya, 2014; Usidamen & Ogirigbo, 2024).

2. Materials and Method

This study used material properties from various sources, including Abdullahi (2024), Sethia and Baradiya (2014), Siddika *et al.* (2017), and Salau *et al.* (2012). Using these properties, bamboo reinforced concrete beams and columns were modeled and the properties are presented in Table 1.

Table 1: Material properties for bamboo reinforced concrete beams and columns

Property	Material	Value(s)	Source / Notes
Density (Kg/m ³)	Concrete	2,400	Standard value
	Steel	7,870	Standard value
	Bamboo (Beams)	B1, B3 - 770 B2 - 900	Abdullahi (2024); Sethia and Baradiya (2014)
	Concrete (Beams)	B1, B3 - 22,977 B2 - 25,000	Abdullahi (2024); Sethia and Baradiya (2014)
Young's Modulus (MPa)	Concrete (Columns)	C1, C2, C3 - 22,977 (M20); C4, C5 - 25,000 (M25)	Siddika <i>et al.</i> (2017); Salau <i>et al.</i> (2012)
	Steel	200,000	Standard value
	Bamboo (Columns)	C1, C2 - 6,500; C3 - 25,700; C4, C5 - 5,993	Siddika <i>et al.</i> (2017) [C1, C2]; Daniel & Sivak. (2016) [C3]; Salau <i>et al.</i> (2012) [C4, C5]
	Concrete	0.2	Standard value
Poisson's Ratio	Steel	0.28	Standard value
	Bamboo	0.26	Standard value
	Steel	210 – 300	Standard range
Yield Stress (MPa)	Bamboo	50 – 85	Standard range
	Concrete (Columns)	C1, C2, C3 - 20 (M20); C4, C5 - 25 (M25)	Siddika <i>et al.</i> (2017) [C1, C2]; Daniel & Sivak. (2016) [C3]; Salau <i>et al.</i> (2012) [C4, C5]
Compressive Strength (MPa)	Concrete (Columns)	C1, C2, C3 - 3.13; C4, C5 - 3.5	Calculated from compressive strength (IS 456:2000)
Tensile Strength (MPa)	Concrete	0.0035	Standard value
	Steel	0 – 0.002	Standard value
Plastic/Inelastic Strain	Bamboo	0 – 0.002	Standard value
	Concrete	35	CDP model parameter
Dilation Angle	Concrete	0.1	CDP model parameter
Eccentricity	Concrete	1.16	CDP model parameter
F _{bo} /f _{co}	Concrete	0.6667	CDP model parameter
K	Concrete	0	CDP model parameter
Viscosity	Concrete	0	CDP model parameter

The values of Young's Modulus for bamboo reinforcement differ between column specimens (C1-C5) because they are not assumed theoretical values, but are instead specific material properties adopted directly from experimental studies used for validation. The values are adopted from the referenced experimental studies to reflect the specific bamboo materials used. For columns BRC-C1 and BRC-C2, a value of 6,500 MPa was adopted from Siddika *et al.* (2017). For column BRC-C3, a value of 25,700 MPa was adopted from Daniel & Sivakamasundari (2016). For columns BRC-C4 and BRC-C5, a value of 5,993 MPa was adopted from Salau *et al.* (2012).

In the ABAQUS model, the materials (bamboo and steel) are modeled using linear elastic and plastic material models. The tensile strength was not explicitly defined in the ABAQUS material module, as the plasticity model uses yield stress and hardening data.

This study employed Finite Element Analysis (FEA) in ABAQUS to simulate the structural behaviour of bamboo-reinforced concrete beams and columns, leveraging its versatility as noted by the International Federation for Structural Concrete (2008).

2.1 Specimen Configuration and Geometry

In this study, there are three beam specimens and five column specimens on which the finite element analysis was conducted. All the specimens have different reinforcement configurations. The geometry and reinforcement details are described below.

2.1.1 Beam specimens

The three beams had rectangular cross-sections (Beam 1 & 3 – 230mm x 230mm and Beam 2 – 150mm x 150mm) and were modeled as simply supported. The specific reinforcement configurations were as follows:

- Beam 1: The 3 meters beam was reinforced with four bamboo sticks, each with a diameter of 20 mm. The bamboo sticks were placed 2 each at top and bottom with 8mm mild steel wire at 250 mm center to center.
- Beam 2: This beam (0.75m in length) was reinforced with four bamboo sticks of a larger diameter of 27.5 mm. Similar to Beam 1, these were configured as the main tensile and hanger reinforcement with 7.5mm bamboo strips at 150 mm center to center.
- Beam 3: This beam (3 m length) was reinforced with 12 mm diameter steel bars at the bottom and 20mm diameter bamboo sticks as hanger bars with 8mm mild steel wire at 250 mm center to center.

2.1.2 Column specimens

The five column specimens designated BRC-C1 to BRC-C5. BRC-C3 has a cross section of 120mm x 120mm while the remaining have 150mm x 150mm cross sections, were analyzed under compressive loading with the following configurations:

- BRC-C1: The 1 meter length column was reinforced with four bamboo strips of 12 mm diameter with 2mm mild steel wire at 150 mm center to center.
- BRC-C2: The column is 1 meter in length and reinforced with six vertical bamboo strips of 12 mm diameter with 2mm mild steel wire at 150mm centers, which provides a higher reinforcement ratio than BRC-C1. The strips were evenly distributed around the perimeter of the cross-section.
- BRC-C3: This column (1.3m in length) has same bamboo reinforcement arrangement as BRC-C1, but the bamboo has different material properties.
- BRC-C4: 1 meter in length, reinforced with four vertical bamboo strips of (8x10) mm, bound with 1mm diameter wire at 100mm centers.
- BRC-C5: This column was reinforced with 6 rectangular bamboo strips of size 8mm x 10mm with stirrups at 100 mm center to center with 1mm diameter wire at 100mm centers.

Bending loads were applied on the beams in order to evaluate load deflection behaviour, ultimate failure loads and maximum deflections. Conversely, the columns were subjected to compressive loading to assess their load-bearing capacity, ductility, and failure modes.

2.2 The Procedure of Finite Element Analysis

The models were created in ABAQUS using the standard static/general procedure. The finite element analysis was conducted using ABAQUS/Standard and followed these steps:

- Material properties were defined (see Table 1) and assigned to the respective parts (concrete, bamboo, steel).
- A perfect bond was assumed between bamboo reinforcement and concrete using the embedded region constraint in ABAQUS. This simplification neglects potential bond slip behavior, which is later discussed as a source of discrepancy in Beam 3.
- The beam and column specimens were assembled and assigned interaction properties. The beam and column parts were created and assembled by creating instances and reorient them within the assembly model. The reinforcement (main bars and stirrups) were positioned at the center of the concrete as per the experimental set up as shown in Figures 1 and 2.

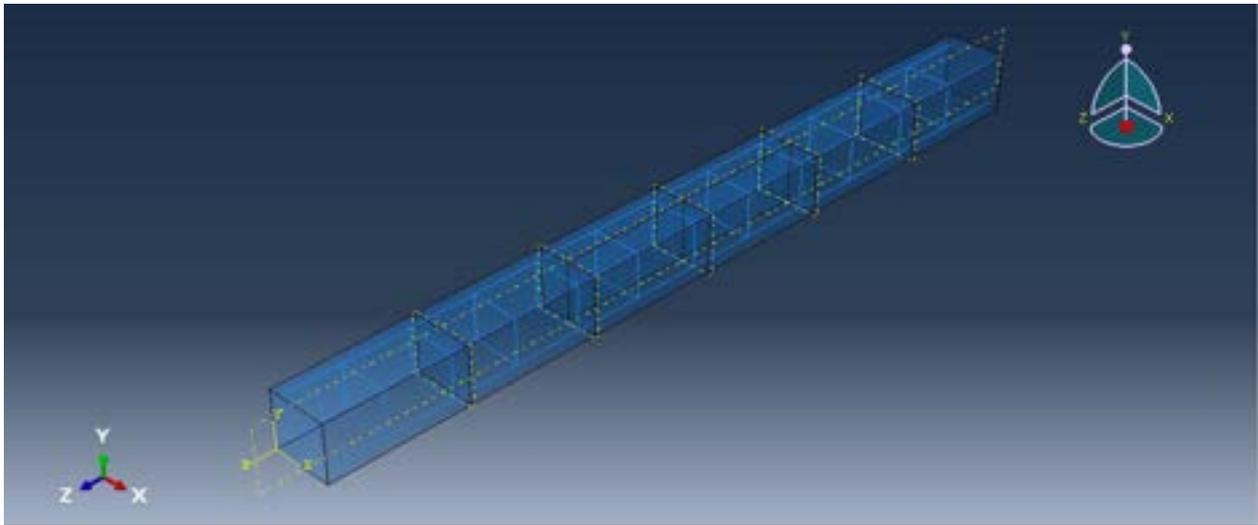


Figure 1: Beam Parts Assembly.

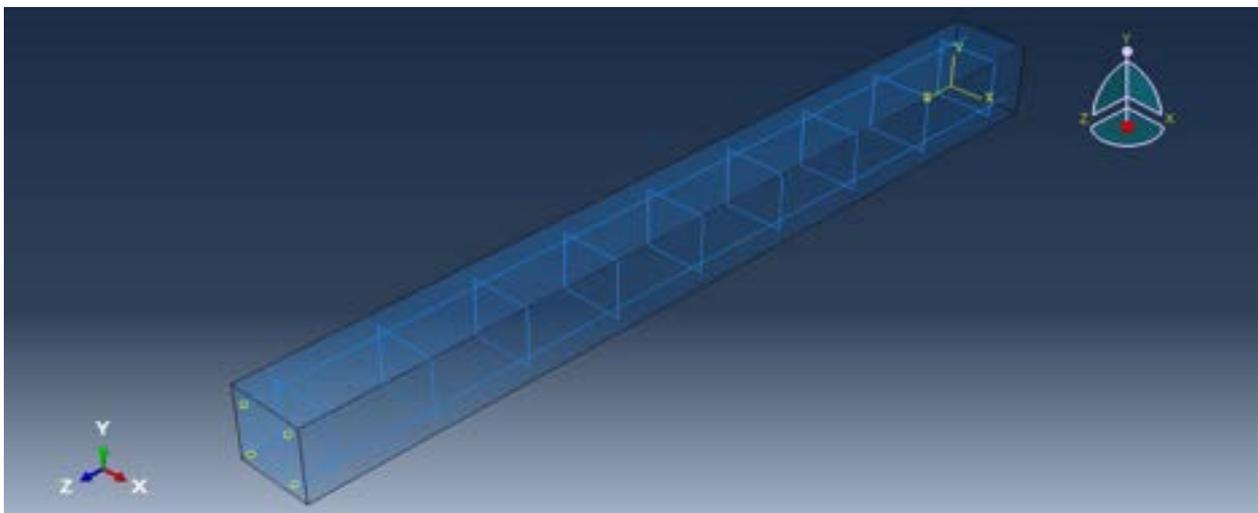


Figure 2: Column Parts Assembly.

- The models were meshed using standard element type for structural applications. For concrete, 3D solid type (beam) was used and for the reinforcement (bamboo and steel), they were modeled as truss elements and embedded within the concrete solid mesh. The mesh global size of 20 was used for the beam and 40 for the column parts. The concrete meshing are shown in Figures 3 and 4.

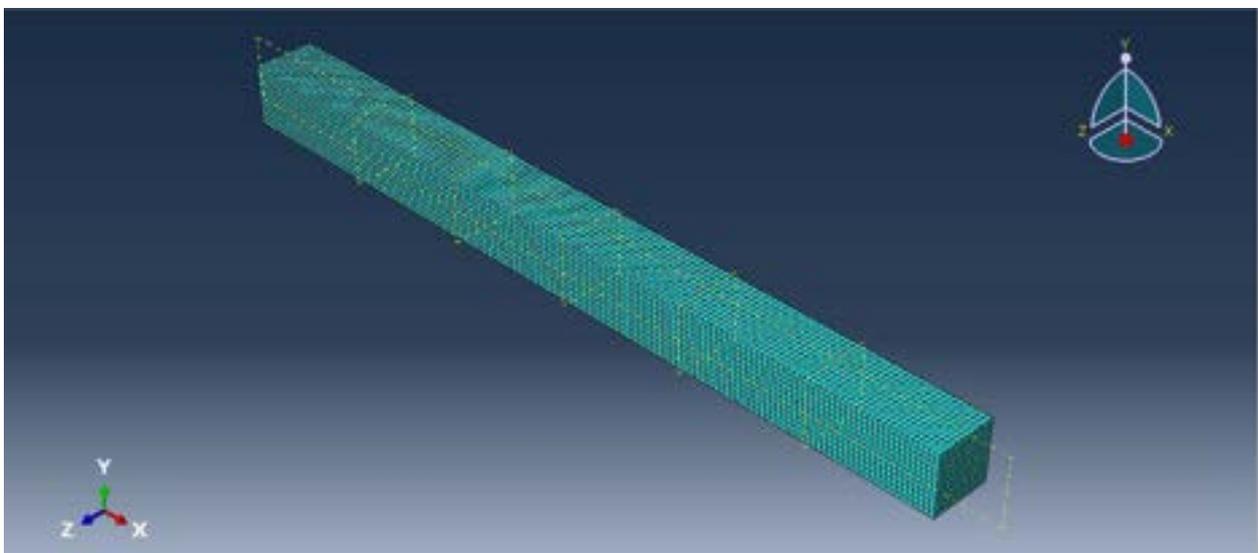


Figure 3: Concrete Beam Meshing.

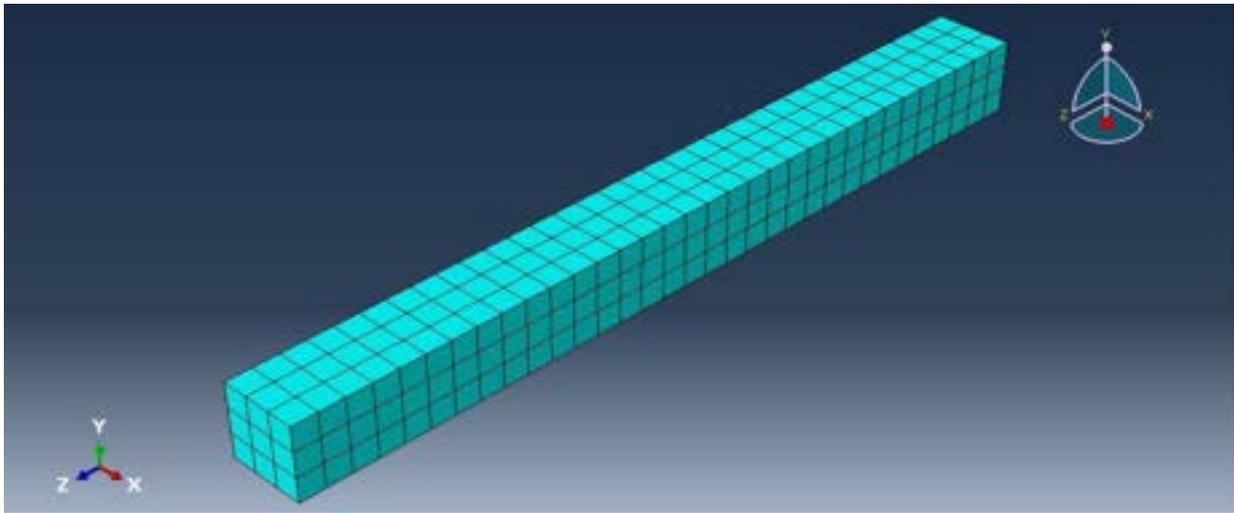


Figure 4: Concrete Column Meshing.

- Boundary conditions and loads were applied to simulate the experimental setup. For the columns, the base was fixed and the top was left free to simulate real world cantilever applications such as boundary walls, light poles. For the beams, pinned supports were used (See Figure 5) and a concentrated load was applied at mid span. As shown in Figure 6 below, the columns were loaded axially at the free end.

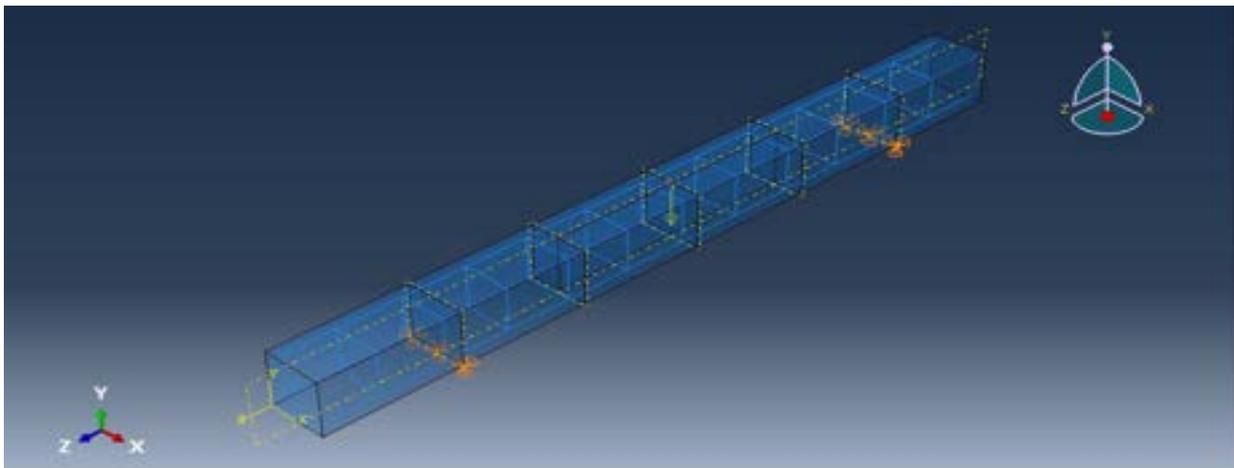


Figure 5: Load and Boundary Condition of the Beam.

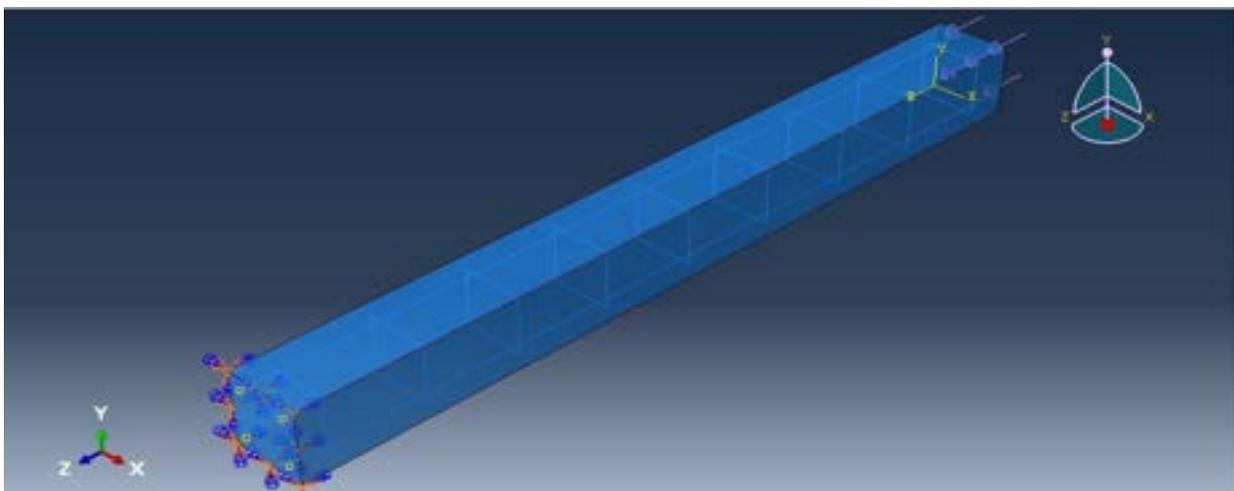


Figure 6: Load and Boundary Condition of the Column.

- The models were analyzed and results for load, deflection, and failure modes were extracted.

To confirm the validity of the models, the numerical results obtained were compared with the results of experimental data adopted from the literatures: Abdullahi (2024); Sethia and Baradiya (2014); Siddika *et al.* (2017) and Salau *et al.* (2012).

3. Results and Discussion

The numerical analysis of simply supported bamboo-reinforced concrete beams was conducted under serviceability deflection limits ($\text{span}/250 \approx 11.2 \text{ mm}$, per IS 456:2000). The experimental and numerical results (See Figures 7 – 30) show close agreement with little variations which are as a result of assumptions made by the numerical model. The key findings are summarized and presented in Table 2.

Table 2: Results of Experimental and Numerical Analysis of Bamboo reinforced concrete beams

Beam Specimen	Ultimate Failure Load (kN)		Maximum Deflection (mm)	
	Experimental	Numerical	Experimental	Numerical
Beam 1	4.8	4.84	1.1	0.7
Beam 2	19.06	18.0	2.03	2.1
Beam 3	2.3	2.89	1.3	0.72

There was a discrepancy as observed in Beam 3, where the numerical failure load of 2.89 kN was obtained which is higher than the experimental failure load (2.3 kN). The 26% difference is a significant discrepancy.

A perfect bond was assumed between bamboo and concrete using the embedded region constraint in ABAQUS in this study. The simplification led to an overestimation of load capacity in configurations where bond failure dominates, such as in Beam 3. The 26% over prediction is attributed to the bond slip behavior at the bamboo concrete interface, which was not captured in the numerical model. The failure of the bond would cause lower strength and an earlier failure in the experimental analysis than predicted in the FEA analysis, this is a challenge noted in numerical studies of bamboo reinforced concrete (Khatib & Nounu, 2017).

Muhtar *et al.* (2016) found that applying water resistant coat on the bamboo reinforcement and introduced hose clamp as mechanical interlocking device will improve the bond between bamboo and concrete. The second beam (Beam 2) was reinforced with larger diameter and demonstrated superior ductility, which aligns with the findings of Mali & Datta (2018) on bamboo concrete composite behaviour. The load deflection behaviour of Beams 1 and 3 (Figure 9 and 15) has shown a hybrid brittle ductile failure mode.

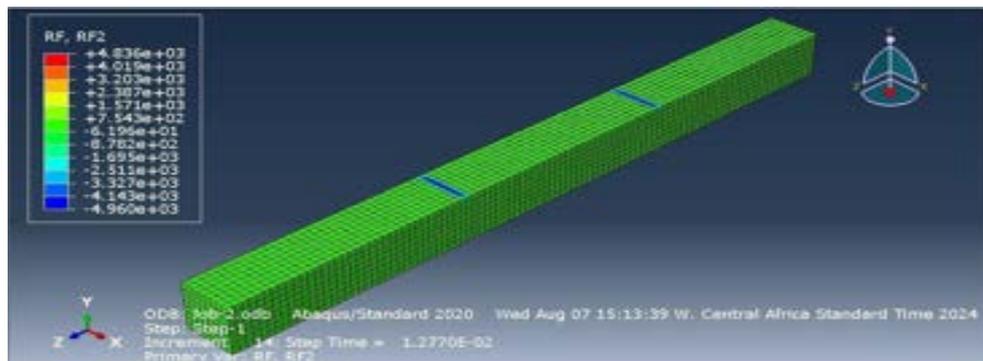


Figure 7: Applied loads on Beam 1

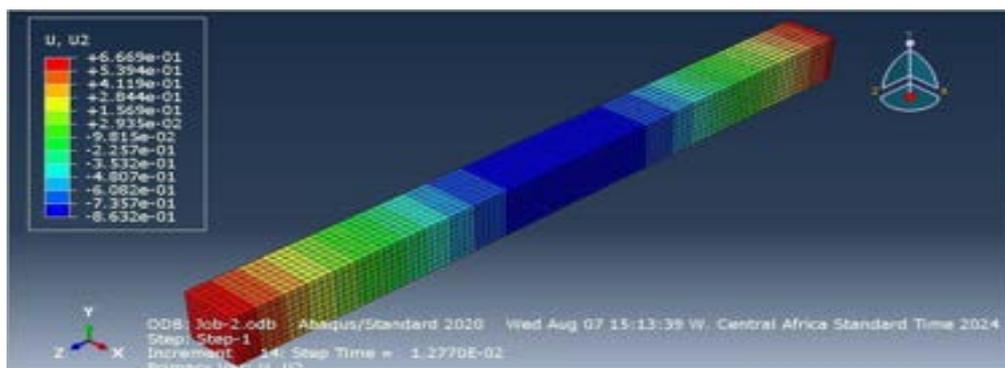


Figure 8: Deflection of Beam 1

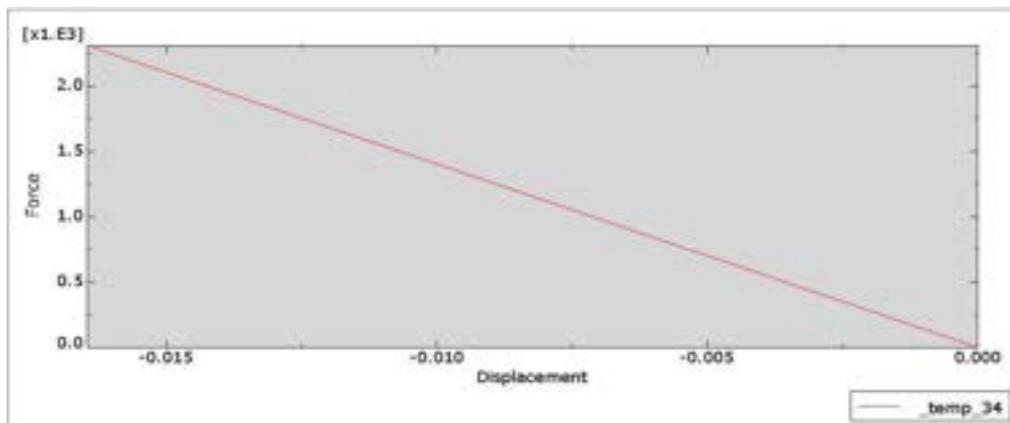


Figure 9: Load displacement curve for Beam 1

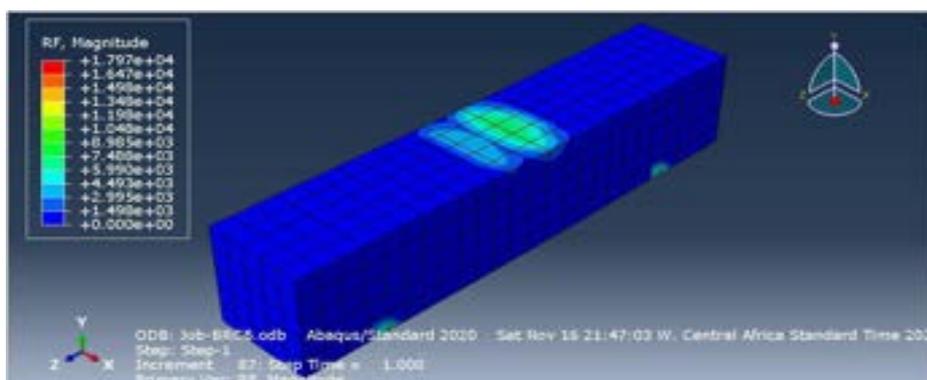


Figure 10: Applied loads on Beam 2

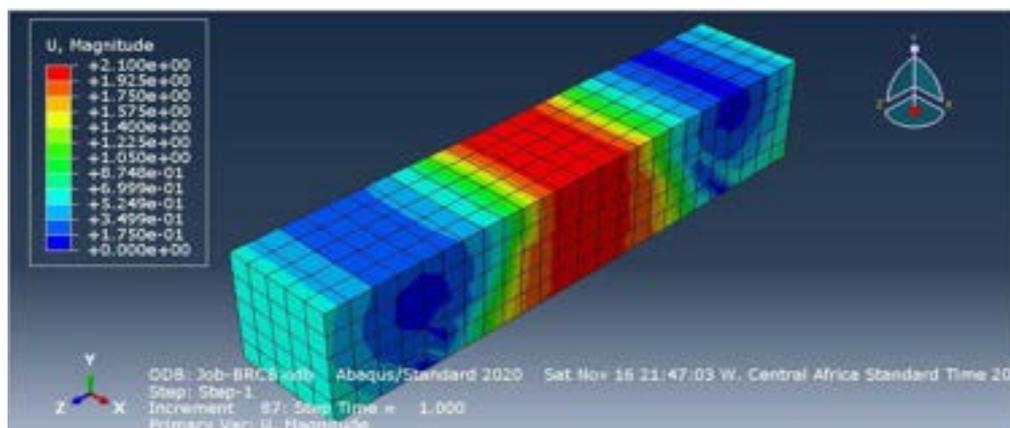


Figure 11: Deflection of Beam 2

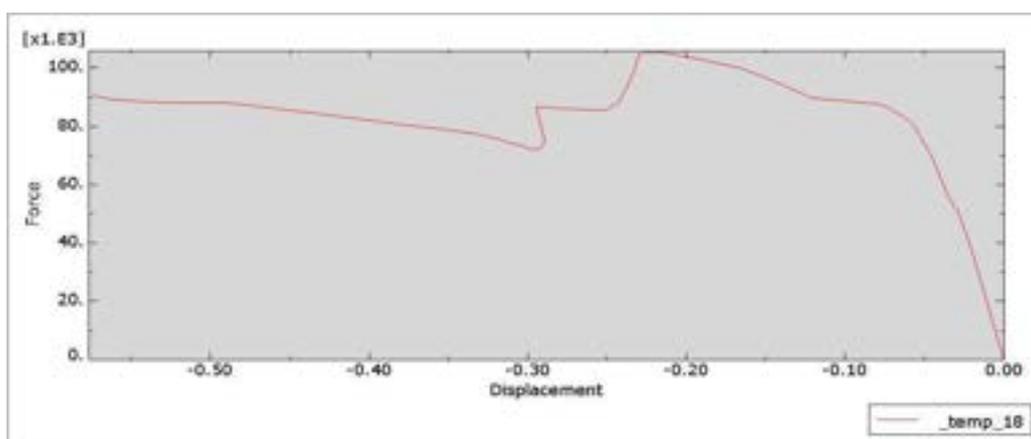


Figure 12: Load displacement curve for Beam 2

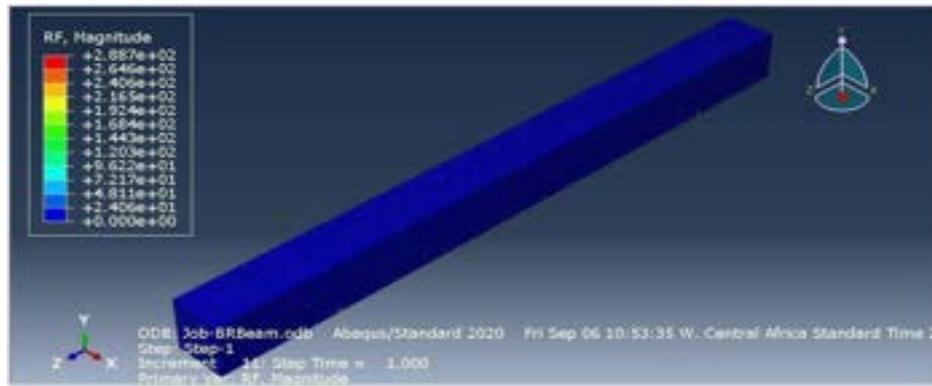


Figure 13: Applied loads on Beam 3

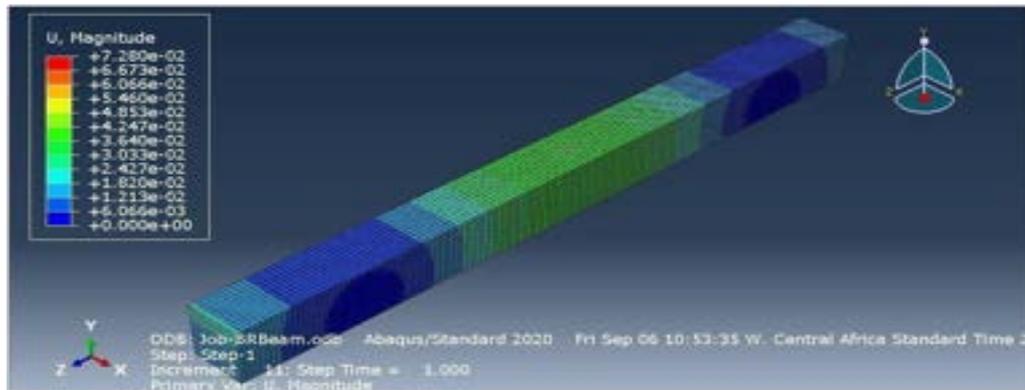


Figure 14: Deflection of Beam 3

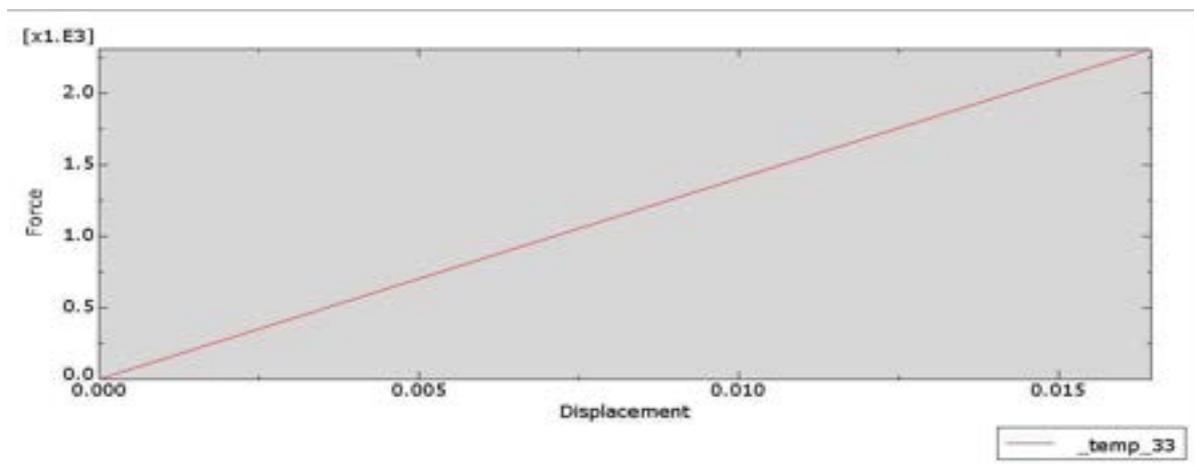


Figure 15: Load displacement curve for Beam 3

The bamboo reinforced concrete beams show brittle ductile failure mode and numerical models provide reliable results when the reinforcement arrangements are correctly modeled. The numerical results obtained showed consistent correlation with the experimental results. The performance of columns improves with an increased number of bamboo reinforcement bars (Ramesh *et al.*, 2021) as shown in Table 3.

Table 3: Results of Experimental and Numerical Analysis of Bamboo reinforced concrete columns

Column Specimen	Ultimate Failure Load (kN)		Maximum Deflection (mm)	
	Experimental	Numerical	Experimental	Numerical
BRC-C1	298	298.6	8	8.328
BRC-C2	321	325.6	9	9.510
BRC-C3	127	142.3	10.642	10.73
BRC-C4	332	318.8	6	6.174
BRC-C5	357	333.9	11	10.41

In Figures 18, 21, 24 and 27, the load displacement curves for the columns show much greater linear elastic behaviour and lead to failure. These behaviours correspond to that of experimental analysis, but with slight variations due to assumptions made by the model.

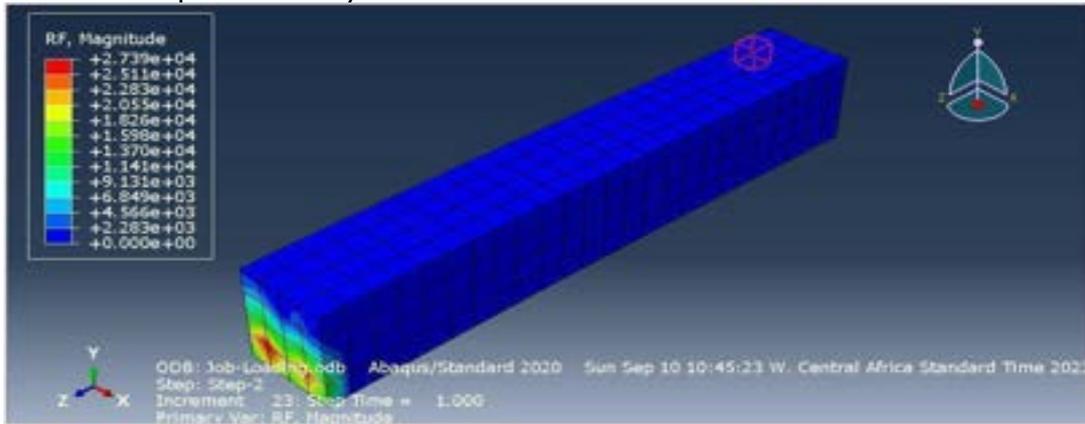


Figure 16: Applied loads on column BRC-C1

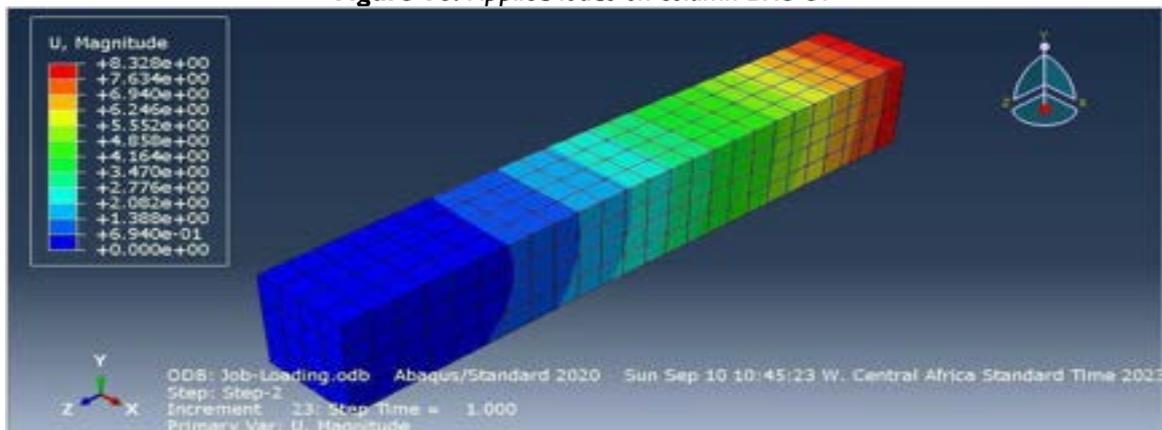


Figure 17: Deflection of BRC-C1 Column

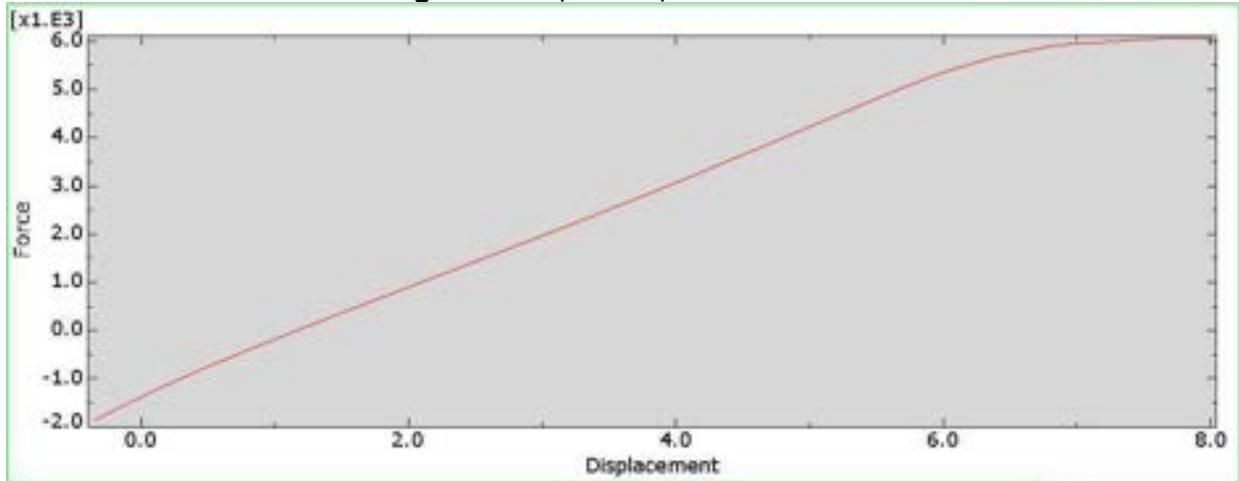


Figure 18: Load displacement curve for BRC-C1 Column

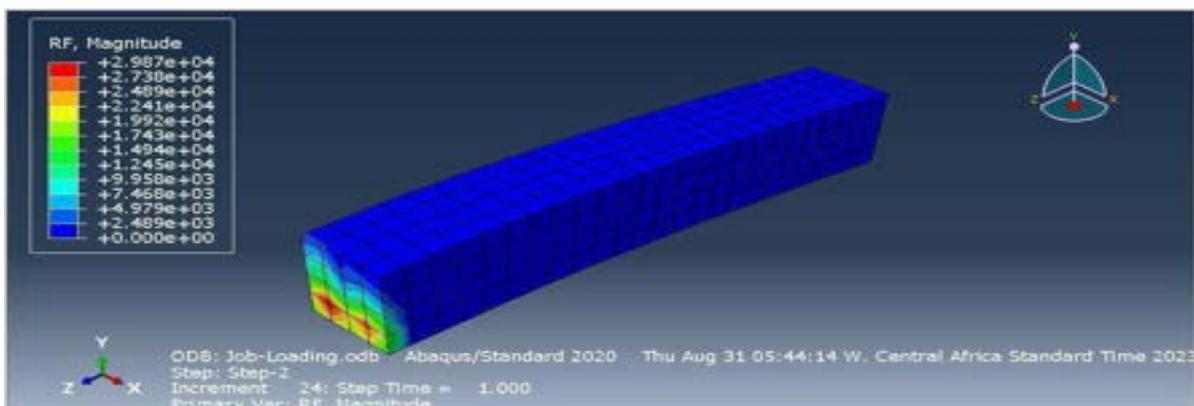


Figure 19: Applied loads on column BRC-C2

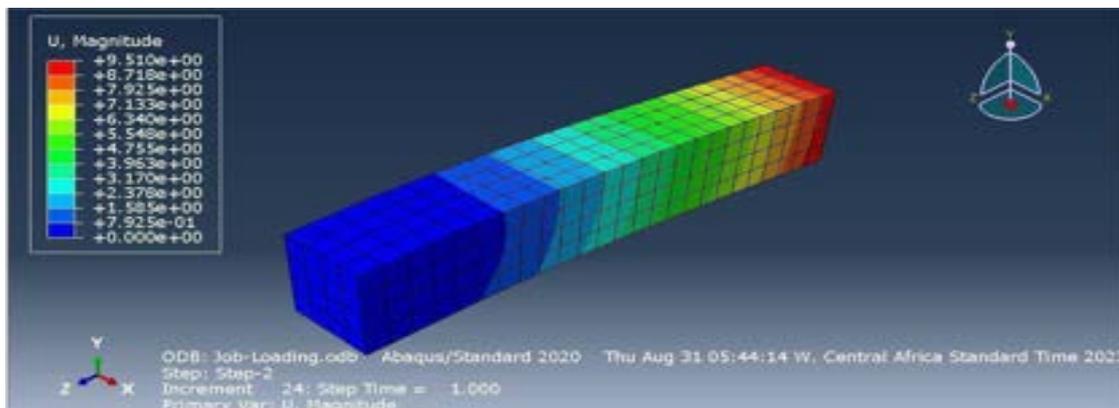


Figure 20: Deflection of BRC-C2 Column

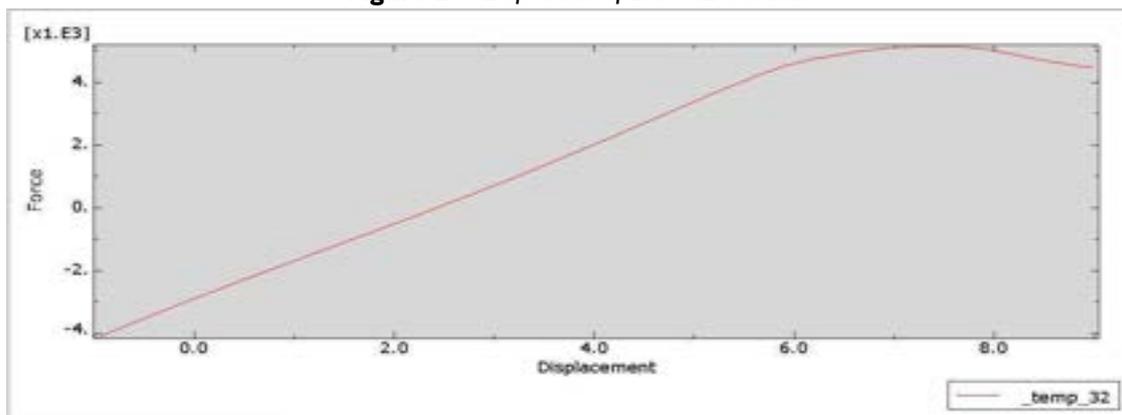


Figure 21: Load displacement curve for BRC-C2 Column

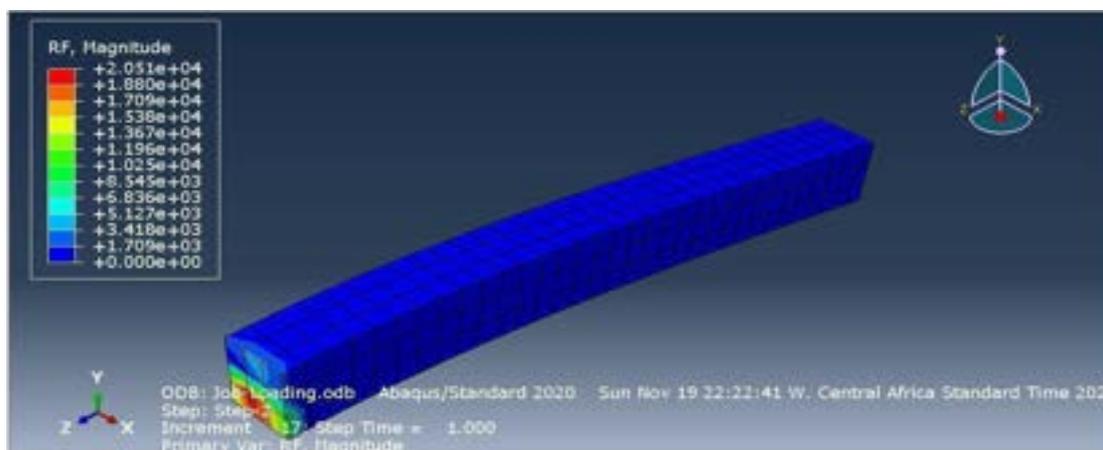


Figure 22: Applied loads on column BRC-C3

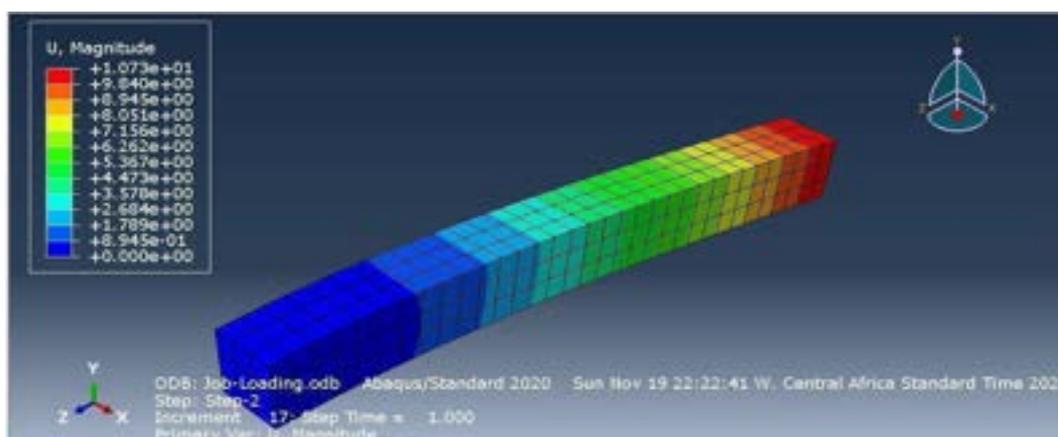


Figure 23: Deflection of Column BRC-C3

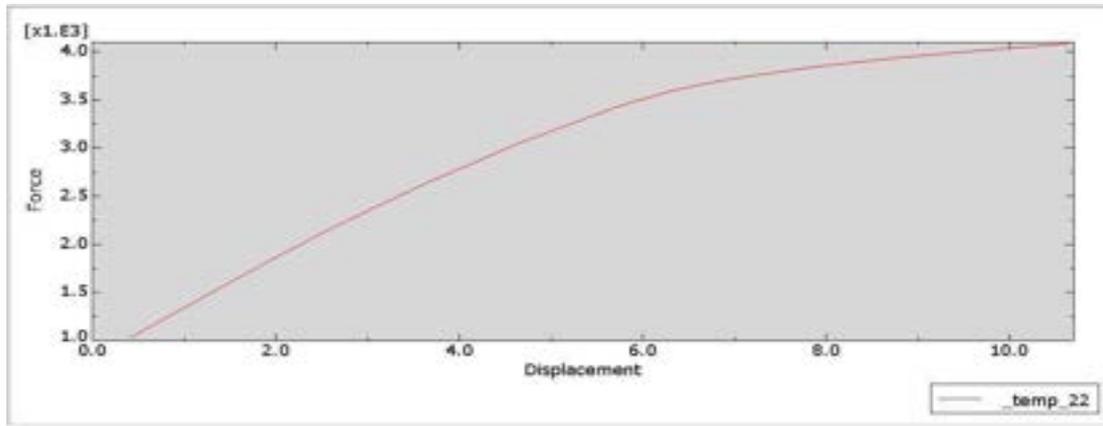


Figure 24: Load displacement curve for BRC-C3 Column

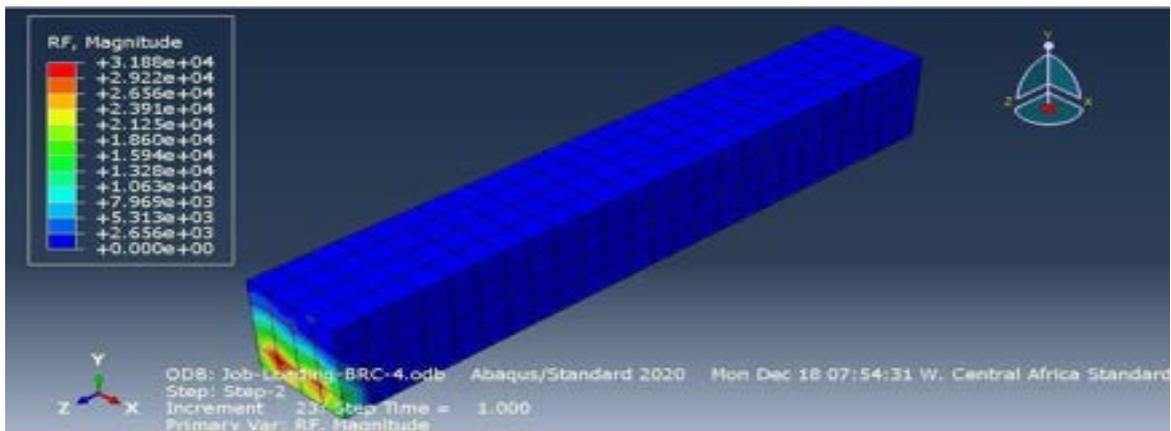


Figure 25: Applied loads on column BRC-C4

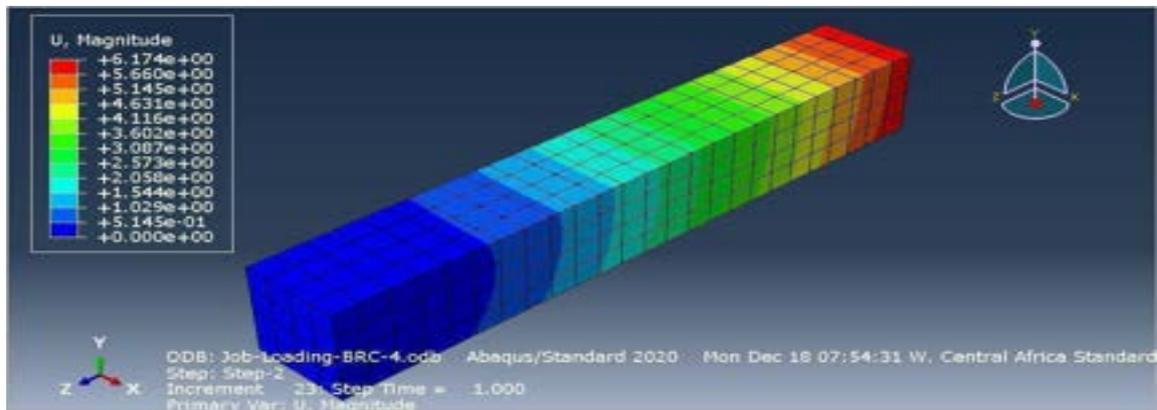


Figure 26: Deflection of Column BRC-C4

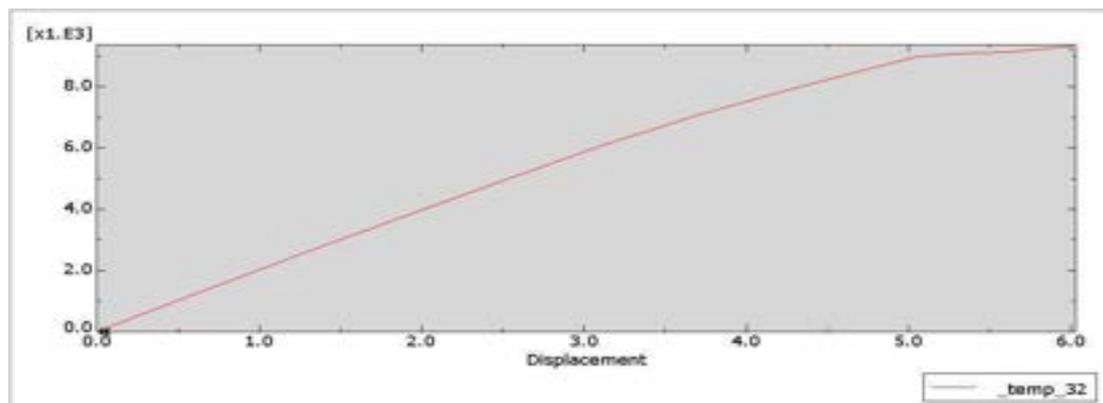


Figure 27: Load displacement curve for Column BRC-C4

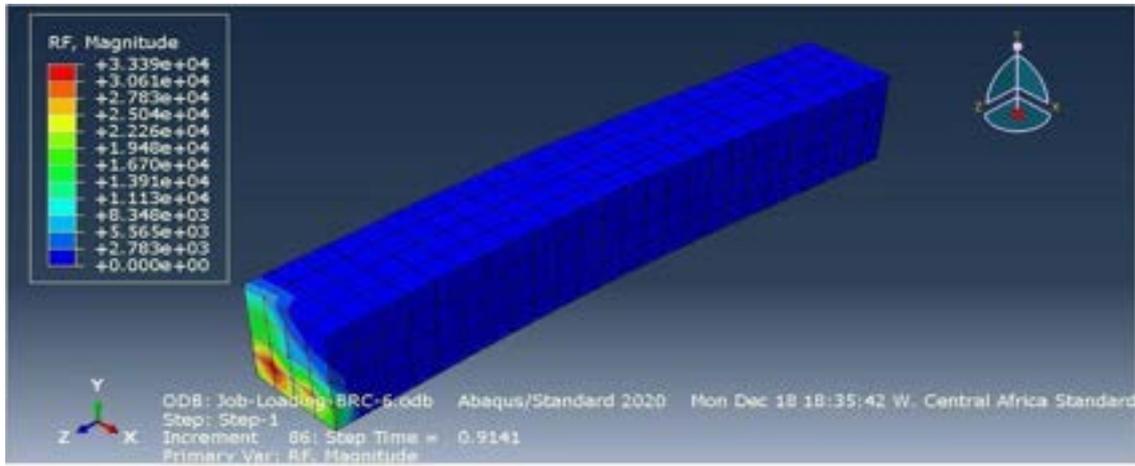


Figure 28: Applied loads on column BRC-C5

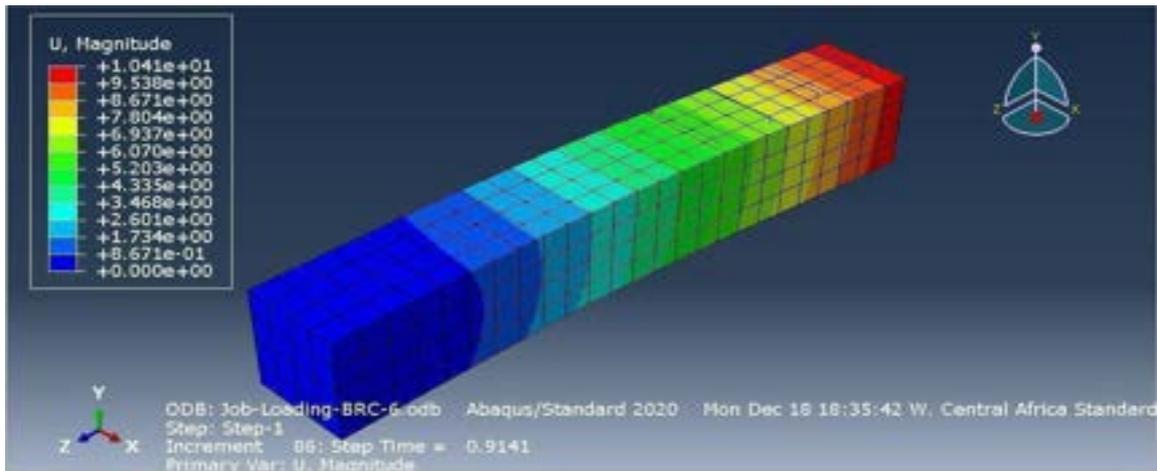


Figure 29: Deflection of Column BRC-C5

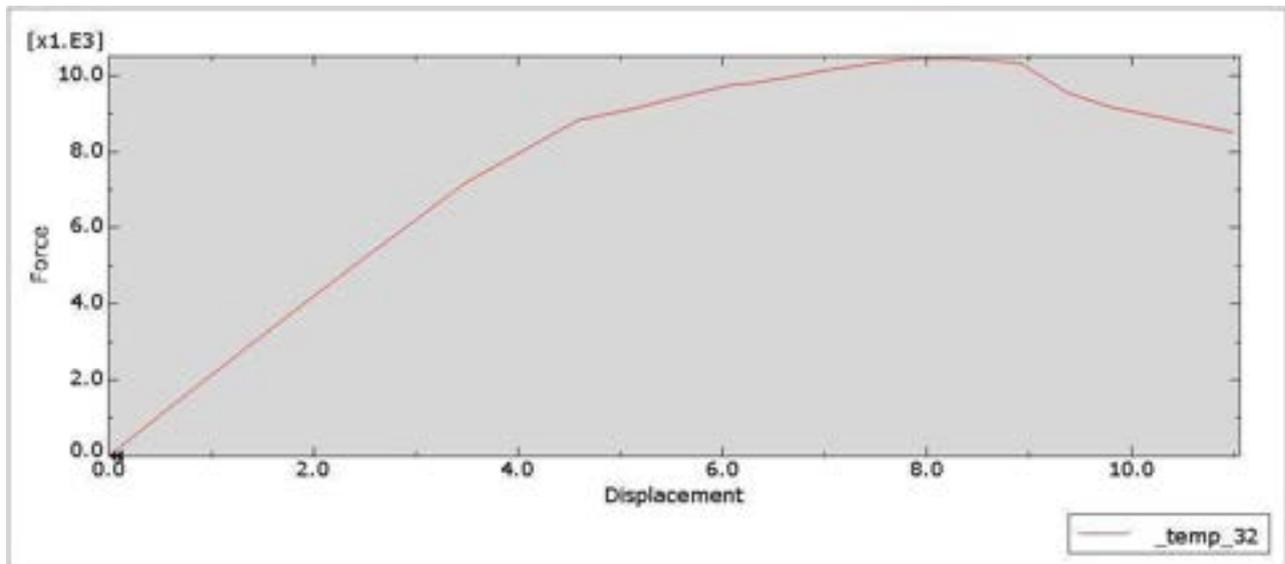


Figure 30: Load displacement curve for Column BRC-C5

The column's behaviour was effectively predicted with a minor variation (<12%) which is attributed to assumptions made by the modeling. The structural performance of bamboo reinforced concrete beams and columns were investigated in this research through numerical simulation (ABAQUS) and compared with experimental analysis. Interestingly, most of the specimens, showed close agreement with notable deviations in Beam 3, as shown in Table 2. The findings are consistent with a recent study on bamboo reinforced concrete (Usidamen & Ogrigbo, 2024).

The reinforcement scheme and the material properties of bamboo governed the behaviour (Gana & Theophilus, 2016; ISO 22156:2021). Therefore, it is evident that the strength and ductility of bamboo reinforced concrete columns increases when the quantity of bamboo reinforcements is increased from 4 to 6 bars. These findings are consistent with the researches done by Siddika *et al.* (2017) and recently (Bin Azuwa, 2024), where the structural performance of augmented bamboo significantly increases.

Bamboo reinforcement in concrete structures offers sustainability and reduced environmental impact benefits (Haryanto *et al.*, 2021; ISO 22156:2021). However, due to high absorption of water and low bond strength with concrete, bamboo presents significant challenges in concrete. The application of waterproofing agents is highly recommended in order to mitigate the issues mentioned (Sharma *et al.*, 2015). This study shows that bamboo is a material that can be used as reinforcement in concrete structures for lightly loaded applications.

4. Conclusion

This study successfully investigated the structural performance of bamboo-reinforced concrete (BRC) beams and columns using finite element modeling in ABAQUS. The following conclusions are drawn from the study:

- i. The developed numerical models accurately predict the behaviour of BRC elements, as evidenced by the strong correlation between the numerical and experimental results, with ultimate load predictions typically within 12% of experimental values. This demonstrates that FEA can serve as a valuable predictive tool for the design of lightly loaded BRC structures.
- ii. It was clear that the performance of BRC elements is influenced by reinforcement type, number and arrangement. Increasing the number of vertical bamboo bars in columns from four to six (BRC-C1 & BRC-C2) enhanced the load-bearing capacity, highlighting the importance of reinforcement configuration in optimizing strength and ductility.
- iii. The bamboo material presents a sustainable and cost effective alternative to steel for lightly loaded applications, its weak bond with concrete remains a critical limitation, as evidenced by the 26% over prediction in Beam 3 where a perfect bond was assumed in the model. Future research should focus on incorporating realistic interface models and exploring surface treatments to improve bond performance.

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