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Deflection-Based Numerical Evaluation of Steel, Bamboo Fibre, and Carbon Fibre Polymer Reinforced Portal Frame

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Abstract. Reinforced concrete, a flexible building material, enjoys worldwide acceptance. Yet, its environmental footprint, especially regarding steel production, is substantial. The extensive mining of iron ore contributes to global warming, prompting the quest for greener alternatives. Bamboo fibre and carbon fibre were employed in sustainable industrial and construction practices to fulfill tensile requirements in reinforced concrete, effectively managing lateral loads on structural elements. This study aims to compare numerically the deflection resistance of portal frames reinforced with steel, bamboo fibre, and carbon fibre polymers using Abaqus version 6.14. The replacement of steel with carbon fibre within the portal frame exhibited comparable effectiveness to that of utilizing steel, whereas the introduction of bamboo fibre was observed to yield relatively diminished efficacy. However, differences between the results for steel, bamboo fibre, and carbon fibre are minimal, and carbon fibre performs similarly to steel. The maximum lateral movement values are 2.43 mm for steel, 2.68 mm for bamboo fibre, and 2.39 mm for carbon fibre.

Key words: Abaqus, bamboo fibre, carbon fibre, concrete, deflection, steel.

1. Introduction

Reinforced concrete structures have gained popularity in modern construction. The process of enhancing, repairing, or upgrading these structures has evolved into a complex science. It involves using both traditional and advanced materials (Nagavally, 2016). Despite decades of experience, concrete still deteriorates from natural factors and human errors. Reinforcement projects are often more intricate than new construction. When reinforcing a structure, it's essential to assess potential failure modes. Strengthening for one purpose may unintentionally weaken another aspect (Claisse, 2008). Also, changes in stiffness can shift critical points within the structure, necessitating a thorough examination of the entire system. Additionally, reinforcement designs should aim to minimize future maintenance and repairs (Frangopol & Liu, 2007; Sakthivel et al., 2019). Concrete shear strength involves two aspects: "pure shear" as a stress state and "shear" as a fracture mode (Vizini & Futai, 2021). Although researchers struggle to find a single testing method due to their incompatibility in heterogeneous materials like concrete. Empirical equations vary in predicting deflection and shear resistance because of factors like sample shape and conditions (Santos & Júlio, 2010). Reinforced concrete is known for its adaptability in construction, as it combines the strengths of steel and concrete to handle different types of forces. This material is widely used globally, and research suggests its demand will continue. However, it's crucial to consider the environmental impact, especially related to steel production, a vital component. The extensive mining of iron ore for steel manufacturing leads to environmental harm and contributes to global warming (Nidheesh & Kumar, 2019). Thus, there is a growing need to address these environmental issues in construction and seek more eco-friendly alternatives.(Damgaard et al., 2009).

Recently, there have been developments in replacing steel with alternative materials such as bamboo (Nayak et al., 2013; Ramaswamy & Mathew, 2019). Additionally, synthetic fibers like rubber (Reda Taha et al., 2008), glass (Yu et al., 2016), natural fibers (Odeyemi et al., 2022), and carbon sheets (Al-Rousan et al., 2013; Toutanji & Ortiz, 2001) have all been examined as potential reinforcements for concrete in tension. These researchers outlined that there were notable positives in the results of the tested elements, as regards flexural strength, failure mechanism, split tensile strength and compressive strength. Furthermore, bamboo fibre, a recreated cellulosic fibre obtained from bamboo a naturally occurring secondary vegetation mostly found in the forest. Starchy pulp is extracted from bamboo stems and leaves through a process of alkaline hydrolysis and multi-phase bleaching. Further chemical processes produce bamboo fibre. However, untreated bamboo fibre has shown signs of poor tensile strength as compared to the treated bamboo fibres, according to (Zhang Kai, Fangxin Wang, Wenyan Liang, Zhenqing Wang, Zhiwei Duan, 2018) it was deduced that treated bamboo fibre gives more tensile strength than untreated fibre. The agent used to treat bamboo fibre is sodium hydroxide NaOH, and it was obtained from experimental procedures that at 6% weight of NaOH the optimal tensile strength will be gotten for the treated bamboo fibre. Also, carbon fibre, made from organic polymers, these polymers contain elongated strings of molecules bonded together by carbon atoms, up to 90% of carbon fibres are produced by applying the polyacrylonitrile (PAN) process, the rest are manufactured through the application of either the rayon or petroleum pitch process (Zahmi et al., 2022). Carbon fibre materials, available in various forms, like yarns, sheets, and weaves, are used to create lightweight yet robust composite parts. These parts offer superior strength-to-weight and stiffness-to-weight ratios compared to steel or plastic, making them valuable in engineering, especially for structural design where reducing weight can lower costs and enhance performance (Bhatt & Goe, 2017). The bamboo fibres and carbon fibres go through a process called pultrusion to get them into the desired forms (Nagavally, 2016).

Previous research has predominantly centered on reinforcing structures using natural-fibre-reinforced polymers such as bamboo, coconut, kenaf and jute. However, there has been relatively little investigation into the use of bamboo-fibre-reinforced composites in conjunction with steel to strengthen concrete structural elements. Nwanko et al. (2020) employed kenaf-fiber-reinforced polymer (KFRP) laminates to enhance the flexural strength of RC beams. The use of KFRP increased the ultimate load of the RC beam by 78% and reduced beam deflection compared to the untreated beam. (Rajesh Kumar et al., 2019) investigated bamboo and steel rebar in environmentally friendly portal frames. They discovered that bamboo outperformed steel in bending strength, making it a suitable choice for lateral loads. In earthquake-prone regions, substituting 25% of bamboo with steel is advantageous because of bamboo's flexibility. (Odeyemi et al., 2023) added coconut fibre to self-compacting concrete (SCC) in three ratios (0.2%, 0.4%, and 0.6%). He suggested that adding 0.2% coconut fibre can enhance SCC strength, offering a cost-effective alternative to synthetic fibres where natural fibres are abundant. Hafizah et al. (2014) explored the performance of kenaf fibre composites with different resins such as epoxy, polyester, and vinyl ester in strengthening RC beams in flexure. Utilizing kenaf fibre epoxy composites increased the beam's flexural strength and reduced deflection. Sen et al. (2013) investigated the flexural strengthening of RC beams using various reinforced polymer composites, including jute fibre (JFRP), carbon textile (CFRP), and glass textile (GFRP). Different techniques like U wrapping, full-wrapping, and strip-wrapping along the entire length of the beam were studied. Awoyera et al. (2021) investigated the structural enhancement of corroded reinforced concrete beams through the application of a bamboo fibre laminate. Placing a single laminate in the tensile region of the corroded beam resulted in a notable increase in the ultimate load-carrying capacity, surpassing that of the corroded beam without any retrofit by up to 21%. Alam et al. (2016) studied the shear strengthening of RC beams using kenaf, jute, and jute-rope fibers in both treated and untreated conditions. They found that natural fiber composite plates exhibited higher ductility and greater failure loads compared to untreated beams. Chen et al. (2023) conducted shear tests and numerical simulations and observed that the inclusion of bamboo fibres enhances the beam's resistance to cracking, with the most significant enhancement at a 31% increase. (Chin, S. C., Tee, K. F., Tong, F. S., Doh, S. I., & Gimbun, 2020) conducted a study on the performance of reinforced concrete (RC) beams containing openings, focusing on their strengthening using a composite material reinforced with bamboo fibers (BFRC) in the shear zone. Their findings indicated that utilizing BFRC for reinforcement could restore the original load-bearing capacity of the beams, achieving up to 98% of the capacity observed in the control beams. Londhe et al. (2010) examined the shear strength and flexibility of concrete beams reinforced with hooked steel fibres. The findings revealed a substantial enhancement in concrete's shear strength due to the presence of these hooked mild steel fibres. As the volume of fibres increased, there was a notable increase in both the maximum load capacity and deformation characteristics, which conversely decreased at lower fibre volumes.

Since the introduction of numerical methods in civil engineering, finite element models, particularly the concrete damage plasticity model, have been widely used to simulate the complete behavior of reinforced concrete, from elasticity to failure and post-failure responses (Akinpelu M A et al., 2021) . The utilization of mathematical models, computational techniques, and experimental validation in structural analysis is pivotal in the creation of secure, efficient, and sustainable structures (Arutiunian et al., 2020; C. Li et al., 2019). This ensures the safety and welfare of occupants while also enhancing the durability of infrastructure systems, thereby playing a central role in shaping the constructed environment. Abaqus is a good modelling software that has been used in various research relating to frames. Li et al. (2021) examined steel portal frame collapses in fires using Abaqus software, merging experiments with simulations. They identified four collapse modes: column lateral collapse, column buckling, inward and outward collapse. The study analyzed factors such as heating conditions, column base stiffness, and fire protection, contributing to improved fire-induced collapse predictions in these frames. Chen et al. (2014) conducted research on midrise light wood-frame buildings featuring both portal frames and shear walls, examining their response to seismic forces. They introduced a technique for calculating the ductility-related force-modification factor, Rd, specifically tailored to these hybrid structures. The findings indicated that adopting an Rd value greater than the minimum value is appropriate. Pouya Pouladi et al. (2019) used Abaqus software to study how the size of External Diaphragms (ED) affects steel frame systems. The results indicate that BW connections have higher stiffness and bearing capacity, while Full Bolted connections offer better ultimate deformation capacity and ductility. The study suggests that ED thickness is more critical than width for seismic performance and recommends a width ratio of 0.1 as a minimum value for structural design. Pavan et al. (2020) employed Abaqus software to investigate the failure behavior of beam-column joints in a moment-resisting frame, comparing dry mechanical and wet connections. Their numerical approach, fine-tuned through finite element analysis software, yielded crucial insights into aspects like spatial displacement patterns, load-displacement characteristics of J-bolt connections, cleat angle with stiffener connections, wet precast connections, and the performance of a monolithic frame. Ibrahim et al. (2017) conducted a study utilizing Abaqus software to assess how reinforced concrete frames withstand blast loads. The findings indicated that modifying the design of external columns, especially by using concrete-filled steel tube sections, enhanced the structural response.

Many studies have not adequately explored the use of bamboo fibre, steel, and carbon fibre in frame construction. Such investigations are crucial for establishing sustainable mass implementation. Therefore, this study aims to compare the deflection resistance of portal frames reinforced with steel, bamboo fibre, and carbon fibre polymers. This will be achieved by assessing the lateral deflection of these frames through numerical evaluations.

2. Methodology

This study presented a numerical investigation into the determination of the deflection resistance of portal frames reinforced with bamboo and carbon fibre polymers. A numerical software named Abaqus was used during the modelling, analysis, design and result phases. To get the deflection resistance of the portal frame reinforced with different materials a lateral force was applied at the edge of the portal *frames*, and the portal frames were modelled to be fixed supported. Three different models were made; RC portal frame reinforced with steel, bamboo fibre and Carbon Fibre Reinforced Polymer (CFRP). The beam has a cross-section of 100mm by 150mm while the columns have a cross-section of 150mm by 100mm as shown in Figure 1.

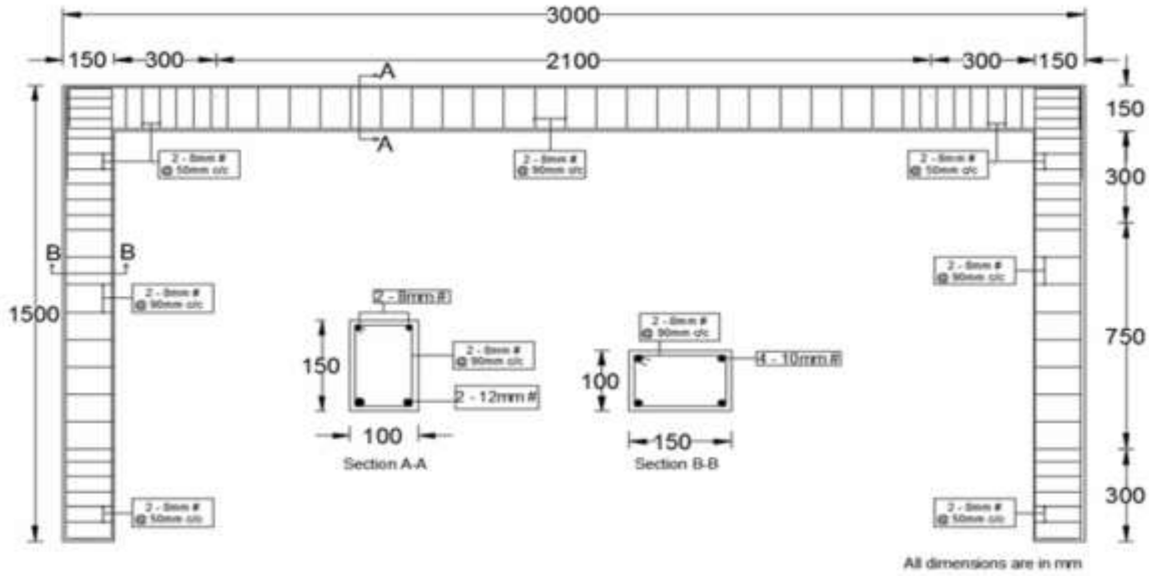

Fig. 1: Reinforcement details of the portal frame

2.1. Constitutive models for materials

2.1.1. Concrete constitutive model

Concrete, a composite material with unique properties, is a specific module within the Abaqus software library. According to Dassault Systèmes (2021), the Abaqus software can incorporate concrete material's elastic behavior through the linear elastic model, this model is highly applicable in structural deformation analysis; the linear elastic model is frequently employed to analyze the deformation behavior of structural components such as beams, columns, and slabs. This model is particularly applicable when assessing deflection under various loading conditions, including static, dynamic, and thermal loads. Researchers utilize it to predict how structures respond to applied forces without undergoing plastic or permanent deformation. Numerous extensive research has gone on the use of the linear elastic model and its applications (M A Akinpelu et al., 2023; Daoud & Ahmed, 2022; Long & Lee, 2015; Shames, 2020; Tošić et al., 2021).

Table 1. Mechanical properties of concrete

Mean compressive strength, fc (N/mm^2)	Average tensile strength, ftm (N/mm^2)	Modulus of Elasticity (N/mm^2)
25.0	2.56[a]	31,475[b]

The mean tensile strength and elastic modulus of concrete were determined through the application of (Arya, 2015), as outlined in Eq. 1 and Eq. 2 correspondingly;

$$f_{tm} = 0.3 * f_c^{2/3} \quad (1)$$

$$E_C = 22[\frac{f_c+8}{10}]^{0.3} * 10^3 \quad (2)$$

According to (Long & Lee, 2015) the Poisson's ratio of 0.2 was used in this research for concrete.

2.1.2. Steel constitutive model

From research Young's modulus of steel was obtained to be 200Gpa and was inputted, a Poisson's ratio of 0.3 was also inputted as part of the constituting parameters for the linear elastic model on Abaqus software as clearly stated by (Long & Lee, 2015).

Table 2: Mechanical properties of steel

Steel	Young's Modulus(GPa)	Poisson's ratio
Rebar	200	0.3
Stirrup	200	0.3

2.1.3. Bamboo fibre constitutive model

A matrix called parenchyma in bamboo provides ductility. This matrix also contains bamboo's strength and stiffness fibers known as sclerenchyma fibers. (Zhang Kai, Fangxin Wang, Wenyan Liang, Zhenqing Wang, Zhiwei Duan, 2018) studied the compressive behavior of bamboo from different locations in the culm wall, each having a different volume fraction (Vf) of vascular bundles (VBs). The compressive behavior of bamboo can be divided into three phases: initial linear elastic, nonlinear, and plateau. Increasing Vf leads to higher initial stiffness and peak stress but reduced ductility due to a decrease in the parenchyma matrix percentage. Shao and Fang investigated the tensile behavior of bamboo with varying Vf and found positive correlations between initial stiffness and maximum tensile strength with Vf. The peak tensile stress is notably higher than the core. Characteristics measuring the effectiveness of bamboo fibre is shown in Table 1. Li et al. (2004) conducted compressive tests on Moso bamboo, observing a doubling of strength and an increase in elasticity modulus. The density increased along the culm. The optimal age for bamboo cultivation is 3-6 years. Moisture content also contributes to mechanical properties, with compressive strength less than half-halved after fibre saturation point. (Zhang Kai, Fangxin Wang, Wenyan Liang, Zhenqing Wang, Zhiwei Duan, 2018) found that treating bamboo fiber with NaOH improved its tensile strength. The best result, 363 ± 103 MPa, was achieved with 6% treatment, and the Young's modulus was 11.2 ± 2.4 GPa. We chose the worst-case scenario for analysis, with a minimum Young's modulus of 8.8 GPa and a Poisson's ratio of 0.2.

Table 3: Characteristics measuring the effectiveness of bamboo fibre (W. Chen et al., 2023; Zhang Kai, Fangxin Wang, Wenyan Liang, Zhenqing Wang, Zhiwei Duan, 2018).

Treatment Percentage (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Density (Kg/m^3)	Elongation at break (%)
0	262 ± 75	-	0.2	848.826	2.5
2	283 ± 71	-	0.2	848.826	2.5
6	363 ± 103	11.2 ± 2.4	0.2	848.826	2.5
10	235 ± 67	-	0.2	848.826	2.5

2.1.4. Carbon fibre constitutive model

Young's modulus for carbon fibre as obtained from research (X. Li, 2004) is 2.32 x 105 MPa was used under the material manager input field for the numerical analysis of this research. The L-L model is a framework for concrete confined with CFRP (Carbon Fiber Reinforced Polymer), that draws parallels between tri-axial tests conducted on soil or rock and concrete confined with CFRP, revealing striking similarities in their stress-strain behavior within the ascending segment of the stress-strain curve. To describe the axial stress (σ_1) in confined concrete, this model utilizes the Mohr-Coulomb failure envelope, which factors in cohesion (c), lateral confined stress (σ_3), and the angle of internal friction (φ) as it is presented in Equation 3. Crucially, the model takes into account various parameters, including the thickness of CFRP layers, the modulus of CFRP, allowable CFRP strain, and cylinder diameter, to calculate the effective confined stress as shown in Table 2. The value of 'a' is contingent on the characteristics of the confinement material (CFRP) and can be ascertained through regression analysis (Gurbuz, 2018).The Piosson's ratio of 0.26 was inputted for carbon fibre to analyze the model, which is in conformity with the range (0.26-0.28) as specified in (Krucinska & Stypka, 1991) for the values of Piosson's ratio of carbon fibre.

$$\sigma_1 = 2c\tan\left(45° + \frac{\varphi}{2}\right) + \sigma_3\, tan^2\left(45° + \frac{\varphi}{2}\right) \quad (3)$$

Table 4: Material properties of carbon fibre (X. Li, 2004)

Material Specification	FAW 250 (g/m^2)
Young's Modulus, Ecf	2.32×10^5 MPa
Tensile Strength	4.17×10^3 MPa
Thickness (per layer)	0.1375 mm
Ultimate Strain	0.018

2.2. Numerical Analysis

This section explains the different procedures used for modelling and analyzing the portal frames on Abaqus. All the procedures are properly represented in the form of the flow chart in Figure 2.

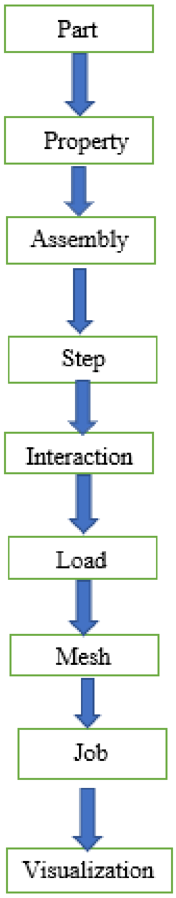

Fig. 2: Flow chart showing the process of modelling and analyzing the portal frames on Abaqus.

Part: This is the section where the shapes and sizes were properly specified to get the proper representation of the model. The interface is as shown in Figure 3.

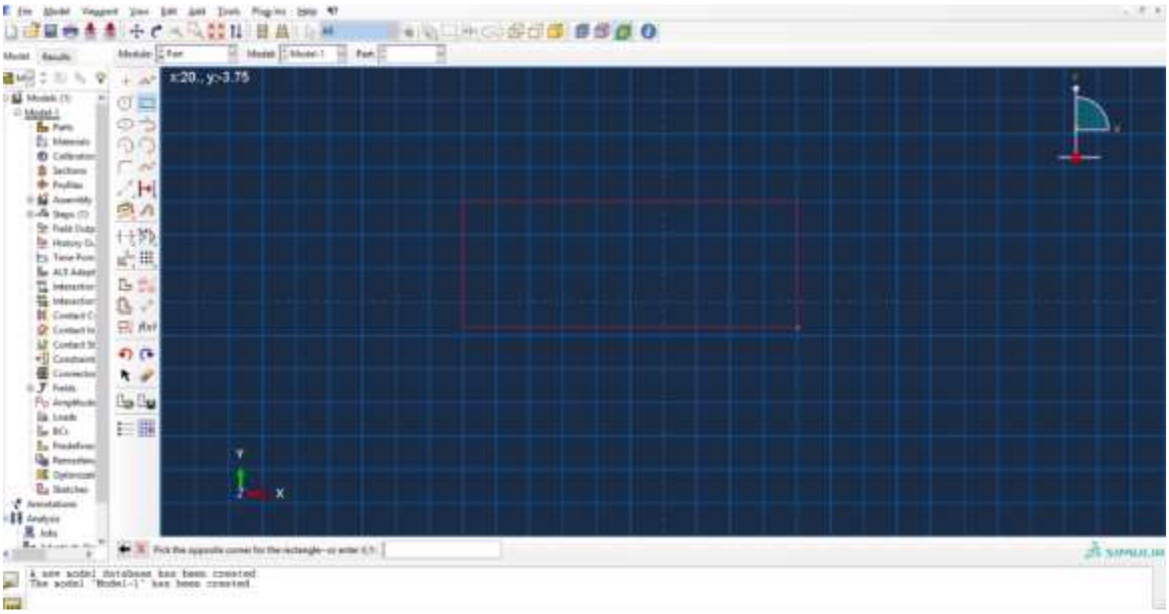

Fig. 3: Part interface

Property: Figure 4 shows the interface where all the elastic and mechanical properties were defined for the materials.

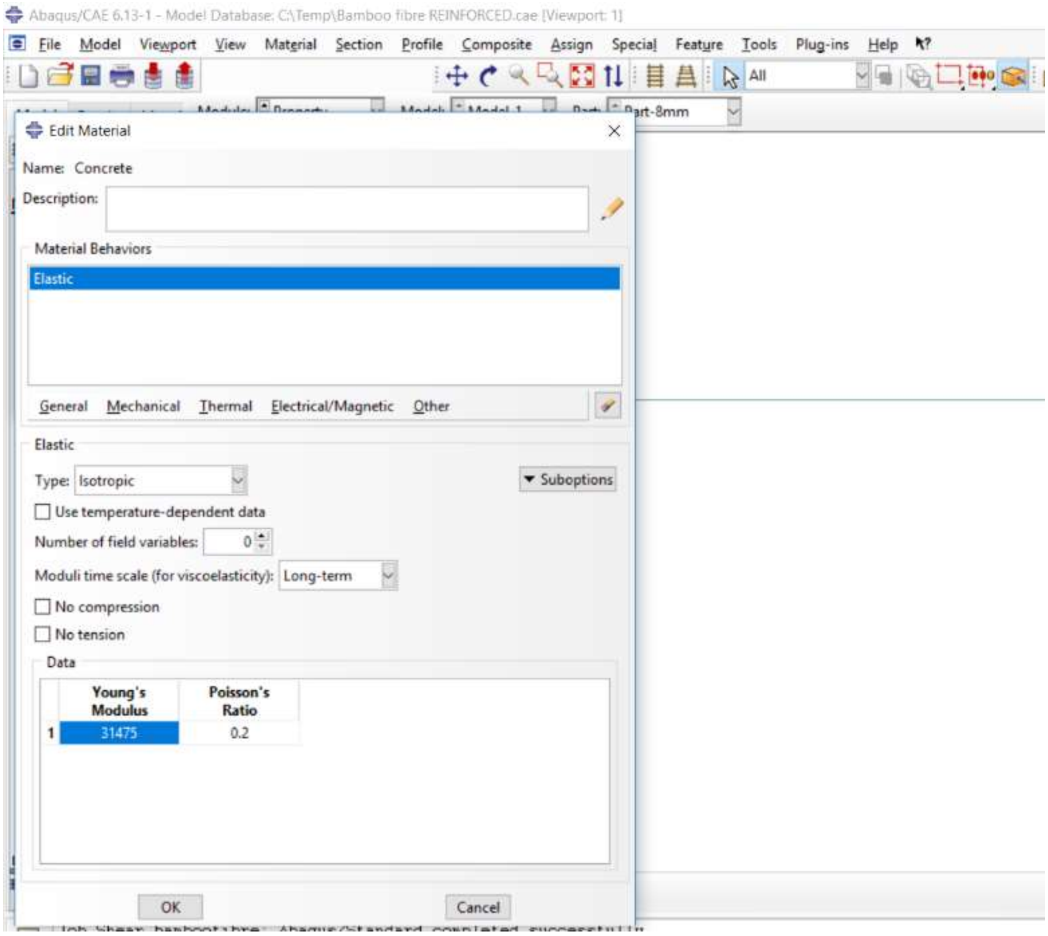

Fig. 4: Inputting material properties for Concrete.

Assembly: The assembly as shown in Figure 5 depicts where all members created in parts were imported into the interface and assembled.

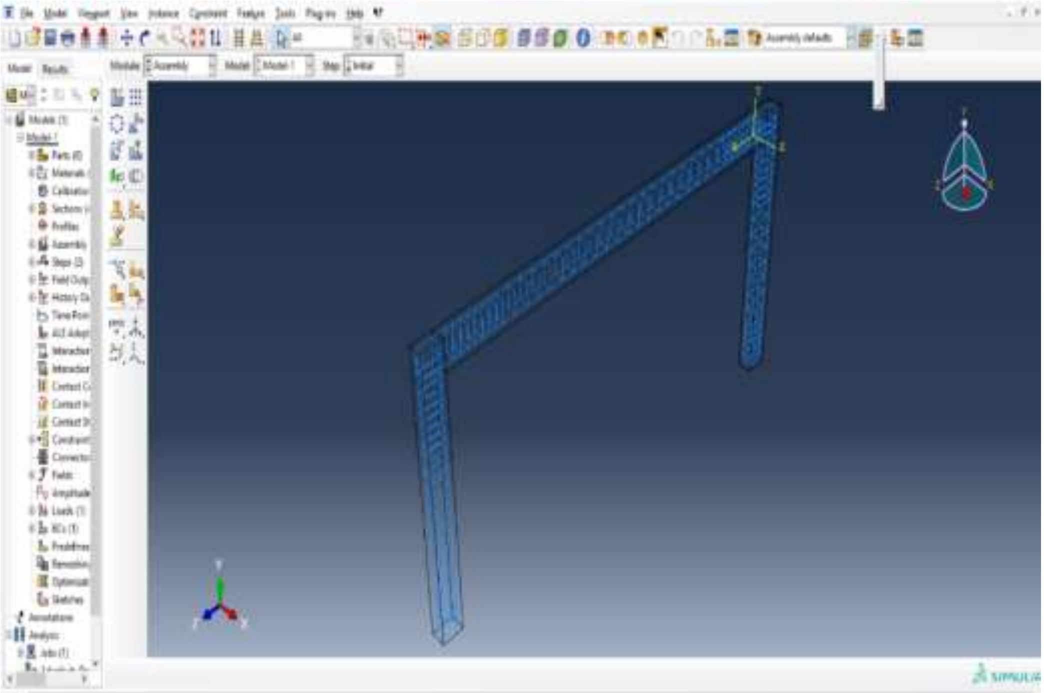

Fig. 5: Modelled portal frame using the reinforcement detailing from Fig. 1

Step: This is a section that was used to create the interface for the different types of load to be applied to the modelled structure.

Interaction: This is where the end conditions were applied. The type of interaction between the faces in contact were properly defined under this segment. The support conditions for the portal frames were fixed, this resists forces laterally, vertically and in bending. This is depicted in Figure 6.

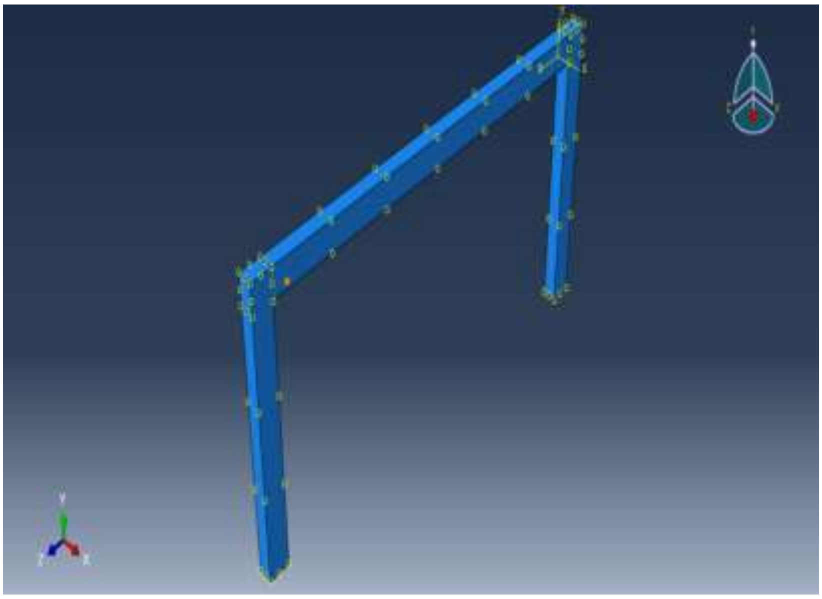

Fig. 6: Defining interface interaction

Load: This is the segment where the magnitude and the exact type of load was applied (point load). The portal frame was loaded with a 10 kN force acting laterally to it, the loading was kept constant for the three different models. The load definition interface is shown in Figure 7.

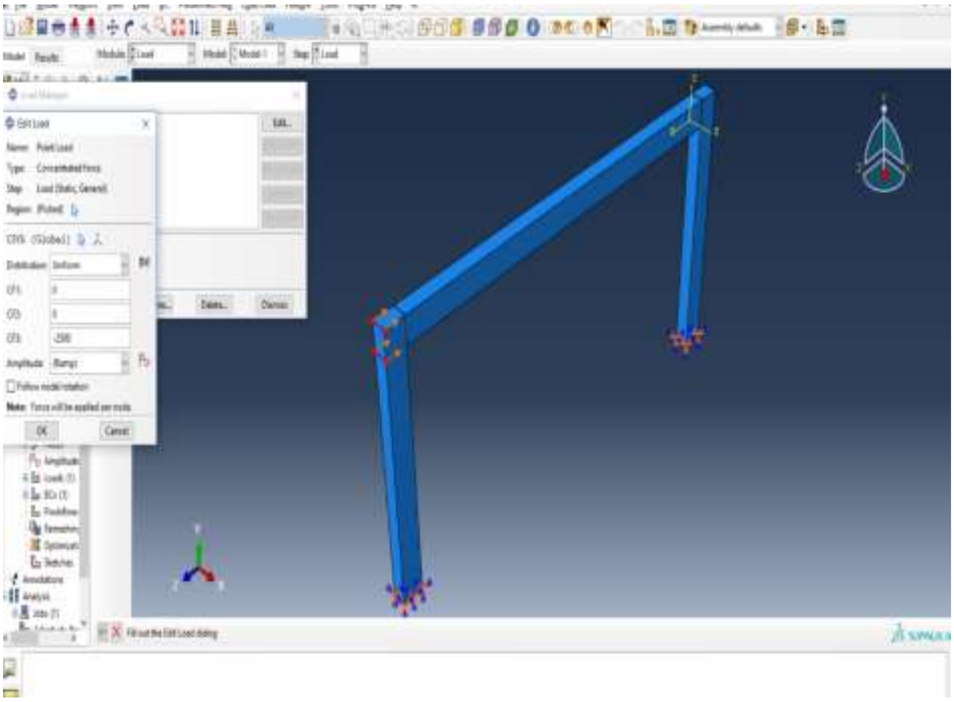

Fig. 7: Assigning loads

Mesh: This is the segment that was used to discretize the portal frame model into smaller elements as shown in Figure 8. The higher the discretization, the better and more efficient the results.

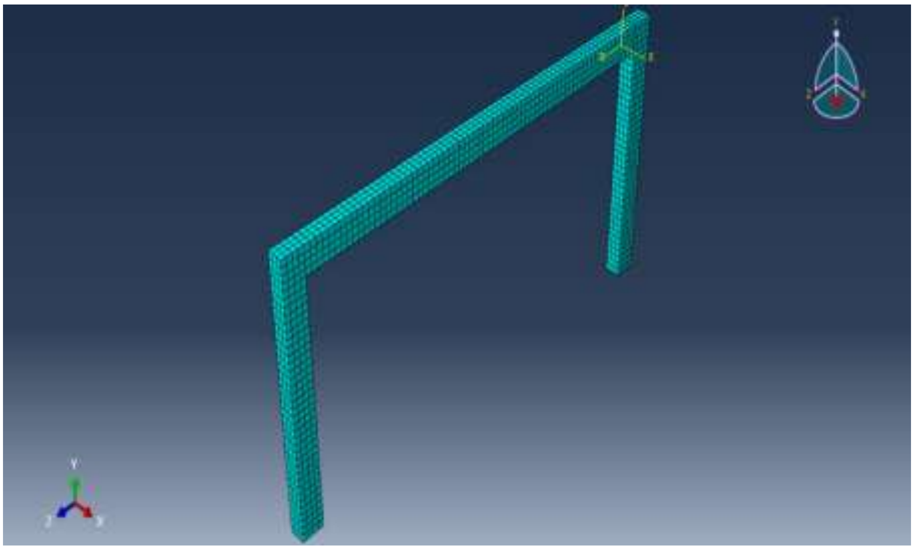

Fig. 8: Meshing

Job: This is the section where the defined data were checked and submitted and results were generated. At this stage, the behavior of the structure was simulated under the given conditions. The goal was to obtain the reaction forces on the structure due to the applied loads and support conditions. The reaction forces might be presented in the form of stress and strain or more specifically moments, displacements, shear forces, axial forces and torsional forces which are used to design the structure. The results and data for the model were then visualized.

Visualization: This is the section that shows the already gotten result for better understanding.

3. Results and Discussion

From the numerical evaluation of the portal frame, the portal frame was reinforced with steel, bamboo fibre and carbon fibre, while keeping other parameters and factors constant, the grade of the concrete which also maintained as M25, the force that was applied was kept constant 10 kN to see the reactions of different reinforcement material in the concrete under a constant laterally distorting force. The following results were gotten, and a graph was obtained to better showcase the deflections of the frames. The deflections of the steel bamboo and carbon fibre reinforced portal frames are shown in Figure 9, Figure 10 and Figure 11 respectively. The deflections of the frames are plotted and shown in Figure 12.

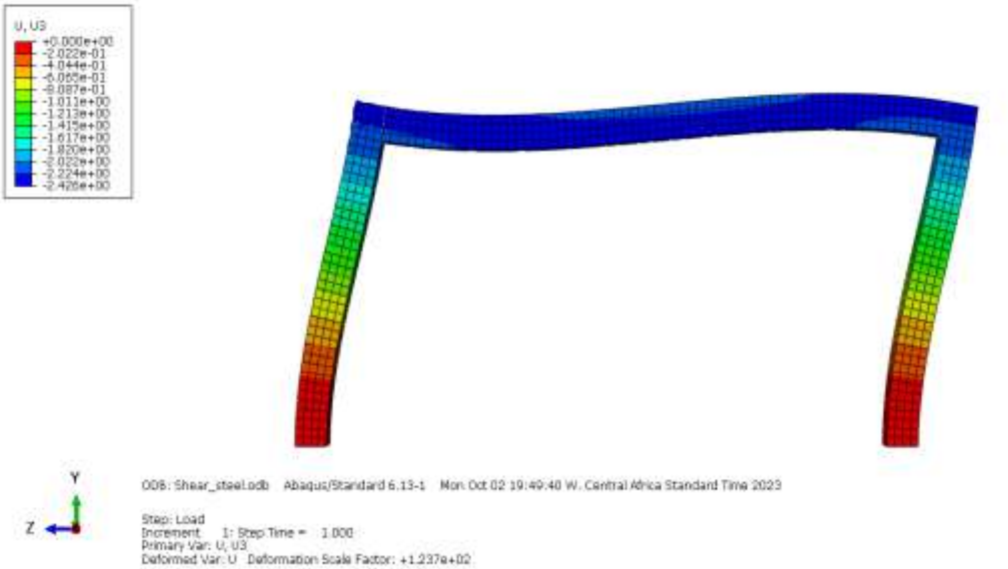

Fig. 9: Result for portal frame reinforced with steel.

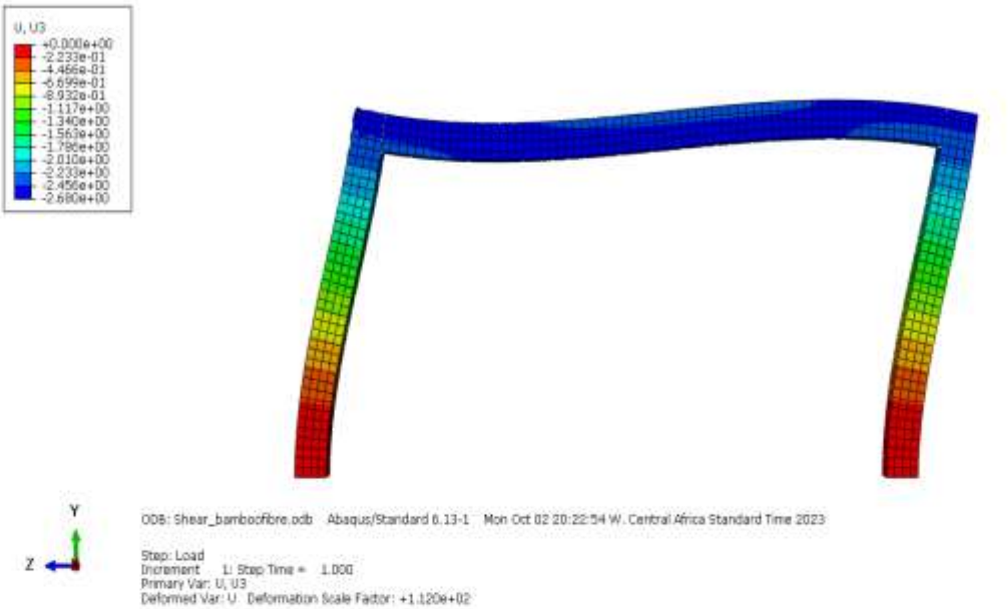

Fig. 10: Result for portal frame reinforced with bamboo fibre.

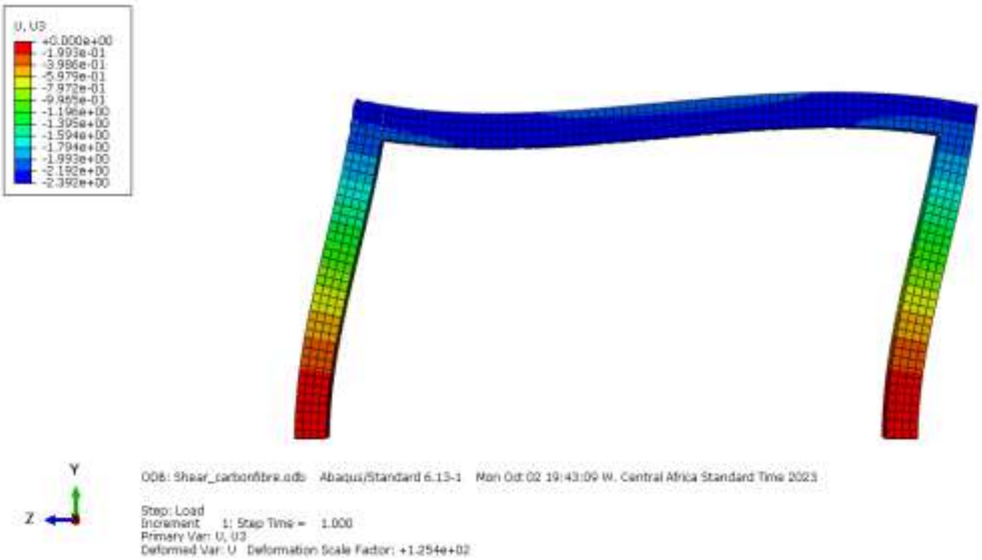

Fig. 11: Result for portal frame reinforced with carbon fibre.

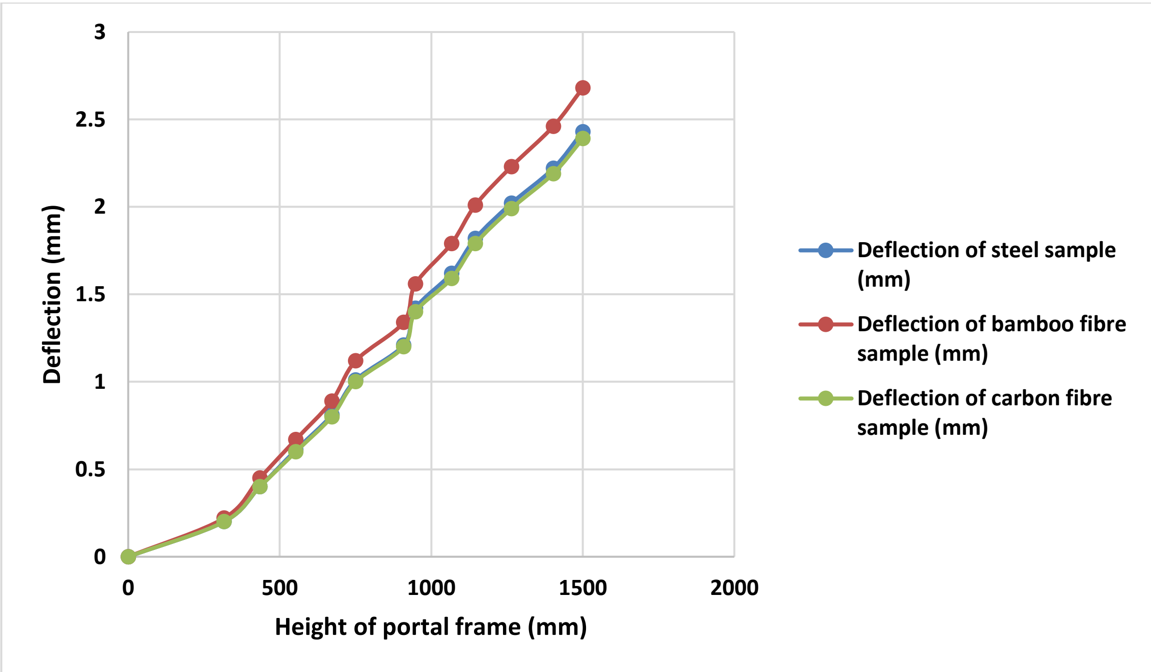

Fig. 12: Graph showing the comparison of the shear deformations.

The graph in Figure 12 shows some variations in deflection within the portal frames. These variations are attributed solely to the diverse reinforcing materials employed in each portal frame configuration. It was noticed that as the height of the frame increased the deflections also increased. The reinforcement types had marginal effect on the deflections of the frames as the maximum deflections recorded at the height of 1.5 m was 2.43 mm, 2.68 mm, and 2.39 mm, for the steel, bamboo and carbon fibre reinforced portal frames respectively.

4. Conclusion

In the course of this research, an extensive numerical investigation was conducted to assess the lateral displacement of portal frames, employing bamboo fibre and carbon fibre as partial replacements for steel reinforcement. The numerical analysis was carried out using Abaqus, a numerical computational software. The conclusions drawn from the study are:

1. Carbon fibre reinforced polymers demonstrates superior resistance in portal frames.
2. The difference in the deflection resisting capabilities of steel, bamboo fibre, and carbon fibre reinforcement are relatively marginal.

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