advances in Technology

Adv. Technol. **2022**, 2(2), 114-123

Full Paper

Performance Analysis of Concrete Slab Reinforced with Steel and Bamboo

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Received: 9 January 2022; Revised: 21 March 2022; Accepted: 25 March 2022; Published: 15 May 2022

Abstract
Concrete and steel are considered the main construction materials in the world today while the cost of steel is rising year by year. Though steel can be recycled, it consumes a significant amount of energy in the manufacturing and recycling stages. Thus, to cope with that risk and reduce the building budget, it will be necessary to start using alternative resources. Studies were conducted to discover the appropriateness of using timber resources (e.g., Bamboo and Palmyra) to substitute steel as reinforcements in concrete. Bamboo is a quick-growing plant and is easily obtainable in the Asia region. Bamboo has a higher tensile strength than other timber resources and strength to weight proportion. However, due to its brittle behavior, bamboo cannot fully replace steel. Characteristics of bamboo differ with its time of life and class. The main aim of this research is to suggest a suitable hybrid reinforcement with steel and bamboo for the construction industry by analyzing the concrete slab element. This paper discusses the behavior of concrete slabs, reinforced with steel and bamboo and the applicability of Finite Element Modelling (FEM) using the ABAQUS software. The numerical model was validated by the experimental investigation in the literature.

Keywords: Bamboo, hybrid reinforcement, concrete, sustainable material

Introduction

Concrete structures play a major role in the construction industry due to their robust construction, higher strength, and adaptability to different environmental conditions. The strengthening of concrete structures, mainly for bearing tensional stresses, the steel reinforcements are included in concrete moulds. Generally, plain concrete cannot be used for structures because concrete is strong in compression but not in tension [1]. Reinforcement can solve this issue, and steel material is used frequently because it has higher tensile strength. Steel reinforcement is required in this scenario at a high cost and with a high degree of energy consumption. Thus, there is a need to identify a suitable substitute material for Steel [2]. The sustainable substitutions for steel in concrete reinforcements were investigated by many studies in the literature considering Bamboo [3] and Palmyra [4]. Bamboo, which is a quick-growing, widely spread tree in the Asian region was focused to investigate as a hybrid reinforcement with Steel, by modeling the Bamboo-Concrete bond using the Finite Element Model (FEM).

Modeling of concrete structures will save the time and cost of laboratory experimental procedures and also can obtain more data than in physical Experiments. Thus, the present study aimed to validate the FEM results by comparing the experimental results by Lewangamage [3].

https://doi.org/10.31357/ait.v2i2.5441

Bamboo as a Reinforcement Material

The replacement of steel in reinforcements by Bamboo should ensure the expected structural and mechanical properties in the design. The comparison of mechanical properties between Steel and Bamboo is summarized in Table 1. The tensile strength to weight ratio of bamboo is six times bigger than that of Steel [5]. Correspondingly the elastic modulus of bamboo is 1/15 of concrete, and it cannot contribute to the reinforced element's flexural stiffness [2] and thus bamboo is a more suitable alternative material for the reinforcement.

Table 1. Mechanical properties of steel and bamboo [2]

Property	**Bamboo**	**Steel**
Tensile Strength (Mpa)	120 -370	420
Compressive Strength (Mpa)	55	250
Average Density (kg/m^3)	700 - 1000	7800

However, insect attacks, induced by starch content and humidity, is a major problem that is commonly found in timber structures in usage, also common to the Bamboo in its durability [6]. Factors such as age, species, the curing condition can influence the durability of Bamboo. Lewangamage investigated the bonding of Bamboo with concrete and concluded that the water-repellent treatment procedure could increase the bonding behaviour of Bamboo with Concrete [3]. Pull-out experiments were also done to predict the bonding of treated Bamboo with Concrete [3] [2]. Water-resistance coatings were used over Bamboo to increase the bonding behaviour of bamboo with concrete [7].

Experimental Section/Materials and Methods

Concrete

The concrete damaged plasticity model (CDP) was selected to represent the behaviour of concrete in tension and compression. According to CDP model, two failure modes are tensile cracking and compressive cracking. When concrete is exposed to uniaxial tension, the stress-strain relationship is linear until it reaches failure stress, at which point the strain curve softens owing to micro cracking.

Elastic modulus of concrete Ec, maximum compressive strength fc', and tensile strength fct are needed to establish the concrete damaged plasticity model. The measured average compressive strength was 30 MPa during the testing phase. Ec and fct were calculated by equations (1) and (2) [8].

$$Ec = 4730\sqrt{fc'} = 25907 \text{ Mpa} \qquad \text{Equation (1)}$$

$$fct = 0.33\sqrt{fc'} = 1.81 \text{ Mpa} \qquad \text{Equation (2)}$$

where fc' is given in Mpa. The stress-strain relationship developed by Saenz's was used to represent the compressive behaviour of concrete [8].

The stress-strain relationship developed by Rasheed [8] was used to represent the tension behaviour of concrete. To eliminate the run time error due to a sudden drop at fail stress modified stress-strain curve was used. The stress-strain relationship of concrete in tension is represented in Figure 3. The Poisson's ratio for concrete was assumed as 0.2 [2]. Grade 30 concrete was used with a water/ cement ratio of 0.55 for slabs. The mechanical properties of concrete are given in Table 2. It is observed that the Concrete behaves linearly within the elastic region until the initial yield. After reaching the initial yield point, Concrete starts acting in a plastic fashion and exhibits some work-hardening up to the ultimate stress. followed by strain-softening.

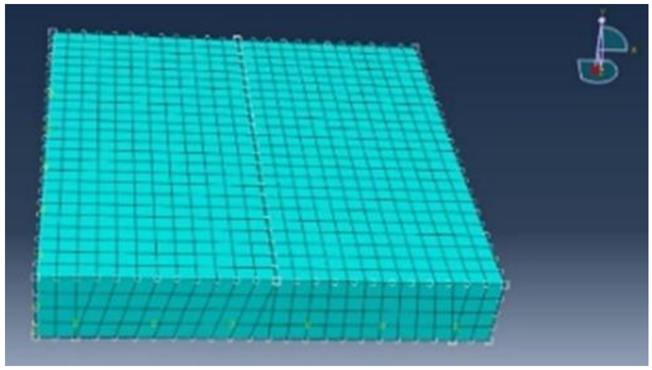


Figure 1. Meshed Geometry of the Slab

Table 2. Mechanical properties of concrete

Density	2400 kg/m^3
Elastic modulus	27983 N/mm^2
Poisson ratio	0.2
Ratio of initial equiaxial compressive yield stress to initial uniaxial compressive yield stress (f_{bo}/f_{co})	1.16
Eccentricity	0.1
The ratio of the second stress invariant on the tensile meridian (K)	0.667
Dilation angle	30
Viscosity	0.0001

The inelastic strains can be calculated using total strain (ϵ_c) and elastic strain corresponding to the undamaged material (ε_{oc}^{el}) by Equation (3) given below [8] [9].

$$\tilde{\varepsilon}_c^{in} = \varepsilon_c - \varepsilon_{0c}^{e_l} \quad \text{Equation (3)}$$

where the elastic strain, is $\varepsilon_{oc}^{el} = \frac{\sigma_6}{\bar{E}_0}$ (E_0 - Initial tangential modulus).

The plastic strain values will be calculated using Equation (4) by the software itself.

$$\tilde{\varepsilon}_i^{pl} = \tilde{\varepsilon}_t^{in} - \frac{d_c}{1-d_c}\frac{\sigma_C}{E_0} \quad \text{Equation(4)}$$

The compressive damage parameter d_c is the ratio between the inelastic strain (ϵc^{-in}) and total strain (ϵ_d). Figure2 and Figure3 illustrate the general stress-strain performance of a concrete member under uniaxial tensile load application. It can be obtained that the stress-strain performance is linear elastic until the peak stress σto. The onset of micro-cracks occurs when the tensile stress reaches the peak point, which leads to strain. The latter impacts the crack growth and may result in unloading regions beyond strain localization, which induces strain-softening post-peak response.

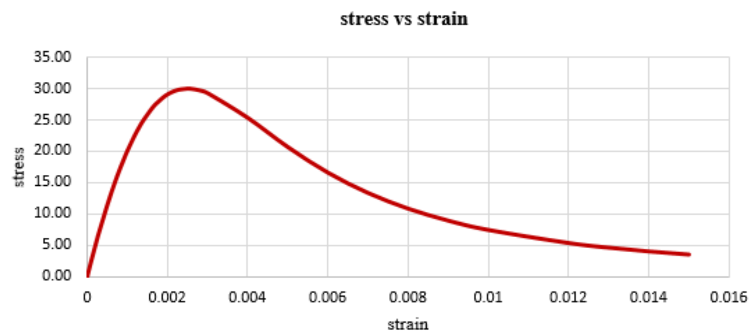


Figure 2. Compressive stress - strain N/mm[2]

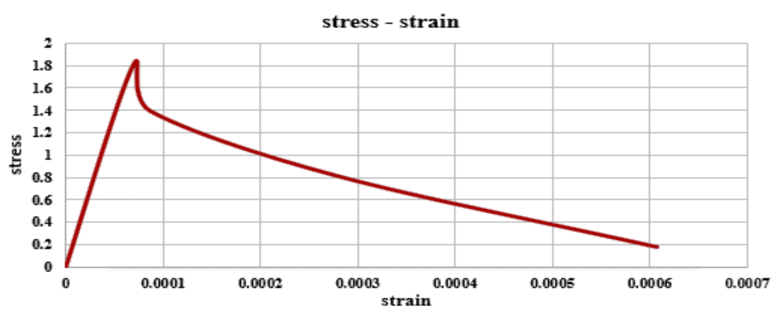


Figure 3. Tensile stress-strain relationship N/mm[2]

The tensile cracking strain can be calculated using total strain (ϵ_t), and elastic strain corresponding to the undamaged material by Equation (5) [8] [9].

$$\tilde{\varepsilon}_t^{ck} = \varepsilon_t - \varepsilon_{ot}^{el} \qquad \text{Equation (5)}$$

The plastic strain values will be calculated using Equation (6) by the software itself.

$$\tilde{\varepsilon}_i^{pl} = \tilde{\varepsilon}_t^{ck} - \frac{d_t}{1 - d_t}\frac{\sigma_C}{E_0} \qquad \text{Equation (6)}$$

Steel

Table 3 shows the properties of steel [3], used in modeling, and Figure 4 indicates how to definethe properties of steel in ABAQUS.

Table 3. Mechanical properties of steel (C.S.Lewangamage, 2015)

Density	8050 kgm^{-3}
Young modulus	20900 Nmm^{-2}
Poisson ratio	0.3
Yield stress	109.7 Nmm^{-2}

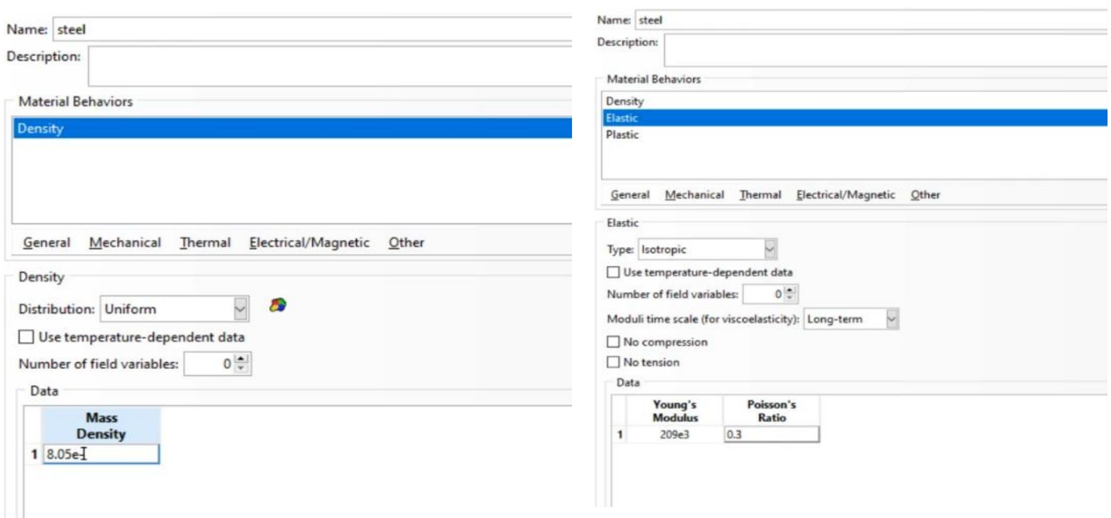


Figure 4. Assigning the properties of steel in ABAQUS

Bamboo

The properties of bamboo were taken from previous studies [3]. Table 4 shows the properties of bamboo, used in modeling, and Figure 5 indicates how to define the properties of bamboo in ABAQUS.

Table 4. Mechanical properties of Bamboo

Density	700 kgm^{-3}
Young modulus	20000 Nmm^{-2}
Poisson ratio	0.2
Yield stress	105 Nmm^{-2}

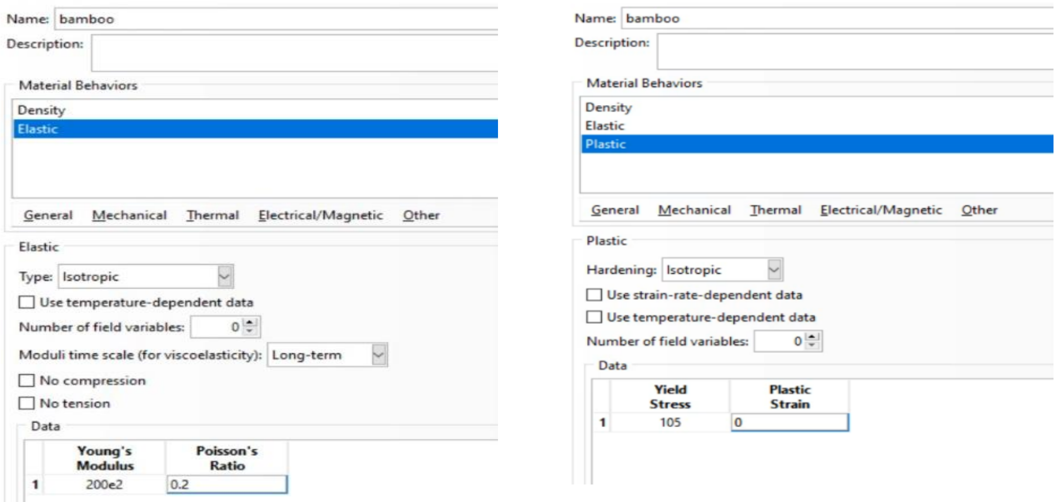


Figure 5. Assigning the properties of bamboo in ABAQUS

Boundary conditions and loading

The boundary condition in the experiment was similar to the partially fixed boundary condition used in the experiment [3]. Both ends of the beams were partially fixed at the ends. Force was applied vertically to the middle of the slab panel. Figure 6 shows how boundary conditions and loading are applied to slab modeling.

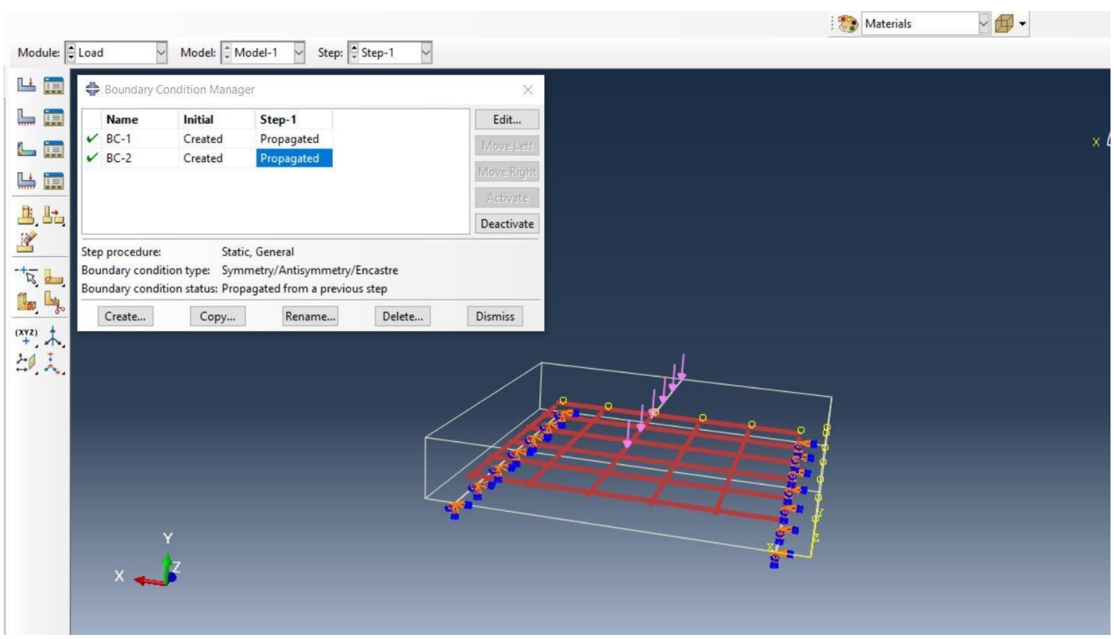


Figure 6. Boundary condition and loading

Numerical Analysis

8-node 3-dimensional solids were used for the reinforced concrete. Reinforcement steel and bamboo were modeled by 2-node 3- dimensional truss elements. Steel bars were embedded into curved beams to provide concrete-steel interaction. Nodes of concrete were selected as hosts and nodes of steel bars were selected as a slave. Crack location and width were identified in the slab. Cracks were modeled in the identified location in the curved slabs by making a suitable gap between the continuum elements.

Results and Discussion Section

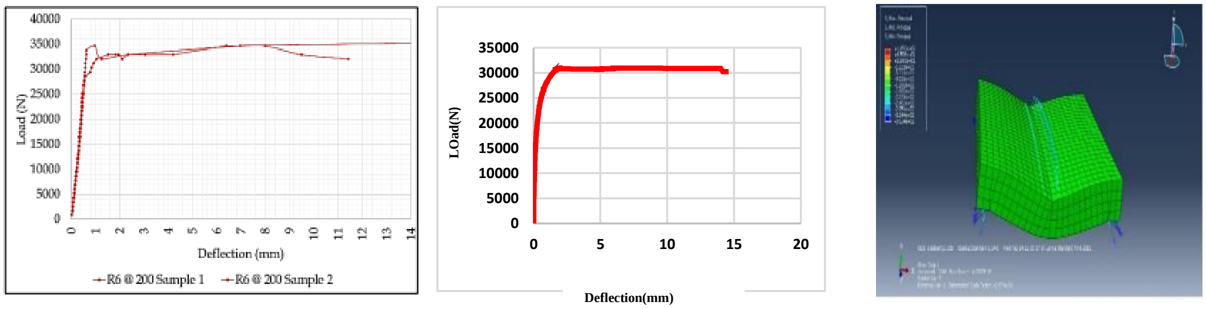
The present paper used the experimental results by Lewangamage [3] on flexural behaviour investigation of bamboo reinforced concrete slab panels to validate the numerical model analysis. Lewangamage [3] examined eight numbers of 600 mm × 600 mm× 100 mm frames which were melted with different bamboo reinforcement arrangements, as shown in Table 5 and tested. Load displacement curve obtained for slabs from the experiment [3] and finite element modeling are shown below.

Table 5. Slab Details

Slabs	Size (mm)	Number of Bamboo r/f	Number of Steel r/f
Slab 1 (Control Slab R6)	600×600×100	-	12
Slab 2(BS13)	600×600×100	12	-
Slab 3(BS13&R6)	600×600×100	6	6
Slab 4(BS25&R6)	600×600×100	6	6

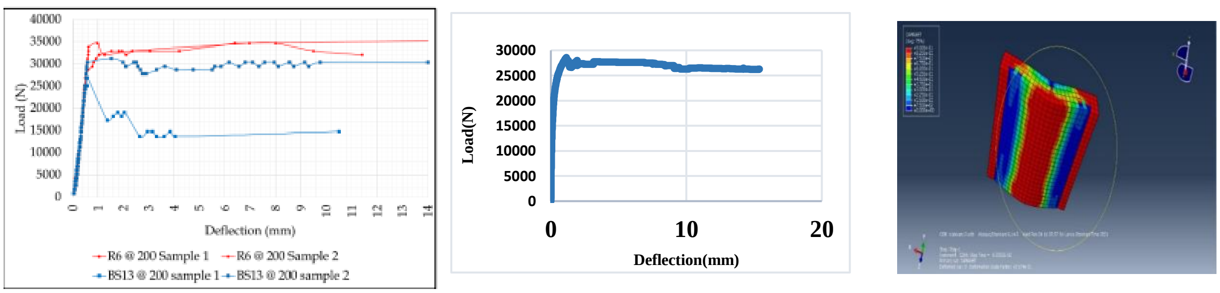
The comparison of model results with the experimental investigation [3] are shown in Figure 7, Figure 8, Figure 9, and Figure 10 considering the Load- deflection curves for different slab panels.

As shown in Figure 7 - Figure 10, the stress-strain graphs for FEM and experimental results for all slab types are well matching with each other, but FEM predictions show a slightly lower value than actual values. FEM predicts slab behaviour to be somewhat stiffer than actual slabs, which might be because a perfect bond was established between reinforcement and concrete interface in the modelling, while bond-slip could occur in the real section. Considering the crack pattern in Figure 7 (c) – Figure 10 (c), in all the slabs, the top surface was found to be crushed and the crack propagation in the soffit was along the line of the force applied. With the increase of the bamboo content number of crack and crack opening widths increased.



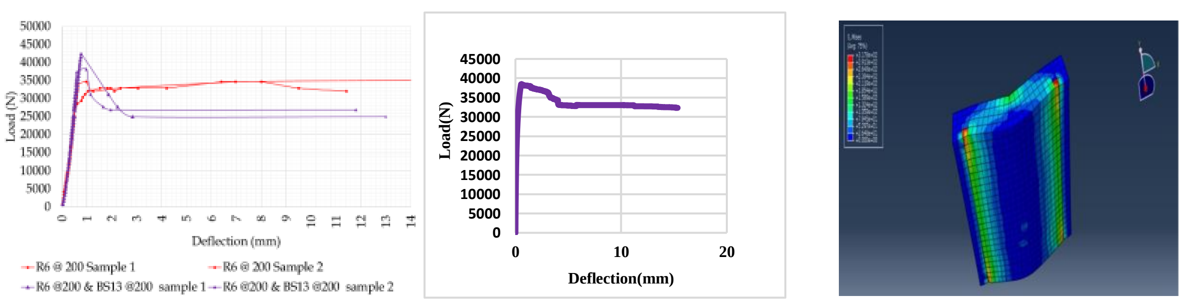
(a) (b) (c)

Figure 7. (a) Load-deflection curve of slab-1 in experimental [5], (b) Load-deflection curve of slab-1 in Model and (c) Crack pattern-slab 1



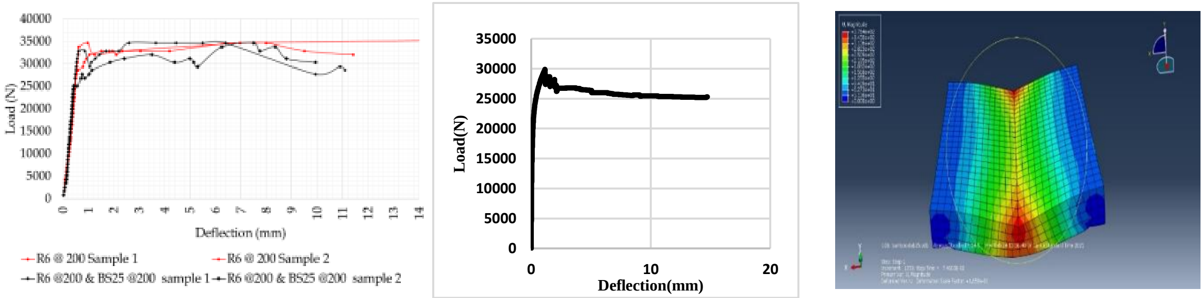
(a) (b) (c)

Figure 8. Figure 8 (a) Load-deflection curve of slab-2 in experimental [5], (b) Load-deflection curve of slab-2 in Model and (c)Crack pattern- slab 2



(a) (b) (c)

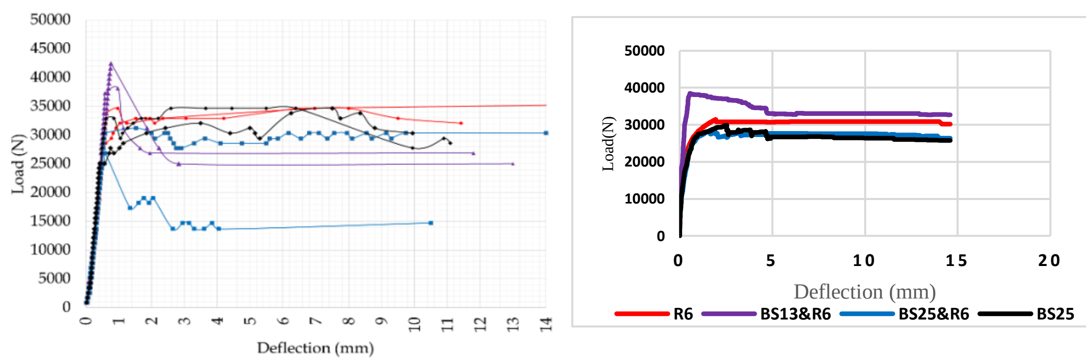
Figure 9. (a) Load-deflection curve of slab-3 in experimental [5], (b) Load-deflection curve of slab-3 in Model and (c) crack pattern-slab 3



(a) (b) (c)

Figure 10. (a) Load-deflection curve of slab-4 in experimental [5], (b) Load-deflection curve of slab-4 in Model and (c) Crack pattern- slab 4

Considering Figure 11, the numerical results and the experimental results, have shown a similar behaviour at smaller loads. Also, the measured failure load of all the slabs' experimental results is a little different than the failure load of numerical results. But both curves act as the same for some load increments. So, improvements must be made in crack modeling to predict the deflection accurately. The loading rate also affects the model's behaviour and leads to differentiating the results from that of the experiment. The behaviour of Bamboo may change with external factors. For this reason, the results of the investigation and the result of FEM may change.



(a) (b)

Figure 11. (a) Experimental Load-deflection curve – all slabs, (b) FEM Load-deflection curve of all slabs in ABAQUS

The experimental and FEM failure loads of each slab are shown in Table 6. The measured failure load of experimental results of the slabs showed a little higher value than the failure load of numerical results. This was due to the extra stiffness provided by the tension stiffing effect. The loading rate also affects the behavior of the model and it leads to different results from the experiment.

Table 6. Experimental and FEM results

Slabs	Failure load experiment (kN) [3]	Failure load FEM (kN)
Slab-1	32.96	31
Slab-2	28.15	29
Slab-3	39	38
Slab-4	28.98	30

Conclusion

Bamboo is identified as a suitable alternative material for concrete reinforcement. When Bamboo is used as a hybrid reinforcement element with Steel, the strength and flexural behaviors are respectable. On the other hand, compared with Concrete and Steel, Bamboo has a low density which helps to make lightweight concrete slab structures and eco-friendly structures. And using Bamboo with Steel as reinforcement will reduce the cost of the design. The experimental failure load and numerical failure load are comparable. The adopted modeling based on the Total Strain crack model implemented in ABAQUS FEA is capable and reliable for predicting a concrete slab's failure. When using the analysis control function in ABAQUS FEA, the load increment steps, and convergence criteria highly affect the modeling results. And concrete constitutive model parameters have to be considered in getting well-agreed results. The tensile strength of Concrete is one of the essential parameters in Finite element modeling. Finally, this study shows the well agreed results for experimental results from the modeled results from ABAQUS FEA. Also, the internal cracking behaviors can be analyzed in modeling than in experiments.

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