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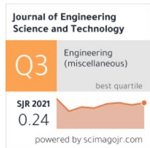

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NUMERICAL PARAMETRIC STUDY ON THE FLEXURAL CAPACITY OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH NON-METALLIC MATERIALS

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Abstract

A modified compression field theory and models developed with Response-2000 using the theory were applied to the prediction of the flexural capacity of reinforced concrete beams strengthened with the assistance of non-metallic material such as bamboo. Data were retrieved from earlier studies conducted in 2017 and two RC beams were used as specimens with one designed as the control beam (BC) while the other was strengthened through a near-surface mounted technique using four bamboo strips (BB). The study showed the accuracy of the models developed in predicting the responses of load-deflection up to the peak load, but underestimated figures were generally obtained from the predictions of beam ductility with an average of 34.41% difference. The models also provided conservative predictions of the flexural capacity for the beams with the ratios of 1.16 and 1.04 for BC and BB respectively. Moreover, the model developed was observed to be efficient in making quick and accurate predictions on the flexural strength based on a normalized mean square error (NMSE) of 0.006 and also has the ability to determine the conditions with the potential to cause the collapse of the reinforced concrete beams. Furthermore, the validated model was later used to study the impact of bamboo diameter, concrete compressive strength, and steel reinforcement ratio on strengthened beams behaviour.

Keywords: Bamboo reinforcement, Flexural capacity, Parametric study, Strengthened beam.

1. Introduction

Considerable focus has been placed on the strengthening of structural elements in previous decades [1] and existing reinforced concrete (RC) beams have been improved in terms of their flexural and shear capacities using different strengthening techniques [2, 3]. Recently, it has become quite common to use steel plates, steel reinforcement and fiber-reinforced polymer (FRP) to strengthen structures [2, 4] and steel reinforcing technique has been discovered to offer greater tensile strength and more ductility, therefore, several researchers have investigated its usage in improving RC beams in terms of their shear capacity. Moreover, steel bars have been used at the soffit to improve the flexural capacity of RC beams [2]. However, corrosion which is common with steel materials is an issue leading to weak bonding between the steel bar and concrete. Furthermore, the roles of steel plates in improving the shear and flexural capacities of RC beams have also been studied [5-7] but the main drawbacks include the materials' heavyweight, complexities in penalization, and steel corrosion. During the past three decades, considerable interest has been shown in studying RC beam strengthened using FRP to enhance the shear and flexural capacities [8-11] based on the high tensile strength relative to the weight of the FRP. It is also highly resistant to corrosion and hence preferred but the sudden rupture associated with this material [12] has led to more investigation on new materials to strengthen structures over the past decade [1].

The inadequacies of steel and FRP materials have compelled researchers to use other materials such as bamboo - a non-metallic material - for strengthening purposes. Bamboo offers the advantages of convenience, cost-effectiveness, and efficiency. It is possible to enhance the load-carrying capacity of RC beams compared to the control specimens by providing different percentages of bamboo fibers using the full wrapping technique around all four sides and bamboo sticks as the strengthening material [13, 14]. Moreover, Haryanto et al. [15] studied the impact of using the near-surface mounted (NSM) technique on the flexural strengthening of RC beams through the use of bamboo strips as the strengthening agent and a 41.7% increment was observed in the flexural capacity of the RC beam strengthened with bamboo strips while a 21.55% decline was recorded in its deflection ductility index. Hidayat et al. [16] investigated nonlinear finite element analysis to evaluate the improvement of the flexural strength of concrete beams through the use of bamboo and concluded that the load-carrying capacity of the specimens was improved due to the placement of bamboo plates. Additionally, the feasibility and benefits of using bamboo in masonry structures were studied through different tests by Xu et al. [17] and the technique was found to be effective, particularly when used in remote areas.

This study was conducted to continue the works of Haryanto et al. [15] by modeling RC beams strengthened with a non-metallic material such as bamboo in order to contribute to the understanding of the response and behaviour of such beams based on the bamboo diameter, concrete compressive strength, and steel reinforcement ratio. Comprehensive outcomes were obtained from experiments, but the outcomes were specific to the placement of strain gauges and LVDTs (Linear Variable Differential Transformers). Moreover, a huge cost and time were incurred in such experimentation with the outcomes specific to particular settings. A Modified Compression Field Theory (MCFT) was applied in a software known as Response-2000 and commonly referred to by its abbreviation R2K [18, 19]. This combination offers users the opportunity to fully comprehend and investigate the responses of beams and columns of any shape and material under the influence of moment, shear, and axial loads. Huang et al. [20] demonstrated the accurate simulation of the mean shear strain of specimens using R2K and this technique was also applied by Lam et al. [21] in modeling the force-deformation behaviour of cracked reinforced concrete with fiber elements. The results showed that all the specimens with different cross-sectional areas were predicted to have comparable moments of resistance. Furthermore, Metwally [22] gauged the efficiency as well as the validity of the R2K software in predicting the shear capacities of reinforced and pre-stressed concrete elements and found its prediction on failure shear to be characterized by an average observed-to-predicted shear ratio equalling 1.05 and a coefficient of variation equalling 12%. Suryanto et al. [23] also supported the accuracy of R2K in terms of its predictions of the load-deflection behaviour demonstrated by shear-critical concrete beams up to the peak load.

2. Description of Experimental Program

2.1. Geometric details

The analysis was established on the research obtained by Haryanto et al. [15] on the casting of two rectangular-section RC beams with normal aggregate concrete. The beams were made to have 150 mm height, 100 mm width, and 1000 mm length while the steel reinforcement had three plain steel bars each having 6 mm diameter and attached to the tensile zone of beams while two plain steel bars having 6 mm diameter were attached to the compression zone. It should be noted that there were no lugs or any deformation on the surface of the plain reinforcing bar and this means it does not have the ability to transfer bond forces through mechanical interlock. Meanwhile, the bond was alternatively transferred through the adhesion between the concrete and reinforcing bar before the occurrence of slip, and by wedging action of small particles which break free from the concrete after slippage [24].

Stirrups with 6 mm diameter were placed at a distance of 50 mm each other in the shear span of the beam to reinforce the beams in order to determine the flexural failure of both the control and the strengthened beams. Moreover, each beam was encased in a clear cover which is equal to 20 mm and the complete details of the tested beams and the designation of specimens for modeling are presented in Table 1. One of the beams was the control beam (BC) while the other was strengthened using four bamboo strips of 6 mm diameter (BB). Furthermore, the NSM technique was used to attach the strengthening materials along the beam's length. The details and illustrations of the RC beam specimens are provided in Fig. 1.

Table 1. Details of RC beams chosen for analysis.

Specimens	*L* (mm)	*h* (mm)	*b* (mm)	Longitudinal reinforcement		Stirrup	Bamboo
				Tension	Compression		
BC	1000	150	100	3P6	2P6	P6-50	-
BB	1000	150	100	3P6	2P6	P8-50	4ϕ6

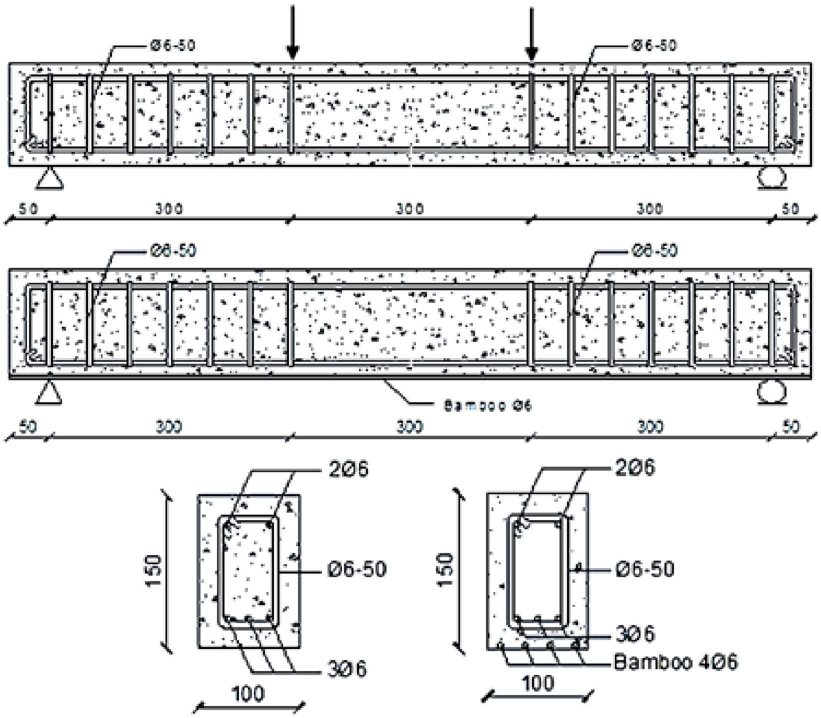


Fig. 1. Geometric features of the examined and modelled specimens of RC beams (unit: mm) [15].

2.2. Loading configuration and material properties

The specimens were tested using a four-point bending system with the same loading scheme and a Universal Testing Machine (UTM) was used to apply two monotonic concentrated loads on the beam specimen as shown in Fig. 2. Moreover, the steel spreader was produced with unused steel members to ensure strong rigidity and the beams were fitted with a dial gauge at mid-span point to obtain readings for the displacement. The value for the average concrete cylindrical compressive strength (f_c') was recorded to be 18.30 MPa on the 28th day after casting.

Furthermore, hot-rolled steel bars and stirrups were used for beam reinforcement in line with SNI 2052: 2014 [25] and the elastic modulus obtained for 6-mm-diameter plain bars was 159.900 GPa, yield strength was 338.75 MPa, and tensile strength was 499.40 MPa. Meanwhile, bamboo has been widely used in civil construction but only a few types are commonly marketed locally in Indonesia and an example is Petung bamboo [26] used in this study.

This bamboo type has some special attributes, and these include its wide stem, thick stem wall, and short internodes which ensures its durability and difficulty in getting curved. These, therefore, makes it an ultimate choice as a sustainable building material [27]. The average elastic modulus and tensile strength of 6-mm-diameter bamboo strips were 15.931 GPa and 666.67 MPa, respectively.

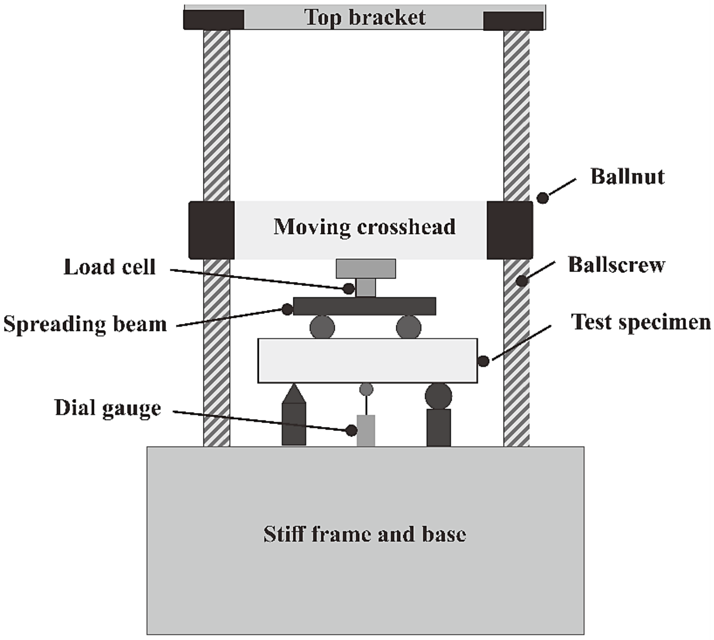


Fig. 2. Experimental setup.

3. Constitutive Laws of the Developed Models

3.1. Concrete

The non-linear characteristics of concrete subjected to compression and stress-strain association were considered in the models developed in R2K. A model was developed by Popovics [28] as expressed in Eqs. (1) to (3) and this was further slightly modified by Porasz [29]. Meanwhile, the stress versus strain curve for every concrete type is presented in Fig. 3.

$$f_c = -\left(\frac{\varepsilon_c}{\varepsilon_{co}}\right) f'_c \frac{n}{n-1+\left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^{nk}} \tag{1}$$

$$n = 0.8 + \frac{f'_c}{17} \tag{2}$$

$$k = \begin{cases} 1.0 & \text{if } {}^{\varepsilon_c}/_{\varepsilon_{co}} < 1.0 \\ 0.67 + \frac{f_p}{62} & \text{if } {}^{\varepsilon_c}/_{\varepsilon_{co}} > 1.0 \end{cases} \tag{3}$$

where f_c is compressive stress of concrete (MPa) at particular strain value ε_c , f'_c is compressive strength of concrete (MPa), ε_{co} is peak compressive strength strain, n is parameter for the curve fit, and k is factor of loss in post-peak ductility for high-strength concrete. Eq. (4) shows R2K used the Bentz model for the non-linear material properties of the concrete which was subjected to tension (f_t) [19].

$$f_t = 0.45\,(f'_c)^{0.4} \tag{4}$$

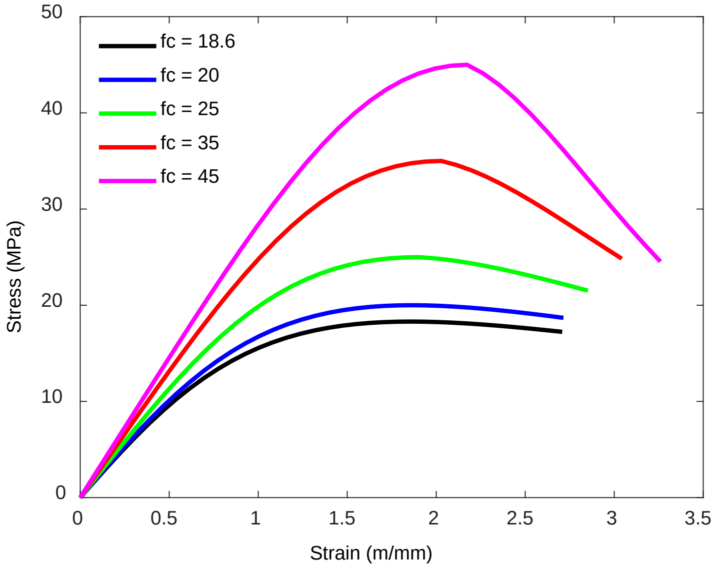


Fig. 3. Compression stress versus strain curve for concrete.

3.2. Steel reinforcement and bamboo strip

The steel reinforcement stress-strain response usually has three components which are (1) the initial linear-elastic response, (2) yield plateau, and (3) strain-hardening phase which is either linear or non-linear up to the rupture. The subsequent discussion on the hysteretic behaviour shows this monotonic stress-strain curve explains the backbone curve presented in models proposed by Seckin [30] or Menegotto and Pinto [31]. Moreover, the formula to compute the steel reinforcement stress, f_s, for both tension and compression is presented in Eq. 5 as follows.

$$f_s = \begin{cases} E_s \varepsilon_s & \text{for} \quad \varepsilon_s < \varepsilon_y \\ f_y & \text{for} \quad \varepsilon_y < \varepsilon_s \leq \varepsilon_{sh} \\ f_u + (f_y + f_u)\left(\frac{\varepsilon_u - \varepsilon_s}{\varepsilon_u - \varepsilon_{sh}}\right)^P & \text{for} \quad \varepsilon_{sh} < \varepsilon_s \leq \varepsilon_u \\ 0 & \text{for} \quad \varepsilon_u < \varepsilon_s \end{cases} \tag{5}$$

where ε_s denotes the strain ($\varepsilon_s = |\varepsilon_s|$), ε_y represents the yield strain, ε_{sh} is the initial strain when strain hardening commences, ε_u denotes the ultimate strain, E_s denotes the elastic modulus, f_y represents the yield strength, f_u is the ultimate strength, and P is the strain-hardening parameter. The phases of the strain-hardening process after the yield plateau can either be linear (trilinear, P = 1) or nonlinear (P = 4). A perfectly elastic stress-strain curve was generated with the trilinear option using bamboo strips as the strengthening materials and the curve generated for all types of steel reinforcement and the bamboo strip is presented in Fig. 4. Meanwhile, the strain hardening modulus, E_{sh} is presented as follows:

$$E_{sh} = \left(\frac{f_u - f_y}{\varepsilon_u - \varepsilon_{sh}}\right) \tag{6}$$

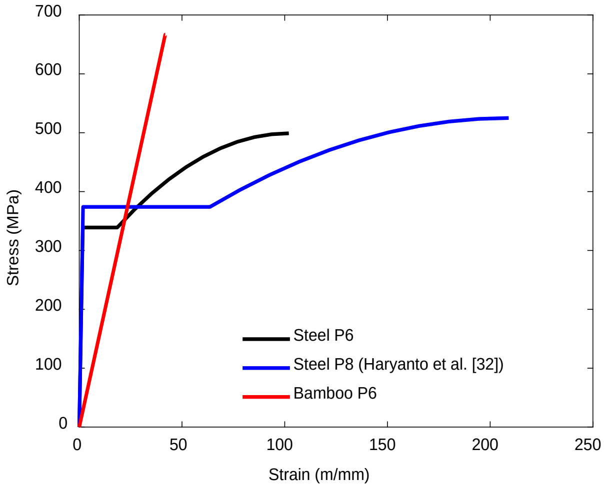
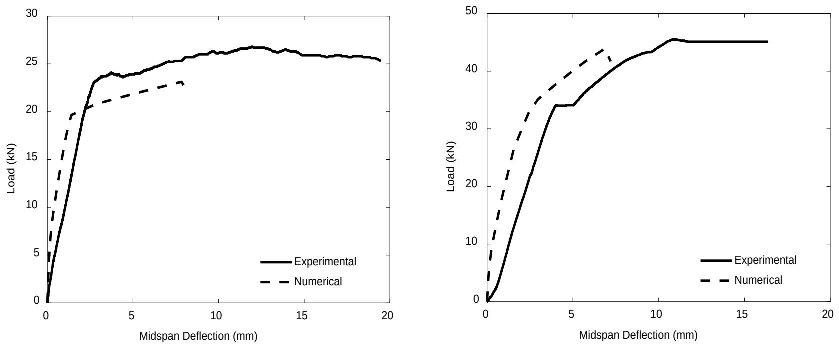


Fig. 4. Stress-strain curves for steel reinforcement and bamboo strip.

4. Model Validation

The models were checked for validity and accuracy by analyzing the two tested specimens and this was followed by the comparison of the data with R2K predictions. The observed and predicted values of the load versus mid-span deflection at each loading are presented in Fig. 5 while the values obtained from the experiment and those predicted for the ultimate attained load (P_u) are compared in Table 2. The ratio of the value observed from the experiment for P_u, denoted by $P_{u\text{-}Exp}$, to the predicted value, denoted by $P_{u\text{-}Num}$ is also presented Table 2.



(a) Beam BC. **(b) Beam BB.**

Fig. 5. Comparison of experimental and predicted load-deflection curves.

Table 2. Verification of results between experimental and numerical models.

Specimens	P_u (kN)		Ratio
	Experimental	Numerical	$P_{u\text{-}Exp}/P_{u\text{-}Num}$
BC	26.80	23.12	1.16
BB	45.50	43.90	1.04

Figure 5 shows the results of the experiment are comparable to the predicted responses and each beam was expected to initially show a linear elastic followed by a transitional nonlinear and finally an almost linear response and this continued up to the peak load. The compatibility is significant due to its impact on the intricacy of the actual response caused by the promulgation of existing cracks and the development of concrete cracks which further causes a decline in the overall rigidity of the beam.

However, the response in the vicinity of the peak was not favourable and there is a particularly high probability of underestimated predictions for the ductility of the beams. It is possible to use several statistical performance measures to compare the model predictions and observations values [33] and these include the normalized mean square error (NMSE) adopted in this study. The NMSE value of 0.006 obtained showed the state of affairs was tolerable when the prediction of flexural capacity as required from the design point of view is considered.

The model developed is applicable at this stage to determine the impact of bamboo diameter, concrete compressive strength, and steel reinforcement ratio on the performance of strengthened RC beams through a design-oriented parametric study.

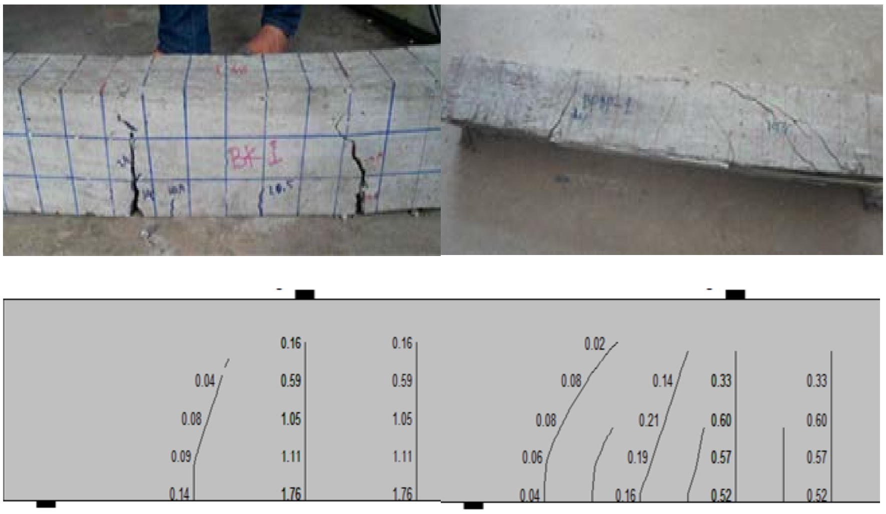
The ability of a structure, section, or material to withstand inelastic deformation before collapse without losing its strength or resistance to a great extent is known as ductility. This structural characteristic is quite favourable due to its ability to provide failure warnings in the form of an increase in deflection and redistribution of stress.

Therefore, ductility index (μ) was also examined in this study, and the results are presented and expressed as the ratio of the deflection at ultimate load with δ_u representing the mid-span deflection at ultimate load to the yield load with the δ_y being the midspan deflection at yield load in Table 3. The BB specimen was observed to be reduced by 48.37% in the experimental test result and 15.63% in the numerical result in comparison with the control beam (BC). The reduction observed in the strengthened beams was most likely due to the increase in the total reinforcement ratio ρ_{tot}. Moreover, the predicted ductility of the beams is generally underestimated with an average of 34.41% disparity.

Table 3. Ductility of the experimental and numerical models

Designation	Experimental			Numerical		
	δ_y (mm)	δ_u (mm)	μ	δ_y (mm)	δ_u (mm)	μ
BC	2.17	11.93	5.50	2.86	7.83	2.74
BB	3.90	11.07	2.84	2.97	6.86	2.31

The modes of failure observed for all the beams are presented in Fig. 6 and the pattern of crack was found to be similar in both the experiment and numerical model. At first, there was a fine flexural crack at the beam's midspan due to the increment in the external load and more cracks were observed at the neutral axis and beyond with a notable increase in the beam's deflection. However, the strengthened beam specimen had narrower and finer cracks in comparison with the control specimen. These findings are associated with the higher stiffness observed in the strengthened beam specimens.



(a) Experimental [15] versus numerical of beam BC.

(b) Experimental [15] versus numerical of beam BB.

Fig. 6. The failure mode of the beams.

5. Parametric Study

5.1. Impact of the diameter of the bamboo

Four models were used to determine the changes in the response of the reinforced beams with the diameter of the non-metallic material, bamboo, adjusted. One beam, used as the control beam, was not strengthened with bamboo strips while the rest of the beams were strengthened using four bamboo strips with different diameters including 6, 8, and 10 mm to determine the impact of a diameter change on the beams' behaviour or response. All the modelled beams were attributed with a 30 MPa concrete compressive strength while the designation for each analysed model as well as the summary and comparison of the predicted value of ultimate attained load (P_u) and the related value of mid-span deflection (δ_u) are presented in Table 4. Meanwhile, a graphical representation of the response curves showing load and mid-span deflection relationship predicted for all models is displayed in Fig. 7.

Table 4 and Fig. 6 show the load-carrying capacity and flexural strength of the beams strengthened with bamboo strips using the NSM technique were higher than those of the control beams (PS-B01) as predicted by the models. This specifically means the bamboo-strengthened beam at 6 mm diameter was significantly better with 86.25% compared to the control specimen based on the load-carrying capacity (P_u). Moreover, increases in the flexural strength up to 92.49 and 109.77% were observed for the beams strengthened by bamboo strips having 8- and 10-mm diameter respectively as shown in Table 4. This proves the direct relationship between the diameter of the bamboo strip and the percentage increase in flexural capacity with a greater diameter found to be causing augmentation in the flexural capacity due to the fact that the increase in the diameter produces an increase in the bamboo strips' tensile force, thereby, leading to a higher flexural capacity of the strengthened beam.

Table 4. Impact of different values of bamboo diameter.

Designation	Bamboo diameter (mm)	P_u (kN)	Percentage increase in P_u over the control beam	δ_u (mm)
PS-B01	-	23.162	-	4.463
PS-B02	6	43.140	86.25	7.685
PS-B03	8	44.584	92.49	5.119
PS-B04	10	48.588	109.77	4.433

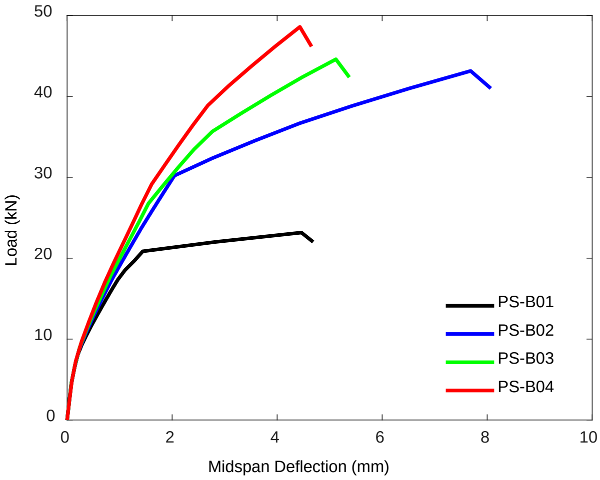


Fig. 7. Impact of the dimension of bamboo over beams' performance.

Table 4 and Fig. 7 also show the mid-span deflection (δ_u) of P_u is comparable for all the beam models. According to Bentz [19], the curvature and shear strain attached to each level of the load was interpolated from the interaction diagram and later integrated into the moment-area method to determine the relationship between the load and deflection including the post-peak load point. The use of this technique enhanced the strength of the beam models while an adequate level of ductility was maintained in the strengthened beams at the same time, and this proves the effectiveness of this method as an alternative to strengthen the RC beams. It is also important to note that the use of 6 mm diameter of bamboo led to the beam model having a total reinforcement ratio ρ_{tot} of 1.488% and keep it as an under-reinforced section. Meanwhile, the use of 8- and 10-mm diameter caused the beam models to have 2.106 and 2.901%, respectively and they were categorized into an over-reinforced section.

5.2. Impact of compressive strength of concrete

The effect of concrete compressive strength (f'_c) on strengthened RC beams' performance was evaluated in this study. This involved the formulation of six models with three used as the control beams while the others were strengthened using 6-mm-diameter NSM bamboo strips. The concrete compressive strengths of the modelled beams were 25, 35, and 45 MPa, respectively. The models developed had 0.701% steel reinforcement ratio. Table 5 shows the beam designation for all the models while Fig. 8 indicates the prediction regarding the curves produced when the load is plotted against the mid-span displacement for each model. Moreover, the values predicted for the ultimate attained load (P_u) were compared with those associated with mid-span deflection (δ_u) in Table 5.

The values shown in Table 5 and Fig. 8 indicate the insignificant impact of the concrete compressive strength on the performance delivered by the control beam specimen and this mainly associated with the significant effect of the reinforcement steel strength on the flexural strength as indicated by the under-reinforced beam specimens [34]. Meanwhile, high effect of the compressive strength of concrete was observed on the response and load-carrying capacity of the strengthened RC beams.

Table 5. Impact of varying the compressive strength of concrete.

Designation	f'_c (MPa)	P_u (kN)	Percentage increase in P_u over control beam	δ_u (mm)
PS-B05	25	22.792	-	4.491
PS-B06	35	23.842	-	4.341
PS-B07	45	22.850	-	3.123
PS-B08	25	40.776	78.90	7.132
PS-B09	35	44.296	85.79	7.628
PS-B10	45	46.030	101.44	7.635

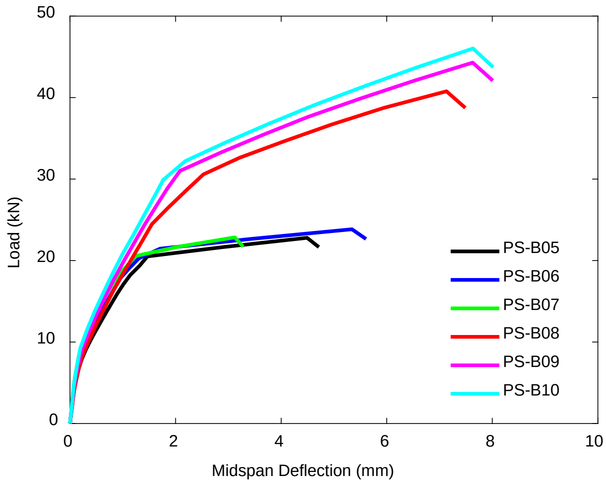


Fig. 8. Impact of compressive strength over beams' performance.

A higher load-carrying capacity was investigated in the strengthened beams in comparison with the control specimens as observed with 78.90% higher for specimen PS-B08 (f'_c 25 MPa), 85.79% for PS-B09 (f'_c 35 MPa), and 101.44% for specimen PS-B10 (f'_c 45 MPa). This was found to be due to the increment in the value of f'_c which led to the increased concrete tensile strength (f_t) and ultimately affected the maximum local bond stress as well as the bond-slip behaviour shown by the strengthening material (bamboo strips in this case) and concrete surfaces they were attached.

5.3. Impact of the ratio of steel reinforcement

This research also explored the effect of steel reinforcement ratio (ρ) on the performance of strengthened RC beams. This involved the development of six models with three used as the control beams while the remaining were strengthened using 6-mm-diameter NSM bamboo strips. The models involved the use of steel flexural bars of three different sizes which are 3P6-, 2P8-, and 3P8-mm bars having ρ values of 0.701, 0.838, and 1.257% respectively while the concrete compressive strength was 20 MPa. Table 6 shows the beam designation and the outcomes for all the models developed while the predictions of the curves obtained when the load is plotted against mid-span deflection for each model are shown and compared in Fig. 9.

Table 6. Impact of different values of the ratio of steel reinforcement.

Designation	ρ (%)	P_u (kN)	Percentage increase in P_u over control beam	δ_u (mm)
PS-B11	0.701	23.486	-	7.645
PS-B12	0.838	26.648	-	2.418
PS-B13	1.257	39.526	-	5.347
PS-B14	0.701	39.374	67.65	7.264
PS-B15	0.838	43.923	64.86	7.099
PS-B16	1.257	56.762	43.61	9.398

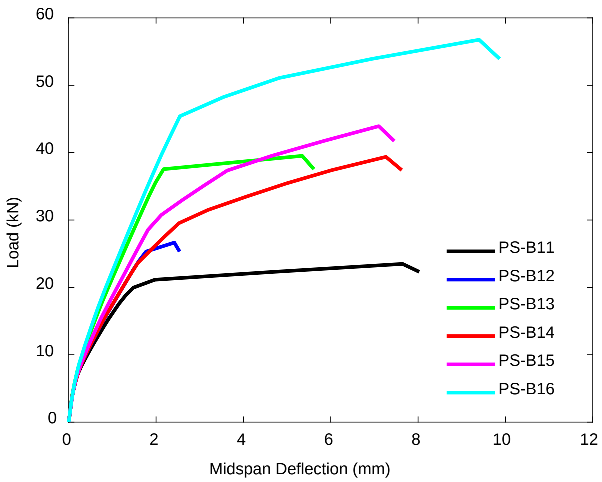


Fig. 9. Impact of steel reinforcement ratio on the beams' performance

Table 6 and Fig. 9 show the under-reinforced beams with a reinforcement ratio of 0.701% exhibited a higher percentage improve in the value of ultimate load-carrying capacity with 67.65% in comparison with the control while over-strengthened beam specimens with greater reinforcement ratios of 0.838 and 1.257% had a lower increase in percentage at 64.86 and 43.61%, respectively. Therefore, it was observed that moving from under-reinforcement to over-reinforcement, a higher steel reinforcement ratio caused a greater reduction in the percentage increment of the flexural strength for the beam specimens strengthened with NSM bamboo strips. This implies the strengthening of RC beams with moderate values of the flexural steel reinforcement ratio proves the effectiveness of NSM bamboo strips as a strengthening material. This concept has also been verified by other researchers using different types of strengthening materials [35-37] and El-Emam et al. [37] argued it was possibly due to the axial stiffness ratio. This ratio (E_bA_b/E_sA_s) was observed in this study to be the relation between bamboo axial stiffness (E_bA_b) and the tensile reinforcing steel axial stiffness (E_sA_s) and E_b and A_b are the elastic modulus and cross-section area of the bamboo, respectively while E_s and A_s are the tensile reinforcing steel bar elastic modulus and cross-section area, respectively.

6. Conclusions

This study aimed to examine the models developed to predict the flexural capacity of RC beams strengthened with bamboo strips through the use of the NSM technique and the predictions were checked for accuracy. Moreover, the models were validated by observing the response of two beam specimens and drawing a comparison between the predicted and observed values. The study first used the NSM technique to strengthen the RC beams with bamboo and later investigated the impact of the dimension of the installed bamboo, concrete compressive strength, and steel reinforcement ratio on the flexural capacity of the strengthened beams. For this purpose, the models were developed and validated with the help of a design-oriented parametric study, and the following conclusions were drawn.

- The models practically demonstrated the flexural behaviour depicted by both the control and specimens strengthened with bamboo strips through the use of the NSM technique.
- The strengthened beams were found to have a higher load flexural capacity.
- A direct positive relation was discovered between the size in diameter of bamboo strips and the flexural capacity of the beams.
- The performance shown by the strengthened specimens of RC beams was only slightly altered as a consequence of changes in concrete compressive strength. The figures obtained showed the load-carrying capacity of strengthened beam specimens was higher than the value for the control specimens. Moreover, the specimens with concrete compressive strengths at 25, 35, and 45 MPa showed increments in the load-carrying capacity of 78.90, 85.79, and 101.44%, respectively.
- The beams strengthened with NSM bamboo strips showed a reduction in flexural strength at higher values of steel reinforcement ratio and this implies improving the strength of RC beams using moderate values of the flexural steel reinforcement ratio shows the effectiveness of the technique.
- It is, therefore, possible to improve the flexural capacity of RC beams by strengthening the beams with bamboo strips using the NSM technique.

Nomenclatures

E_s	Elastic modulus, MPa
E_{sh}	Strain hardening modulus, MPa
f'_c	Compressive strength of concrete, MPa

f_c	Compressive stress of concrete at particular strain value, MPa
f_s	Steel reinforcement stress, MPa
f_t	Tensile strength, MPa
f_u	Ultimate strength, MPa
f_y	Yield strength, MPa
k	Factor of loss in post-peak ductility for high-strength concrete
n	Curve fit parameter
P	Strain-hardening modulus
P_u	Ultimate load, kN
$P_{u\text{-}Exp}$	Experimental ultimate load, kN
$P_{u\text{-}Num}$	Numerical ultimate load, kN

Greek Symbols

δ_u	Mid-span deflection at ultimate load, mm
δ_y	Mid-span deflection at yield load, mm
μ	Ductility index
p	Steel reinforcement ratio, %
p_{tot}	Total reinforcement ratio, %
ε_c	Particular strain value
ε_{co}	Strain at peak compressive strength
ε_s	Strain
ε_{sh}	Initial strain when strain hardening commences
ε_u	Ultimate strain
ε_y	Yield strain

Abbreviations

FRP	Fiber Reinforced Polymer
MCFT	Modified Compression Field Theory
LVDT	Linear Variable Differential Transformer
MCFT	Modified Compression Field Theory
NMSE	Normalized Mean Square Error
NSM	Near Surface Mounted
R2K	Response-2000
RC	Reinforced Concrete
UTM	Universal Testing Machine

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